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A digital twinning reference model to facilitate multi-stakeholder decision-making

Roy Damgrave[a*], Maaike Slot[b], Lieke van der Worp[a], Eric Lutters[a,c]

[a] *Department of Design, Production and Management, University of Twente, Enschede, The Netherlands*
[b] *Fraunhofer Innovation Platform for Advanced Manufacturing, University of Twente, Enschede, The Netherlands*
[c] *Department of Industrial Engineering, Stellenbosch University,Stellenbosch, South Africa*

* Corresponding author. Tel.: +31 53 4895 364; *E-mail address:* r.g.j.damgrave@utwente.nl

Abstract

In product development, stakeholders aim to make decisions based on the available information. This information is not always complete, coherent, unambiguous, or reliable. By contextualising the information content, stakeholders from various perspectives are supported in decision-making. Currently, the available information is often process-centred, which originates from legacy systems and interfaces. The information needs to become perspective dependent to be relevant for all stakeholders involved. Perspective dependent information usage allows for adequate filtering and selection. To ensure sufficient flexibility in the uncertain context of product development, the digital twinning approach can be instrumental. This digital twinning approach supports in facilitating contextualised and unambiguous information for multiple perspectives. To allow for a structured and transparent digital twinning approach a sound foundation is required, for which this paper introduces a reference model. It facilitates a function-oriented development of digital twinning solutions, ensuring the integration of multiple perspectives. A use case scenario is used to verify and validate the reference model.

Keywords: digital twinning; reference model; multi-stakeholder; decision-making

1. Introduction

Production environments have a wide variety of stakeholders, each with their own intents, goals, and needs. Where digital twinning aims to facilitate all these stakeholders in their decision-making, this paper discerns between stakeholders who use a digital twinning solution, and developers who are involved in the process of implementation and instantiation of such digital twinning solutions.

All stakeholders aim to make decisions based on the available information. To facilitate multi-stakeholder decision-making, information systems (like ERP, PLM, and MES systems) process the data involved with different time-horizons and with different perspectives. Often, legacy systems provide information to stakeholders through process-oriented interfaces. A process-oriented interface focuses on the information in a specific process step and does not always allow for incorporation of other relevant information from different process steps (e.g., learning from MES data during product development). Consequently, current information systems confound stakeholders with incomplete information. Subsequently, stakeholders are forced to use multiple interfaces from different information systems to provide and obtain information, distracting them from their primary task: product development. The complications of dealing with multiple interfaces and systems include potential miscommunication,

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missing, double, and ambiguous data within different systems and thus erroneous and ill-informed decision-making. In order to reach multi-stakeholder decisions effectively and efficiently, stakeholders should be provided with the relevant information, in interfaces that are tailored to their needs and perspectives. In this context, a perspective is the way in which (a group of) stakeholders interpret information and reach decisions given their field of expertise, experience, the domain in which they work, and their role in the decision-making process.

1.1. Digital twinning approach

When making decisions in development cycles, stakeholders rely on the available information content, where processes and activity descriptions are mere tools. Each stakeholder plays a different role in development cycles and uses the same information in different ways. Therefore, it is instrumental to put more focus on the availability, reliability, and applicability of tailored information. For this purpose, the digital twinning approach (DTA) aims to provide stakeholders with the appropriate information, at the appropriate moment, for the appropriate perspective. With that, digital twinning is the approach that leads to purposeful development, implementation, usage, and management of purposeful information backbones, such as digital twins. A digital twin functions as a conglomerate of data, information, models, methods, tools, and techniques representing a physical entity (either existing or under development) that exposes its past and current behaviour [1,2]. In this context, a digital twin functions as a tool that provides contextualised information and brings together data and information from different sources via perspective dependent interfaces. The aim of the digital twin is to transcend the domains to achieve cohesion between perspectives.

In literature, many different frameworks for digital twins exist that describe how a digital twin should be developed or how it should work. These frameworks are often on a domain and application specific level [3–5], and they are habitually based on different (sometimes even ambivalent or multi-interpretable) definitions and terminologies [6,7]. Furthermore, these frameworks hamper flexibility in product development since they often are merely appropriate for a specific situation in, or stage of, the product development process. Accordingly, they often allow for interaction with only a limited number of perspectives. In general, defining such a specific set of perspectives a priori does not do justice to the dynamics and uncertainties encountered in reality [8]. Consequently, a digital twin will never match all actual perspectives, priorities, expertise, and domain knowledge inherent to all stakeholders. This results in digital twins that are intrinsically ambiguous, and consequently cannot facilitate reliable decision-making. As an alternative approach, this research exploits the DTA as an intermediary between the characterisation of (dynamic and changing) perspectives involved and the depiction of functional mechanisms in purposeful decision-making.

The DTA, in aiming to provide perspective dependent information, requires integration of information from different perspectives, sources and states (the past/current, as well as envisaged and potential future states). To coordinate this volatile, incomplete, and uncertain information provision with all complexities involved, the so-called Digital System Reference [1] (DSR, see Fig. 1) is proposed. The DSR relates

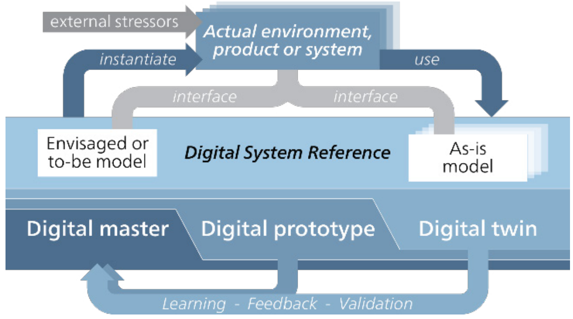

Fig. 1. Digital System Reference based on [9]

the information to the physical entities involved, while also correlating the different states involved [2,9]. In this, the digital twin captures the current and previous conditions of an entity, the digital master captures the definitions of the envisaged future state, and the digital prototype allows to test what-if scenarios by using simulations based on the design intent and the measured and predicted data of an entity [1,2].

The information that is available for the stakeholders from the different sources is not always complete, coherent, unambiguous, or reliable. An underlying cause for this is the fact that the interpretation of data is context-sensitive [10] and consequently is different for all perspectives of stakeholders. Therefore, the stakeholders require the information in the DSR to be represented in the adequate, perspective dependent context [11]. This, for example, implies that stakeholders need to be able to interpret information against the design intent of the system/aspect under consideration. Consequently, a DSR is not merely a supplying repository; it rather is an evolving entity with its own life cycle. This DSR life cycle has two distinct components: the part of the life cycle in which the DSR is developed/implemented and the part of the life cycle that accompanies the use of the DSR in real-life situations.

To facilitate adequate development of a DSR, an unequivocal foundation for development is required, for example to ensure that the DSR can cater for changes in the number of perspectives involved. Moreover, this foundation should make the usage of the implemented digital twinning solution a logical outcome of the development cycle of the DSR. As the DTA relies on an information-driven rather than a process-driven approach [2], the foundation for establishing a DSR cannot be defined in terms of process-steps or a stepwise method. Rather, the foundation can be depicted in terms of the set of function(alitie)s that should be available – irrespective of how this function(alitie)s are implemented or realised.

2. Function-oriented guideline for the digital twinning approach

The development process of a DSR entails many different components, functionalities, and perspectives. Since each of these components, functionalities and perspectives are also often interdependent, starting the development process using the DTA can be complex. Therefore, this research will focus on identifying the components and functionalities that play a role within the DTA. This research focuses on structuring these components and functionalities of the DTA in an unequivocal foundation that allows for adequate development of a DSR. This foundation is intended to provide a pragmatic foundation for the development and use of a DSR that facilitates effective and efficient multi-stakeholder decision-making. A foundation for development, that focuses on the function(alitie) inherent to the system under development, is usually referred to as a reference model [12]. In order to structure the engendering of the reference model, the reference model shall:

- Provide stakeholders with access to the information that is relevant for their perspective;
- Prevent stakeholders from being hampered by the variety of information systems and details involved;
- Enable stakeholders to benefit from the variety of perspective involved;
- Bridge domain specific applications by facilitating the development of the DSR tailored to the required perspectives;
- Serve as a function-oriented guideline for the development cycle of the DSR based on the DTA;
- Support the development of a DSR under changing conditions, varying constraints, and changing numbers and types of perspectives.

A reference model establishes the association between different elements in a system in a structured way [12]. Here, a system element denotes a group of interdependent, interacting components or entities. For this research the components and functionalities related to the DTA are grouped into meaningful clusters. These clusters are referred to as elements. Consequently, the reference model is intended to illustrate the DTA as a conglomerate of interrelated elements, highlighting the relations and without pre-determining how these relations should be facilitated.

The identification of elements that will constitute the reference model are based on literature review, expert sessions, and case studies. This includes the review of existing frameworks related to digital twinning and multi-stakeholder decision-making. The frameworks that are analysed include the 5Cs [13], the advanced manufacturing landscape [1], frameworks for digital twin(s)(ning) [14–16] and cyber physical systems [13,17]. These analyses resulted in a set of elements that provide the required function(alitie)s in the reference model:

- Context: the undefinable set of external stressors that are not yet known or relevant.
- Environment: the definable/describable sphere of influence including the known external stressors.
- Instantiated system: a specific subset of the environment for which a solution is being developed.
- Intent: the purpose of the instantiated system that originates from, for example, a company strategy, stakeholder needs, external stressors, events, etc.
- Stakeholder(s): an entity that is involved in or relevant for the instantiated system and possibly interacts with the DSR.
- Consequence: the outcome of activities and representations thereof that, based on the intent, could be expected, envisaged, or encountered by the stakeholders. The outcome can lead to or influence subsequent decisions.
- Activity: the intended or realised execution of tasks and actions.
- Content: the data and information that is captured
- Representation: the visible content
- Interpretation: the content as experienced by the stakeholder in the corresponding perspective

These elements, together with their mutual relations, form the reference model for the DTA (see Fig. 2). Where the elements themselves are identifiable entities, the relations between them are less explicit. Further elaboration is required to make these relations instrumental in thinking about establishing a DSR with the DTA. For the reference model to meet the described requirements, the relations between the elements must be further explored. To do this three dimensions are explored, respectively relating to discussion vs solution space [18] (section 2.1), data vs information vs knowledge [19,20] (section 2.2), and the actor-artefact network [21] (section 2.3). Each of these dimensions helps to explain the relation between elements and supports the verification of the relations between elements within the reference model.

2.1. Discussion vs solution space

In establishing and using a DSR with the use of the DTA, multiple stakeholders make joint decisions to come to the most appropriate and balanced solution. In doing so, they continuously balance the design intent against the potential outcomes of the design/decision process. The design intent, combined with the collection of all wishes and demands (requirements) of all perspectives is referred to as the discussion space. The potential outcomes of the design/decision process are captured in the so-called solution space. The explicit changes and decisions between the discussion and solution space will guide the process of convergence towards the best fitting solution [18].

In the reference model, the discussion space defines the environment in which the DSR is used for a specific intent for (multiple) stakeholder(s). It represents the allotted design freedom for the development cycle of the DSR, expressed in terms of the requirements that determine suitable solutions. In coherence with these requirements, the solution space can encompass multiple proposals for instantiated systems that are feasible for the different stakeholders involved. Analysing the interface between the discussion and the solution space can

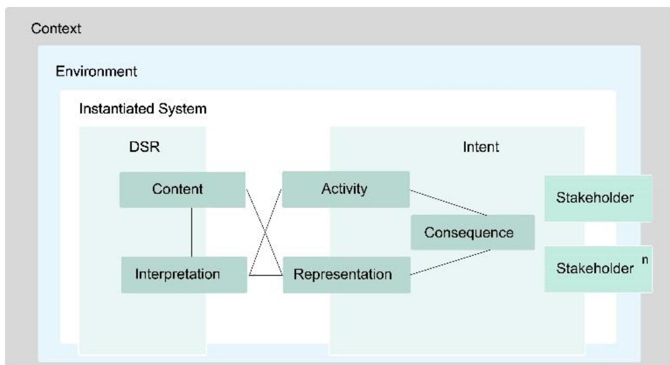

Fig. 2. Reference model for the digital twinning approach

reveal the relations between the elements, instantiated system, environment, and context. Moreover, the interface also reveals the relation between these elements and the elements stakeholder and intent.

Based on the relations between the elements, there can be multiple instantiated systems per stakeholder and thus the DSR can consist out of different instantiated systems (in their respective solution space) and vice versa. This allows for the development of a perspective dependent DSR that can be made adaptable to other perspectives and can be build based on already existing content, interpretation, stakeholders, and intents. Therefore, the reference model can support in the development of DSRs under changing conditions, varying constraints, and changing numbers and types of perspectives.

Additionally, the conversion from discussion space to solution space allows stakeholders to express their needs, requirements and wishes more easily without worrying about the details. This prevents the stakeholders from being hampered by the variety of information systems and details involved and enables stakeholders to benefit from the variety of perspectives instead.

2.2. Data vs information vs knowledge

The discussion and solution spaces focus on the convergence from context to shared decision of an instantiated system which is based on the stakeholders and their intent. In addition to the elaboration of these elements, it is relevant to deconstruct the element content and its typification. This is instrumental as this element has purposeful relations to the element's interpretation, representation, activity, and consequence. First and foremost, the knowledge pyramid [22] makes a rudimentary distinction between data, information, and knowledge as components of the element content. This hierarchy is closely related to the Advanced Manufacturing Landscape [1] which serves as an input for the analyses described in section 2. For this knowledge pyramid, the following characterisation [19–22] applies:

- Data represents unprocessed facts;
- Information represents the meaning that is assigned to data by utilising known conventions in relation to, and specific for, the perspectives involved;
- Knowledge represents the (tacit) expertise/ behaviour of a stakeholder that cannot be captured directly.

As stated in the element description, the content comprises of the captured data and information. Data is suitable for communication, interpretation, or processing by humans or automated systems. The DSR should contextualise the data into meaningful information for a particular intent, representation, or activity. The reference model facilitates this contextualisation by means of the interpretation element.

Since not all content is relevant, accessible, or interpretable by the DSR (yet), the content and interpretation elements partly extend outside the DSR, to accommodate the tacit components of the knowledge involved. Consequently, the reference model ensures that the DSR provides stakeholders with access to the appropriate information that is relevant to their perspective. Together, the content, interpretation, and representations provide an embedding for activities that are (to be) executed. Consequences of such activities – either (un)intended or (un)expected – allow for subsequent decision-making by stakeholders or in a more autonomous manner. In the reference model, this means that the elements activity and representation become the explicit bridge between the element consequence and the elements content and interpretation.

2.3. Actor- Artefact network

The relations between the elements as identified in sections 2.1 and 2.2 capture the logical dependencies between many of the elements in the reference model. However, so far, the behaviour of stakeholders in the decision-making process is not yet captured. For this purpose, the Actor-Artefact network [21] is used to identify the relations between the intent and consequence elements that can influence stakeholder behaviour. The actor-artefact network focuses on integrating the information on product development from different perspectives, in terms of the product definition and product information from the current and previous product development cycles [21]. With that, the actor-artefact network is instrumental in aligning information and decision-making for multiple perspectives involved. It additionally prevents and deals with the archetypal miscommunication that frequently occurs between different perspectives.

The reference model shows a relation between the DSR (through the content and interpretation) with the representation and activity. This relation allows the DSR to align the appropriate information to support the stakeholder's decisions. Based on the actor-artefact network, the DSR should connect the stakeholder's activities with their intent, the content, and interpretations.

Additionally, the incorporated actor-artefact network theory in the reference model will allow for a perspective dependent development of the DSR for aligning decisions. The reference model focuses not only on the performed activities or representation but also on the intent, the consequences, and the reason why these activities are performed. Therefore, the reference model supports in bridging the domain specific applications by facilitating the development of the DSR tailored to the required perspective.

2.4. Proposed reference model

The incorporation of the elements and theory-based relations helps to verify the requirements that were formulated for the reference model as shown in Fig. 2. In combining the different elements depicted as components of the reference model, as well as the mutual relations between them, the reference model is conducive in compartmentalising the DTA. In dissecting what the components of that DTA are, the reference model becomes a support in formulating, developing, implementing, and evaluating the roles of the different elements. In this, attention explicitly is on 'what' the elements can contribute to the DTA, while avoiding prescribing 'how' these elements would/should do that. In this, the reference model is completely function-oriented: it distinguishes capacities/capabilities rather than solutions. With that, the reference model foremost aims to facilitate establishing digital twinning approaches by allowing all stakeholders involved to address their specific perspectives in terms of a conjoint set of functions/elements. During the development and use of the DSR, this will lead to more transparent, better underpinned decision-making, and to a more deterministic and traceable development cycle. Moreover, different stakeholders/perspectives will gain more overview of all perspectives involved and will be able to better interpret or reconstruct decision-making, thus leading to more weighted and underpinned outcomes.

3. Application of reference model

Where the reference model is a corollary of the requirements discussed in section 2, its aptness for underpinning a DTA can be inferred. However, the feasibility and value added for realistic development cycles needs to be assessed. Where the proposed reference model is currently applied in long-running implementation trajectories in industry, here a scenario is used to concisely capture the essence of such a trajectory. Furthermore, the research findings are rooted in an industrial use case.

3.1. Application scenario

For the validation of the reference model, a scenario is compiled based on an industrial research project. This project addresses a number of challenges in an existing, yet expanding, factory environment, in which discrete components are produced and products are assembled on a flow-oriented line. The assembly line is characterised by a high variety product mix in single product to small batch production. The research project focuses on the development of a DSR to facilitate multi-stakeholder decision-making within this factory environment. The reference model was developed later than the development of the DSR. Therefore, the scenario will be used to evaluate whether the reference model is suitable and valuable for the development cycle of the DSR.

Many stakeholders are involved in the manufacturing process of the products, each with their own perspective, such as production, assembly, procurement, sales, and IT. Habitually, the stakeholders have limited capabilities and capacity to immerse in the other, and even adjoining, perspectives. Yet, design choices are often related to multiple domains. The reference model can help in determining which domains and stakeholders are involved in the environment and which should be considered within the instantiated system. In the case of the factory the reference model would have ensured an effective scope of the instantiated system.

The envisaged DSR, when implemented, should support production by providing tangible insights into decisions and their consequences. However, in practice, from the start, every perspective involved will have different expectations of the DSR. Such different perspective will apply dissimilar terminology and methodology. Whereas the activities seem detached, in reality all perspectives are involved in the same production environment. In this, the reference model can facilitate the discussion to find the shared responsibilities and address the functions that are common to all perspectives. Moreover, it can support in determining the functionalities that should be incorporated in the instantiated system, and thus should be facilitated by the to be developed DSR.

With the elements in the reference model being shared ‘stepping stones’, the different perspectives can be brought together to effectively discuss the connection and similarities between their perspectives: what aspects need to be included (activity), what information (content) is required and how can this content be interacted with (representation). At this point, it is clear that the reference model simultaneously serves as a tool for developers of the DSR and for users of the DSR. Stakeholders focusing on the ‘actual production environment’ under development can start using the reference model from the element’s representation and activity, extending this into content and interpretation needs – in line with the actor-artefact network. At the same time, the developers of the DSR can examine the structure(s) that underly the activity of the users, and they can establish e.g., the IT-infrastructure, IoT solutions and databases accordingly. In other words, the DSR-users can focus on how the elements in the reference model contribute to more aligned, transparent, and underpinned decision-making for the production environment under consideration. At the same time the DSR-developers can focus on how the elements in the reference model contribute to more aligned, transparent, and underpinned decision-making. In both cases, all stakeholders can work together because of the function-oriented depiction of the elements and their mutual relations in the reference model.

3.2. Industrial use case

Within this research an industrial case study is performed at a manufacturing company which specializes in producing composite parts. The company's objective is to use information to enhance their production processes, thereby increasing efficiency, quality and reducing costs. By leveraging digital twinning technology, the company aims to improve its production process and stay ahead of the competition. For the purpose of the case study, the researchers specifically examined an edge sealing machine used to apply resin on the side of composite parts. One of the company's key goals is to use the DTA for increasing the flexibility and scalability of the technology. The digital twin should be able to provide multiple stakeholders with decision support for optimization of the machine, this includes simulating the effects of changes. These simulations can for example be providing insight in the consequences on speed, quality and costs. Currently there is a limited set of first stakeholders known. The number, type and role of the involved stakeholders will continuously change over time. Due to these changes in involved stakeholders, a common reference model is essential for the mutual understanding of the digital twin. Therefore, the reference model for the DTA will be used to handle continuous changes to the digital twin in line with changing information needs and requirements.

3.3. Evaluation

Whereas it is beyond the time-horizon of this paper to depict a full, multi-annual, implementation trajectory for a DSR and DTA, the use case shows the potential of the reference model.

Overall, this research provides valuable insights into the potential of this model and its potential use in practice. The findings highlight the need for further research in this area, including efforts to further refine the model and assess its performance in a variety of settings. These efforts will ultimately be crucial in determining the usefulness of the model and its potential impact on different areas. The applications, as well as in discussion with industrial partners, gives an initial indication that the reference model is valuable in bringing various perspectives in decision-making together. With that, the reference model can meet the objective of being a foundation for digital twinning approaches.

However, it should be noted that the application of the model is still speculative and has not yet been tested in a real-world environment. Despite this limitation, the results of this study represent a promising first step in the development of the reference model. Further research is needed to validate and valorise the model. This will include a more detailed investigation of its practical applications and the extent to which it can be implemented in real-world scenarios.

4. Concluding remarks

To support multi-stakeholder decisions effectively and efficiently, stakeholders should be provided with information that is relevant, reliable, and timely for their perspective. Moreover, this information should be available understandably and hence in a contextualised manner. The digital twinning approach aims to provide this perspective dependent information. Yet, this approach relies on the availability of a central foundation that depicts the system under consideration in terms of the functionality required for information provisioning. This foundation is postulated, based on literature research, a scenario, and a use case in industry, by means of a reference model. This reference model is generic enough to cater for a wide variety of use cases, yet specific enough to express the functionality required in the digital twinning approach. The reference model is verified based on the requirements specification deduced from the function-oriented analysis of the digital twinning approach. Subsequently, a use case scenario is employed to validate the role of the reference model as a common foundation and functional guideline to facilitate the development cycle of the DSR in such a way that it can facilitate multi-stakeholder decision-making.

Given the time-horizons of typical IT-implementation trajectories in industry, current validation is still limited. Consequently, further evolvement and validation of the reference model will be an ongoing topic of research. In this, more and more, the role of multiple perspectives and the corresponding uncertainties and ambiguity will increase. These incertitudes not only provide a basis for further validation, but they also challenge future research to focus not only on the decision-making itself, but also on the underlying drivers of such decision-making. With that, future research can additionally focus on the underpinned definition of case-specific architectures for digital twinning solutions while using the reference model as a foundation.

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