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TOWARDS A GENERALIZED DIGITAL TWIN DEFINITION

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Abstract

Several definitions exist for Digital Twins, which are based on industry 4.0 technologies. Going beyond, a wider definition is proposed which is focused on obtaining knowledge and foresight to improve re- and pro- active decision-making, for enhancing validation, assessment and control. A six-level classification schema is proposed, equally applicable to buildings, embedded systems and processes at all phases from design to demolition. A digital twin is seen as the marriage of semantic with numeric, namely the fusion of semantic methods with numerical methods first of all computational engineering but also sensing, data mining and Artificial Intelligence methods.

Introduction

During the last decade the concept of Digital Twin (DT) has becomes very popular and several definitions have been proposed, based on newest technical features of Industry 4.0, namely sensing, data mining, Artificial Intelligence (AI) and web data technology. The most popular one is from mechanical engineering (Fuller et al. 2020), which constrains DT to a system where beside a digital model also a physical counterpart has to exist and bilateral automatic information exchange flow has to serve for a continuous updating of the digital model and continuous corrective measures on the physical object happen preferably full automatically. Following this definition some definitions for DTs in construction have been recently proposed, which are focused on the circular construction economy (Meda et al. 2021) and on the construction process (Sacks et al. 2021, Boje et al. 2020). They developed sound concepts for DTs based on extended literature reviews bringing together different existing methods and technologies. All three pointed out the importance of linked data technology in order to properly relate the bi-directional information flow to the digital model namely the integration of dynamic with the static building data for which a specific linked data approach based on ifcOWL was recently proposed by Mavrokapnidis et al. (2021). All these definitions have been undertaken for the sake of developing methods beyond BIM. Therefore, they favor the highest functional level of Industry 4.0 concepts applying the most advanced technologies whereas some important and past developments for defining a DT classification schema are underrepresented.

What is missing is a classification schema for DTs that is not necessarily constraint by Industry 4.0 technologies and that appreciates the value of numerical mathematical methods, which provide wisdom, besides the AI methods which provides shadowed wisdom. Meda et al. (2021) have included current concepts in their definition namely Digital Data Templates (DDT) and Digital Building Logbook (DBL) and hence came up with seven maturity levels. However, their criteria are data interoperability, sensing and AI and they followed the meta classification of Fuller et al. (2020) namely digital model, digital shadow and digital twin. They didn`t consider the important potential of numerical methods in particular computational engineering methods for gaining knowledge and decision-support information through foresight. Their definition is based on data and semantic information mining neglecting the huge source of deducing knowledge through numerical engineering methods and in particular in high level combination with semantic methods in order to get also what you don´t see. Numerical engineering method can often play the role of a x-ray system, because variated assumptions deduced from semantic models can be validated by brute-force methods which opens new perspective far beyond the power of logic reasoning, e.g. Description Logic (DL) and web technologies. The new objective is to gain a foresight of semantically modeled objects, systems or processes. Technologies of current definitions of DTs become sub classification criteria.

A digital twin is now broadly defined as being only the twin of the physical object. It is also the DT of the envisioned object. The DT objective can be either on the product or the process or both. This broaden very much the view of a DT. In the early phases, i.e. the design phases, the DT is the twin of the envisioned object; in the construction phases the DT is the bi-twin of the envisioned object and the physical arising object where the DT objective is focused on the process; in the maintenance phase the DT is the twin of the physical object, which is changing, aging and deteriorating over time; in the refurbishment phase the DT is the bi-twin of the physical object and envisioned refurbished object and in the demolition phase the DT is the twin of the physical object, where the DT objective is focused on the process.

Historical Roots of Digital Twin Systems

The roots of DTs were originally fostered by simulation methods and there in particular, a valuable push was provided by the computational power of graphic cards (GPUs) and cloud computation. Without doubt, it is very attractive to build a simulation model reflecting the reality and to study with this digital simulation model the behavior of the building as to have a digital twin of the real or envisioned building and related processes. However, both the quality of the simulation engine as well as the simulation model determines the usefulness of the target foresight, namely whether it is just a smart colorful visualization fake or a near to reality foresight.

The next main push towards DTs came from the digital monitoring and sensing technology shifting from analogical paper based monitoring or analog electrical based systems to digital monitoring. This provided already a revolutionary impact on engineering decades ago like the monitoring of wind pressure, water pressure and earthquake acceleration process in the early 1980s. This was the first time that these natural hazard processes could have been quantified and related hazard resistant buildings like off-shore platforms, long span bridges, tall towers and nuclear power plants have been able to be objectively and safely designed applying simulations based on real forces and processes but location adjusted.

This push from digital monitoring together with the later appearing Industry 4.0 technology like the Internet of Things (IoT) enabled a continuous observation of the building, its behavior and its usage - at least in an ideal way and hence opens the possibility of re- and pro-active decision-making by the expert watching the reality in front of a dashboard. Replacing the expert with an AI system to control the system an ultimate intelligent system arises. However, is such an intelligent system reliable enough to be created for any kind of system? It is often postulated that only such an automatic system with a control component is a true DT (Fuller et al., 2020), which is also called a Cyber-Physical System (CPS). This is a strong requirement that strongly narrows the type of DTs (Madni et. al., 2019). Such an autonomous intelligent DT, that reliably maps reality, in particular for complex buildings and systems with many parameters and interdependencies, is currently still out of scope.

The origin of the name DT for the related concept was born in the mechanical industry in about 2003 (Grieves, 2014). There, products with quite different complexity exist and the market is highly competitive. Quite different from construction any drawback in functionality, appearance and intuitive operation can be an economic disaster for the product. Starting with products with low complexity about three decades ago, DTs have been developed first and step by step entered more and more into complex products (Fuller et. al., 2020) accompanied with many drawbacks like the crash of an Airbus on a hill near Strasbourg due to AI control in the mid 1980s. An early DT in construction, that became very popular, was the automatic control of shadowing systems. The DT already showed the basic ingredients, namely monitoring and control based on an automatic decision system. First this was governed by a deterministic threshold function. In order to avoid the nasty high frequency alteration between opening and closing fuzzy algorithms have been developed. Later they are migrated to Neural Networks (NN) algorithms based on several sensors and applied image recognition methods for the cloud process. Those DTs show limited functionality and mostly consist of a one-of-a-kind digital model. The functionality was the center of interest and not the geometrical or semantic BIM model. Their data structures have been arbitrary even though the semantic object oriented data structure methods have already been highly developed and standardized by ISO 10303 STEP (the first pre-release of the first part was about 1988), the mechanical engineering counterpart of ISO 16739 IFC (the first pre-release was about 1996 as Version 0.8).

Before the Digital Twin name arose this kind of systems but without an automatic feedback control functionality and focused on mathematical based simulation applications were called virtual engineering labs (Windisch et al. 2012 a). Virtual labs do have a long tradition in the automotive, aircraft and space industry (Glaessgen, 2012). In particular, in the space industry expensive crash tests which have been very common in the automotive industry would have been not fundable and hence most developments in simulation have been triggered by the space and the aircraft industry. Therefore, the forerunners of today´s DTs were motivated to test extensively before built and hence before the product existed. However, this was not limited to the pre-built phase but quickly approached the post-built phase, due to failure research and improvement investigations. It is not surprising that the push for development of digital object oriented models, which resulted in ISO 10303, STEP was coming from those two industries. Another push for the simulation DT was coming from the automotive industry due to the cost pressure to reduce full scale tests. Today, only about a tenth of the former full scale tests are carried out. They are necessary to scale the material laws and the nonlinear geometrical deformation algorithm of the nonlinear numerical (mathematical) models in order to correctly map the real physical behavior to the digital model in order to be able to simulate with a high fidelity the digital ultimate crashes. This means real tests have been mapped to digital models in order to adjust the digital model to the real object often in an iterative adjustment process.

The construction industry was lagging behind because their digital models are much more complex with millions of elements for large buildings and are always a one-of-a-kind product. It is too expensive to create for any kind of building all possible individual simulation models from scratch for all the product and process aspects of interest for the design, construction and operation. In addition, there was no competitive pressure for simulation models because every stakeholder was in the same situation and there was no identifiable competitive advantage, which would have justify the expense of creating an individual simulation model.

However, when the semantic modelling, i.e. Building Information Modelling (BIM) was developed in construction due to the competitive advantages of the BIM models concerning the strong reduction of geometrical conflicts in design and construction the collaborative design tools become attractive, cheap enough and highly beneficial. This triggered the success process of BIM. Contrary to the mechanical engineering domain, where the DT and the virtual engineering lab were the first, in construction the semantic standardized data model ISO 16739, IFC and the simulation technology, were firstly developed and the DT was added later as an added value. Therefore, the DT appeared in the construction industry quite late, about two decades ago, namely in the appearance of virtual engineering labs (Windisch et al. 2012 a) based upon the BIM model.

Evolution towards the Digital Twin Method

As described above, simulation of the behavior of the as-designed model for validation purposes was the first evolutionary step towards DTs. One of the first introductions to virtual engineering laboratory in the context of BIM was published by Katranuschkov et al. (2003). The application was for the assessment of buildings in an earthquake prone area. There, three different consecutive levels of virtual engineering labs have been developed. As level 1 an earthquake sensitive check for a building was proposed that uses as input a simplified BIM (box-type) model and rules of thumb. This DT can be operated by an architect or even a lay-person on a public website. As level 2 a standard earthquake analysis according to the building code was suggested, based on a lean BIM model which can be carried out by an experienced structural engineer or an earthquake engineer collaborating via Web based database access or file based data exchange using Step Physical File (SPF). Ultimately, as level 3 a sophisticated ultimate limit state simulation with a sophisticated non-linear structural analysis engine as suggested that can only be carried out by a structural engineer who creates the digital experiment online together with an experienced computational engineer advanced in fracture mechanics in order to control the numerical fracture mechanics algorithm, i.e. to control convergence of the nonlinear stiffness equations. Everything, i.e. the start of deformations on the BIM model and the damage process was provided by online video, as being in a real physical test laboratory (Katranuschkov et. al. 2001). The objective of the DT is the assessment of the behavior of the envisioned building as-designed before it is built. On each of the first two levels the results have been accompanied by an assessment of whether the analysis level is sufficient to objectively classify the building as earthquake safe or whether the next level is suggested to be carried out. Today Virtual Reality (VR) and Augmented Reality (AR) features can much better mimic a virtual building like a real one in a real environment with online interaction. This may become the DT for the future application for building permission.

Further developments covered the simulation of thermal (Baumgaertl, 2011) behavior and airflow (Windisch et. al. 2012 a) around a building for energy-efficient and structural design. The target goal was to find the most near zero energy design. Therefore, the ill-conditioned objective function of energy-efficiency was automated through a brute-force algorithm. There, model parameters like material parameters, location of objects, e.g. outlets of HVAC and the variation of objects, e.g. using products with other properties and functionality, the orientation and location of the building and the amount of windows were merged in design templates (today named DDTs) and have been automatically variated. The naming of the simulation lab was extended to intelligent Virtual Engineering Lab (iVEL) in order to express the automation for design optimization (Baumgaertl et. al., 2016). On this level the DT was applied for automatic finding the optimal design, i.e. the DT was still based on the building model as-designed and the DT was used for a kind of sensitivity and optimization study to find out optimal design possibilities. This was only possible due to cloud computing and the total process was fully automatic, with most parts in OWL.

A further development of the DT was the real time simulation of crowd behavior under building hazards, like fire, toxic gas or panic triggering events and hence a hybrid iVEL (Scherer et. al., 2018b). There, the behavioral parameters of people have been automatically variated as well as building material parameters and some building objects. In addition, the fire spread out space was dynamic which means the fluid dynamic space model was changed during simulation as a consequence of the interaction of the three systems (models) concerning key objects. For instance, in the event that a door opens or it will is by people or fire a new space object is introduced and added to the existing space model for the fluid dynamic simulation and the crowd simulation as well. In the event that a door is closed several space objects are removed from the model. Also when the sprinkler is switched on, a new material (water) is introduced in the fluid dynamic calculation. It is a triple iVEL when using the as-designed BIM model. However, when the as-built BIM model is used as it is the case for training of rescue teams interacting in real time on a real asset a triple real hybrid DT arises with a building DT, a human DT and a fluid dynamic DT, (Al-Sadoon et. al.,2022). The extensions of such hybrid DTs with VR and AR provide another new dimension for training rescue teams on real buildings and scenarios.

An important extension of the iVEL was the integration of sensors in order to monitor the usage of the building and control the interior climate via control actions on the HVAC system. Building parameters are not altered, but only those of the HVAC system. This means only one domain model is variated, which completely alter the simulation scenario. The iVEL was extended by three ingredients, namely monitoring, forecasting and control. As long as one room has to be controlled, the DT worked well. However, for several rooms with different usage such DTs are still operating suboptimal due to the arising complexity problems and hence becomes an application field of AI.

Another extension with a long tradition is the application of stochastic methods for modeling building material parameters and in particular their aging process for the sake of forecasting. These trades back about four decades. With stochastic simulations (Monte Carlo or Lattice Hyper Cube) the forecasting of the building concerning its future behavior was possible and hence building assessment considerations could have been undertaken concerning maintenance planning and life span prognoses. This is applied to as-designed, as-built and as-deteriorated building and has become a profound method, for off-shore platforms, power plants (Brosinsky et. al., 2018) and wind turbines (Vrabic et. al., 2018).

A breakthrough in the evolution of DTs was the replacement of the as-designed BIM model with the as-built BIM model, e.g. applying the BIMification process (Scherer et. al., 2018). There, we have to distinguish between three different as-built processes, namely the existence of products (objects, elements), the geometrical appearance of the building and its elements and the material behavior. For the first two processes laser or cameras are applied to obtain a geometrical model. However, the mapping of the surveyed geometry to a semantic model is still under research. For the material functions, there are already various non-destructive methods that provide weak results when cheap, and can be exorbitantly expensive when highly reliable results are requested. Therefore, a DT with a real physical twin counterpart is not a simple monitoring task, but can result in a complex, expensive effort in case the building is complex and in addition, as-aged and as-deteriorated models with nonvisible properties have to be considered.

Digital Twin Definition

The evolution of the DT concept showed that there is not one generalized DT but many different types, which are defined by their functionalities and their application goals. Accordingly, six functionality levels are suggested. These levels are to be understood in such a way that all features and functionalities of one level will be inherent to all successive levels and can be activated there on demand. These levels are not maturity levels, but only functionality levels serving a dedicated purpose. The intention of introducing these levels is to avoid unnecessary modeling, data maintenance and computation. Each DT level is equal important, but a DT does not have to show all functionalities inherited from other levels. From the evolution of the DT process, it can be easily imagined that the BIM model is the basic entry model of a DT. As a consequence, it is defined as DT level 1. The BIM model in this context has to be defined in a more generalized way as used in practice. The main goal of a DT is to get an overview of a complex structure like a building that owns several systems and to get an understanding of the building and systems performance, i.e., to get foresight to validate them before they are built, including any kind of retrofitting and renewal. In such it provides pro-active decision making and ultimately intervene or control the system irrespective of whether this is done manually or automatically. The DT definition for buildings given below holds equally for systems of and in buildings as well as processes, like the construction, maintenance and demolition process.

1. Level: Visualization and compatibility - geometrical design

used for the validation of the design of a new building concerning the geometry. The physical counterpart of the DT still does not exist. The DT represents the geometrical vision of the future building.

The DT is used to a) visualize the design in order to assess its appearance, b) check the geometrical compatibilities of its components (clash detection) applying mathematical algorithms or by visual inspection, c) check its functionality and functional compatibilities through visual inspection and interpretation by experts and d) give the owner of the building a realistic impression in order that he can better articulate his visions, wishes and functionalities (Borrmann et. al., 2018). On this level, the DT model is identical to the BIM model, defined as BIM level 3 (Brew et. al., 2011).

2. Level: Simulation - functional design

used for the validation of the design of a new building concerning functionality. The physical counterpart of the DT still does not exist. The DT represents the functional vision of the future building.

The simulation of the performance helps the designer a) to test the functional design before build (Bazjanac, 2004), b) to check the completeness of the functional systems, c) to find the optimal functional design applying numerical simulation engines, d) to design for construction by the architect through simulation of construction process and e) to find optimized construction processes by the constructor through simulations based on the design (Ismail et. al., 2017). The systems to be checked are physical and infrastructure ones of the building. In addition, the buildability, design for construction, construction processes, cost and the sustainability are investigated and optimized based on the simulation findings. On this level, the DT is identical to the Virtual Engineering Lab or BIM Lab (Baumgaertl et. al., 2011), also defined as BIM level 4 there.

3. Level: Forecasting

used for the forecasting of the behavior, usage, aging or deterioration of the building, applying stochastic methods (Novak et. al., 2023). Mathematically based stochastic methods are seen as very sophisticated and cost intensive and hence they are not very popular in civil engineering practice. They are only applied for outstanding buildings and risks, like nuclear power plants. More commonly used are semi-stochastic methods (Novak et. al., 2023), expert knowledge like deterministic rules-of-thumb based on statistical values or individual experience. As a new favored method, Machine Learning (ML) methods are applied with quite different reliable results. The forecasting is based either on the building as-designed, e.g. in order to design for a target lifespan, for the construction time, costs or risks, or the as-built, as-changed, as-aged or as-deteriorated building for maintenance and refurbishment issues. An attractive application is the forecasting of construction time, cost and risk based on the as-is status of the construction process (Sacks et. al., 2020). This needs methods of DT level 4.

4. Level: Assessment - as-is Model

used to create a model of the real physical building, i.e. to create a) the as-built model after construction, b) the as-changed model during operation and maintenance, c) the as-aged model and as-deteriorated model due to usage and environmental or hazard impacts. There exist many different methods to undertake create such models as generically defined by Scherer (2018). Currently the most popular are high resolution cameras and scanners. The still open problem is to transfer the obtained point clouds and related surface model in a semantic and related geometrical, morphological BIM model, consisting of building elements. Methods for creating these as-is models can be classified into directly measurable and indirectly measureable ones and further into viewable changes and in non-viewable changes. Many of the latter changes can only be measured using complex monitoring methods based on DT level 5. The DT level 4 is only meaningful when using some functionality inherited from DT level 1 and 2, applying the objective of DT level 1 or 2.

5. Level: Monitoring

used to watch the building over a longer time period (hours up to years) in order to supervise usage and performance of the building in a holistic way (Mavrokapnidis et. al., 2021) or to undertake system identification procedures in order to identify not directly observable items or to determine deterioration processes (Lin et.al., 2020). There, one has to distinguish between hidden or not viewable items and items that cannot be directly measured but must be deduced from other measurable ones and transferred either 1:1 or n:1 or even hidden values, e.g. damages below the surface, for which first a model has to be assumed, where the inverse function reveals the sought values. This is also a crucial problem for identifying processes on the construction side (Srewil et. al., 2013). Usually all observed values are displayed on a dashboard, providing responsible people with a broad overview and a deep understanding of the current state, e.g. providing them information for decision-making.

Monitoring is usually applied to observe the performance of the building, the building systems or the usage of the building, i.e. temperature in rooms, the stress in bearing elements, damages on or in the building, the status of dynamic elements or the number of people in a room or on the construction side, the work progress, the equipment activities, faults in construction, low quality, to mention only a few.

It has to be distinguished between singular, periodic and permanent monitoring. It has to be further distinguished between simple, i.e. 1:1 and complex n:m monitoring and it has to be distinguished between direct and indirect monitoring, where indirect monitoring is defined as the target parameter that cannot be obtained directly but only through an inverse analysis of the building or the building system. This means that the sought properties cannot be measured but only be deduced from the sensor measurements via the assumed system model and hence the deduced properties are biased due to their assumptions because they are a part of the assumed model. An example is the detection of hidden damages on bridges. They can be identified through the local changes of the structural stiffness. Changes of structural stiffness can, for example, be measured through strain gouges in a very small area of about 10cm in diameter. As a consequence, strain gouges have to be placed at 20cm distance in each direction resulting in millions for a large-scale bridge, which is not feasible. However, the measurable properties are the corresponding tuples of load and deformation. The sought degraded stiffness properties have to be first assumed. In the second step the correct ones can be identified in a manual try-and-error approach as it is the current practice. However, only 3 to 5 trials are carried out because of the efforts and costs. Therefore, each trial has to be set-up by a very experienced engineer. In contrary the DT approach enables an automatic procedure through applying a brute-force algorithm for all reasonable damages and their combinations to identify the best fitted as-is local stiffness, from which the damage can be deduced. Today this is computationally possible through applying Cloud Computing. This simulation based system identification method developed by Lin et. al. (2020) provides a very exact identification of the sought values in an objective way, because millions of trials can be carried out in a short time and reasonable costs.

6. Level: Control - Cyber Physical Systems

used for intervene on the building, the building system or the construction process based on identifying the actual state and much better to get a forecastinging, in order to improve performance or to adapt the system to changes of the environment, the usage or any other impacts on the building like hazards, accidental loads or even just temperature changes during the day or due to different usages or applied to trigger a warning to responsible people or to transfer automatically the building, the building system or the construction process into a save mode or simply to trigger a warning or even shutdown. A very popular example is the automatic stop of the Shinkansen train at Japan, triggered by an earthquake. Advanced AI methods like Convolutional Neural Networks (CNN), Deep Reinforced Learning (DRL) and Large Language Models (LLM) are preferably applied for non-existential risks namely adjustment problems like control and fine tuning of systems like HVAC, shadowing and lightiveg systems. Cyber Physical Systems become very popular as an industry 4.0 method and has been seen as the only right DT (Fuller et.al., 2020). They were applied to any kind of complex problems. For simple or medium complex problems respectful results have already been achieved in case the DTs namely their wisdom kernel have been well prepared and strongly focused on a limited, e.g. pre-constrained problem range.

It is not obligatory to use at a certain DT level all inherit functionalities of the super levels. For instance, on level 5 sensor data may only be used together with level 1, namely to visualize the monitored data, like the temperature of rooms or to visualize the temperature deviation from the comfort temperature, in order to highlight as a warning those rooms that are too hot or too cold. Also for level 6 it is very popular to model only the controlled system on level 1 now without geometry and hence using only the basic topology and the semantic and to visualize both as a quite abstract model often only as a schematic 2D representation on the dashboard. Such kind of watching and controlling systems are trading back over 100 years in mechanical engineering. Dashboards have been originally invented and built as analogue systems. In mechanical engineering, in particular in HVAC and electrical systems it is very popular to create only the functional model and visualize the DT only as a schematic diagram on the dashboard.

BIM Model Morphology

In practice BIM models are usually seen as one model. However, a BIM model does have different appearances, which can be firstly categorized through their Level Of Detail (LOD) and secondly through their defining at least three different partial models. These are the Topological Information Model (TIM) (Windisch et. al., 2012 b), also called the Building Ontology Topology model, BOT (Mads et. al. 2021), by the Linked Building Data, LBD, group), the Geometrical Information Model (GIM) and the Semantic Information Model (SIM) (Scherer et.al., 2011). If we further accept that there also exist a LOD of 0, i.e. a still empty model, then one can imagine that there exists a BIM model without a TIM (LOD=0) and without a GIM (LOD=0) namely only showing a SIM model (LOD = xx), which just describes the set of the governing objects of the BIM model by name and some functionality. This is the usual BIM model used for a feasibility study in order to draft the scope of a building and estimate its total cost using functional based cost templates and visualize the result in business charts. Such an approach can be used, too, for DT level 2, e.g. to find the optimal cost not using any geometrical or topological information, but only the semantic ones restricted to the rooms, their functionality and quality level. Simulations are carried out through variation of the quality and number of rooms. This is a usually applied approach for the feasibility study of hotels or hospitals or other very expensive buildings in order to find out which category of building and related functionality is most feasible at which location to obtain the optimal or a certain threshold of the Return Of Invest (ROI). Today this is extended to environmental impact values using Life Cycle Cost analysis (LCC) and Life Cycle Assessment (LCA) approaches. After the decision of the investor the first geometrical and topological BIM is created.

Multi Digital Twin

Buildings do not show only one system but hosts several. As a consequence, a multi DT is proposed with the federated BIM model as the kernel model, following the concept of the multimodel method (Fuchs et. al., 2017). This would avoid too complex DTs, which are hardly to be maintained or further developed. In a federated multi DT each single DT or elementary DT can be as lean as possible due to its independency from the other DTs showing its individual LOD and can extract from the BIM multimodel (Baumgaertel et.al., 2016) the minimal needed information. In addition, different DT levels can be mixed in a multi DT and hence the most lean multi DT can be created. Each elementary DT should be on a human scale, i.e. it should be straight forward and controllable by humans. DTs that are interacting can nevertheless be defined as two or more separate DTs complemented by an interaction model like the linkmodel of the multimodel method as defined in ISO 21597. Such three interacting DTs have been defined as a hybrid DT for a fire hazard scenario with one DT for the fire modeled through fluid dynamic methods, one for the crowd simulation and one for the dynamic building model. As an overarching approach, a semantic based scenario manager was developed to model the interaction. (Scherer et.al. 2018). A related generic information and a related generalized workflow management system are currently under development (Polter et. al., 2020).

BIM levels contra Digital Twin Levels

The intention was to define a DT in a wider sense than to be focused on industry 4.0 and other new technologies and their integration in frameworks or platforms. The goal was to define the DT as a method to gain the most foresight at each lifecycle step. The guiding principles have been that

1. The computer provides us to create a mapping of the reality in the digital world;

2. The computer provides us to create a mapping of our vision in the digital world;

3. The computer provides us an objective foresight and forecasting in the digital world.

All three are seen as equally important steps forward in the technical evolution of DTs. Therefore, the DT was defined to cover all three principles and order them accordingly to the application of additional technologies from one DT level to the next DT level.

Accordingly, the six levels of DT arise:

DT L1 Visualization &Compatibility -geometrical design

DT L2 Simulation - functional design

DT L3 Forecasting

DT L4 Assessment - as-is Model

DT L5 Monitoring

DT L6 Control - Cyber Physical Systems

They are starting with the BIM model as defined as BIM level 3 by Brew & Richards (2011) and hence integrating the BIM technology partially namely the functionalities of validation, forecasting, decision making and control under the umbrella of DT.

In a similar approach, one may define these DT technologies as new BIM levels. In doing that we have at first slightly redefined the 3 BIM levels as defined by Brew & Richards (2011) according to the current state of the technology. Then we can add in a straight forward manner the DT levels in the BIM definition and come up with 8 BIM levels:

BIM L1 BIM drafting in 2D or 3D

BIM L2 BIM semantic modelling

BIM L3 Federated BIM; coordination point, MM

BIM L4 Simulation BIM, i.e. VEL, iVEL, (DT L 2)

BIM L5 Forecasting BIM (DT L 3)

BIM L6 Assessment BIM – BIM as-is model (DT L 4)

BIM L7 Monitoring BIM (DT L 5)

BIM L8 Control BIM (DT L6)

There the DT levels are mirrored in the same granularity as they are defined under the umbrella of the DT definition, but they now have to follow the BIM definition principles. However, not all five added BIM levels show very strong BIM discriminators. A short cut would be to introduce only three new BIM levels.

BIM L1 BIM drafting in 2D or 3D

BIM L2 BIM semantic modelling

BIM L3 Federated BIM; coordination point, MM

BIM L4 BIM Lab for simulation, forecasting, assessment

BIM L5 BIM as-is model - BIMification

BIM L6 BIM DT for monitoring and control

This means that DTs at BIM L6 are defined in their narrower sense, namely as-is buildings and processes, i.e. as CPS. This changes of course the starting axiom that everything showing simulation for validation and forecasting is a DT, now to the axiom that only what has a real counterpart is a DT as defined by Fuller et al. (2020)

Conclusions

This paper outlined and argued for a generalized unique DT definition where each one can classify his application easily in a straight forward manner and anybody who likes to order a DT can uniquely define his order and hence create a fair contract with the producer.

Using the definition of the DTs as an extension of the BIM definition one has to keep in mind that BIM does not mean the building model, shortly BIM model, but means Building Information Modeling and hence the total digital process and management of the building, construction, operation and demolishing, i.e. overall lifecycle and hence the construction digitalization process as a whole. Then of course the extension of the BIM definition may be the more appropriate one, because the addition of numerical methods to the BIM process results in new BIM levels – and the fusion (or marriage) of the semantic with the numeric methods creates new BIM levels. The remaining new BIM DT level represents then only the Industry 4.0 technologies, namely the CPS.

In summary we can postulate that the DT definition by 6 DT levels is a product description, which portray an order of the product namely a DT, whereas the extension of the BIM definition through 8 or 5, respectively, BIM levels is a working definition, as the term BIM expresses working quality levels and is important to describe Use Cases (UCs), roles and qualification levels.

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