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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

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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 quatitative 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 maintanence 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 facilitiy 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 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; 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.

Table 2. The Gemini Principles and statements (this table is modified according to [20]).

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
Trust	Security	The digital twin must enable security and be secure itself
	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
Function	Federation	The digital twin must be based on the secure interoperability of data
	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.

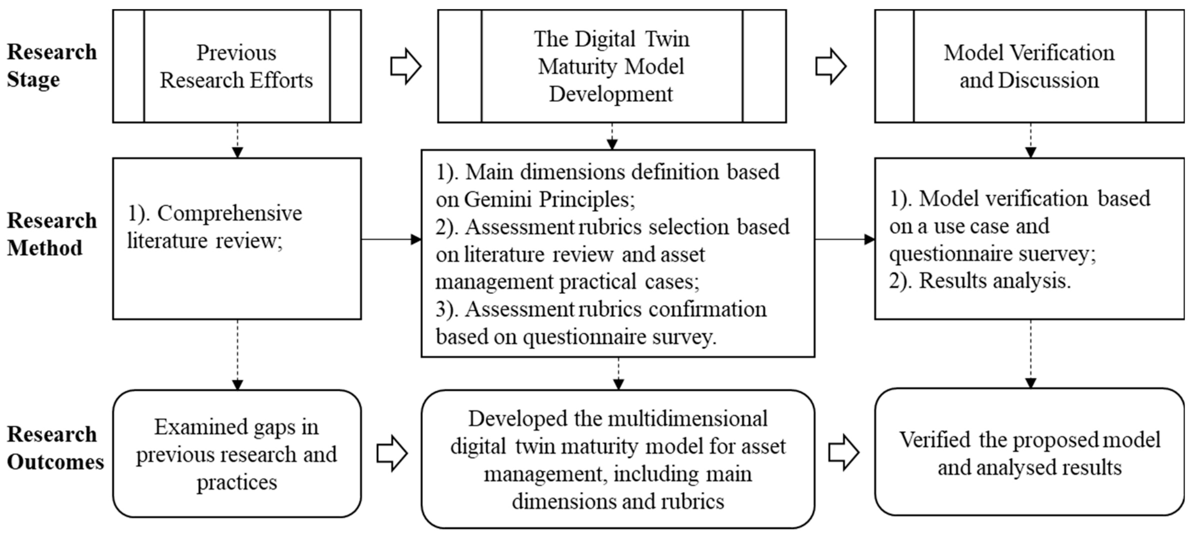

Figure 1. Research design and approach in this study.

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:

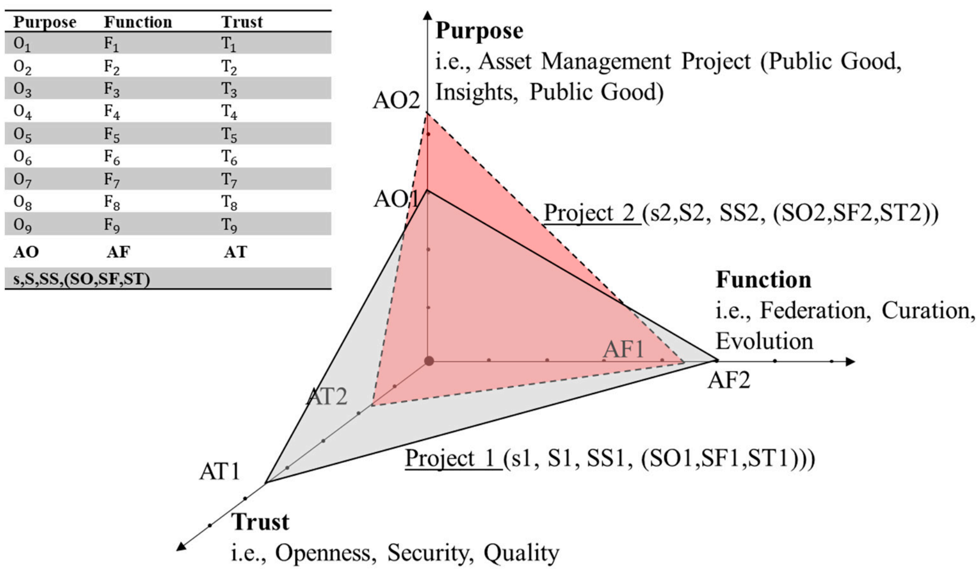

Figure 2. The presentation of the developed maturity model.

Table 4. The designed evaluation form of the maturity model.

Purpose	Assessment Rubrics	Function	Assessment Rubrics	Trust	Assessment Rubrics
O_1		F_1		T_1	
O_2		F_2		T_2	
O_3		F_3		T_3	
O_4		F_4		T_4	
O_5		F_5		T_5	
O_6 O_7		F_6 F_7		T_6 T_7	
O_8		F_8		T_8	
O_9		F_9		T_9	
$\mathbf{AO} = \sum_1^9 \mathbf{O_i}$		$\mathbf{AF} = \sum_1^9 \mathbf{F_i}$		$\mathbf{AT} = \sum_1^9 \mathbf{T_i}$	

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

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

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

$\mathbf{SO} = \mathrm{AO} - \mathrm{s}$; $\mathbf{SF} = \mathrm{AF} - \mathrm{s}$; $\mathbf{ST} = \mathrm{AT} - \mathrm{s}$

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

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 descripted 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 Intelligent	Semi-automatic/automatic managing asset, intelligent decision-making support on its own and instigating actions	≥ 36 && ≤ 45

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.

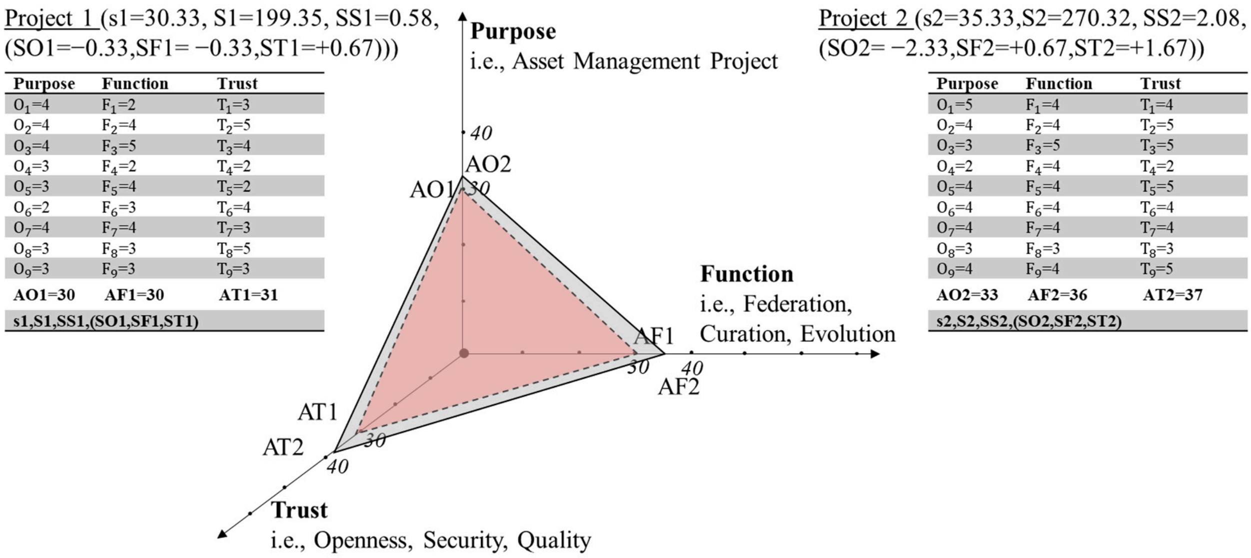

Figure 3. The cross-comparison of two projects using the developed maturity model.

a. Two projects all achieve the stage of Interactive referring to the Table 6 (36 > s1, s2 $\geq$ 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 developed and designed 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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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki. This study was approved by University of Cambridge with the project 'West Cambridge Digital Twin Research Facility' in 2018 firstly. In order to keep up-to-date information, Ethics Committee of University College London further reviewed this study in 2021.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Conflicts of Interest: The authors declare no conflict of interests.

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
Purpose	Insight	O1: Project target/objective	Lu et al. [45]	4.00	0.71	0.000	P1
		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
	Value Creation	O4: Improved management perfomances 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

Table A2. *Cont.*

Main Dimension		Rubric	Reference	Mean	SD	Sig. (2-tailed)	Symbol
Fuction	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
	Federation	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
	Evolution	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
Trust	Security	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	T6
	Openness	T4: Removal and replacement reminders and records	Kang et al. [50]	3.32	0.56	0.000	T4
		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	T3
	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 serives 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 $\alpha = 0.01$, tc (40,0.01) = 2.704.

References

1. National Infrastructure Commission. Data for the Public Good. 2017. Available online: https://www.nic.org.uk/wp-content/uploads/Data-for-the-Public-Good-NIC-Report.pdf (accessed on 20 July 2018).
2. Pärn, E.; Edwards, D.; Sing, M. The building information modelling trajectory in facilities management: A review. *Autom. Constr.* **2017**, *75*, 45–55. [CrossRef]
3. Lu, Q.; Lee, S. Image-based technologies for constructing as-is building information models for existing buildings. *J. Comput. Civ. Eng.* **2017**, *31*, 04017005. [CrossRef]
4. Kekana, T.G.; Aigbavboa, C.O.; Thwala, W.D. Building Information Modelling (BIM): Barriers in Adoption and Implementation Strategies in the South Africa Construction Industry. In Proceedings of the International Conference on Emerging Trends in Computer and Image Processing, Pattaya, Thailand, 16–17 January 2017. Available online: http://bim.pu.go.id/downloads/Barriers%20in%20BIM%20adoptions.pdf (accessed on 20 February 2018).
5. Giel, B.; Issa, R.R.A. Framework for evaluating the BIM competencies of building owners. *Comput. Civ. Build. Eng.* **2014**, *2014*, 552–559.
6. HM Government. Level 3 Building Information Modelling—Strategic Plan. 2015. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/410096/bis-15-155-digital-built-britain-level-3-strategy.pdf (accessed on 20 July 2018).
7. GE Digital. Digital Twins: The Bridge between Industrial Assets and the Digital World. 2017. Available online: https://www.ge.com/digital/blog/digital-twins-bridge-between-industrial-assets-and-digital-world (accessed on 20 July 2018).
8. Gartner. Prepare for the Impact of Digital Twins. 2017. Available online: https://www.gartner.com/smarterwithgartner/prepare-for-the-impact-of-digital-twins/ (accessed on 20 August 2018).
9. Glaessgen, E.; Stargel, D. The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. In Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Structures, Structural Dynamics, and Materials and Co-located Conferences, Honolulu, HI, USA, 23–26 April 2012; p. 1818.
10. Motawa, I.; Almarshad, A. A knowledge-based BIM system for building maintenance. *Autom. Constr.* **2013**, *29*, 173–182. [CrossRef]
11. Innovation, CRC Construction, Adopting BIM for facilities management: Solutions for managing the Sydney Opera House. Cooperative Research Centre for Construction Innovation. 2007. Available online: http://www.construction-innovation.info/images/CRC_Dig_Model_Book_20070402_v2.pdf (accessed on 1 August 2018).
12. Lainhart, J.W. COBIT™: A methodology for managing and controlling information and information technology risks and vulnerabilities. *J. Inf. Syst.* **2000**, *14*, 21–25. [CrossRef]
13. SEI. *Capability Maturity Model Integration Standard (CMMI) Appraisal Method for Process Improvement (SCAMPI) A, Version 1.2—Method Definition Document*; Software Engineering Institute/Carnegie Melon: Pittsburgh, PA, USA, 2006.
14. Osman, H.; Nikbakht, M. A game-theoretic model for roadway performance management. *Built Environ. Proj. Asset Manag.* **2014**, *4*, 40–54. [CrossRef]
15. *The Indiana University Architect's Office—IU BIM Proficiency Matrix (Multi-Tab Excel Workbook)*; IU (Indiana University): Bloomington, IN, USA, 2009.
16. Succar, B. Building information modelling framework: A research and delivery foundation for industry stakeholders. *Autom. Constr.* **2009**, *18*, 357–375. [CrossRef]
17. Mulej, M.; Ženko, Z. Introduction to systems thinking with application to invention and innovation management. *Manag. Forum* **2014**. Available online: https://www.researchgate.net/publication/246530878_Introduction_to_Systems_Thinking_with_Application_to_Invention_and_Innovation_Management (accessed on 20 June 2020).
18. Mulej, M.; Bastic, M.; Belak, J.; Knez-Riedl, J.; Pivka, M.; Potocan, V.; Rebernik, M.; Ursic, D.; Zenko, Z.; Mulej, N. Informal systems thinking or systems theory. *Cybern. Syst.* **2003**, *34*, 71–92. [CrossRef]
19. Succar, B.; Sher, W.; Williams, A. Measuring BIM performance: Five metrics. *Arch. Eng. Des. Manag.* **2012**, *8*, 120–142. [CrossRef]
20. Bolton, A.; Butler, L.; Dabson, I.; Enzer, M.; Evans, M.; Fenemore, T.; Harradence, F. Gemini Principles. (CDBB_REP_006). 2018. Available online: https://www.cdbb.cam.ac.uk/Resources/ResoucePublications/TheGeminiPrinciples.pdf (accessed on 16 April 2021).
21. Lu, Q.; Parlikad, A.K.; Woodall, P.; Ranasinghe, G.D.; Heaton, J. Developing a Dynamic Digital Twin at a Building Level: Using Cambridge Campus as Case Study. In Proceedings of the International Conference on Smart Infrastructure and Construction 2019 (ICSIC), Cambridge, UK, 8–10 July 2019.
22. Chen, L.; Whyte, J. Analysing Interdependencies of Complex Engineering Systems Using a Digital Twin-Driven Design Structure Matrix. In *Construction Research Congress 2020*; American Society of Civil Engineers (ASCE): Tempe, AZ, USA, 2020; pp. 417–426.
23. Lu, Q.; Chen, L.; Li, S.; Pitt, M. Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings. *Autom. Constr.* **2020**, *115*, 103183. [CrossRef]
24. Khaja, M.; Seo, J.; McArthur, J. Optimizing BIM metadata manipulation using parametric tools. *Procedia Eng.* **2016**, *145*, 259–266. [CrossRef]
25. Xia, J.; Poon, D.; Mass, D.C. Case study: Shanghai Tower. Council on Tall Buildings and Urban Habitat, II. 2010. Available online: http://global.ctbuh.org/resources/papers/download/12-case-study-shanghai-tower.pdf (accessed on 18 April 2021).
26. Lu, Q.; Xie, X.; Parlikad, A.K.; Schooling, J.M. Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. *Autom. Constr.* **2020**, *118*, 103277. [CrossRef]

27. Centre for Digital Built Britain (CDBB). Year One Report-Towards a Digital Built Britain. 2018. Available online: https://www.cdbb.cam.ac.uk/Resources/ResoucePublications/CDBBYearOneReport20 (accessed on 16 April 2021).
28. Cavka, H.B.; Staub-French, S.; Pottinger, R. Evaluating the alignment of organizational and project contexts for BIM adoption: A case study of a large owner organization. *Buildings* **2015**, *5*, 1265–1300. [CrossRef]
29. Kiviniemi, A.; Codinhoto, R. Challenges in the Implementation of BIM for FM—Case Manchester Town Hall Complex. In Proceedings of the Computing in Civil and Building Engineering, American Society of Civil Engineers (ASCE), Orlando, FL, USA, 23–25 June 2014; pp. 665–672.
30. Teicholz, P. (Ed.) *BIM for Facility Managers*; John Wiley & Sons: Hoboken, NJ, USA, 2013; ISBN 1118417623.
31. Sattenini, A.; Azhar, S.; Thuston, J. Preparing a Building Information Model for Facility Maintenance and Management. In Proceedings of the 28th International Symposium on Automation and Robotics in Construction, International Association for Automation and Robotics in Construction, Seoul, Korea, 29 June–2 July 2011; pp. 144–149, ISBN 9781510804296.
32. Akcamete, A.; Akinci, B.; Garrett, J.H. Potential Utilization of Building Information Models for Planning Maintenance Activities. In Proceedings of the International Conference on Computing in Civil and Building Engineering, Nottingham, UK, 30 June–2 July 2010; pp. 151–158, ISBN 978-1-907284-60-1.
33. Liang, C.; Lu, W.; Rowlinson, S.; Zhang, X. Development of a multifunctional BIM maturity model. *J. Constr. Eng. Manag.* **2016**, *142*, 06016003. [CrossRef]
34. Socha, D. The Digital Twin Maturity Continuum. 2018. Available online: https://www.smart-energy.com/industry-sectors/business-finance-regulation/digital-twins-maturity-continuum-david-socha/ (accessed on 16 April 2021).
35. NIBS (National Institute of Building Science). *United States National Building Information Modeling Standard, Section 4—Information Exchange Content*; National Institute of Building Sciences: Washington, DC, USA, 2007; pp. 75–82.
36. CIC. *BIM Planning Guide for Facility Owners*; Pennsylvania State University: University Park, PA, USA, 2012; Available online: http://bim.psu.edu (accessed on 30 March 2018).
37. Kam, C.; Senaratna, D.; McKinney, B.; Xiao, Y.; Song, M. *The VDC Scorecard: Formulation and Validation*; Center for Integrated Facility Engineering, Stanford University: Stanford, CA, USA, 2013.
38. Dawson, P. Assessment rubrics: Towards clearer and more replicable design, research and practice. *Assess. Eval. High. Educ.* **2015**, *42*, 347–360. [CrossRef]
39. Dunham, W. Problems for Journey Through Genius: The Great Theorems of Mathematics. *Convergence* **2015**, 113–132. [CrossRef]
40. CSIC and ICE Publish Guidance Paper, Intelligent Assets for Tomorrow's Infrastructure. 2017. Available online: https://www.ice.org.uk/getattachment/knowledge-and-resources/best-practice/how-best-to-adapt-to-the-big-changes/ICE_Intelligent_Assets_for_Tomorrows_Infrastructure_Guiding_Principles.pdf.aspx (accessed on 28 August 2018).
41. ISO Standard. ISO 55000-Asset Management—Overview, Principles and Terminology. 2014. Available online: https://www.iso.org/standard/55088.html (accessed on 6 March 2018).
42. Sebastian, R.; Van Berlo, L. Tool for benchmarking BIM performance of design, engineering and construction firms in The Netherlands. *Arch. Eng. Des. Manag.* **2010**, *6*, 254–263. [CrossRef]
43. Gao, J. A Characterization Framework to Document and Compare BIM Implementations on Construction Projects. Ph.D. Thesis, Stanford University, Stanford, CA, USA, 2011.
44. Du, J.; Liu, R.; Issa, R.R.A. BIM cloud score: Benchmarking BIM performance. *J. Constr. Eng. Manag.* **2014**, *140*, 04014054. [CrossRef]
45. Lu, Q.; Chen, L.; Lee, S.; Zhao, X. Activity theory-based analysis of BIM implementation in building O&M and first response. *Autom. Constr.* **2018**, *85*, 317–332. [CrossRef]
46. Volk, R.; Stengel, J.; Schultmann, F. Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Autom. Constr.* **2014**, *38*, 109–127. [CrossRef]
47. Shen, W.; Hao, Q.; Mak, H.; Neelamkavil, J.; Xie, H.; Dickinson, J.; Thomas, R.; Pardasani, A.; Xue, H. Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. *Adv. Eng. Inform.* **2010**, *24*, 196–207. [CrossRef]
48. Chen, H.-M.; Hou, C.-C.; Wang, Y.-H. A 3D visualized expert system for maintenance and management of existing building facilities using reliability-based method. *Expert Syst. Appl.* **2013**, *40*, 287–299. [CrossRef]
49. Kang, T.-W.; Choi, H.-S. BIM perspective definition metadata for interworking facility management data. *Adv. Eng. Inform.* **2015**, *29*, 958–970. [CrossRef]
50. Zanella, A.; Bui, N.; Castellani, A.; Vangelista, L.; Zorzi, M. Internet of things for smart cities. *IEEE Internet Things J.* **2014**, *1*, 22–32. [CrossRef]
51. Costin, A.; Shaak, A.; Teizer, J. Development of a Navigational Algorithm in BIM for Effective Utility Maintenance Management of Facilities Equipped with Passive RFID. In *Computing in Civil Engineering*; American Society of Civil Engineers (ASCE): Reston, VA, USA, 2013; pp. 653–660.
52. Pishdad-Bozorgi, P.; Gao, X.; Eastman, C.; Self, A.P. Planning and developing facility management-enabled building information model (FM-enabled BIM). *Autom. Constr.* **2018**, *87*, 22–38. [CrossRef]
53. Seng, L.C. Singapore BIM Guide. 2015. Available online: https://www.corenet.gov.sg/media/586132/Singapore-BIM-Guide_V2.pdf (accessed on 30 July 2018).