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## Model Based Systems Engineering applied to Digital Twin engineering: why and how to?

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**Abstract:** In addition to inheriting concepts and methodological principles from System Engineering, Model-Based Systems Engineering (MBSE) emphasizes the role of modelling and models in engineering processes. Different types of models are then constructed and used, each being a digital representation of a system that is undeniably partial, but also necessary. It highlights and enables the analysis of certain characteristics of this system, e.g. its behaviour, its functions or its composition to make relevant design choices. Digital Twins are the ultimate representation of a system, expected to be faithful and realistic for the purpose they serve, as well as to be connected and synchronized to the modelled physical asset. Hence, they support stakeholders to manage, train or optimize the target system when implemented and put into operation. However, defining and engineering Digital Twins remains a difficult process, with little methodology available to build and ensure it remains faithful to a continuously evolving reality. MBSE provides concepts and a methodological framework that are well adapted to solve complex engineering problems with many constraints. This position paper introduces a MBSE based Digital Twin engineering framework foundation, applied to an manufacturing system.

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**Keywords:** Digital model, Digital Twin, Digital Thread, Model Based System Engineering, Method, Digital Twin Architectural framework, Digital Twin system

### 1. INTRODUCTION

Digital Twins are now seen as an important tool in the industrial environment. Industrial systems are becoming increasingly complex in terms of organisational (centralised vs. decentralised, multi-company or intra-company), logistical, technological and human concerns with numerous objectives of safety, security, environment and energy consumption, performance as well as **maintainability**. The Digital Twin (DT) is a digital, synchronised image of a physical entity, such as manufacturing system, referred to in the following as the Physical Twin. A DT can be used to meet some needs of control and supervision, parameterisation, testing and optimisation, or even as a support for operator training. However, DTs design and development remain time-consuming, costly and complex. Fittingly, System engineering (SE) provides methodologies and concepts to handle complex engineering projects with numerous constraints. SE guides the design process to make the most fitted technical solution emerge. Hence, the aim of this position paper is to demonstrate the relevance of SE to engineer DTs of manufacturing systems. In line with this, the article is structured as follows, starting with an analysis of the issues raised, followed by the integration of this work in a current knowledge context. The methodology adopted and its application to the engineering of DTs of manufacturing systems are then presented by applying the technical processes of SE.

### 2. ISSUES

SE (INCOSE, 2015) promotes both a prescriptive framework and a working method for the design, development, maintenance and end-of-life of complex systems. In addition to strong systemic principles, it emphasises technical engineering processes (ISO/IEC/IEEE 15288.2015, 2015) and management processes to guide and structure engineering work (ISO/IEC/IEEE 15288.2015, 2015).

Model-based systems engineering (MBSE) inherits these principles and processes by promoting modelling and the use of models in each of these processes, with recognized benefits (Fosse, 2012). The aim of modelling is to describe a system, phenomenon or element according to views (e.g. functional, behavioural, requirements or organic) by respecting the conventions of a modelling language or Domain Specific Modelling Language (Combemale et al., 2014) e.g. SysML (OMG, 2023). However, a model responds to a purpose and objectives specific to the stakeholder who is modelling, e.g. analysing performance, formalising a set of requirements that must be SMART or an operational scenario. Each model therefore expresses a point of view, a level of detail, to serve the analysis (ISO/IEC/IEEE 24641:2023, 2023) and reasoning, to explain, prescribe or argue a choice (Chapurlat et al., 2022). All the models resulting from the current or previous designs, as well as the data, information and knowledge (DIK) that result from them, or that are captured during the operation of the system in use, must be shared between all the stakeholders. To this end, the concept of the Digital Thread has emerged to ensure the consistency, traceability, sharing and exploitation

of models, DIK throughout the life of the system. (AIAA Digital Engineering Integration Committee, 2023; Blampain, et al., 2022; Podskarbi & Knezevic, 2020; Q. Zhang, et al., 2022). When the system is finally put into operation, or is already operational, the needs of the stakeholders can be to control and pilot the system, train the operators or facilitate the parameter optimisation or maintenance. All the models and DIKs accessible in the Digital Thread can then be used to facilitate the emergence of a DT. A DT is a solution that is currently recognised and developed to meet one of the needs described above. Several DTs could be requested for a same production system but for distinct usages. However, the definition of Digital Twin remains plural in the literature (Semeraro et al., 2021), (Negri et al., 2017). (Grieves, 2014) proposed in 2014 a structure composed of: the physical twin, i.e. the production system concerned, the DT and a communication device between them. (Tao & Zhang, 2017) adds to this definition of service and data storage. More recently, a DT is defined as a “*Digital representation of an observable manufacturing element with synchronization between the element and its digital representation*” (ISO 23247: 2021, 2021). In the following, we will use the respective notions of a Digital Twin System (ISO/IEC 30173:2023, 2023) made up of different subsystems summarised in Figure 1, interacting around a digital model of the Physical Twin, then called the Digital Twin System (DT System).

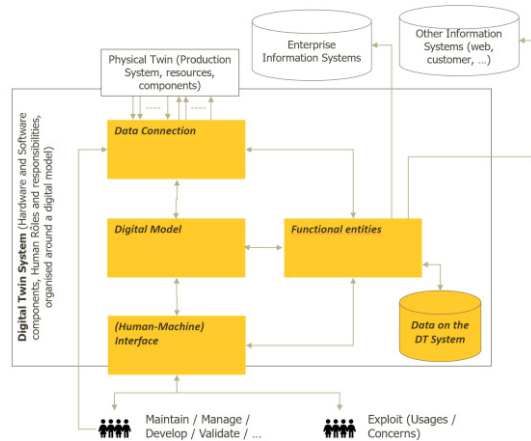


Figure 1: Structure of the Digital Twin System

DT System involves several elements that enable it to perform its functions: sensors for data extraction from the physical twin, data storage and processing devices, interfaces and connection protocols, and software tools. (ISO23247-2: 2021; Tao and Zhang 2017). The DT is supposed to be sufficiently realistic and adapted to the uses expected by stakeholders. However, the reuse and maturation of models and DIK contained in the Digital Thread remains an open question (Bone et al., 2018). (Jones et al., 2020; Semeraro et al., 2021) noticed that there are no established methodologies for maturing existing models to track the evolution of the Physical Twin from one phase of its lifecycle to the next. Yet this would present numerous opportunities to support the development of both the Physical Twin and the DT.

Secondly, the engineering of a DT System remains difficult, poorly formalised, time-consuming and costly in terms of means and resources. It is often carried out case-by-case, using different tools and methods such as: the finite element method (Podskarbi & Knezevic, 2020), data (Guo et al., 2019) or object recognition techniques (Sommer et al., 2019). (Liu et al., 2021; X. Zhang et al., 2023) applied MBSE approach for DT engineering respectively for Industrial Robots and shop-floors. Their applied research show the relevance of MBSE principles for DT Systems engineering of complex systems and highlight the need of generic MBSE methods based for DT Systems engineering. The aim of this process is to achieve a result that matches both the Physical Twin and the expected DT System purposes, i.e. the usage for which DT Systems is engineered. Last, any DT Systems must be maintained in operational conditions in order to remain conform to any Physical Twin evolutions, to take technological evolutions into consideration, and to rethink and adapt DT System to end users' expectations and even new usages (NF EN 17666:2022, 2022). This engineering must be carried out in two cases:

- The Physical Twin is currently being designed (Bickford et al. 2020; Braun et al. 2023). The engineering of the DT System can then be based on the models generated by the design (functional, behavioural, architectural, simulation, optimisation, etc.) which will be developed and enhanced during operation to meet the operator's objectives.
- The Physical Twin is in operation, in which case the models of this Physical Twin may be partially obsolete for various reasons, but production, operating or maintenance data, etc. relating to the Physical Twin are supposed to be available. Reverse engineering approaches (Sommer et al., 2019) (Ayani et al., 2018; Qie et al., 2021) can be used to fill these gaps by making use of the system's operating data (performance data, failure and shutdown characteristics, geometric characteristics, etc.). This case will be the one studied in this paper.

The research presented here is a first attempt, using strong hypotheses that are twofold: 1) models and data can be accessed and used to produce DT System faster and more accurately, considering a number of obstacles are to be overcome (e.g. interoperability of models, modelling languages and tools, different levels of detail, scope and objective of modelling, point of view described), and 2) Both SE and Model Based System and Software Engineering (MBSSE) promotes modelling and structuring processes guiding the work and applicable here in the case of DT System engineering. The contribution proposed in the next section is therefore a method for carrying out model and data-based engineering of DT System.

### 3. CONTRIBUTION

This article intends to present the main elements of the method for engineering and maintaining in operational conditions a DT System seen then as the System of Interest (SoI) of the engineering project (ISO/IEC/IEEE 15288:2023). Being

model-based and process-oriented method, request at least to dispose of modelling artifacts and activities:

- **modelling artefacts** to guide and support engineers during various model and data-based activities requested for engineering any system in classical sense but adapted here to DT System engineering. These artefacts currently remain under formalization and validation stage, so they are just introduced and illustrated in the following. They have been established considering (ISO/IEC 30173:2023, 2023) and (ISO 23247:2021, 2021) standards, which provide respectively a standardized definition of basic concepts and elements and a standardized functional architecture for DT Systems. These standards will be supplemented by functions linked to the specific use for which the DT System is being designed. The whole of modelling artifacts is defined independently from a usable modelling language, adopting then a tools-free approach.

- **These activities** are then organized and managed by adopting classical process oriented organizational approaches. A **processes cartography** is proposed by two standards for mapping the processes needed to structure and organise, manage, and steer a DT System engineering projects:

- o (ISO/IEC/IEEE 15288:2023, 2023) provides a large number of processes;
- o (ISO/IEC/IEEE 24641:2023, 2023) promoting MBSSE approach within processes.

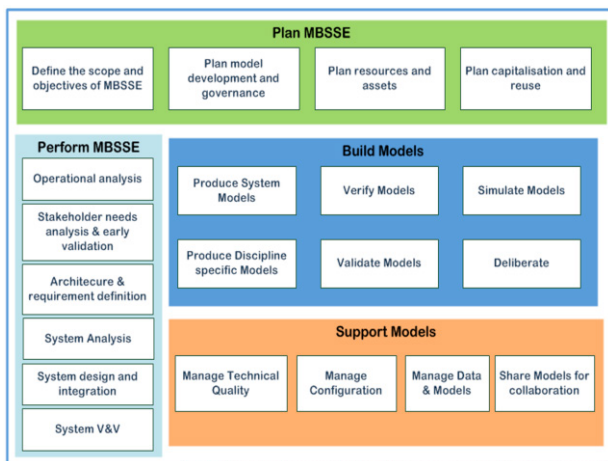


Figure 2: MBSSE process cartography (ISO/IEC/IEEE 24641:2023)

The essential activities underlying these processes and the modelling artifacts used are therefore based on a set of predetermined elements, sometimes derived from proven standards, but also from practices and principles that are systemic. They must be expressed and submitted to the stakeholders involved in a generic form that can be understood and adapted from one stage to the next to ensure the mission of a DT System and consider the uses and needs of these stakeholders as they arise.

The aim of the proposed method is to reduce the engineering time required, improve collaboration and build trust between all the project's stakeholders. The principle is to consider the DT System with two complementary views:

1) **Problem statement:** to define the contours of the DT System and its inputs/outputs:

- Its mission (what does the DT do and for what purpose is it designed and developed and then used?)
- Its purpose (why does it exist and how can we justify the need for it? Are there not, for example, other existing or simpler alternatives?)
- Its objectives characterise the expected end result, essentially in terms of performance and usability (what criteria will allow to certify that all the needs of future end-users have been met at the time of its operational qualification and its entry into the production phase?)
- Its life cycle, made up of alternating stages of development and milestones between each stage. These milestones can be differentiated but are often associated with the proposed reviews to assess the progress of results throughout the processes of the organisational framework.
- Stakeholders, i.e. any person or organisation concerned by, involved in or impacted by the development project and the implementation of DT System at each stage of its lifecycle. Stakeholders research can then follow the recommendations of (Gomez et al., 2018).

- Its operational context(s), which is displayed in Figure 4, describes the other systems that interact with it at each stage of its lifecycle. For example, a DT System used for control purposes constantly interacts with its Physical Twin when the latter is in operation. These interactions are then modelled in the form of services. These are the functions that manage the inputs/outputs of the SoI that must be provided by or expected by the DT System to fulfil its mission, while remaining true to its purpose. Each service is itself detailed in the form of: the flow (of matter, energy or data) exchanges that this service requires, links (e.g. physical links, or communication and exchange protocols) that will have to ensure the transfer of these flows between the SoI and these systems. Interfaces required a priori by the DT System to remain interoperable and allow the physical or logical connection with these external systems. This analysis of services can also reveal a set of functions (e.g. connecting, disconnecting, or sending requests) which seem to be concretely required by the DT System to provide each service.

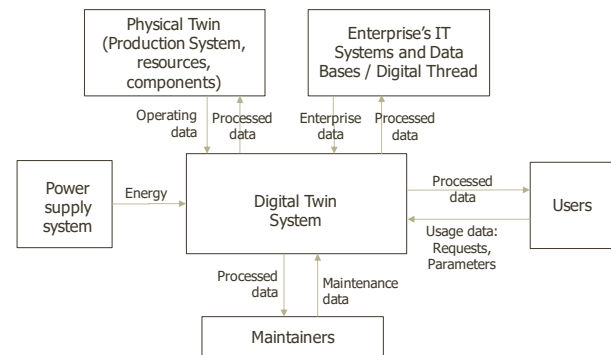


Figure 3: Generic context representation of DT System

- The operational scenarios (Figure 5), which describe, however briefly or informally, how these services are to be

provided or expected, and how they will be linked and synchronised to fulfil the mission. Each scenario therefore describes the expected behaviour of the DT System depending on the state, configuration, and current operating mode of the SoI (e.g. normal operation, degraded operation, shutdown, maintenance). The set of operational scenarios provided at this stage is important because it must trace or illustrate the overall behaviour required to fulfil the mission in each of these operational modes and various situations.

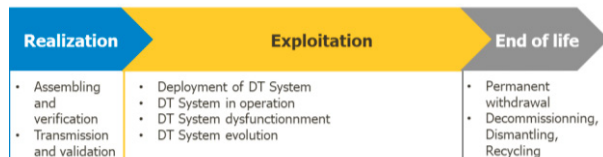


Figure 4: Generic list of operational scenarios

(ISO/IEC 30173:2023, 2023) already provides a framework with an operational context, a lifecycle and stakeholders. The contribution, currently being formalised and briefly illustrated in Figure 3 and Figure 4 is therefore intended to provide generic elements available to the stakeholders in the engineering project to guide and secure their results.

2) **Solution definition:** the aim then is to design, develop and validate the DT System in concrete terms, considering the previous results, but evolving until convergence and agreement of the stakeholders. By definition, the logical architecture of DT System is given in Figure 1. This figure shows the following five sub-systems:

- Sub-system **connection:** the connection elements between the DT System and the Physical Twin. This sub-system enables to gather operational data from the Physical Twin as well as transmitting instructions.

- **HMI** sub-system: is the interface between the users and DT System, thanks to which user can input requests, parameters or have access to results of simulation and analysis performed by the DT System.

- **Data Repository** sub-systems: described as a subset of the Digital Thread interconnected to all the company's information systems on which the Digital Thread is therefore implemented as it gathers data that can be processed in information and knowledge. It also includes a repository for data specific to the DT Systems.

- **Functionalities:** this is the expected functional architecture of the DT System described below Figure 8.

- The **Digital Twin**, defined here as a Digital Model as defined in Figure 5 (Chapurlat et al., 2022; Fosse, 2012), i.e. a federation / composition of heterogeneous models (system models and business models i.e. discipline models) which focus on different views of the same SoI. This federation/composition is the subject of numerous studies and techniques (e.g. semantic alignment, FMI/FMU-type encapsulation, or model transformation) currently being integrated into the method. Its main aim is therefore to provide a more realistic overall picture of the same system, and to resolve the interoperability issues between these models and DIK, as well as the modelling languages and tools which are

then implemented at the request of engineers, according to their modelling uses and habits.

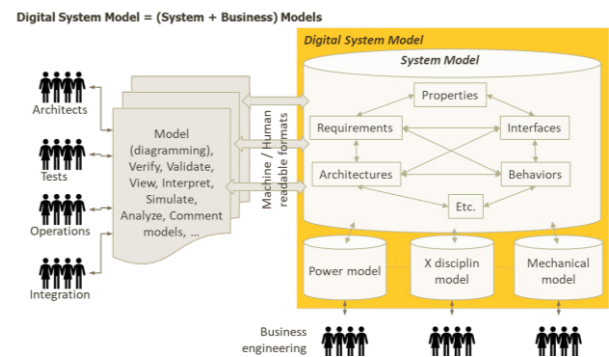


Figure 5: Digital Twin defined as a Digital Model (Chapurlat et al., 2022)

The activities involved in modelling, checking and validating, then developing and putting a DT System into operation are summarised as follows:

- Carrying out an analysis of the needs of the stakeholders and engineering the resulting DT System requirements. The aim is to have a repository of SMART (INCOSE, 2023) functional and non-functional requirements (including performance, security and interoperability requirements, as summarised in the Figure 6), thus setting the course for the architectural design work that follows.

- Modelling what the DT System does independently of any technical solution, i.e. its functional architecture such presented in Figure 8.

- Modelling what the DT System must be composed of to execute these functions in all situations, in all modes and in each of the operational scenarios specified above. Several alternative logical architectures are then possible. These prefigure the different possibilities for implementing the DT System, i.e. the physical architecture alternatives and therefore the DT System product expected by the stakeholders. They also have an impact on the requirements repository through the specification of new requirements induced by the development choices or alternatives.

- Verifying from one stage to the next, evaluate and compare, then validate with stakeholders the results of each stage (requirements repository, architecture alternatives).

- These activities are iterative, allowing us to notice the similarities with an agile engineering approach (Karagiannis, 2022) at each iteration, leading to reasoned and confident progress.

Here again, (ISO 23247: 2021, 2021) offers a general functional view of a digital twin, but it remains partial. The contribution of this work is therefore threefold:

- Providing a generic requirements repository to guide those involved in the engineering project and a SMART requirement engineering approach.

A repository of two types of functions: technical functions for the management of the DT System itself, more traditional and promoted by (ISO 23247: 2021, 2021), and functions that are necessary and dedicated to meet the requirements of stakeholders (uses / concerns / constraints) (Figure 7). These

functions are then proposed in the form of an ideal functional architecture (Figure 8), enabling designers to be guided more quickly towards the real added value of the DT System they wish to develop.

#### 4. CONCLUSION

In conclusion, this work proposes the development of a Model and Data Based Systems Engineering framework and method for the engineering of DT System, specifically applied to production manufacturing systems. To do this, the outlined contributions integrate different standards. This methodology is based on (ISO/IEC/IEEE 15288:2015, 2015) while considering the MBSSE process cartography (ISO/IEC/IEEE 24641:2023, 2023). It explores the DT standards (ISO 23247:2021, 2021) and (ISO/IEC 30173:2023, 2023).

The next challenge of this study aims to refine the methodological approach while challenging the assumption that all models are readily available. In this purpose, two distinct scenarios for DT System engineering emerge, depending on Physical Twin existence and DIK availability. Several issues may be solved by adding cases in the methodology defined previously, depending on Physical Twin existence and DIK quality and availability. For this reason, the concept of Digital Thread as an organization and container of data across the whole Physical Twin lifecycle, ensuring their storage, traceability, consistency, and integrity may withhold opportunities for DIK exploitation and structuration to support DT System engineering.

On one hand, Physical Twin can be already in operation, but the associated models may be unavailable or outdated. In this case a reverse engineering process to recreate models and DIK is necessary. Generating DIK and models, intentionally managed, enable and support Digital System engineering by creating an appropriate data and modelling context for its engineering. On the other hand, if the Physical Twin does not yet exist, an adaptation of the SE methods will be needed for simultaneous engineering of the system's TO-BE and TO-BE-IMPLEMENTED. In this situation the Digital Thread is used to create a digital continuity of DIK related to the Physical Twin, allowing their exploitation from the origin of the engineering process across the whole lifecycle until the end of life thanks to a consistent and intentional strategy.

This dual approach involves feeding of generated DIK throughout the engineering process in each case thanks to the Digital Thread. Next research steps will be focused on the organisation and exploitation principles of DIK contained in the Digital Thread to support each scenario of DT System engineering. However, exploitation of Digital Thread data withholds interoperability, integration, and organizational challenges that need to be tackled in order for the Digital Thread concept to support DT System engineering (Q. Zhang et al., 2022).

Type of requirements	Requirements	Refined requirements
Functional requirements (based on ISO23247 standard)	The DT System communicates with its Physical Twin	The DT System collects data. The DT System identifies data. ...
	The DT System has a Human Machine Interface	The DT System displays analysis results. The user can interact with HMI. ...
	The DT System has interconnection entity	The data are translated. The data remains accurate and integrate. ...
	The DT System models the physical twin	The DT System provides a digital representaion. The DT System is synchronised with physical twins. ...
Non Functional requirements	The DT System is interoperable.	The DT System is interoperable with Physical twin. The DT System is interoperable with IT system of enterprise. ...
	The DT System is safe.	Data are back-up. There are protocol security agains cyber attacks. ...
	The DT System is fast	Simulation results are given within defined time span. ...

Figure 6: Partial view of the generic requirements repository

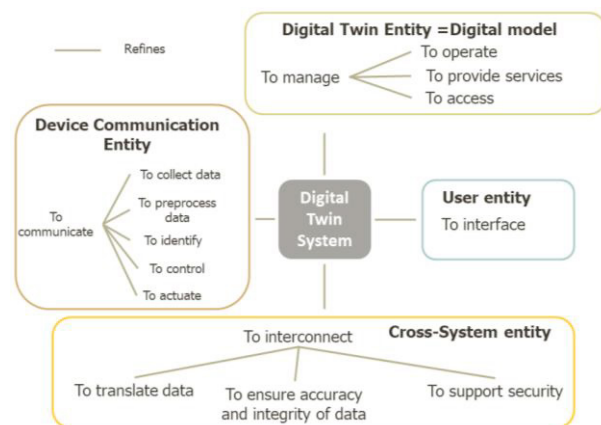


Figure 7: Partial list of functions (ISO 23247: 2021, 2021)

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