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DIGITAL TWIN OF A DESIGN PROCESS: AN EXPLORATORY STUDY

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ABSTRACT

Digital twinning is a new approach to enhance the management of design, planning and construction operations. A construction digital twin aims to enhance the reality capture of ongoing operations using sensing technologies and AI functions to enable proactive process management. While a digital twin is clearly defined in the context of construction operations, where a digital replica is generated out of a physical site; a design digital twin lacks a clear framing as both twins are digital. This paper explores an approach to creating a design digital twin using agent-based simulation to mimic real BIM-based design projects. Accordingly, a digital replica is generated as an agent-based model. In addition, several KPIs are introduced to capture data related to BIM model dynamics. The results show that the suggested KPIs can increase the transparency of the design process, capture development dynamics at the level of BIM model elements, increase situational awareness among designers related to model development status, and identify higher clashing risk zones.

KEYWORDS

Lean Construction, Visual Management, Process, Design Digital Twin

INTRODUCTION

The importance of the design phase in overall construction project performance has been revealed in several studies (Said and Reginato, 2018; Li and Taylor, 2014; El. Reifi & Emmitt, 2013, Sacks et al., 2009). It is in the design phase where the project value is formulated and developed among different stakeholders (Khalife and Hamzeh, 2019). Several characteristics make the design process challenging to manage. Being fragmented, iterative, and exploratory in nature (Berard, 2012), the design phase is complex to plan, schedule, and control. However, despite the complexity and uniqueness of each design project, looking at design from the information generation perspective can help streamline design activities and standardize and automate design tasks.

Seeing design as an information generation process became clearer when Building Information Modeling (BIM) was introduced as a platform to create and share design

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deliverables (Barlish and Sullivan, 2012; Hartmann, 2010). Design always incorporates information generation; even with 2D drawings, it is about creating design information while solving the corresponding design problem. However, most design information was neither clearly spelled in the drawings nor connected. In this context, it is on each designer to read, understand, and connect information together as an input to his/her specific design task at any moment during the design phase. This requires each designer to always be up to date with the latest information created by other designers, which consumes time and is inefficient in increasingly complex projects (Sawhney and Maheswari, 2013). However, this is very challenging in a highly dynamic environment where information cannot be automatically traced and where management is more on the reactive side.

The use of BIM emphasizes the role of information generation during design by combining geometrical and information modeling. With BIM, design data is clearly attached to model elements in an object-oriented environment where realistic elements are created (van Nederveen et al., 2010). Thus, ideally, every designer can obtain information about a specific model element at any moment during the process. While this has enhanced transparency and access to design information among designers, tracing the dynamics of information generation is still lacking. Thus, while BIM enhances the transparency of design at the product level by visualizing corresponding geometry and information, it has less impact on the transparency of design at the process level.

Beyond BIM, the construction industry is currently witnessing the development of digital twins as a new form of managing the design, planning and production operations of construction projects. A construction digital twin aims to leverage data streams from a variety of sources, including site monitoring technologies and AI functions, to enhance reality capture and to enable proactive process management (Sacks, et al., 2020; El Jazzar et al., 2020). The research on digital twin is still in the early stages, and several academic and industrial efforts are starting to invest more in this new framework.

Digital twins are clearly framed in the context of construction execution, where the digital twin renders a real site into a digital model. Sensing technologies are installed on-site as a source of data to feed the digital model. Thus, a digital twin is continuously mapping the real brother. Sacks et al. (2020) concluded that by taking advantage of the opportunities offered by the digital twin, construction managers and workers could become more proactive through improved situational awareness. In dynamic environments, however, situational awareness is largely affected by the limitations of human working memory and attention, which can be addressed in several ways, such as automating data collection (Endsley, 2004). It has been argued that the utilization of the large amount of information contained in the digital twin in design also requires the utilization of some sort of automatic "sensing system" of design, such as those proposed by Sacks et al. (2020) and Garcia et al. (2021).

In design, digital twinning is feasible; however, both twins are happening in the digital world. This is the main difference between digital twins in the construction phase and digital twins in the design phase. In design, there are no physical dynamics, such as those happening on site, where sensors can be used to detect changes. Instead, the design dynamics are happening at the social level on one hand, and at the level of BIM models at the other hand. While tracking social dynamics can be investigated as an approach to creating design digital twins, this study focuses solely on tracking dynamics at the BIM model level. In this regard, a digital twin is developed to map a BIM model where different design dynamics are taking place. This could be thought of as putting a camera to record BIM model dynamics at the level of model elements and their attached data.

Accordingly, the broad research questions can be stated as follows: (1) what kind of useful information can this camera capture? (2) What are the key performance indicators (KPI) that should be developed to serve as camera lenses? And (3) How can we use the tracked KPIs to help a project manager better maneuver a complex design process?

Therefore, this study explores the first steps in developing a digital twin for the design process by investigating which design aspects can be automatically detected from the BIM model. This approach has not been thoroughly investigated before. Accordingly, the study suggests four KPIs that will monitor some dynamics occurring in the BIM model. There was no specific process's aspect targeted while developing those KPIs, instead, the focus is on which dynamics can be automatically detected, or sensed, in the BIM model. Once the data stream is generated through these KPIs, the authors reflected on their possible relations to actual project dynamics. In this context, agent-based modeling is used to simulate a project scenario where different model's dynamics are occurring. The simulation results are used to reflect on the suggested KPIs. Future research will include real project KPI results and will engage corresponding practitioners to give their reflections on the generated KPIs' information streams.

RESEARCH METHOD

Design science research (DSR) is the research method employed in this study. DSR enables the development and testing of innovative concepts and tools and is adequate when addressing practice-based research (Rocha et al., 2012). DSR is a constructive research method that involves first the creation of an artefact and second evaluating its performance in use (March and Smith, 1995). In this regard, DSR is iterative and incremental where several testing/application loops can take place before reaching the final desired artifact (Hevner, et al., 2004). This study follows the typical steps of the DSR method, which begin with the awareness of the problem and progresses to conceptualizing the problem and suggesting a solution to the problem, after which an artifact can be developed to solve the problem, which is finally tested and validated to draw conclusions (Dresch et al, 2015).

Models are an example of artefacts that can result from DSR research. The developed models aim to represent a sub-set of a real phenomenon by means of creating constructs and associations among them to resemble reality (Weber, 2013). In this study, an agent-based simulation model is developed following the guidelines advocated by Hevner, et al. (2004). Hevner's (2014) guidelines for the use of DSR are: (1) design as an artefact, (2) problem relevance, (3) design evaluation, (5) research rigor, (6) design as a search process, and (7) communication of research. Regarding the first and second guidelines, the aim of this study was to create an artefact arising from practical problems. Regarding the third and fourth guidelines, they will be dealt with in a limited way in this conference paper; however, in the next phase of the study, these guidelines will also be considered more comprehensively. Guidelines 5 and 6 are part of the iterative nature of the DSR method, in which this conference paper plays the role of the first iteration. As for the seventh guideline, this conference paper is the first public presentation to an academic audience. The expert panelists will be used in the latter phase of this research for feedback, and practitioners' judgments will be then gathered.

SIMULATION MODEL DEVELOPMENT

An agent-based simulation was developed to model BIM as a population of different elements as shown in Figure 1. This simulation model is considered a "Digital Twin" for an assumed BIM model. In the simulation environment created using the Anylogic software, architectural elements (in red) are added to the model space (imaginary 2D space for simplification) along with structural elements (in blue). The geometry considered in the simulation environment is simplified to a 2D space measured in pixels (overall simulation area assumed randomly at 500x500 pixels where all created elements will be randomly added). Note that the pixel scale is used in this study as no real BIM model dimensions are considered. Moreover, the geometry of the elements was not taken into consideration. Instead, unified squares of 5x5 pixels are used for each element. Also, the number of elements, their production rate, and their corresponding movement serve only as a demonstration of the research idea.

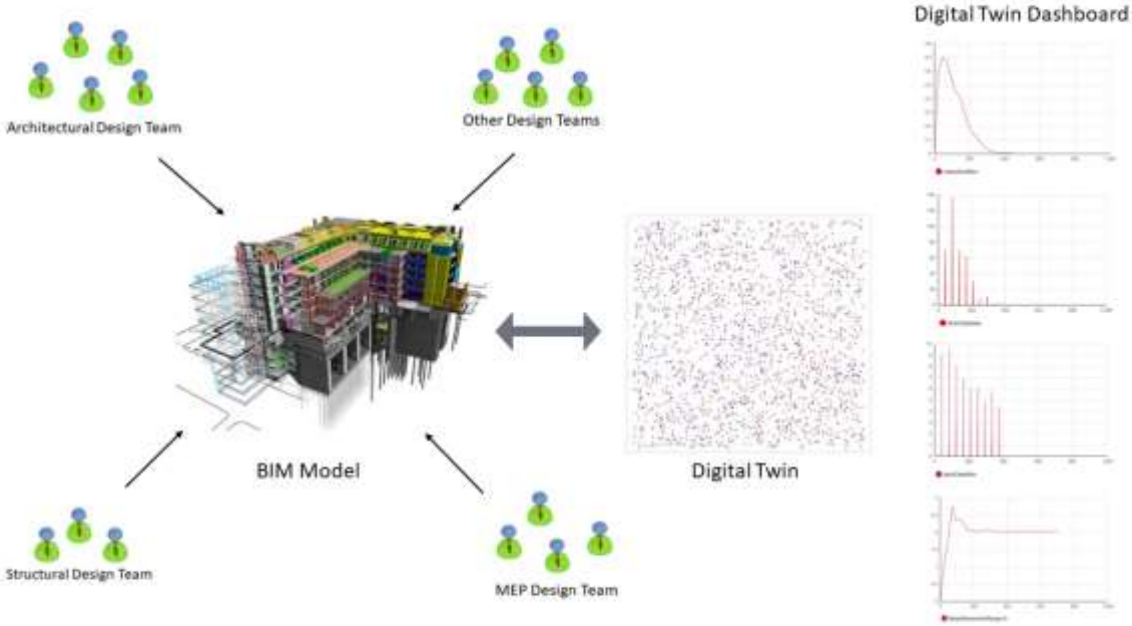

Figure 1: Design Digital Twin Schematic Representation
(BIM Model Image ©STW Architects)

An agent type is defined in the simulation model to represent all BIM model elements added to the simulation environment. Only architectural and structural elements were considered in this study for simplicity. Every element follows different states during the simulation, as shown in Figure 2. The element is first created in the simulation model at a certain location, and then it might change the location while developing the design. It is assumed that the probability of changing to a new location will decrease with time as the design converges to its final state, and, as such, more elements converge to their final positions in the BIM model.

Weekly, all elements move to a “Coordination” state where clashes are resolved. If elements clash, location adjustment is considered to remove the clash to mimic the actual elements’ location coordination in an actual BIM model project. As such, elements will also witness movement after the coordination state if they clash. Note that clash detection in real projects can occur daily, weekly, biweekly or at any duration interval. We assumed in this study that clash detection is occurring weekly to demonstrate the concept only.

Table 1 summarizes the numerical values assumed in this study to run the simulation model. These values are not based on real data, nor do they represent actual model development; they are assumed to make the study tangible at this phase of the research. Future studies will replace those assumed values by actual project data to capture realistic model dynamics. For the architectural and structural element production rates, it is assumed that the production rate of elements will linearly decrease with time as the design progresses. For instance, at the beginning of the design process, the frequency of adding elements is higher, while towards the process end, most elements will be already present in the model where fewer number of new elements are expected to be added.

Other numerical values are also assumed in Table 1. The clash detection process is assumed to occur once every week (40 working hours). The final size of the architectural and structural BIM models is 1500, and elements that are in the range of 5 pixels to each other are assumed to be clashing. These numerical assumptions serve only this paper's scope and future studies can reveal more data related to those variables.

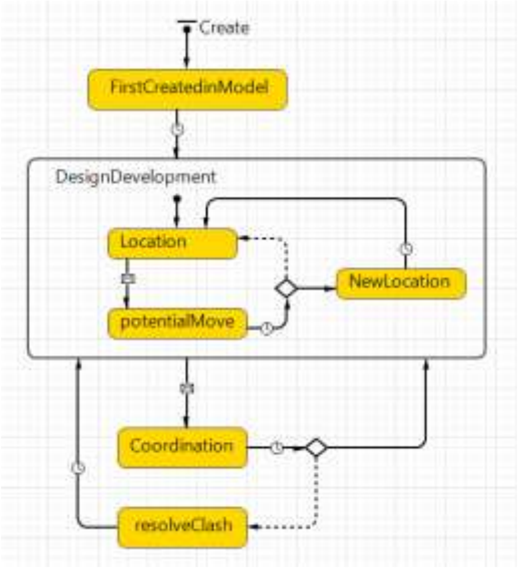

Figure 2: BIM Element State Chart

Table 1: Simulation Parameters Value Assumption

Parameter	Description	Assumed Value
Arch. Elements Prod. Rate	The rate at which architecture elements are added to the simulation environment	20 – 0.01 x (t)
Str. Elements Prod. Rate	The rate at which structural elements are added to the simulation environment	5 – 0.05 x (t)
Clash Detection Interval	Clash detection meeting intervals	40 hours
Arch. Model Size	The total number of architecture elements reached in the simulation environment	1500 Elements
Str. Model Size	The total number of structural elements reached in the simulation environment	1500 Elements
Clashing Element Range	The range at which an element agent in the simulation environment is considered clashing with another element	5 Pixels

KEY PERFORMANCE INDICATORS

Several studies have introduced different KPIs to measure aspects in the design process. The developed KPIs were highly affected by the model used to conceptualize the design process. For instance, Ostergaar and Summers (2007) introduced metrics inspired by the electric current approach where a KPI similar to electric resistance was suggested to measure the resistance value of each design task. In a different conceptualization inspired by fluid mechanics, metrics like velocity, viscosity and volatility of fluids were suggested to measure information flow (Krovi et al., 2003). Similarly, Tribelsky and Sacks (2010) developed metrics based on a Lean conceptualization of the design process suggested before by Ballard (2000) and Koskela (2000).

Previous research also introduced several KPIs tailored to the BIM-based design process. Abou-Ibrahim and Hamzeh (2020) developed a dashboard that qualitatively monitors changes occurring in the BIM model, revealing geometry changes, property changes, and model size changes. However, the dashboard is not automated and only reveals the nature of changes happening in every consecutive model version without touching on the size of these changes. Manzione et al. (2011) introduced Lean-based KPIs to monitor BIM workflows, focusing on the process level not the inner BIM model dynamics. Several studies were also done based on the Level of Development (LOD) concept as a measure to reflect the detailing level of an element (Abou-Ibrahim and Hamzeh, 2016; Hooper and Ekholm, 2012); however, the LOD concept is not designed to detect overall model status and is only used to reflect a specific element's detailing level. Nonetheless, LOD detection and monitoring are not yet automated.

In this regard, this study tries to address this gap in monitoring the dynamics occurring at the level of BIM model elements by suggesting a new set of KPIs; that will serve as sensors for the suggested Design Digital Twin. In other words, those KPIs will be used to continuously stream information related to BIM model dynamics. While several KPIs are needed to comprehensively reflect all model dynamics, this study introduces only four KPIs based on the number of elements and their movements. Different KPIs need to be developed in future studies to reflect on elements information, model quality, and design value. Table 2 summarizes the introduced KPIs, while the following sections detail the use of each of them based on the simulation results.

Table 2: BIM Model-Based Key Performance Indicators

KPI	Description
Average Movement of Elements (AME)	Average movement of elements during the overall design period
Number of Elements Clashing (NEC)	Total number of elements clashing
Average Movement due to Clashes (AMC)	Average movement of elements after resolving clashes
Elements In Range (EIR)	The average number of elements in range for a specific zone in the model or the entire model

RESEARCH LIMITATIONS

The current research effort is performed at the conceptual level to explore design digital twinning. The results of this paper are based on numerical assumptions, not on actual data from real projects. Therefore, the results cannot be generalized; however, they serve the purpose of the paper to explore insights related to design digital twinning. Future studies will include real projects' data to test the digital twin accordingly. Moreover, a limited set of KPIs was introduced in this study, which is not sufficient to comprehensively reflect on different BIM model dynamics, specifically aspects related to design value and model quality. Future studies are expected to develop new KPIs to fill this gap.

RESULTS AND DISCUSSION

The design of the simulation model was done through several iterations, where the simulation output was monitored in every iteration to ensure the model generated reasonable and realistic results as to mimic a real project according to researchers' experience. This section highlights the use of the digital twin to better understand the dynamics occurring at the BIM model level. As such, the introduced KPIs can potentially enhance situational awareness among designers, improve process transparency, and help design managers better manoeuvre design progress and information sharing.

AVERAGE MOVEMENT OF ELEMENTS (AME)

This metric reflects the average movement of elements in the model during the overall design period. It can target the entire BIM model, a specific discipline, or even a specific category of elements. Figure 3 shows the AME metric for the architectural (red) and structural (blue) BIM models respectively. Both graphs show that at the beginning of the design process, the average movement of elements increased in both models reflecting the changes occurring in models' shapes that go with the development of design.

At one point, the graphs peak and start decreasing reflecting that more elements reached their final design locations in the model and fewer elements are still witnessing movements. As such, the models start converging to their final shape as the design solution is refined. Another important aspect revealed by the graphs is the rate at which each BIM model converges to its final design. For this example, it shows that the architectural model converged faster to its final design state (around 400 manhours) than the structural model (around 600 manhours). This information is important to balance the production and development of both models especially for coordination purposes.

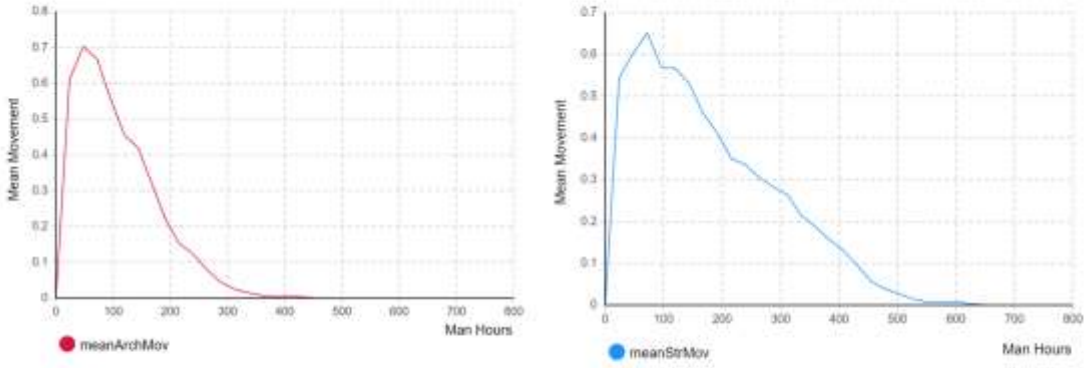

Figure 3: Average Movement of Elements (AME)

This metric also has important use at the level of BIM model categories of elements. For instance, if the design manager is monitoring the development of specific categories of elements (e.g. architectural walls and structural columns), AME can be used to track their locations changes. In this context, the design manager can wait until the architectural walls almost reach their final locations in the model, which represents the corresponding layout design, before the structural engineers can start adding the structural columns. As such, the structural designers do not have to wait for the entire architectural BIM model to be finished, thus enabling partial and continuous sharing of information among involved teams as to overlap design tasks when feasible.

At the planning level, the design manager can plan the development of different BIM model categories according to this AME metric. Collaborative planning can be done among different involved designers to plan the sequence of categories' modelling based on information dependency and model uses at each phase. The design team will have a model-based timeline showing the expected pace of BIM model development and the expected delivery of each category of elements. The design digital twin and involved metrics can be used to monitor and control the development of design with accordance to the generated AME baseline as shown in Figure 4.

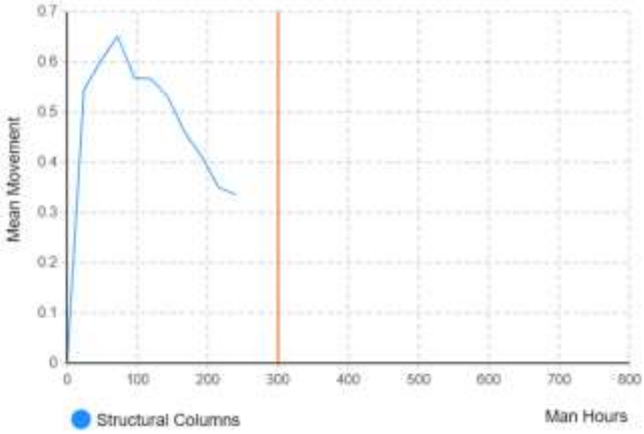

Figure 4: AME-Based Planning Example

Assume the structural columns are expected to reach their final design locations after 300 manhours (Orange Line) as per the plan. The actual movement of the elements in this category revealed by the blue graph reflects that with current development pace, the columns are less likely to reach their design state by the planned time. Based on this information, the design manager can act proactively on the situation and try to avoid the delay in delivering this category; therefore, minimizing the risk of information flow interruptions or delays for downstream activities. These expectations will be further explored in future research based on actual data.

NUMBER OF ELEMENTS CLASHING (NEC)

This metric reveals the number of elements clashing in the model. Figure 5 shows the total number of elements that clash in both the architectural (in red) and structural (in blue) models. This shows that the architectural model witnessed more clashes at the beginning of the process as compared to the structural model. This can be related to the difference in production rates of both models as assumed in Table 1.

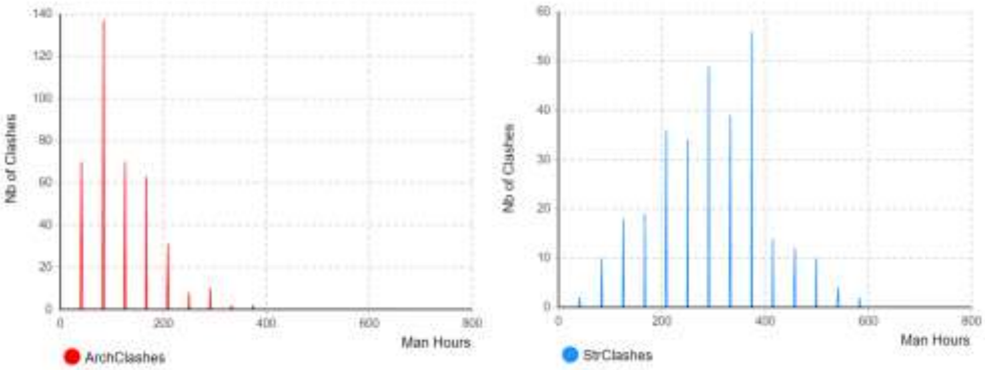

Figure 5: Number of Elements Clashing

As more elements are added to the architectural model, a higher probability of clashes is expected at the beginning of the process. More clashes would appear early, and therefore be resolved early in the process. But, as the structural production rate is relatively lower, fewer clashes are likely to appear in the structural model at the start of the process; however, more clashes will appear in later design stages as more elements are added. Comparing these two graphs shows that unbalanced model production in different design disciplines can lead to an unbalanced generation of clashes in each discipline, which can lead to continuous changes and rework throughout the process.

AVERAGE MOVEMENT DUE TO CLASHES (AMC)

These KPIs follow the specific movement of elements due to clashes. In real projects, designers sometimes need to change the locations of some elements to resolve geometrical clashes occurring within and outside their specific disciplines. Every time a clash is resolved, one or a few elements need to be moved. The AMC metric follows the average value of movement for all elements affected after resolving a clash. Therefore, the AMC values can be used to show the effects of clashes on model shape changes.

Figure 6 shows an example of the AMC graph where the average movement of architecture elements, that were moved to resolve a certain clash, is monitored. In this example, higher values are witnessed at the beginning of the process. As the design progresses, the effect of clashes reduced, and elements are therefore witnessing fewer location changes towards the end of the design process. This declining trend of the AMC graph highlights that the architecture design is converging to a final solution, where clash coordination is no longer causing big changes.

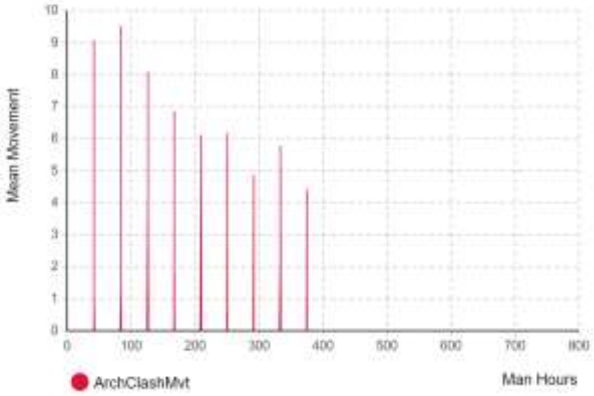

Figure 6: Average Movements of Architecture Elements due to Clashes (AMC)

ELEMENTS IN RANGE (EIR)

The last metric introduced in this study is the “Elements In Range” (EIR) shown in Figure 7. The idea behind EIR comes from the need to assess the risk of clashing among elements in the model before they occur to proactively address them. This KPI is calculated as follows; each element will have a number of elements in a specific predefined geometrical range, and then the average of all those numbers will be calculated. Therefore, this metric can reflect the congestion of elements in a specific zone or even the entire BIM model space. With enough data from real projects, a correlation can be made between EIR values and clashes, which in turn can be used later to monitor and mitigate clashing risks. EIR can also be used to assess the effects of suggested design changes in specific model zones. The effect of changes occurring in areas with higher EIR values is expected to be higher as more nearby elements can be affected. Therefore, the risks correlated with design changes can be better understood before proceeding with the change.

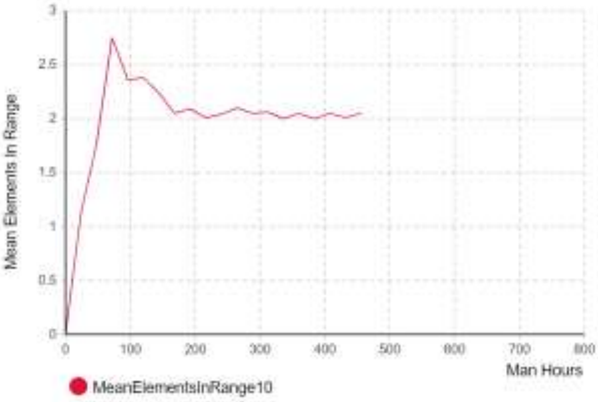

Figure 7: Elements in Range (Architecture Model)

CONCLUSION

This paper explores the concept of digital twins in the design process. Digital twins are more framed in the construction phase where a digital twin is created for an actual site; however, digital twinning in design is less intuitive where both twins are digital. Sensing is key when creating a digital twin where sensors are the source of data streaming necessary to create an informative digital replica of the ongoing project. For instance, actual sensors and cameras are installed on site as data streams for the digital twin.

In design digital twinning, sensing is also important to capture needed information about the design process. The design process has a social aspect as well as a digital aspect represented by the BIM model. This study focused on proposing sensors at the level of the BIM model to generate information that can be used for design management purposes. While actual sensing tools are not feasible in this case, some KPIs are introduced to serve as sensors to reveal BIM model dynamics. The introduced parameters reveal dynamics related to BIM model elements, and they are used to create a dashboard to visualize the corresponding data stream. The KPIs can be used by design managers to better understand the dynamics of the BIM model which can be reflected in a better understanding of the design process status as discussed in the results section for each KPI.

An important outcome of this research is related to determining the nature of the desired design digital twin itself. In this study, the dashboards created from the KPIs (model sensors) were used to analyse BIM model dynamics. Those KPIs can be directly generated from the BIM model without the need for an intermediary separated digital twin. In this context, the following questions can guide future research efforts: (1) Can the design digital twin take the shape of dashboards to monitor BIM model dynamics based on suggested KPIs? (2) Is there additional value in creating a separate digital model for the design process? Future research can update the simulation model using real data to mirror an actual BIM model into a simulation environment. Actual IFC models can be tracked and needed information can be automatically extracted to serve as input for the simulation model. The data-driven simulation model can then be tested as a design digital twin of BIM. Therefore, future research could examine the ability of a developed simulation model to fulfil the requirements of digital twinning in construction. Practitioners and design managers can play a major role in shaping the development of this digital twin and testing its value.

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