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APPLYING VIDEO GAME DESIGN TO BUILDING DIGITAL TWIN CREATION

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Abstract

There is growing interest in Digital Twins (DTs) across the construction sector. Increasingly, researchers are expanding DTs from early BIM representations to add functionality through machine learning and advanced simulation applications. Video game technology can facilitate DT operationalization, however there is little guidance on how to achieve this. This paper presents a conceptual framework collaboratively developed by researchers in BIM/DT development and video game design, along with Facility Management input to guide Building and Infrastructure DT creation by construction professionals. This was then used to operationalize on a full-scale building DT created in BIM, demonstrating its value in practice.

Introduction

A building digital twin (DT) is being developed for a pilot campus building and was initially developed using the as-built Building Information Model (BIM), simplified and populated it using a semantic linked data approach, and integrated it with live data streaming to provide interactive 2D and simplified 3D visualizations (El Mokhtari, et al., 2022). However, a more immersive and readily-interactive environment is desirable to improve the user experience. The approach used to develop this DT has been presented in previous literature (El Mokhtari, et al., 2022).

In order to test this application, proofs of concept are being developed for two use cases with different audiences: wayfinding (visitors), and equipment identification and data acquisition (facility management (FM) personnel). The current implementations are usable by FM staff familiar with 2D and 3D building representations (e.g. BIMs and floorplans) but to extend this user base (to visitors, maintenance technicians, etc.) a more complex, high-fidelity, immersive environment capable of providing the interactivity and complexity of interaction and data display is necessary. Such a display will also support the longer-term ambitions of the DT of event detection and scenario analysis for emergency planning, virtually testing new control strategies, and predicting equipment failure.

Increasingly, scholars are turning to video game technology to develop the complex and immersive environments required for DT operationalization. DTs are valuable for Human-Building Interaction applications and are a subject of increasing, albeit limited, research (Barricelli & Fogli, 2022). As with video games, DTs require active participation rather than simply observation, requiring the end-user to navigate complex, data-rich, immersive environments. Because of its extensive library of ready-made objects and algorithms, open-source format, and Twinmotion and Datasmith plug-ins that enable the rapid import of BIM, Unreal Engine is particularly well suited to building content.

The creation of DTs poses several challenges (Rasheed et al., 2022). While there has been significant interest in video game technology within the architecture, engineering, construction, and operations sector, for example (Guo et al, 2022), there has been very little development of digital twins for building FM applications, most notably (Azfar et al., 2022). To guide construction professionals in such development, this paper presents the application of video game design principles to operationalize a DT and applied to a full-scale building and concludes in the presentation of a conceptual framework for DT creation.

Background: Elements of Video Game Design

Due to their immersive and interactive qualities and the way they facilitate human learning, video games are a popular form of entertainment. Purpose-driven game design is an approach to create video games that focuses on the intended purpose or goal of the game. This approach emphasizes the need for game designers to understand specifically *why* they are creating the game and what players can experience through playing it. Purpose-driven game design can help designers create games that are more effective at achieving specific goals, such as educating players or promoting social change (Hunicke et al., 2004). To provide these qualities, games are designed around three fundamental elements:

mechanics, dynamics, and aesthetics (MDA) (Hunicke et al., 2004).

Mechanics are the rules and systems that govern its operation and the actions players can take; these are referred to as 'affordances' (Gibson, 1979). *Dynamics* refers to behaviors of the aforementioned mechanics, via the affordances of the interactive space. *Aesthetics* refers to the video game's visual and auditory design, including its art style and sound effects. While these elements can be applied in all types of games, because of their immersive nature, CDTs most closely resemble *video* games (as opposed to board games, for example) and thus that application type is the focus of this research.

The MDA framework can be viewed as complementary to agile methodologies via iterative specificity; game design requires careful and intentional resource use. For the purpose of this research, the MDA framework provides a structured way of thinking about the various components of a game, complementing lean and agile methodologies, which provide tools and techniques for implementing and refining those components in an efficient and effective manner. It can be used also to identify the key components of a video game, after which lean and agile methods can be used to iteratively test and refine these elements via rapid prototyping and user feedback.

Mechanics:

Within game mechanics, the concepts of *player autonomy, affordances*, *signifiers,* are the core considerations relevant to DT development.

The degree of *player autonomy* in a game must be determined during video game creation; the same is true for a DT. The designers must determine the bounds of player autonomy, whether related to where they can navigate, what can be manipulated, what players can see, and accompanying semantic information. Player autonomy in video games refers to the extent to which players are able to make decisions and take actions independently (Johnson, 2020). This can include both in-game elements such as available choices and actions and the broader rules and limitations governing them.

Affordances relate to the action options made available to the player in order to explore or manipulate a game environment. (Norman, 2013). Affordances are a crucial component of game design since defining how a player can interact with a world, the ways they think about and navigate the world are shaped. By providing the user with clear affordances, the game may facilitate a more intuitive and pleasurable experience (Cardona-Rivera, 2013).

Affordances in a video game environment can be indicated by a variety of signifiers*,* including visual cues, aural cues, and other sorts of feedback. For instance, a bar on a door may imply that the player may open it by pushing it open, but a handle on a drawer may indicate that the player can open it by pulling it open (Norman, 2013). These indicators convey to the player what actions are available and how they can be executed.

Dynamics:

Dynamics play a critical role in designing sites for player engagement and motivation, specifically because it aims to provide nuanced descriptions of 'when', 'how', and 'where' players will engage. The detailed breakdown is usually specific and detailed, outlining elements, and, for example, how long elements are present, like when the user receives on-screen prompt, for how long, and within which context. This is necessary for the developer of the experience, such as a computer programmer or world builder. Focusing on the MDA framework as a starting point allows DT designers to better establish the goals of the experience and establish how they will be experienced from the player perspective. Further, when in-experience, playtesting is a critical step in gauging the levels of success between expected and actual player behaviors.

Player engagement is one of the most complex aspects of game design, and it is the crux of Games User Research, which helps to define how to motivate and engage players. Multiple strategies of integrating audio, text, video, and interactivity are implemented in video games to maintain player motivation and engagement (Koster, 2010). Haptic feedback may also be used, , in addition to in-game elements like rewards (e.g. in-game currencies like points, badges, or other incentives for completing tasks or achieving particular milestones) to motivate players to continue playing and accomplish specific objectives (Claffey & Brady, 2019). These prizes can help stimulate and retain players' interest in the game by providing a sense of progression and accomplishment. Checkpoints, and in-game markers, such as levels or experience points, allow players to track their progress toward these goals, while specifically being made aware of their success or failure throughout an experience.

Within game dynamics, traversal, challenge, fellowship, participant expression, and feelings of randomness via probability distribution are some of the most critical considerations relevant to DT development (Hunicke et al., 2004). The dynamics are a critical component of the 'illusion' of space design, as participants will need to connect with the DT as a means of engaging with the properties of the space. One critical example from DTs would be control systems for building equipment (e.g. supply temperatures, air quality, etc.). throughout a building. Once congruence between queries of control parameters and user intractable items, such as drop-down menus in the investigation mode or adjustment of a dial in the optimization mode, signifying interaction with HVAC are established, participants connect their actions to the affordances of the world.

Effective traversal in video games often relies on a combination of guidance and affordances. In effect, drawing the players attention to where they need to go in order to proceed, and then providing them the pathway and tools to do so. Significant video game design theory explores intuitive and effective communication strategies (Kapadia & Badler, 2013). Further, every element of a player's navigation in a virtual environment must be broken down into a series of heavily studied forms of interactivity, see (Crawford, 2003) for a detailed discussion.

A significant amount of planning and prediction is necessary to teach players how to navigate game environments intuitively and smoothly, where to find tools, and how these new tools change how the player can navigate the game world (Sutton, 2018). Several game mechanics are critical to effective navigation. Boundary Conditions define what elements of a world are navigable, and the limits of a player's exploration (for example, the edge of a field the player is exploring might be walled off with thick forests or tall cliffs). Affordances are the systemic rules of a world and how the player can interact with and navigate the environment (for example, ladders and platforms allow the player to move vertically in an environment); Signifiers inform the player that certain affordances exist. In addition, *levels* allow the designer to constrain or contain the player within certain areas or challenges as a way to structure progress or ease the graphical pressure on the computer and consequently ease loading times.

Wayfinding refers to the process of navigating through the game environment. Wayfinding is critical as it helps to guide the player through the game and ensure that they are able to successfully complete the various tasks and challenges presented (Nisbet, 2016). Good wayfinding design increases enjoyment and engagement, while poor wayfinding can cause frustration and disengagement. Wayfinding is enabled using *signifiers*, intuitive navigational aids, in order to point players to both the navigational goal and affordances to do so (Norman, 2008). In many cases, bright colors are used to draw the eye as flags for key information or architectural magnets are placed in such a way to stand out in the environment (Sutton, 2018). These systems are advantageous because they are intuitively "in-world", which helps them to feel more immersive and part of the explored environment (Sutton, 2018). This can be further underscored through the use of key lighting to indicate specific interactive elements in the environment (Veloso, 2019).

Leveraging Unreal Engine as a foundation for a Digital Twin permits many design efficiencies in programming and logic. Navigational logic, for example, is a fundamental tool used for game systems to allow entities in a game that are not directly controlled by the player to navigate the environment autonomously. These entities, commonly referred to as Non-Player Characters (NPCs), do not inherently know how to navigate a game environment. Instead, logic needs to be written for each NPC on how its movement relates to the environment. For example, such rules could dictate how a monster searches for the player, and how one could hide from it. Traditionally, navigational logic in games is handled through variations of a Path Search Algorithm, one of the most common of which is the A* algorithm (Yap, 2002). Path Search Algorithms lay out a series of navigational flags through the environment and place the shortest line along these nodes between an entity and the desired destination. Other NPCs logic focuses on determining the preferred destination, which may be leveraged to access facility data to inform priority areas that can then be visited using the Path Search Algorithm.

Given the ubiquity of Path Search Algorithms in video games, engine tools like Unreal Engine have many solutions for such pathfinding ready-made and adaptable to unique circumstances. Any pathfinding tools which are deployed to a Digital Twin as a result do not need to create such algorithms from scratch, or define custom logic. Simple navigational points need to be populated into the digital twin, and then heuristic algorithms already available in Unreal Engine can plot the navigational data.

This can have a marked impact on the total work required to plan and develop navigational aids for users of a digital twin at both the base user and advanced user levels. A simple navigational map can be created to guide an individual to a desired location in the building on-demand; or a member of the maintenance team can be guided to a fault as part of a support ticket, improving response times.

Aesthetics

Game aesthetics offer significant value for DTs to enrich contextual information for its users. Audio, text, video, interactivity are the core ways in which humans obtain information and are more effective when combined. Because a DT 'game' serves as a learning device for building users or facility managers, the integration of these elements will allow them to rapidly and autonomously absorb pertinent information from the 1:1 replica of a space. Though some games can afford multiple perspectives, view limiting, or frustum is a critical component of both memory usage, and player scaffolding. For clarity, frustum refers to the amount that a player can see at a given time, one example from the real world would be the view down a street on a clear day, and the view down that same street at night, or on a foggy day. The frustum, in game design, refers to how far players are allowed to see, and this can be done via wall placement, or effects such as darkness or weather conditions.

There is a wealth of literature regarding effective user interfaces for FM, see (Gruhn, 2011; Araskiewicz, 2017; Duan et al., 2011). Key strategies of potential value for DT creation are the use of representative colors patterns, and/or linetypes for different type, or the absence of, data (Pin et al., 2018;), the use of color intensity indicate issue severity or deviation from normal values (ASM Consortium, 2009), and the development of a hierarchy of views to support navigation at the room, floor, and whole-building levels (ASM Consortium, 2009).

Within video game design, a similar design language exists to provide contextual data interpretation cues for players, defined by color use as a *signifier,* sound cues, text, prompts, quick time events - short input windows for user input. Referred to in the game design field as the **User Interface** (**UI**) or **User Experience** (**UX**), elements such as wayfinding, object identification, and data acquisition are crucial for DT development. Video game design offers several valuable insights to make the DT as simple as possible for facility personnel to use. First, data presentation can either augment or complicate navigation. The use of informational colors (e.g. red=bad/stop; green = good/go) or spectra (neutral/white = normal with increasing colour saturation to show potential issues) (Pin et al., 2018), symbols, or context-specific displays are widely used to reduce player cognitive load (Brunken & Plass, 2003). Context-specific displays are also valuable for user interface design, permitting in-context, or just-in-time information if and when needed throughout the experience. This is especially relevant when a participant would like to access specific information briefly, to continue with interaction shortly after information is obtained.

DT Development as Video Game Design

In order to translate the DT requirements into a video game design document, the DT project leaders collaborated with video game design experts to define and develop the core DT 'gameplay' using the MDA approach. Working together, the authors first defined the game purpose and expected user needs and used these to define game mechanics, dynamics, and aesthetic requirements, which were used to develop the proof of concept included in this paper. Three modes (visual, wayfinding, and troubleshooting) have been implemented, while the latter two (optimization and training) are outstanding as they rely on ongoing research to develop new algorithms and the input from the Facility Management team regarding training interface preferences, respectively.

Purpose-Driven Digital Twin (Game) Design

In order to ensure that the digital twin is valuable for end-users, it is important to first identify them, developing user profiles for each, and then understand their requirements to develop appropriate use cases for each. engage them in the design process. User-centered design is a key strategy to actively engage the end-user, focusing on understanding their needs and priorities, and developing prototypes and mock-ups to gain input at each iteration.

The following priorities were communicated by the Facility Management team in a previous study (Pin et al., 2018): (1) immediate identification of the most problematic areas; (2) visualization of clusters of issues within buildings to understand their behavior over time; and (3) the ability to differentiate between types of issues and their distributions. Since that time, new members of the FM team have also expressed interest in online fault detection and diagnosis and energy optimization.

Integrating these, four user profiles were developed:

Building Stakeholders are a diverse group of individuals with a measure of interest in the building, whether as neighbors, building occupants, donors, campus members, etc. They are seeking to gain high-level insights on the building such as its layout, sustainability initiatives, etc. Use cases required: visualize the building at the room, floor (level), and whole-building level and access publicly-available data on building performance, if available.

Building Visitors are individuals with minimal building familiarity who are seeking to navigate to a particular building location. Use case required: wayfinding.

FM Trades Personnel are individuals with moderate to high building familiarity who need to quickly identify and locate equipment in order to undertake maintenance and/or repair. They require limited – if any - access to building data. Use cases required: equipment location; faulty equipment identification (individual and by floor/zone); and current performance information.

FM Engineers & Operators are individuals with extensive building and system knowledge who are seeking to identify and/or troubleshoot faults and fault patterns and optimize systems. Use cases required: all of the above, plus historical data visualization; scenario analysis; optimization and recommender system access.

Once established, these profiles with corresponding use cases were used to define game mechanics, dynamics, and appropriate aesthetics.

Defining DT Game Mechanics

In the DT, player autonomy was based on the user's mode. Five modes were identified of value to DTs: visual, wayfinding, investigation, optimization, and training modes. These are described in the following sections.

Visual Mode (See it)

The visual mode was developed for *Building Stakeholder* users. In this mode, the player is represented as a camera and is not limited by either gravity (i.e. vertical travel is possible even without stairs) or physical barriers (the view may pass through ceilings and floors). Figure 1 presents this mode in a top-down 3D view, providing end-users the ability to see all equipment on a level simultaneously. This mode can also incorporate buttons directing building stakeholders to public reports and other data.

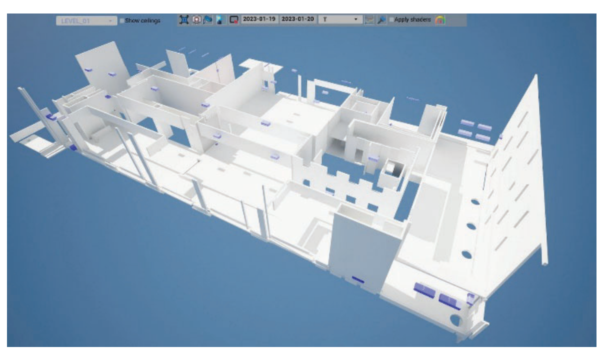

Figure 1 "See it" mode showing standard display of walls (shaded) and equipment

Wayfinding Mode (Navigate it)

The wayfinding mode was developed for the *building visitor* end-user. Within wayfinding mode, the user is represented as a person limited by the laws of physics - i.e. they are limited by gravity and cannot pass through solid objects such as walls. This ensures that transversal logic algorithms do not provide unrealistic navigation routes but rather direct users via vertical transportation elements (stairs, elevators) and constrain paths to enter rooms via doorways.

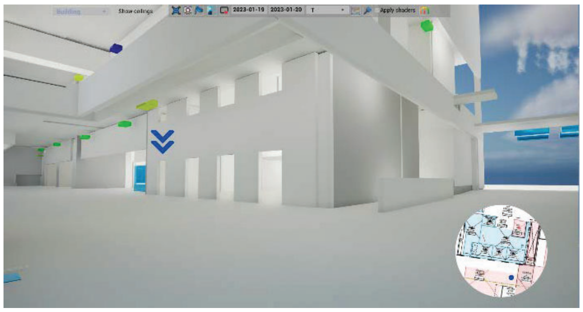

Figure 2 Wayfinding Mode indicating the recommended path of travel (blue arrows) and a key plan of the user's location (bottom right)

Investigation Mode (Look inside it)

The investigation mode was developed for the *FM Trades* user. As in visual mode, users are not limited by gravity and may fly to any vertical location inside or outside the building, pass through walls and ceilings without obstruction, and look inside devices. Further, users are afforded the ability to view current and historic data associated with the selected element as well as any issues flagged by fault detection and diagnosis (FDD) and other event detection algorithms.

Figures 3-6 present a compilation of images of this mode, showcasing the progression of how a facility manager may use this mode. Figure 3 shows how turning the wall's transparency on can allow them to survey a level (or the whole building) all at once to identify unusual or faulty equipment performance. Figure 4 illustrates how this mode supports the inspection of all data points for an individual piece of equipment, either that was identified in that survey or has been otherwise flagged for investigation. Figure 5 displays how data trends may be displayed for a data point exhibiting an unusual value, while Figure 6 shows how this can be contextualized by comparing this data trace with those for similar equipment.

Optimization Mode (Operate it)

The optimization mode was developed for the *FM Engineering Staff* end-user type to provide the maximum data access and functionality. All of the affordances granted in *investigation mode* are provided, plus the ability to access advanced predictive and optimization algorithms from within the DT. Two new overlays extend this mode from the previous. The first supports future data visualization, accessing machine learning to

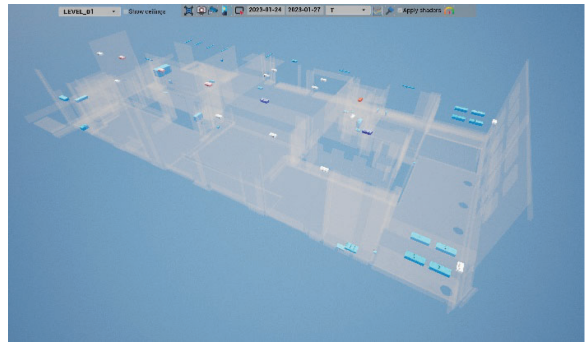

Figure 3: Investigation Mode Overall level view with transparent walls and all equipment, color-coded based on AI event detection algorithms) to permit rapid identification of equipment malfunction.

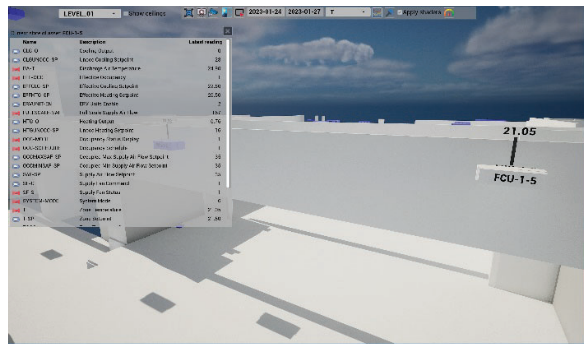

Figure 4: Investigation Mode: Close-up of a single piece of equipment with pop-out displaying all streamed data points with current values.

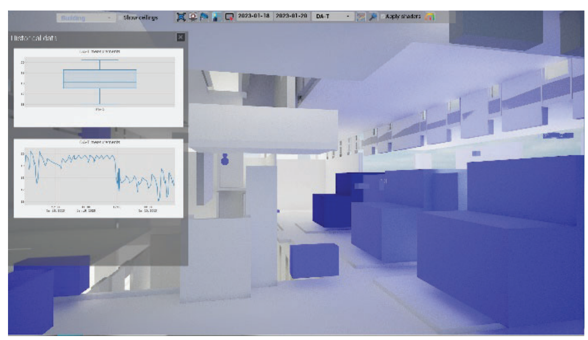

Figure 5: Investigation Mode: Historical view for a piece of equipment showing historical boxplot and time-series data for selected data point

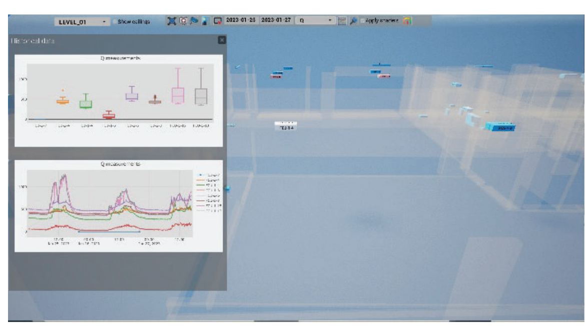

Figure 6: Investigation Mode: Multi-equipment historical view showing data traces and box plots for each of the selected equipment

estimate 24-hour look-ahead energy consumption for the equipment or system and/or the predicted time to equipment failure. The second is a recommender system interface, allowing both user-generated queries to identify potential control system modifications, for example supply temperature setpoints, and algorithm outputs recommending additional potential changes. In this mode, virtual buttons and dials are overlaid on the equipment that can be manipulated by the facility manager to run scenario analysis in these windows or export them to a downloadable report.

Training Mode

Similar to video game tutorials, the training mode is an interactive tutorial mode, teaching end-users how to access the DT functionality and build general user skills. Because each user profile has a distinct set of affordances based on its associated mode, a modular approach to training mode elements is required.

Defining DT Game Dynamics

The navigational system was developed using Unreal Engine navigational tools. A navigational mesh was created, laying over the floor surfaces of each of the building's game "levels". Within each level, navigational links were defined to help generate a robust set of navigational pathways. The Digital Twin is then able via a prompt to trace a guided pathway from the user location to the nearest node and then onwards to each subsequent node on the way to the target destination in the most efficient pathway as determined by the navigational logic. To accommodate transversal between levels, vertical transportation elements (elevators, stairs, etc.) are defined and can be used as part of the user path.

The building's architecture, which includes a large number of static meshes and mechanical equipment, can be resource-intensive to load into memory. To optimize this process, these objects are stored in Unreal engine library and an internal table is generated that includes metadata such as the level to which the static mesh belongs and its type (wall, ceiling, floor, etc.). When the user selects to view a specific level, non-interactive static meshes are dynamically loaded into the viewport first, while interactive assets (actors using blueprints and/or C++ code) are created in a second stage. Sometimes, the user may choose to view the entire building to navigate or monitor sensor data throughout.

Data is the foundation of a DT and is essential for its operation. The DT relies on two primary sources of data: an ontology database and a time-series database. The ontology database describes all entities within the building and their relationships, such as HVAC equipment and their underlying sensing points or the relationship between equipment and building locations. The ontology metadata is fixed and updated when changes occur in the building or equipment. The time-series database ingests sensor readings in real-time from the building. These two data sources reside in the cloud and can be accessed through secure API endpoints. The Unreal engine front-end translates user requests into API calls, sending back data in an interpretable format. Event-driven blueprints or C++ object classes then process the data and act on the dynamic actors in the viewport subsequently.

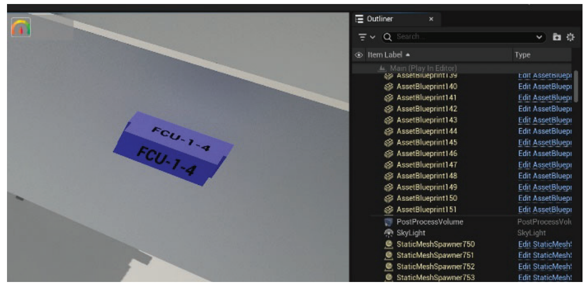

Figure 7 Screenshot of Unreal DT interface indicating the device dynamic hierarchy used to limit visible elements to improve load speed and reduce computational requirements.

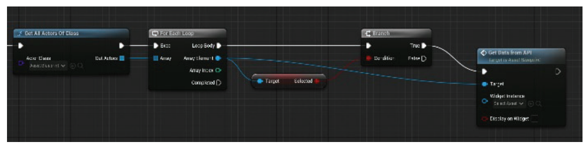

Figure 8 Screenshot of Unreal DT interface indicating blueprint definitions supporting API integration and queries from the DT data lake. C++ code is utilized to handle the low-level API interactions.

Defining DT Game Aesthetics

The color of an asset is determined by the selected sensor's reading. Following the industry best practices identified, a three-color gradient was defined, where the normal data range is displayed as white (with black text), data below the normal range is displayed with increasing blue saturation from 5% just below the normal range and increasing to 100% at 50% of normal values. Similarly, data above the normal range is displayed in increasingly red saturation with the same relative scale. The 'normal range' can either be prescribed or inferred from historical data. Sensor readings are displayed prominently as call-outs on top of each asset, and can be configured to update at regular intervals for continuous monitoring, such as monitoring CO2 levels in the building.

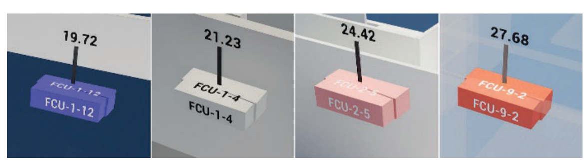

Figure 9 Temperature ranges are indicated by color shades based on a prescribed operating range of 20°C-24°C.

Conceptual Framework for DT Creation

The proof of concept demonstrated the application of video game concepts to develop a DT. These concepts and considerations and guiding questions to apply them are illustrated in a conceptual framework designed for construction professionals to use in DT creation in Table 1.

Table 1: Conceptual Framework for DT Creation

Objective	Concepts	Guiding Questions and Design Considerations
Create end-user value	Purpose: User-Centered Design	*Who are the expected DT user groups?* For each group, define a user profile outlining: 1) how they will interact with the building, 2) the building data they will need to access, and 3) the DT use case(s) they will require.
Provide an appropriate degree of autonomy to each type of end-user	Mechanics: Modes & Affordances	*How should each user group be allowed to interact with the DT?* *What rules must be determined with respect to data visibility and navigational constraints for each user group?* Determine the appropriate mode(s) of interaction most suitable for each user group, for example (view-only, wayfinding only, inspection, and operation) and the rules governing player interaction and navigation for each. In addition, define a modular training mode to teach each user group how to use the DT.
Guide end-users in the availability of actions and potential navigation paths	Mechanics & Aesthetics: Signifiers	*How will potential actions and limitations be communicated to end-users?* Define a visual, haptic, audio, or other cue to indicate the presence of an interactive DT element or affordances or constraints on navigation.
Guide player navigation	Dynamics: Wayfinding Path Search Algorithms	*How much guidance do end-users require to navigate through the DT?* Develop appropriate wayfinding signifiers (arrows, maps indicating routes, etc.) to guide end-user navigation. Where directions are required, define horizontal and vertical transversal paths to implement a path search algorithm to automatically create a user path to their destination.
Present information intuitively and allow its contextual interpretation	Aesthetics: UI/UX Design	*What data or information is critical end-users?* *What are the expected data ranges for each type?* Work with end-user groups to define the typical and 'danger' ranges for each data type and an intuitive colour spectrum to alert them of relevant events.

Conclusions

Digital Twins have the potential to fundamentally transform both building occupant experience and FM practices. As demonstrated in this paper, video game design practices, including both purpose-driven game design and the mechanics-dynamics-aesthetics (Hunicke et al., 2004) framework, are extremely valuable to guide immersive virtual twin development. Key benefits of this approach are the ability to provide more immersive visitor experiences, more intuitive navigation, more sophisticated data access, and access controls set by end-user mode and its associated affordances and signifiers. Within the context of the DT the signifiers can be found in the UI map overlays, floating arrows above context specific details such as elevators, and in the starting direction of the player when the experience begins.

The key limitation of this study is its application to a single case study, albeit a complex and reasonably well-developed one. Future studies to apply the purpose-driven MDA design framework in other contexts will be valuable to confirm the generalizability of this approach. Second, the aesthetic development to date is limited. As evident from the images, the proof of concept shared in this paper represents an early version of the DT with limited graphical development. A photorealistic version of the building (adapted from its as-built BIM) is currently under development and will populate future versions of this model; to enable this, all of the DT development has been automated to permit its rapid update following such an upgrade. Finally, there are few signifiers present in this proof of concept; this is due in part to the simplicity of the building model (e.g. there are no internal doors) and in part because the optimization mode remains undeveloped and thus signifiers to indicate equipment controls modifications have not yet been included.

Several avenues of future research have substantial potential benefits. First, user testing would be valuable to determine both whether the complex and immersive DT environments enabled by video game technologies prove easier to use for – or more readily accepted by - FM personnel than Building Information Model (BIM) DTs. Particularly for such users with limited BIM experience or familiarity with 2D drawings, such environments may prove more accessible and such insights could help to enable adoption of FM DTs. Second, the ever-expanding diversity of prediction, classification, and optimization algorithms offer significant potential to develop more realistic and interactive simulation of building system operations, allowing building operators to explore and experiment with various scenarios, testing and refining their management strategies in a controlled environment. Finally, the use of *pedagogical scaffolding* - increasingly complex challenges and tasks to support learning and skill development – could assist in building the knowledge and expertise of building operators over time, thereby enhancing their capacity to manage and maintain complex systems. Moreover, providing users with a high degree of autonomy, or the ability to make their own choices and decisions within the game, could encourage building operators to take an active role in the management and operation of their buildings by fostering a sense of ownership and responsibility. These game design principles and techniques have the potential to help the Building Operations industry create a more effective and engaging training and simulation environment.

Acknowledgments

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