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HUMAN-DATA INTERACTION IN INCREMENTAL DIGITAL TWIN CONSTRUCTION

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Abstract

An incremental approach to deploying Digital Twins (DT) can potentially highlight their gradual usability and practical development for the Architecture, Engineering, Construction, and Owner-Operator industry (AECOO). At the same time, a significant volume of multiple stakeholders' digital data on virtual and physical assets may be transacted. Therefore, investigating Human-data Interaction (HDI) over DTs will improve awareness and compliance on data acquisition and use. This paper conceptualises a framework of incremental interaction between HDI and DTs. Through this, new levels of HDI are defined over DT increments, including HDI-requirements, HDI-linkages, HDI-as-proposed, HDI-connected, HDI-training, HDI-learning, and HDI-independent.

Introduction

Human Data Interaction (HDI) involves, among others, the evaluation of the implications of collecting and using data in the Architecture, Engineering, Construction, and Owner Operator (AECOO) industry – while applying paradigms and regulations to understand the impact of this interaction on the actors/stakeholders involved. To investigate these topics, the European Council on Computing in Construction (EC3) established the Human-Data Interaction (HDI) Committee in July 2019, placing human data at the core of digital transformation for AECOO.

One of the most complex digital transformation concepts is the one of Digital Twins (DTs). Still, for the purposes of AECOO, it is essential to understand that the realisation of DTs starts in a project's early phases and then incorporates an increasingly larger number of dimensions when moving towards the construction process – and until reaching the use (operation and maintenance) phase and the project's end of life. Utilizing DTs in AECOO should therefore start by managing the construction sites to optimise ongoing design, planning and production (Sacks et al., 2020). Moreover, to enable higher maturity in the use of data, particular attention needs to be given to the use phase – so that data can be structured early enough to suit potential human interaction use cases (Kor et al., 2022).

Studies such as the ones mentioned above indicate the value of implementing DTs on multiple levels (or increments) and show that an evolutive mindset can allow AECOO to conceptualise and implement DTs, thus interconnecting the project phases, achieving project objectives, and increasing project performance. However, there is a lack of knowledge regarding which human-related data is connected to which DT increment, as well as how the corresponding interactions go and who the enacting stakeholders are. Therefore, this study aims to frame the HDI perspective over an incremental Digital Twin deployment in construction (Incremental Digital Twin Construction – IDTC), highlighting barriers and opportunities to achieve the highest maturity levels of the respective implementation increments. Stemming from this aim, this study's objectives are to identify the relevant actors, the data collected from them, and the data they will manipulate (e.g., assets) for a full DT deployment.

The introduction of this paper is followed by the research method and background sections. Then, the conceptualisation of HDI in the context of IDTC will be framed, explained, and discussed. Finally, the study will conclude with some final remarks.

Research method

The research approach of this paper is graphically described in Figure 1 and includes a literature review, an empirical study based on a focus group analysis, and a synthesis of the findings from the two methodologies mentioned above into the conception of the proposed incremental framework.

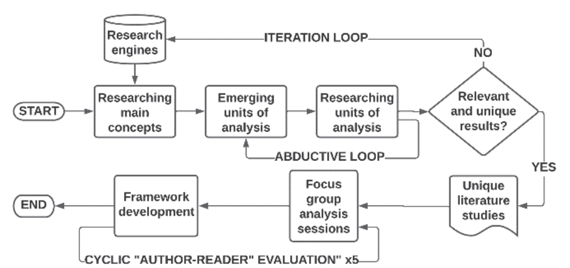

Figure 1: Research method

In more detail, the conception of the incremental framework followed the study and understanding of the relevant literature, and was realized through a focus group analysis (Knodel, 1993) across five sessions. The focus group featured the authors, who then iteratively reflected upon their insights after each session through cycles of the "author-reader" evaluation method (Kassem et al., 2014).

On the one hand, the goal of the focus group was to gradually develop the framework combining the different levels of DT development and HDI maturity, and was informed by the author's understanding of the literature on the relevant concepts through a cyclic process of qualitative abduction (Bell et al., 2019). On the other hand, the goal of the "author-reader" evaluation was to reflect upon the validity of the previously conceived incremental framework by considering the research findings of the EC3 HDI committee, including their definition of HDI in the context of the built environment (Kassem and Kifokeris, fo.).

Background

Human-Data Interaction

Through the analysis of personal data, inferences can be made about decision-making actions (Mortier et al., 2014; Wilke and Portmann, 2016). That interaction with human data is often opaque to the stakeholders (Mortier et al., 2014; Wilke and Portmann, 2016). Adding to this opaqueness is the multiplicity of sensors in intelligent systems (such as smart buildings; see definition below) in order to acquire data in real-time, near real-time, or in batch (see, for example, Line et al., 2022). It should be noted that multiple sensors might be embedded in the buildings and shipyards to collect environmental and personal data (Edirisinghe, 2019; Jakobi et al., 2019; Jia et al., 2019; Calvetti et al., 2020b).

Particularly, a smart building is a multi-stakeholder ecosystem where people cohabit as data producers and data consumers (Chowdhury and Dhawan, 2016; Xie et al., 2021). Data ownership and the decision to profile or not profile users are issues permeating GDPR and ethical concerns on data (Bennett, 2019; Calvetti et al., 2020a). Data ownership business cases may vary from more open models (e.g., unrestricted and semi-restricted data uses) to monetary approaches (e.g., license-restricted and paid per usage) and fully restricted use for vulnerable information (e.g., health care, military) (Chowdhury and Dhawan, 2016).

HDI principles aimed at system development allow for gaining the maximum benefit from a user interface (UI) of a DT system that learns on its own and keeps itself in check while being able to take corrective and preventive actions (Fjeld, 2020). While human interaction is not explicitly requested at this level (Fjeld, 2020), some compliance assurance processes should be followed (Mêda et al., 2022) to check how well the systems are connected to IDTC.

Despite attempts such as the above to raise HDI-related issues in the context of AECOO, a definition of this emergent concept is not yet established. Nonetheless, a *working* definition has been proposed in the seminal white paper of the HDI Committee of EC3: *"HDI is about understanding the interactions between actors and data across the planning, design, production, operation, and use of built assets, in order to improve the outcomes (e.g., economic, environmental, and societal) and value of data to the involved and the affected actors"* (Kassem and Kifokeris, fo.).

Incremental Digital Twin Construction (IDTC)

This IDTC vision targets a data-driven platform emphasising digital data, the Internet of Things (IoT), and, eventually, decision-making based on artificial intelligence (AI) (Calvetti et al., 2022). The maturity levels of IDTC, forming the increments the name implies, are conceived to be the following (also represented in Fig. 2 – see the next section):

- Static Twin (level 100)
- Detailed Twin (level 200)
- As-built Twin (level 250)
- Sensored Twin (level 300)
- Responsive Twin (level 350)
- Adaptive Twin (level 400)
- Intelligent Twin (level 500)

At the Static Twin level, there is some "static" information concerning requirements/specifications to allow the development of the building's graphical representation (often in 3D) (Mêda et al., 2022) - thus representing a "digital model" of the physical assets (Tchana et al., 2019).

Next, detailed data enriches the modelling of the Detailed Twin construction products - mainly based on digital data templates (DDT) in accordance with sources describing information needs, as per ISO 23387:2020 (Mêda et al., 2022). Also, detailed information concerning the construction processes is specified. With this, studies pertaining to, e.g., project lifecycle assessment and constructability, can be performed.

At the As-built Twin level, all information regarding the products and processes of the construction phase must be verified and validated (Mêda et al., 2022). A digital building logbook (DBL) (Mêda et al., 2022) can potentially start being established here to catalogue all building-related information. Until this level, unidirectional information is still integrated from the physical into the virtual environment (Fjeld, 2020).

Following the previous increment, when IoT sensors are being implemented in the construction phase (sensored construction sites), but also when moving into the operation and maintenance phase (smart buildings), the level of Sensored Twin is reached (Mêda et al., 2022). At this point, there is a bidirectional integration from the physical to the virtual environment and vice versa (Mêda et al., 2022).

Considering the sum of existing information and modelling artefacts in levels 200, 250, and 300 (Detailed Twin + As-built Twin + Sensored Twin), a "digital shadow" can be defined (Tchana et al., 2019; Mêda et al., 2022). The digital shadow is characterised by a high level of entanglement with the physical asset but nonetheless exhibits a lower level of twinning than the following levels of IDTC. This is due to the data processing being still dependent on operators providing information and interacting with the physical and virtual assets (Fjeld, 2020; Mêda et al., 2022).

Afterwards, sensing technologies deployed with AI-based processes can augment the bidirectional interaction between the physical and virtual assets mentioned above. This interaction serves as a transition from the digital shadow to the next level of IDTC, namely the Responsive Twin. Here, an operator conducts limited pre-established rules over the physical twin (Fjeld, 2020). At this level, it is possible to, e.g., assess temperature and electricity consumption, open and close doors and windows, and turn equipment and systems on and off (Mêda et al., 2022).

Afterwards, through the Adaptive Twin level, it is possible to deploy more autonomous rules with a system capable of simulating scenarios and implementing actions over the physical environment (Mêda et al., 2022). However, human observation is still required to calibrate the system and verify decisions made by machines (Mêda et al., 2022).

Finally, at the Intelligent Twin level, a fully bidirectional integration of the physical asset and its virtual twin is envisioned to be possible (Mêda et al., 2021). A self-learning and self-regulating twin system will be able to conduct corrective and preventive actions (Fjeld, 2020). Human interaction is not requested at this level (Fjeld, 2020). However, human observation is still required to calibrate the system, verify machine decision-making, and perform compliance assurance processes to verify the IDTC systems' performance (Mêda et al., 2022).

Human-Data Interaction in Incremental Digital Twin Construction

This conceptualisation highlights HDI-specific domains and levels of maturity correlated to the IDTC framework and its increments.

Stakeholders and data interaction over the evolutive levels of incremental DTs

During the lifecycle of a building, stakeholders that are potentially relevant in different parts of the DT spectrum will use its data in different ways. According to Chowdhury and Dhawan (2016), most stakeholders are either data providers or data users (consumers). Figure 2 (see next page) shows the AECOO actors in the IDTC vision. Here is a description of each identified stakeholder, the main data they will interact with, and whether they are more likely to be data consumers or providers:

- Owners: Interacting with strategic information emanating from the business itself, and information (either asset-related or personal) collected over sensors. Mostly data consumers.
- Designers: Interacting with strategic information emanating from the business itself. Mostly data consumers.
- Construction managers and contractors: Interacting with strategic information emanating from the business itself, and information (either asset-related or personal) collected over sensors. Mostly data consumers.
- IT technicians: Emphasising IT, they interact with strategic systems development from the business itself, as well as raw data (asset-related or personal) collected over sensors. Mostly data consumers.
- Data scientists: Emphasising data science, they interact with strategic information management from the business itself and raw data (asset-related or personal) collected over sensors. Mostly data consumers.
- System operators: Collecting data (either asset-related or personal) acquired through sensors. Most data consumers.
- Facility managers: Collecting data (either asset-related or personal) acquired through sensors. Mostly data consumers.
- Engineering suppliers: Sharing data related to their products/services and personal data. Mostly data providers.
- Procurement and construction suppliers: Sharing data related to their products/services and personal data. Mostly data providers.
- Construction workforce: Sharing data related to their performed work and personal data. Mostly data providers.
- Facility workforce: Sharing data related to their performed work and personal data. Mostly data providers.
- Facility suppliers: Sharing data related to their products/services and personal data. Mostly data providers.
- Building users: Sharing data related to their use of the built asset and personal data. Mostly data providers.

Those stakeholders identified as data consumers are more prone to use the data for different purposes based on their roles. For example, designers may use data to conduct specifications and estimations, and construction managers may use it to manage contracts and oversee craft workers. On the other hand, data providers are more prone to have data collected from their work or even from conditions related to their own person – for example, data collected from construction workforce activity outcomes, or from users of an office room inside a built asset.

Given the aforementioned descriptions and reflecting back on the definitions gained from the literature (see "Introduction" and "Background"), we can then start combining the levels of DTs and HDI. Figure 3 (see next page) depicts this incremental connection, with each level being elaborated on in the following. It should be noted that as IDTC levels become more complex, so do the corresponding HDI dimensions.

HDI to Digital Twin - general considerations

The human-data interactions linked to an incremental level of DT deployment highlight HDI domains that might

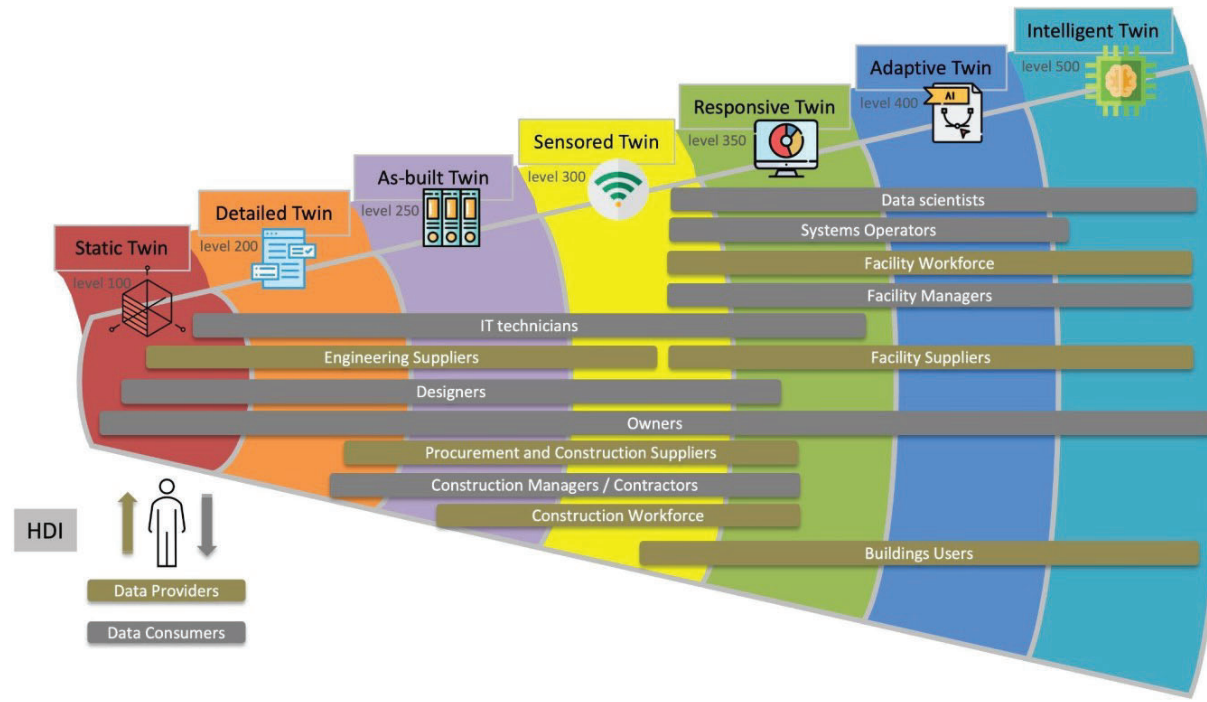

Figure 2: HDI stakeholders in IDTC

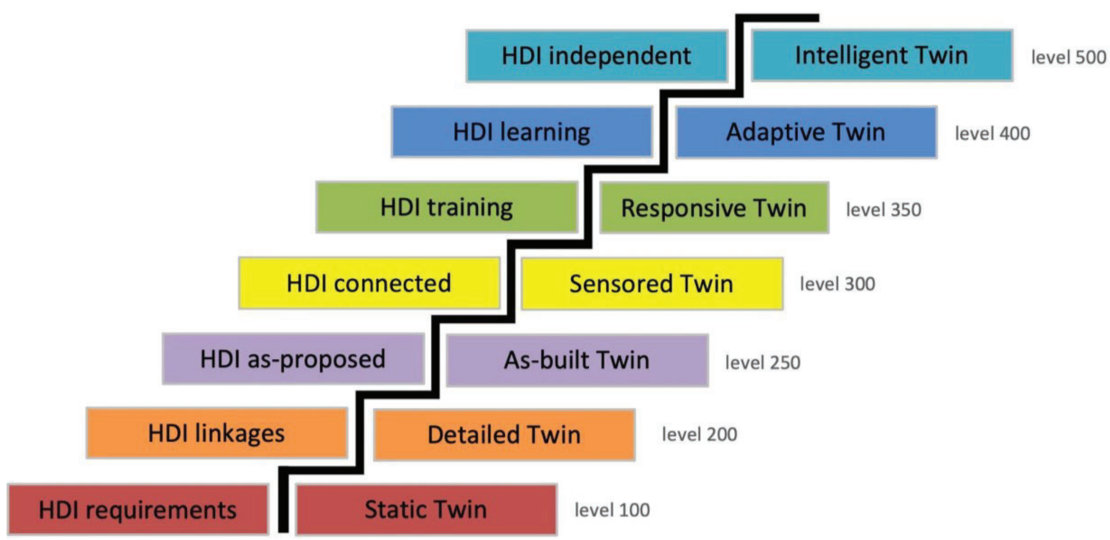

Figure 3: HDI Levels in IDTC

support the success of projects. Regardless, many barriers to DT development emanate from human activities and data-related issues. Therefore, a gradual data interaction enrichment might be more consensual and validated step-by-step. Moreover, applying HDI domains can bring opportunities to improve UIs. HDI plus IDTC can thus be a driver for change in the implementation of DTs.

Data interaction frequency increases as the DT evolves, growing in terms of information acquisition, the number of stakeholders, and data threads. Throughout IDTC, data acquisition starts with information requirements; then, data threads are linked to increasing interoperability; afterwards, information is enriched by surveying and checking the as-built asset (thus increasing the data volume, interactions, and even threats). At the same time, different actors are added to the DT processes over its incremental development.

The deployment of sensing technologies and the start of an AI-powered, bidirectional data interaction between the virtual and the physical environment add yet more actors, interactions, and data. However, moving towards more intelligent and independent DT increments (see Fig. 2) can result to the need for fewer human operators and the decrease of required human resources. On the other hand, data misuse and breaches might also increase, threatening legal, ethical, and cultural aspects. Systemic failures and cyberattacks might also put human lives in danger – e.g., opening and closing compartments and rooms, controlling air quality and quantity, and manipulating indoor temperature can be threatening to the users' health. Table 1 presents a summarised qualitative analysis of the aspects discussed above.

Table 1: HDI incremental levels: a qualitative analysis regarding interactions, stakeholders, and threats

HDI levels	Data interaction frequency	Number of stakeholders	Data threats (e.g., security)
HDI requirements	Very low	Low	Very low
HDI linkages	Low	Moderate	Low
HDI as-proposed	Moderate	High	Moderate
HDI connected	High	Very high	High
HDI training	Slightly high	Very high	Slightly high
HDI learning	Moderately high	Moderately high	Moderately high
HDI independent	Very high	Slightly high	Very high

Level 100: HDI requirements in the Static Twin

Most of the data interaction happens over the data containers or 3D models and is based on what the owners and designers want. IT technicians are strategically valuable in supporting software and database development. Still, at this level, surveying data, as well as putting it into software and relevant databases, requires a lot of manual work. Information for lead procurement is exchanged in a primarily manual process.

In this first level, most stakeholders may still be relatively uncertain (or even reluctant) about what data they need to deliver and how. Overcoming this uncertainty and reluctancy is vital to identifying, organising, and bringing the required data content into the twinning process – for example, via a common data environment (CDE) (Jaskula et al., 2022).

Level 200: HDI linkages in the Detailed Twin

Linking data makes it possible for more people and groups to interact and be involved in the evolutive (and increasingly more autonomous) twinning process. However, data shareability also gives rise to considerations on information security. Moreover, digital interoperability is important for setting up a DT, and the right flow of data can affect the success of a project.

For this scenario to work, one needs to be able to sort out data linkages. For that, linking requirements need to have already been set. Thus, the understanding of how to use structured data, its potential applications, and supporting systems, can be facilitated.

Level 250: HDI as-proposed in the As-built Twin

Information about the built asset on this DT increment is complicated because it is based on multifaceted data from products and work performance. Data can add profile identification regarding multiple actors – such as craftsmen, inspectors, and managers. Again, more layers of stakeholders are found. Data ownership and fair use are critical elements at this level of interaction.

The difference between this level and the one before is that data is more organised and linked, and technologies are put in place so that analysis can be performed in multiple ways. In this increment, encompassing platforms like a DBL can enable data shareability (Mêda et al., 2022). Here, the main processes associated with HDI are surveys and performance checking.

Level 300: HDI connected in the Sensored Twin

On this level, data acquisition is increasing at a high rate thanks to the implementation of sensing technologies. The interaction between the physical built asset and its virtual representation is made possible by sensors and their associated components.

Multiple stakeholders are required to deal with sensors and systems. As a result, IT expert support is required. In the 4.0 era, many IoT devices are envisioned to be connected to the work elements, workers, and building users. Also, dealing with human profile data can bring up problematisations, such as making sure that GDPR rules are followed (Calvetti et al., 2020a).

Level 350: HDI training in the Responsive Twin

Here, the collected data is processed and used for the process of acting in the physical building. Users' feedback from data interaction outcomes is critical to developing rules and new techniques. The DT operation, while still human-based, is supported by enriched information.

HDI is here envisioned to be at its highest frequency; everything is supposed to be working, and there is a lot to process. Human skills, knowledge, and wisdom are vital to understanding what to do with the available data. Some things need to be checked on all the time, while others only need to be looked at every so often. This is the most demanding level, as humans will be responding to the data they are seeing and analysing, and at the same time, they will be setting strategies on how to automate some or all of these aspects. At this level, it is essential to understand how data interacts for the best training of AI algorithms.

Level 400: HDI learning in the Adaptive Twin

On this level, the digital twin increases capacity by learning from human decisions and user interaction. Autonomous data interaction and simulations empower pre-established algorithms' actions. This means that models trained in the previous phase can now get validated against a new set of test data. This can lead to the virtual twin being able to change its activities and routines based on how people are using the building.

The rules and actions that govern the physical environment should focus on how well buildings work (both when they are being built and when they are in use) and how comfortable people feel. Keeping track of how well the monitoring works depends on how system performance and user satisfaction affect each other.

Level 500: HDI independent in the Intelligent Twin

In an envisaged fully autonomous and intelligent twin, the virtual machines will interact with the physical building without human intervention. Real-time data collection and independent actions will ensure facility management during the whole lifecycle. Robust systems will adapt and respond to human interaction. At this level, machines will lead data interaction using information gathered from the environment and human activities.

At the same time, multiple concerns may be raised, such as human safety and the redundancy of controls and drives. Systems blackouts or malicious cyber-attacks could lead to catastrophic situations. However, our incremental approach is envisioned to address such scenarios – as the described step-by-step entanglement between IDTC and HDI is envisioned to tackle issues as they appear in their respective phase, and facilitate incremental training, learning, and security improvement. It is conceptualised that this could guarantee a fully intelligent and independent digital twin environment.

Discussion

Digital Twins (DTs) in the Architecture, Engineering, Construction, and Owner Operator (AECOO) industry can exhibit benefits associated with their implementation levels and/or the range of systems with which they interact. However, despite emerging studies addressing this topic, it is still in its infancy. Therefore, more elaborating studies are needed.

One of the main aspects of DTs is their relationship with Building Information Modelling (BIM). The discussion on what is the same and what is different, the data, the systems' and workflows' overlap must be done. That might lead to tensions, as different understandings and practices exist from side to side. A clear definition of the possible boundaries or the range of the overlaps needs to be discussed. The key assumption is that BIM will tend to be mostly driven for the construction project life cycle and DTs for the built object life cycle. Further developments in the BIM methodology and its supporting standards – especially related to data management and processes management – should accommodate requirements and purposes that may be needed in the early design phase or only come at the moment of commissioning when the built object begins it service life. Some examples are the actions taking place on the Level of Information Need (LOIN) and Information Delivery Specification (IDS).

Related to this, collaboration and communication issues among stakeholders have been one of the main concerns in BIM. The development of standards is a work-in-progress action to tackle the problem and provide evidence of how communication and collaboration among stakeholders can be facilitated. As mentioned, the scope of DTs is broad (meaning that other stakeholders beyond the ones directly responsible for the asset's development can be involved), and the realisation of value for all related actors needs to be considered. Although some already developed standards might be applicable, more tests and use cases are needed to showcase all the relevant needs before jumping to problem-solving.

This is especially relevant for when real-time monitoring is required and involving different parties. Many can easily perceive this during the built object's use phase, but this starts during the construction process, where real-time monitoring of construction sites and worker safety through DTs is important. Again, some components, namely in terms of technology, might be the same. However, when looking from the monitoring perspective, construction workers' monitoring during the construction process is different from the building users' monitoring for the DT system of systems. The monitoring purposes, the aimed benefits, and the data ownership, sharing and use must be clarified, especially in the case of construction workers where the action can be more invasive.

As presented, two main dimensions share the DT. The human dimension during the construction process and the built asset dimension during its life cycle. Regarding the first one and considering everything said above, there are is a need for extensive training and mindset adjustments in the workforce towards DT adoption. Safety has all the conditions to be the driver for it. On the other part, DT enables on-time monitoring of buildings and all their parts. Predictive and preventive maintenance can be enhanced as we move up the increments in IDTC.

Both dimensions can benefit from improved automation and learning capabilities of DT. The use of machine learning and AI in developing and implementing DTs in construction can be a game-changer. However, there should be caution (especially at the Responsive and Adaptive Twin levels), where human knowledge needs to be brought to evaluate best what can be improved, where humans can be replaced by AI and where they should not. Human control cannot be eliminated at this point – AI systems still lack explainability. There should be ethical considerations, context awareness, and knowledge of the use case to successfully perform checks on the AI system (Calvetti et al., 2021).

In a related problematization, more evidence on tackled issues and use cases needs to be provided for some IDTC aspects. Standardization is, as mentioned, a way to provide sound guidance and rules for certain issues. In BIM, we see the work developed, and it should be questioned if the same is to happen with the development and implementation of IDTCs to ensure interoperability – as well as compatibility with existing systems and workflows and the eventual boundary definition in terms of scope and deliverables. In this, we can question if BIM should be understood as a subset of DTs.

Focusing on data, there are two main aspects: How are the accuracy and validity of the data collected and used in DTs, as well as its impact on decision-making in AECOO, ensured? What kind of quality checks can be performed on such multifaceted data? Previously, an access and ownership framework was set, based on the data consumers and/or providers. Yet, clear definitions must be worked on further and be associated with who owns the DT data (single or multistakeholder), who has access to it and where it is stored. This last aspect is aligned with concerns associated with cybersecurity (what kind of risks and data breaches might exist, and how security should be prioritised from the outset).

One final aspect is related to the reflections on the integration between the physical and the virtual world, where we should question: Even in IDTC, how seamless should the integration of DTs with the physical world be, how accurately should they represent it, and will the envisioned HDI dimensions play the role conceived in the current paper?

Finally, all this IDTC environment is being set to benefit humans. Therefore, a human-centred design must be the aim, and in that sense, DT technology should be developed and implemented in a way that considers the needs and concerns of people who will be interacting with it – hence the need for careful considerations regarding HDI. The biases in data collection and analysis and the impacts they could have on decision-making need to be forewarned.

Conclusions

The incremental approach to Digital Twins (IDTC) aims to enable its gradual understanding and implementation in the Architecture, Engineering, Construction, and Owner Operator (AECOO) industry. Underlying the usability and maturity for doing it is the awareness of the human (and other) data needed for the interactions between the physical and the built assets. Therefore, the human-data interaction (HDI) domain is a strategic piece of the puzzle towards DT adoption in AECOO, and should be investigated accordingly. This paper initiates the tackling of issues related to this domain, by conceptualising a framework of incremental interaction between HDI and DTs. Through this, new levels of HDI are defined over DT increments, including HDI-requirements, HDI-linkages, HDI-as-proposed, HDI-connected, HDI-training, HDI-learning, and HDI-independent.

The work developed can be framed as introductory or exploratory, meaning that the objective was mostly on the broad perception and settlement of a conceptual framework liking IDT maturities with HDI levels and their definition.

Future work will continue to offer further details on specific aspects of the IDTC vision implementation and address the previously discussed concerns.

Increased research efforts are being made towards HDI in AECOO. From our perspective, the HDI concept is at the centre of all actions and dimensions that are relevant to AECOO in terms of human-centric systems and solutions that are being advocated as the background for Industry 5.0 – but construction is still away from accomplishing the 4.0 paradigm. Therefore, this work aims to provide awareness and tools to understand better and refine data acquisition and use towards a more digital and sustainable construction.

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