AN APPROACH TO THE ESTIMATION OF DIGITAL TWINS TECHNOLOGICAL COMPONENTS

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Abstract

The Digital Twin (DT) concept in the Architecture Engineering Construction and Operation (AECO) sector is gaining momentum. Various studies and case examples highlight its benefits. However, for broader implementation within the sector, there is a need for a standardised method for estimating the cost of DTs. This paper proposes an extension of the UK New Rules of Measurement 2 (NRM2) for estimating the technological components of DT systems based on the desired capabilities. The DT capabilities are identified through the analysis of the theoretical framework, which, combined with the analysis of current industry standards, enables the development of the NRM2 extension. The need for this extension has also been validated through a set of semi-structured interviews with industry experts in the UK. This research contributes to reducing ambiguity in the identification and estimation of technological components of DTs in buildings.

Introduction and background

The benefits of the digitalisation of the construction sector (still poorly digitised) are many and include addressing major challenges such as carbon reduction, resources and energy efficiency, labour shortage and competitiveness (European construction sector observatory, 2021). The digitalisation trend has been accelerated in recent years by the introduction of the DT concept, which can be broadly defined as "*A digital twin is a virtual model of an object, a system, or a process. It is connected to its real-world counterpart by a 2-way flow of right-time data, meaning it mimics it in all aspects. This helps us test decisions before we make them and understand how different actions might affect the real world.*" (UK Department for Business & Trade, n.d.). Though it is known that the DT concept has been investigated in several other sectors as aerospace and manufacturing (Grieves, 2016), there is no agreement on the components that should be included in a DT implementation (Shahzad *et al.*, 2022), thus it is hard to drive the digital transformation in the construction industry, with nothing more than a concept and a number of few custom applications.

In fact, the digital transformation in Architecture, Construction, Engineering and Operations (AECO) is not confined to the economic cost for the deployment of a new set of technologies. In the case of DTs, these costs can include for examples the change management activities required at the ecosystem level, training and workforce upskill, security, together with the hardware and software costs.

In the construction industry, innovation dynamics and therefore also the digital innovation, are often realised through projects (Xue *et al.*, 2014) and is well known that the success of a project is related to the careful estimation of the time, cost and quality of the desired outcomes (Association for Project Management, 2019). Within this context and with a focus on the economic dimension of projects, a careful cost estimation is key to understand in depth the required efforts to deliver the desired outputs and realise the client requirements and objectives. This is crucial, especially in the pre-construction phase in order to avoid cost overruns which could deviate completely the project scope.

The Bill of Quantities (BoQ) techniques are fundamental tools in the construction sector, used to control the project costs. To develop the BoQ it is essential to involve methods of estimations which respects standards in the way that different stakeholders will be able to understand it. One of the widely acknowledged standards is the NRM2 from the Royal Institution of Chartered Surveyors (RICS, 2021), which is used for detailed measurements of building works.

This paper proposes a method to estimate the technological components of DTs, required to deliver a finite set of general capabilities, identified from existing DT implementations. The method of estimation of DT in this paper is considered as a case of digital innovation in AECO which has not been completely explored and therefore requires further investigation. The paper also proposes a research roadmap on the study of the cost associated with the digital transformation in AECO.

The rest of this paper is organised as follows: the method section identifies the research methodology and tools used, the analysis of the theoretical framework analyse and identifies capabilities and technologies for DT systems, the NRM2 extension section showcases the developed standard for estimation and the preliminary validation through expert interviews, the discussion and conclusion refine what has been done against the identified research gap, and inform on the research limitations and gives direction on future steps.

Method and tools

The methodology used for the study is related to the design science research methodology (Peffers *et al.*, 2007), which is used for information systems as this allows the design of a method for the estimation for DT systems. The research methodology consists of six activities which are developed in sequence, the first activity, entails the identification of the problem statement, the second activity relates to the definition of the objective for a solution, the third consists in the design and development, the fourth is the demonstration, the fifth is for the evaluation, and the sixth consists in the communication.

Of the above-mentioned activities, the research focuses on the first three activities with the latter three and an outline of the next steps being discussed in the discussion and conclusion section.

The first activity is presented in the analysis of the theoretical framework, and results with the need for the development of a method of estimation for DT systems, which is needed for solving the identified research gap.

The second activity is identified through an understanding of existing standards of estimation and the relative implementation of estimation of DT systems, as currently, the research did not identify standards of estimation, this would accomplish a better identification of the DT systems in the phase of design and their related capabilities, and better define the DT requirements needed in the project.

The third activity includes the design and development stage, which is centred towards a developed method of estimation for DT systems for buildings, this is developed in the analysis chapter through the design of a method of estimation with the identified DT technologies capabilities.

Furthermore, a validation of the proposed method of estimation was undertaken through structured interviews in order to understand the experiences of the various construction experts involved in digital construction and in specific DTs.

NRM 2 to estimate DT systems

There are different guidance and standards used for estimation, and one of those standards, which is accepted internationally, is the New Rules of Measurement (NRM) collection, formed by NRM1, NRM2 and NRM3 and utilised as a guidance for estimating the building works throughout the lifecycle.

Furthermore, NRM can be taken into account in legal proceedings (RICS, 2021) and can be used to produce BoQs which follow the standard methods of estimation and can be attached as a contractual document in standard form of contracts.

The NRM1 is used for initial cost planning, the NRM3 is used for the estimation of building maintenance works, and the NRM2 is a standard for the estimation of building works during the pre-phase of construction and can also be used as a contract document which allows to obtain a total price for completing building works. This allows to evaluate the project variations and to support the management of the cash flow, implementing value engineering tasks. The NRM2 can be used as a tool to extend methods of estimation of DT, since it contains a method of measurement for quantifying the related systems and for the exclusion of the components already quantified using other parts of the standard (RICS 2021). Therefore, the proposed NRM2 extension aims at linking the DT capabilities with the technological implementation of both the hardware and software parts of DTs in buildings.

Analysis of the theoretical framework

To define the current costs associated with DT systems and their related technological components, in this section, we identify the current approaches that deliver the capabilities of systems, as described in the ISO 23247 series (ISO, 2021a). This standard provides a guidance for the development of a DT reference architecture and its correlation to the functional entities. Likewise, the DT application in building systems, assets and whole infrastructure involves the use of different capabilities that are summarised in Table 1. It has to be noted that the application level does not cover the use of DT systems for the benefit of the construction site.

The data acquisition capability (ISO, 2021b) is the functional entity for data acquisition and might also contain an Internet of Things (IoT) network, which links sensors, actuators and the collected data, supporting automation. Furthermore, data can be retrieved from historical building systems, as for example the Building Automation Systems (BAS) and Building Management Systems (BMS) (Lu et al., 2020).

The data modelling reflects the need to create a digital representation of the building and its features. It includes different data formats and their requirements (ISO, 2021c), which can enable data, process and system interoperability. For example, in Xu *et al.* (2023), the Industry Foundation Classes (IFC) standard and the semantic information in JSON file format are combined and converted into the 3D tiles standard for its interoperability.

The data analytics capability allows to gain insight or prediction from the data provided in the digital representation, as for example, in the case of Hosamo *et al.*, (2022), who describe the use of "the algorithms Artificial Neural Network (ANN), support vector machine (SVM), and decision trees to predict severe Air Handling Units (AHU) faults".

The actuation capability allows the use of the outcomes of the data analytics to automate processes and plan maintenance. This capability can be enabled through advanced functionalities of the IoT network which can enhance applications, as for instance the control of the Heating Ventilation and Air Conditioning (HVAC) system based on room occupancy as outlined in García-Monge *et al.* (2023). The curation of the DT system involves the maintenance of the whole system, this is done through the creation of appropriate data storage and its maintenance.

Table 1: Case studies and related capabilities

Application level	Purpose	Data Acquisition	Data modelling	Data Analytics	Actuation	Curation	Author
Asset	Human robot collaboration in Facility Management	Robot sensing data, asset data capture.	RDF and entity relationship diagram	Control flow for anomaly detection	Physical actuators and robot motion	Cloud based server, DB, web platform and BIM for visualisation	(Lu *et al.*, 2023)
Asset, system, building	Real-time monitoring of the hospital facility	Data on facility users, data on facility and processes	Web service, JSON Schema, Connection adapters, MOM	OLAP,HDFS, OLTP	Process control, defect detection, alarm rate of monitored points	BIM for visualisation, WebGL and JSON DB	(Han *et al.*, 2023)
System	Predictive Maintenance AHU	IoT sensor network, environmental sensing, and system monitoring	Brick ontology based on COBie data and IFC	ML, ANN, SVM and decision trees	Planning of maintenance	Sensor data DB and BIM for visualisation	(Hosamo *et al.*, 2022)
System	Anomaly detection of centrifugal pumps	Tags, environmental sensing, system monitoring, historic building data	Multi-source data through IFC and COBie	CUSUM and BOCPD	Anomaly detection and reduction of false alarms	BIM of the building and web based DT platform	(Lu *et al.*, 2020)
System	Fault detection and diagnosis of HVAC	Environmental sensing, and system monitoring	JSON file brick model with fault tags to form a hierarchical structure	Goodness-of-Fit test with Kullback–Leibler divergence	Unsupervised and supervised fault detection	Adaptive City Platform digital twin platform, which integrate brick schema	(Xie *et al.*, 2023)
System	Fan coils units fault detection for HVAC	Environmental sensing, system monitoring, IoT sensor network	Integrated data using BIM platform and NPM modules	Integrated anomaly detection flow chart	Fault detection	BIM and web based program	(Villa *et al.*, 2021)
Systems, spaces	Energy optimisation of HVAC	Environmental sensing, system monitoring, tags, data on facility users, IoT network	Integration of data through proprietary developed application	Quantitative data analysis	Decision through data analysis to improve efficiency	Web user interface	(García-Monge *et al.*, 2023)
Spaces	Monitoring of room occupancy	Image recognition and historical data	SQL database coupled with BIM model	Defined thresholds	Decision-making through a cost model	SQL Cloud server and BIM for visualisation	(Mannino *et al.*, 2019)
Building	Structural Health monitoring of building	Structural sensing, environmental sensing, computer vision	BIM with IFC and JSON for data exchange and 3D tile standard	Dynamic and static mechanical analysis	Building Structural health monitoring	SQL server to store data and 3D engine for visualisation	(Xu *et al.*, 2023)
Building, system, spaces	Indoor environmental quality, energy consumption, estimation of unobservable elements	Environmental sensing, systems monitoring, structural sensing	MATLAB backend software for data exchange between local software and the simulated building	CFD and ODEs for building zone dynamics	Detection of air contamination and test of fault diagnosis to improve protocols	Desktop application, cloud platform for remote access and as is BIM model	(Hadjidemetriou *et al.*, 2023)

This also involves the use of security systems for the collected and stored data, for example in a SQL database and a Building Information Modelling (BIM) model as showcased in Mannino *et al.* (2019).

Table 1 summarises not only the applications of the DT concept to several assets levels (i.e., assets, systems, spaces, and buildings), but also allows to identify the technologies implemented for each individual capability in the analysed DT case studies. This forms the knowledge basis used for the development of the NRM2 extension. The identified technologies are in fact generalised and indicated as possible cost which must be considered in the design phase, for the estimation of built asset DTs.

The NRM2 extension

The developed method of estimation is outlined in Figure 1 which showcases the different types of components needed for estimation and avails of the current format of the NRM2 estimation standard which also includes a section including items already incorporated in the NRM2. The estimation method designed includes sections for components which are identified through Table 1. The multiple technologies needed for each capability are differentiated between hardware components and software components. The costs related to the hardware technological components is estimated as their prime costs as the supply rate for goods (RICS, 2021). On the other hand, for software technological components, the cost is related to time-related variables.

Data acquisition

The data acquisition includes within sub-component 1.1 the cost of installation of the data acquisition source and its associated prime costs, these data acquisition sources can be and are not limited to sensors of different kinds and QR Codes tags. These sensing technologies should be considered in addition to the BMS/BAS parts and are typical of DT implementations (e.g., occupancy monitoring sensors, air quality, indoor comfort etc.)

As this requires the installation of a physical element the quantities will be enumerated (nr) and for systems which could include multiple data acquisition sources, the quantities might be itemised (item). These data acquisition technologies have all different costs associated with their installation and require separate analysis.

A time related charge is allowed for the process related to its installation and the duration that the data acquisition source will have to stay in position during the construction phase which could include the protection to other type of works undertaken on site.

Furthermore, by following the process of installation of the data acquisition technologies, there is the need for installation and temporary maintenance of communication technologies. Thus, the sub-component 1.2 in the data acquisition section could require batteries or cabling - such as an ethernet cable as seen in the ISO 23247-:2021(ISO, 2021c) - directly to the data acquisition source, hence quantities might be itemised for systems or numbered for single priced components with a fixed charge or time-related charge. Furthermore, the NRM2 extension allows the possibility of integration of historical building data (sub-component 1.3), as outlined previously. For example, through BMS/BAS data, quantification can be itemised and have a fixed charge which would describe the type of data and the related cost for provision.

Data engineering

The data engineering includes the capabilities identified in the data modelling and the curation detected in the analysis of theoretical framework. The sub-component 2.1 includes the preparation of a digital model for the target assets processes and their interrelations. For this purpose, the BIM approaches can be used as well as other Modelling and Simulation (M&S) methods which should be identified and quantified as items. BIM, in fact, is an information management technique that follows the project life cycle. For this reason, a complete data management platform needs to be developed and costed, in support of the DT functionalities which need to be curated along the DT lifecycle. The included sub-component 2.2 includes the data storage and its related maintenance. Sub-component 2.3 regards the implementation of security systems and their quantification is itemised. Sub-component 2.4 regards the data access and interoperability which reflects the need for producing and using structured information in DTs. This allows systems, processes, and data interoperability. Since multiple methods could be used, quantities need to be itemised with each system separately, to identify the associated costs and pricing method (e.g., fixed charge or a time-related charge).

Data analytics

As there are multiple approaches for data analytics which could be developed, with different systems and which needs distinct correlated works, each individual data analytics techniques might identified (as outlined in Table 1). The data analytics method should be stated, and the quantities separately itemised and quantified to identify the associated costs and pricing method (e.g., fixed charge or a time-related charge).

Actuation

The actuation includes the sub-component 4.1: the installation of actuators of the building systems which facilitate the building control and automation of the spaces and equipment. These components should be considered in addition to the BMS/BAS. Furthermore, the included sub-component 4.2 will have to include the installation and temporary maintenance of communication technologies, which could require installations with batteries or cabling such as ethernet cables as in examples outlined in the ISO23247:2021(ISO, 2021c).

Digital Twin System

Component	Included (Sub-Component)	Unit	Pricing method	Excluded
1 Data acquisition.	The type of data collection source to be provided should be stated, with each type separately quantified: **1.1** Installation charge of data collection source.	item/nr	**1** Fixed charge **2** Time-related charge	**1** Operation and maintenance manuals (included in B.12 Contractor's cost items: completion and post-completion requirements). **2** Preparation of handover plans (included in B.13 Contractor's cost items: completion and post-completion requirements). **3** Inspection (included in B.13 Contractor's cost items: completion and post-completion requirements). **4** Training of building user's staff in the operation and maintenance of the building engineering services systems (included in B.13 Contractor's cost items: completion and post-completion requirements). **5** Information model and information management for BIM (included in A.9 Employer's requirements: building information modelling (BIM)). **6** Mechanical services system (included in Work section 38: Mechanical services). **7** Electrical services system (included in Work section 39: Electrical services).
	1.2 Installation and temporary maintenance of communication technologies.			
	1.3 Provision of historical building data.			
2 Data engineering.	The type of digital representation should be stated and if the representation avails of a BIM model: **2.1** Preparation of digital asset/process representation.	item	**1** Fixed charge **2** Time-related charge	
	2.2 Data storage and maintenance.			
	2.3 Implementation of data security system.			
	The method used should be stated with each method separately quantified: **2.4** Data access and interoperability.			
3 Data analytics.	The method used should be stated with each method separately quantified: **3.1** Work related to data analytics with supplied data and prediction algorithms.		**1** Fixed charge **2** Time-related charge	
4 Actuation.	The type of actuator to be provided should be stated, with each type separately quantified: **4.1** Installation charge of actuators.	item/nr	**1** Fixed charge **2** Time-related charge	
	4.2 Installation and temporary maintenance of communication technologies.			

Figure 1: Proposed method of estimation for DT systems based on the NRM2 structure.

Excluded components

Other tables and existing components already included in the NRM2, which may overlap, are excluded for clarity purposes. These are the operation and maintenance manuals (included in B.12 contractor's cost items: completion and post-completion requirements), the preparation of handover plans (included in B.13 contractor's cost items: completion and post-completion requirements), the inspection (included in B.13 contractor's cost items: completion and post-completion requirements) and the training of building user's staff in the operation and maintenance of the building engineering services systems (included in B.13 contractor's cost items: completion and post-completion requirements), the information model and information management for BIM (included in A.9 employer's requirements: building information modelling - BIM), the mechanical services system (included in Work section 38: Mechanical services), the electrical services system (included in Work section 39: Electrical services).

Validation of DT Systems designed method of estimation

The next stage of the research concerns the validation of the proposed NRM2 extension. For achieving this, a series of interviews with four experts was carried out. The participants were high-profile professionals in the fields of digital construction and have been selected based on their standing in the UK industry.

A total of eight open questions were asked in semi-structured interviews and are summarised in Table 2.

Table 2: Interview questions.

Question	
1	What is your current profession and your expertise in the AEC industry?
2	How would you define your experience in DTs generally? Also, do you have any experience in estimation for building works?
3	Do you think that DTs are beneficial?
4	What is your current opinion about DTs system for operation and maintenance?
5	Do you think the current proposed section can be used in your profession and why?
6	Can you suggest any improvements to the proposed new section of the NRM2?
7	Would you adopt this section for future implementations of DTs?
8	Do you think the current section could help other professionals in future implementation of the DT systems in the built environment?

The experts' profiles are summarised in Table 3.

Table 3: Summary of interviewed experts

Expert	Profession and expertise
P1	Planning and project management
P2	Works with a built environment professional body withing the standards team
P3	Chartered quantity surveyor working in academia
P4	Specialised in DTs and strategies

The analysis of the interviews is presented in the following section and focuses on the validation of the NRM2 extension while identifying possible further developments of the proposed work.

Validation and benefit of the NRM2 extension for DT systems

The experts P1, P2, P3 expressed the possibility of using the proposed NRM2 extension in their work. There are several reasons for that. For example, the interviewee P1 confirms that using a standard such as the proposed designed NRM2 extended method of estimation for DT systems allows a better understanding and breakdown of possible costs and this would increase the transparency of the DT design and development process.

P3 explains that the proposed approach gives the professionals involved in the cost process the possibility to better understand and quantify what should be covered in DT implementation. Furthermore, P2 explains that implementing standards for estimation for DT systems would be beneficial, and professionals should make sure that this is on their agenda when people are looking at creating new assets, so the DT components would be inserted in the programme and subsequentially costed from day one.

Possible Improvements of the NRM2 extension for DT systems

The experts expressed different suggestions for improving the NRM2 extension too. For example, one participant suggests to expand each sub-component, since there are many things needed to define certain aspects of the DTs. However, for effective pricing of these components it is understandable to have a broader description.

Other participants explains that the proposed extension has covered few or most grounds of the DT concept and this work should not be the end of the elaboration of the designed method and the proposed extension should be taken further and take into consideration DT systems generally and identify the parameters that can be measured. Also, the methods to effectively measure them should be studied.

Additionally, the NRM2 extension interlaps with methods of estimation already existing on BMS systems. However, since a DT system main value is to track data that is currently not tracked, the proposed extension should focus on the data interoperability aspect, the information and where this information needs to be stored as an essential part of the DT system. Finally, understanding the system architecture that needs to be implemented and how to link all the data from different sources should be taken into account, as well as focusing on the two essential aspects of DTs: fidelity and frequency.

Discussion and conclusions

The key objective of this research is to develop a method of estimation for DT for aiding the digital transformation process, and this sheds light on how digital technologies which fit within the DT concept can be effectively costed. In fact, the DT implementations play nowadays a central role in the construction industry digitalisation and, given the wide breadth of applications, represent a significant case of digitalisation in the construction industry.

To address the research gap, we looked into current standards and approaches utilised for DT systems implementation and through the analysis of the theoretical framework we identify some key capabilities: data acquisition, data modelling, data analysis, actuation and curation. These capabilities are analysed from the technological point of view and the enabling items to be estimated are identified. For this purpose, the NRM2 is used, and this aids the development of a method of estimation for the DT system during the phase of design which can be used for tendering. This research has been developed using a mixed evidence-based method and a literature analysis approach.

One of the main benefits is that the proposed method of estimation contributes to creating a standard for the estimation of the DT technological components, which streamlines the budgeting activities and improves the design and value engineering of the system.

Further studies should explore in more depth the DT capabilities and identify the detailed costs of DT systems proposed in the research within the NRM2 extension which includes the unit of measure and the applied pricing method. For example, the cost functions for each of the DT components have not been defined, as well as the total cost function. This would form part of the future development of this research.

Moreover, the last three steps of the design research method should be addressed, these include demonstration, evaluation and communication. Accordingly, the NRM2 extension should be implemented in a pilot design process, so that the results would be evaluated on a real testbed. The validation phase (an additional one to the preliminary validation carried out through interviews with the industry experts) can be carried out using a comparative evidence-based approach, assessing the effectiveness of the proposed method as opposed to the traditional estimation methodologies and through an additional round of interviews.

Also, further studies should explore the possibilities of life cycle costing for the implementation of the system and its financial/economic benefits throughout the life cycle of the building. This would contribute to a better understanding of the costs related to digital transformation.

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