Gemini Principles-Based Digital Twin Maturity Model for Asset Management

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Abstract: Various maturity models have been developed for understanding the diffusion and implementation of new technologies/approaches. However, we find that existing maturity models fail to understand the implementation of emerging digital twin technique comprehensively and quantitatively. This research aims to develop an innovative maturity model for measuring digital twin maturity for asset management. This model is established based on Gemini Principles to form a systematic view of digital twin development and implementation. Within this maturity model, three main dimensions consisting of nine sub-dimensions have been defined firstly, which were further articulated by 27 rubrics. Then, a questionnaire survey with 40 experts involved is designed and conducted to examine these rubrics. This model is finally illustrated and validated by two case studies in Shanghai and Cambridge. The results show that the digital twin maturity model is effective to qualitatively evaluate and compare the maturity of digital twin implementation at the project level. It can also initiate the roadmap for improving the performance of digital twin supported asset management.

Keywords: digital twin; maturity model; asset management; Gemini Principles

1. Introduction

Computerisation and digitisation are emerging to have a wide impact on the way the lifecycle of physical/engineering assets is managed [1,2]. For instance, it is predicted that artificial intelligence (AI) could add 10% to the UK economy by 2030 [1]. In addition, improved data sharing could result in lower consumer bills, reduced impact on the natural environment, and realise smart asset management [1]. A number of technologies have matured and are ready to extend to industrial applications, such as Building Information Model (BIM) at the operational and maintenance (O&M) phase (i.e., as-is BIM) [3–6]. However, data need to be stored and shared safely and securely, and technologies should be designed to ensure security and efficiency [1].

A digital twin, as a dynamic representation of an asset that mimics its real-world behaviours, can be a promising solution to manage, plan, predict, and demonstrate assets safely and efficiently [1,7]. The digital twin has been developed for decades and is now gaining popularity in the architecture, engineering, construction (AEC), and facility management (FM) sector, and it will be used by half of large industrial companies by 2021 [8]. For instance, NASA adopted the digital twin to run complex simulations of spacecraft [9]. Motawa and Almarshad proposed a Case-Based Reasoning (CBR)-integrated BIM system for building maintenance to improve the efficiency of decision making and communication among different stakeholders [10]. The restoration team of the Sydney Opera House
also designed a unified central data repository integrating different resources to support effective O&M management [11]. Although the implementation of digital twin is increasingly growing, it is lacking in a clear-defined and well-organised model to evaluate the stages of implementation and further initiate roadmaps for future development. Without such a comprehensive model or guidance, they are susceptible to omitting some possible improvement and several limitations.

In order to support such increasingly popular implementation of digital twin and fill the gap, the maturity models have been proposed for assessing and improving the performance of digital twin. For instance, the capability maturity model integration (CMMI) is developed as a process improvement approach with five maturity levels [12]. The control objects for the information and related technology (COBIT) maturity model are developed as an IT governance tool used to measure the management processes development [13]. Some maturity measurement tools have also been designed for BIM specifically [14], such as BIM Proficiency Index [15] and BIM Maturity Matrix [16]. However, these tools only focus on limited specific aspects, e.g., technology and process, etc. while lacking strong theory-supported evidences [17,18]. Furthermore, most tools are designed for evaluating BIM utilisation rather than digital twin within a single organisation and cannot stimulate the improvement in the future [19].

This research aims to fill this gap through developing a digital twin maturity model in a systematic and quantitative manner. It firstly reviewed the digital twin principles and past efforts in maturity assessment. Drawing on the literature review, the digital twin maturity model for asset management has been developed, which consists of three main dimensions, nine sub-dimensions, and 27 rubrics. A questionnaire survey was further designed and conducted to examine these rubrics, which attracts 40 valid responses from experts in asset management. The model was finally illustrated and validated by two case studies in Shanghai and Cambridge.

The structure of the paper is organised as follows. The definitions, principles, and applications of digital twin are introduced in Section 2; the research methodology is designed in Section 3; Section 4 will develop the digital twin maturity model for asset management; case studies will be introduced in Section 5; and the discussion and conclusions are in Section 6.

2. Literature Review
2.1. Digital Twin for Asset Management

The concept of digital twin was firstly proposed in 2002 and defined as a virtual representation of physical products. Then, it was further clarified as “realistic digital representations of physical things. They unlock value by enabling improved insights that support better decisions, leading to better outcomes in the physical world” [20]. Through fusing with a broader range of sources of data and techniques of data analytics, digital twin is able to learn and update from past patterns, and it can represent and predict the current and future conditions of physical counterparts correspondingly and timely [1,3]. The digital twin usually consists of five layers, including a data acquisition layer, transmission layer, digital modelling layer, data/model integration layer, and application layer [21]. Although the building digital twin is closely related to BIM, the concept of digital twin is not limited to BIM modelling, which is a broader concept in terms of data richness and interoperability. BIM modelling is one of the modelling approaches and datasets for digital twin in the digital modelling layer, and it can be further integrated into heterogeneous digital products and asset data to form the semantically-rich integrated model, i.e., the digital twin [16].
Attentions has been increasingly drawn to the development and use of digital twin in the management of construction projects across phases and scales, such as design change management of infrastructures [22], operation and maintenance of campus buildings [23], etc. As the complexity of building and infrastructure assets increases, the implementation of digital twin in asset management has also been becoming popular (Table 1). For instance, Khaja et al. developed a digital prototype based on Dynamo BIM for computer-aided facility management, which was able to automatically transfer information between BIM models and FM systems [24]. Xia et al. developed a digital prototype based on BIM integrating information from FM systems, closed-circuit television (CCTV), sensors, and mobiles [25]. Lu et al. developed a digital twin-enabled anomaly detection system for asset monitoring in daily O&M management [26].

Table 1. Selected cases of digital twin-supported asset management.

| Selected Cases | Case Objectives | Developed Approaches | Reference |
|---------------|-----------------|----------------------|-----------|
| The Kerr Hall East Building, Ryerson University | To automate information transfer between BIM models and FM systems for multiple FM purposes, including space management, occupancy tracking, work order tracking, inspection recording, and report management. | A digital twin prototype based on Dynamo BIM for computer-aided facility management. | [24] |
| Shanghai Tower | To improve the efficiency of O&M information management and optimise the performance of equipment, e.g., energy consumption. | A digital prototype based on BIM integrated with FM systems, CCTV, sensors, and mobiles. | [25] |
| University of British Columbia Campus | To understand the potential and the challenges of transitioning from a paper-based to a model-based approach in handover and operations. | A digital twin supported framework to characterise the alignment between organisational constructs, available technology, project artifacts, and owner requirements. | [28] |
| Manchester Town Hall Complex | To document issues involved in the adoption of BIM in FM and identify the enablers and barriers to BIM implementation in FM. | A BIM-supported map for reactive maintenance process. | [29] |
| Sydney Opera House | To demonstrate significant benefits in digitising design documentation and using standardised BIM to support FM. | An Industry Foundation Classes (IFC) BIM-based digital platform for asset management. | [11] |
| USC School of Cinematic Arts | To demonstrate the importance of BIM for FM and the need for integration and user interfaces for effective decision making. | A BIM-supported digital facility management system. | [30] |
| Construction Management Building, Auburn University | To link information needed by facility managers with BIM or digital twin model for future facility management. | A newly defined digital facility model based on Autodesk Revit and integrating information needed for facility management. | [31] |
| Anonymous Campus Building | To deliver rich information from design and constructing phases to facility management and update such information for planning maintenance activities based on BIM. | A BIM-supported digital system for planning maintenance activities. | [32] |
| Institute for Manufacturing (IfM) Building, West Cambridge | To develop a digital twin-enabled anomaly detection system for asset monitoring in daily O&M management. | A digital twin prototype based on Forge and AI techniques for facility monitoring and management. | [26] |
Based on the development of digital twin and its uses, and aiming to create an ecosystem of connected digital twins for greater value, the Gemini Principles have been proposed by the Centre for Digital Britain (CDBB) for the national digital twin (NDT) across scales. The NDT will become a national resource for improving the performance, quality of service and value delivered by assets, processes, and systems in the built environment [20,27] not only in the UK but also around the world. Thus, the Gemini Principles will set strong founding principles to guide the development of NDT and to bring alignment across the built environment, which also provides a good template for the maturity assessment principles [20].

The Gemini Principles are organised under three overarching headings: purpose, trust, and function (Table 2). The ‘purpose’ indicates that digital twin must have clear purpose; the ‘trust’ indicates that digital twin must be trustworthy; and the ‘function’ requires that digital twin must function effectively [20]. These three headings are further demonstrated by nine principles, defining the state-of-the-art requirements for the development and use of digital twin.

| Headings | Principles | Statements                                                                 |
|----------|------------|-----------------------------------------------------------------------------|
| Purpose  | Public good| The digital twin must be used to deliver genuine public good in perpetuity  |
|          | Value creation| The digital twin must facilitate value creation and performance improvement |
|          | Insight   | The digital twin must provide additional insight into the built environment or surroundings |
|          | Security  | The digital twin must enable security and be secure itself                  |
| Trust    | Openness  | The digital twin should be open (e.g., open data schema implemented)        |
|          | Quality   | The digital twin must be built on data of an appropriate quality            |
|          | Federation| The digital twin must be based on the secure interoperability of data       |
| Function | Curation  | The digital twin must be clearly owned, governed and regulated              |
|          | Evolution | The digital twin must be able to adapt, develop, and extend as technology advances |

2.2. Previous Efforts in Maturity Models

Although the implementation of digital twin is growing, the diffusion, development, and maturation of this emerging knowledge domain have yet to be explicated [33]. Some past efforts have been made related to the digital twin maturity in industry. For example, Smart Energy International [34] discussed the evolution of digital twin and briefly classified it into six stages, including reporting, analysing, predicting, integrating, prescribing, and autonomous decisioning. However, there is no available clearly defined maturity model for digital twin implementations in current markets.

Since BIM is usually used in the digital modelling layer of digital twin, this section would mainly focus on studying the advantages and limitations of existing BIM maturity models with the basis of digital twin principles, which would be the fundamental references for digital twin maturity tools development. Beginning with the pioneering efforts of BIM maturity model in 2007 [35], various tools have been developed and aimed at evaluating BIM performance in the AEC/FM industry. This study evaluated eight commonly used BIM maturity measurement tools based on the Gemini Principles (Appendix A Table A1).

From the purpose aspect, the scope and value creation of a project/organisation using BIM are significant and foremost. Clear insights, which allow the continuous improvement according to the attributes and demands of users, are only considered completely in a few tools. For instance, Pennsylvania State University published a BIM assessment profile in a guideline that supervised facility owners in the O&M phase. In order to evaluate the BIM maturity for facility owners, this assessment profile is composed of 6 areas, 20 measures, and 5 maturity levels [36]. This BIM Assessment Profile established BIM goals and objectives, which would help provide a direction such as reducing operational or lifecycle costs [36]. Through following the tools and guidelines, facility owners can determine the BIM maturity levels of their projects and figure out approaches to further
improve BIM implementations. However, this tool is specially designed for facility owners and lacks quantification evaluation.

From the trust aspect, the quality, openness, and security of a system are the basic guarantee of a data-driven project. The Virtual Design and Construction Scorecard is an assessment methodology including 4 Areas, 10 Divisions, and 56 Measures, which is considered to be adaptive, quantifiable, holistic, and practical [37]. However, it did not set clear requirements related to trust and information aspects. BIM Quick Scan includes information structure and information flow in its evaluation design, but it missed the security and openness issues. As shown in Table A1, this aspect is ignored by the majority of measurement tools.

From the function aspect, it is the foundation of an asset management project, including management, technology, and process. Many measurement tools fully considered this aspect (Table A1). However, due to the lack of established standards/theory, various classification structures of current tools were only limited to this aspect. For example, BIM Maturity Matrix followed their own classification method and was defined as three BIM fields, namely technology, process, and policy [19].

In general, previous studies have made great efforts to develop maturity measurement tools, including the creation of measurement frameworks, determination of divisions and sub-divisions, and design of evaluation approaches. However, it is still lacking a comprehensive maturity model specified for asset management with strong theory and visualisation supported [1,2,4]. A new maturity model is needed to fill the gap of digital twin implementations in asset management. Hence, a digital twin maturity model for asset management is thus proposed in this study. The Gemini Principles are adopted in this study to provide a foundation that describes and explains the basic framework of the proposed model in a more systematic and theoretical grounded way. Then, a visualised rubric-based evaluation representation is provided to enhance this novel model using a quantitative method.

3. Research Methodology

This research consists of three stages (Figure 1). In the first stage, the comprehensive literature review has been conducted to identify and examine what kinds of maturity models used in the previous research and practice. The outcomes revealed the necessity of developing a new maturity model to identifying and examining for asset management in a systematic and quantitative manner.

Figure 1. Research design and approach in this study.
The second stage is to develop the digital twin maturity model for asset management, including main dimensions and assessment rubrics for each dimension. Three main dimensions of the proposed model were developed based on the Gemini Principles. With the foundation of digital twin principles provided by CDBB, the assessment rubrics of each dimension were selected through analysing limitations and advantages of eight practical cases and comprehensive literature review. Eight typical cases were selected to provide key references (both in advantages and limitations) of asset management in practice (Table 1). A comprehensive literature review was also conducted in this stage and provided evidences of rubrics selection from research aspects. Thus, this study was performed for both industry and the academic community in the delivery of digital twin for improving the reliabilities and intelligence of asset management.

Then, the assessment rubrics of each dimension were further confirmed and verified according to the questionnaire survey. The online questionnaire survey of this study was conducted via a survey application. A wide range of professionals (Table 3) who have rich experience and knowledge in asset management, building O&M, facility management, and BIM were invited to collect data about their understanding of digital twin implementations. In this survey, the assessment rubrics were identified using a five-point Likert scale where 1 represents Not important and 5 represents Very important. This questionnaire was sent out to the total number of 100 experts. Forty-one responses were collected after three weeks, and the response rate was 41%. Among these responses, one response was incomplete and omitted. The 40 valid responses were analysed in this study.

Table 3. Summary of the valid survey respondents.

| Parameter                        | Value                  | Frequency | Percentage (%) |
|----------------------------------|------------------------|-----------|----------------|
| Year of experience               | Less than 2 years      | 4         | 10.0           |
|                                  | 2–4 years              | 18        | 45.0           |
|                                  | 5–7 years              | 16        | 40.0           |
|                                  | More than 8 years      | 2         | 5.0            |
| Profiles of respondent organisations | University and professional bodies | 6 | 15.0 |
|                                  | Industrial Institutions | 5 | 12.5 |
|                                  | Government departments | 2 | 5.0 |
|                                  | Manufacturers and suppliers | 3 | 7.5 |
|                                  | Contractors            | 4         | 10.0           |
|                                  | Estate and facility managers | 6 | 15.0 |
|                                  | Engineers              | 5         | 12.5           |
|                                  | Architects             | 3         | 7.5            |
|                                  | Developer and clients  | 6         | 15.0           |
| Knowledge of computerised O&M activities | Yes                  | 40        | 100            |
|                                  | No                     | 0         | 0              |

This collective consideration of three perspectives (i.e., purpose, trust, and function) is helpful to understand the implementation of digital twin for asset management projects within a comprehensive context.

Lastly, based on the results of the previous analyses, the proposed model was verified based on two real cases (i.e., Shanghai Tower and the CDBB West Cambridge digital twin pilot) using the questionnaire method. Opportunities and results have been discussed to accelerate digital twin implementation.
4. Developing the Digital Twin Maturity Model

Assessment rubric is an effective tool used in the process of assessing works, which usually includes evaluative criteria, quality definitions for those criteria at particular levels, and a scoring strategy as three essential features [38]. In this study, assessment rubrics are presented in a table format and used to provide quantitative evidence for each main dimension (i.e., purpose, trust, and function). The assessment rubrics are a core part of the digital twin maturity model to make it computable. They include a set of verified criteria with detailed descriptions, as shown in Table A2. In this study, these assessment rubrics were selected by examining eight practical cases and a comprehensive literature review firstly (Table A2). Then, the resulting rubrics were evaluated by questionnaire surveys. According to the responses provided on the five-point Likert scales for the importance of each rubric, nine assessment rubrics of each main dimension have been further confirmed as the final set (Table A2).

For the purpose dimension, nine assessment rubrics are used to evaluate whether the digital twin project can deliver genuine public good (such as O7: role and responsibility and O9: communication strategies), facilitate value creation and improve the overall performances (such as O6: digital twin value creation), and provide additional insights and further improvement into the surroundings or within the organisations (such as O1: project target and O3: plans). For the trust dimension, nine assessment rubrics are used to evaluate whether the digital twin project can enable security (such as T2: information security assurance and T3: formal standards and protocols), support open (such as T5: open data schema implemented and T6: integrity, accuracy, and openness of collected information/data resources), and be built on data of an appropriate quality (such as T8: continuous quality assurance mechanism/rules). For the dimension function, nine assessment rubrics are used to evaluate whether the digital twin project can secure interoperability of data (such as F1: data/model updating), enable the digital twin can be regulated (such as F5: asset integration), and enable the digital twin adapting, developing and extending as technology advances (such as F7: digital model/data generating and updating process/technology).

The format of the digital twin maturity model is presented in a triaxial coordinate system with an evaluation form, as shown in Figure 2. Using the main dimension for methodology as an example, the digital twin implementation of Projects 1 and 2 could be scored using the rubric described in Table A2 and compared using the evaluation calculation form in Table 4. The main evaluation parameters are listed as following:

![Figure 2. The presentation of the developed maturity model.](image-url)
Table 4. The designed evaluation form of the maturity model.

| Purpose | Assessment Rubrics | Function | Assessment Rubrics | Trust | Assessment Rubrics |
|---------|--------------------|----------|--------------------|-------|--------------------|
| O₁      | F₁                 |          |                    | T₁    |                    |
| O₂      | F₂                 |          |                    | T₂    |                    |
| O₃      | F₃                 |          |                    | T₃    |                    |
| O₄      | F₄                 |          |                    | T₄    |                    |
| O₅      | F₅                 |          |                    | T₅    |                    |
| O₆      | F₆                 |          |                    | T₆    |                    |
| O₇      | F₇                 |          |                    | T₇    |                    |
| O₈      | F₈                 |          |                    | T₈    |                    |
| O₉      | F₉                 |          |                    | T₉    |                    |

AO = \sum_1^9 O_i \quad \text{AF} = \sum_1^9 F_i \quad \text{AT} = \sum_1^9 T_i

s = \left(\frac{1}{3}\right) \times (AO + AF + AT)

S = \sqrt{P \times \left(P - \left(\frac{1}{3}\right) \times \sqrt{AO^2 + AF^2}\right) \times \left(P - \left(\frac{1}{3}\right) \times \sqrt{AT^2 + AF^2}\right) \times \left(P - \left(\frac{1}{3}\right) \times \sqrt{AT^2 + AF^2}\right)}

SS = \sqrt{\left(\frac{1}{3}\right) \times (AO - s)^2 + (AF - s)^2 + (AT - s)^2}

SO = AO - s; SF = AF - s; ST = AT - s

Note 1: P = \frac{1}{4} \times (\sqrt{AO^2 + AF^2} + \sqrt{AT^2 + AF^2} + \sqrt{AT^2 + AF^2})

s (the sum of three main dimensions): used to confirm the corresponding maturity stage of the target project.

S (the area of the formulated triangular) [39]: used to compare the maturity with other projects.

SS (the variance of three main dimensions): used to evaluate the uniformity development of three main dimensions.

(SO, SF, ST) (the deviation of each main dimension from the mean value): used to determine the most unbalanced dimension during the digital twin development.

In order to create a pathway towards intelligent infrastructure asset, ICE defined seven maturity stages for asset information maturity scales [40]. Thus, according to these asset management maturity stages, five maturity stages of digital twin implementation for asset management are defined and described in this study (as shown in Table 5), which would be benefit for matching with the five-point Likert scales using each rubric.

Table 5. Digital twin maturity stages (this table was created based on [40,41]).

| Maturity Stage         | Description                                                                 | Score Range |
|------------------------|-----------------------------------------------------------------------------|-------------|
| Unaware                | Base project (non-IoT devices, non-inventoried assets, and less database supported) | 0           |
| Identifiable           | Assets are partially identifiable and registered; design data are linked to asset identity | < 9         |
| Aware                  | Assets are identifiable and registered; IoT devices are partially integrated to monitor as-is conditions; digital model is used | ≥ 9 &≤ 18   |
| Communicative          | Ontology is defined; assets and data are able to share in a standardised format; technology is implemented reasonably | ≥ 18 &≤ 27  |
| Interactive            | Ontology is defined and performed clearly; suitable methodology is implemented to support information retrieve and asset integration; shareable knowledge and value is provided | ≥ 27 &≤ 36  |
| Instructive and        | Semi-automatic/automatic managing asset, intelligent decision-making support on its own and instigating actions | ≥ 36 &≤ 45  |
| Intelligent            |                                                                             |             |
5. Case Studies

Two practical projects were selected as case studies to evaluate this proposed model, namely Shanghai Tower (Project 1) and the CDBB West Cambridge digital twin pilot (Project 2). In order to evaluate the proposed model and also collect data needed, field research was conducted for two projects separately. The target cases include technical and management groups of two projects. Brief descriptions of two cases are listed in Table 6. Moreover, collected data were calculated based on Table 5 and summarised in Figure 3. Through evaluating two real cases using the proposed maturity model, the results are summarised as following:

Table 6. Brief descriptions of two real cases.

| Project Name                  | Location      | Project Description                                      | Target Group                                                                 | Supported Applications                                                                 | Integrated Data Resource                                                                 | IoT Devices                      |
|-------------------------------|---------------|----------------------------------------------------------|------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|----------------------------------|
| Shanghai Tower (Project 1)    | Shanghai, China| A mixed-used space, which includes restaurants, shops, offices, and hotels. | Principal Director of the FM-BIM Management Platform                          | Visualised model, effective information query, safety management (including CCTV and effective escape routes), asset management | BIM, BMS, Facility Management System                                                      | BMS embedded sensors, QR code, RFID |
| The CDBB West Cambridge Digital Twin Pilot (Project 2) | Cambridge, UK | The IFM building, including study, office, research and laboratory spaces. | Core Researcher of the Cambridge Digital Twin Project                        | Visualised model, integrated data resources, space management, real-time monitoring, asset management | BIM, BMS, Asset Management System, Space Management System, Asset Register System        | BMS embedded sensors, wireless sensors, QR code |

Note 1: BMS: Building Management System.

Figure 3. The cross-comparison of two projects using the developed maturity model.
a. Two projects all achieve the stage of Interactive referring to the Table 6 (36 > s1, s2 ≥ 27);

b. The level of digital twin maturity: the level of project 2 is higher than project 1 (S2 > S1), which can also be visualised using this model (as shown in Figure 3);

c. The uniformity development: project 1 is designed and developed uniformly in the perspectives of ontology, methodology, and knowledge and value (SS1). Project 2 slightly decentres towards the methodology (i.e., technology and process) and knowledge and value aspects (SS2);

d. The roadmap of the future improvement: Project 2 needs further improvement from the ontology aspect (SO2 = −2.33) especially. For instance, project 2 should improve the daily management pattern when digital twins involved in (O4 in project 2). The methodology and knowledge and value aspects (SF2 and ST2) are developed and implemented successfully. Project 1 needs to be improved from the perspectives of the ontology and methodology in the future development (SO1 and SF1).

The results proved that this proposed digital twin maturity model can provide a visualised, systematic, and quantitative method of measuring the digital twin implementation conditions and future development roadmap for self-evaluation and cross-comparison with other projects. However, digital twin development at a city level or even the national level would have different influences and therefore cannot simply be mirrored via the counterparts at a project level. Moreover, the digital twin development at a city or national level will be highly led and affected by the local culture and policy. Hence, future studies will further study the multifunctional digital twin maturity model in city and national levels and fulfill these gaps.

6. Discussion and Conclusions

The diffusion, implementation, further development, and maturation of digital twin for asset management should be properly guided by a well-designed digital twin maturity model. Based on existing maturity models, practical projects, digital twins definitions, and Gemini Principles provided by CDBB, this study developed a digital twin maturity model for asset management in a hierarchical and innovative structure, which is able to provide a comprehensive and quantitative maturity evaluation within a project or cross-comparison with other projects. Rather than only providing an overall maturity evaluation, the model can visualise and present the maturity stages of digital twin development and implementation from a visualised, systematic, and quantitative view and in three key dimensions (i.e., ontology, methodology, and knowledge and value). This implies that digital twin development is not only about methodology (e.g., technology) but also is related to its objective and knowledge. Then, two practical cases (i.e., Shanghai Tower and the CDBB west Cambridge digital twin pilot) were selected to evaluate this digital twin maturity model. In general, this model provides a visualised and solid benchmarking, knowledge and references for researchers, company development managers, or public policymakers to propose comprehensive digital twins construction, development, and maturation strategies. In the future works, an expert pool will be used in the evaluation stage. Moreover, our research team will improve this maturity model in city levels and figure out how to use this digital twin maturity tool for optimising city services such as power, waste, transport, and understanding the impacts on wider social and economic outcomes.
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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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### Appendix A

**Table A1.** Major measuring aspects of evaluated maturity measurement tools.

| Maturity Tools                     | Developers               | Purpose          | Trust          | Function       | Evaluation Methods | Reference |
|-----------------------------------|--------------------------|-------------------|----------------|----------------|--------------------|-----------|
|                                   |                          | Public Good | Value Creation | Insight | Security | Openness | Quality | Federation | Curation | Evolution |           |           |
| Capability Maturity Model         | Research Institutions    | √            | √              | √       | √        | √         | √        |            |          |           | 1         | [35]      |
| BIM Proficiency Index             | Research Institutions    |              | √              |          |          | √         |          |            |          |           | 2         | [15]      |
| BIM Maturity Matrix               | Research Institutions    | √            | √              | √       | √        | √         | √        |            |          |           | 1         | [16]      |
| BIM Quick Scan                    | Industry                 | √            | √              |          |          | √         |          | √           |          |           | 3         | [42]      |
| Characterisation Framework        | Individual Scholars      |              | √              |          | √        | √         |          | √           |          |           | 1,4,5     | [43]      |
| BIM Assessment Profile            | Research Institutions    | √            | √              |          |          | √         | √        | √           |          |           | 1         | [36]      |
| Virtual Design and Construction Scorecard | Research Institutions | √            | √              |          |          | √         |          | √           |          |           | 1,3,4,5   | [37]      |
| BIM Cloud Score                   | Individual Scholars      |              |                |          | √        | √         |          |            |          |           | 4         | [44]      |

Note 1: 1 stands for scale (5 or 10 level); 2 stands for self-scoring from 0–1; 3 stands for multiple choices; 4 stands for quantitative blank fillings; 5 stands for open ended questions.

**Table A2.** Survey results on the importance degree of rubrics (1: least important, 5: very important).

| Main Dimension   | Rubric                                                                 | Reference            | Mean | SD  | Sig. (2-tailed) | Symbol |
|------------------|------------------------------------------------------------------------|----------------------|------|-----|-----------------|--------|
|                  | O1: Project target/objective                                           | Lu et al. [45]       | 4.00 | 0.71| 0.000           | P1     |
| Insight          | O2: Organisational business process map                                | Giel and Issa [5]    | 3.60 | 0.58| 0.000           | P2     |
|                  | O3: Organisational operational plan                                    | Teicholz [30]        | 3.80 | 0.41| 0.000           | P3     |
| Purpose          | O4: Improved management performances with digital twin involved        | Messner and Kreider [36] | 3.88 | 0.60| 0.000           | P4     |
|                  | O5: Qualified consulting company/expert supported                       | Lu et al. [45]       | 3.52 | 0.59| 0.000           | P5     |
|                  | O6: Digital twin relevant experience and aptitude of professionals and value creation | Giel and Issa [5]   | 3.88 | 0.60| 0.000           | P6     |
| Public Good      | O7: Role and responsibility definitions within the organisation        | Liang et al. [33]    | 3.92 | 0.81| 0.000           | P7     |
|                  | O8: Well-organised training programs within the organisation           | Volk et al. [46]     | 3.76 | 0.78| 0.000           | P8     |
|                  | O9: Communication strategies among different stakeholders and within the organisation | Lu et al. [45] | 4.12 | 0.67| 0.000           | P9     |
| Main Dimension | Rubric                                                                 | Reference                                | Mean  | SD    | Sig. (2-tailed) | Symbol |
|---------------|------------------------------------------------------------------------|------------------------------------------|-------|-------|----------------|--------|
| Curation      | F1: Data/model updating/collecting techniques based on as-is conditions for effective information collection (e.g., camera, sensor systems) | Lu et al. [3]; Shen et al. [47]          | 4.00  | 0.58  | 0.000          | F1     |
|               | F2: Data/model storage, exchange and sharing method (e.g., cloud-based storage technology) | Motawa and Almarshad [10]               | 3.76  | 0.72  | 0.000          | F2     |
|               | F3: Information visualisation technology                               | Chen et al. [48]                        | 3.68  | 0.56  | 0.000          | F3     |
|               | F4: Data integration (e.g., centre database, data warehouse)          | Kang et al. [49]                        | 4.00  | 0.58  | 0.000          | F4     |
|               | F5: Asset integration                                                 | Shanghai Tower [25]; Zanella et al. [50] | 3.56  | 0.65  | 0.000          | F5     |
|               | F6: Asset register techniques implementation (e.g., RFID, QR code)     | Costin et al. [51]                      | 3.56  | 0.65  | 0.000          | F6     |
| Federation    | F7: Digital model/data generating and updating process/technology      | USC School of Cinematic Arts [30]; University of British Columbia Campus [28] | 3.96  | 0.61  | 0.000          | F7     |
|               | F8: Information/model sharing process/technology                       | The Karr Hall East Building of Ryerson University [24] | 4.12  | 0.60  | 0.000          | F8     |
|               | F9: Asset data updating and capturing process/technology               | Manchester Town Hall Complex [29]; Pishdad-Bozorgi et al. [52] | 4.00  | 0.50  | 0.000          | F9     |
| Evolution     | T1: Integrity and accuracy of as-is digital model (e.g., BIM)          | Cavka et al. [28]                       | 4.20  | 0.58  | 0.000          | T1     |
|               | T2: Information security assurance                                     | Seng [53]                               | 3.76  | 0.66  | 0.000          | T2     |
|               | T3: Formal standards and protocols as the basis                       | Giel and Issa [5]                       | 3.80  | 0.71  | 0.000          | T3     |
| Security      | T4: Removal and replacement reminders and records                       | Kang et al. [50]                       | 3.32  | 0.56  | 0.000          | T4     |
| Openness      | T5: Interoperability/IFC or COBie support (e.g., openBIM)              | Sydney Opera House [11]; An Anonymous Campus Building [32] | 4.00  | 0.71  | 0.000          | T5     |
|               | T6: Integrity, accuracy and openness of collected information/data resources (e.g., space information, asset information, building management information) | Auburn University’s Construction Management Building [31] | 4.16  | 0.55  | 0.000          | T6     |
| Quality       | T7: Digital twin for asset management implementation guide             | National Infrastructure Commission [1]   | 3.88  | 0.83  | 0.000          | T7     |
|               | T8: Continuous quality assurance mechanism/rules                       | Seng [53]; Lu et al. [45]               | 3.88  | 0.73  | 0.000          | T8     |
|               | T9: Formal services and data delivery provision (e.g., data exchange standard) | Pishdad-Bozorgi et al. [30]             | 3.92  | 0.57  | 0.000          | T9     |

Note 1: Significance level (p-value, 2-tailed) less than $\alpha = 0.01$, $t_c (40,0.01) = 2.704$. 
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