Towards Architectural Coordination for Digital Twins

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Abstract: Digital Twins (DTs) carry the promise of supporting better decision-making, monitoring, and learning in relation to the twinned entity, by integrating novel technologies, including digital models, symbolic and sub-symbolic artificial intelligence, as well as advanced optimisation, simulation, and visualisation techniques. However, delivering such a promise requires considerable investments, which can only valorise in the long run, as DTs tend to be 'data hungry', in need of ample sensors, actuators and serious computing power. Yet, most current approaches to DT development focus on isolated scenarios, which not only limits the understanding of the value of DTs, but also their broader implications. The introduction of DTs, generally, also entails a wider digital transformation in an (inter-)organisational context, while such transformations need to be properly managed. We also observe that, since DTs are fundamentally a class of (highly advanced) information systems, this inevitably makes them an integral part of an enterprise's broader (inter-organisational) portfolio of information systems. In line with this, we argue that, in order to (also) improve the socio-economical sustainability of DT solutions, their development, deployment and evolution need to be subject to *architectural coordination* within the broader frame of enterprise architecture management (EAM). From this perspective, we discuss some potential directions of research in (enterprise) architectural coordination of DT development, in order to help address some crucial challenges of socio-economically sustainable development and evolution of DTs as part of a broader portfolio of information systems.

Keywords: Enterprise Architecture, Architectural Coordination, Digital Twins

1 Introduction

The concept of Digital Twin (DT) was coined by NASA [Al21] in the context of digitally mirroring and predicting the behaviour of space-crafts during space missions. The original definition of DT conceived it as providing a virtual model of a *physical entity*, designed to collect, transmit and analyse real-time data, facilitating a bi-directional relationship [Jo20] between the virtual model and its counterpart, and offering real-time monitoring, simulation, and optimisation functions. Over time, the scope of entities 'twinned' by DTs broadened beyond *physical entities* to include complex socio-technical systems in e.g. urban planning [No21], management of pandemics [Eu24], and business processes [Ba22]. In these contexts, DTs are considered to have a potential added value towards a variety of complex decision-making problems. To achieve this, advanced digital models, symbolic and sub-symbolic AI, optimisation, simulation, and visualisation techniques are integrated. Combined, these functions enable their users to take *informed decisions* pertaining to

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'twinned subject', and often even allow them to *actuate* these decisions. As such, DTs are fundamentally a class of advanced (active) information systems, and should, in an enterprise context, be treated as an integral part of the larger portfolio of information systems.

Twinning also requires serious computing power [Th24], numerous IoT sensors and actuators, large quantities of data, as well as considerable investments. At the same time, the promise of twinning can only be realised with a significant change in managing technological landscapes and involved data (eco)systems, as well as a profound shift in decision-making culture. This vertical impact on socio-economical (eco)systems subject to twinning has to be properly managed.

Enterprise Architecture Management (EAM) is positioned [Op09] as a discipline to enable informed decision-making in managing and coordinating structural planning challenges in enterprises, and their portfolio of information systems in particular. The aim of EAM, as a discipline, is to provide structured approaches to align technological, information, and organisational architectures to strategic objectives, and to coordinate (digital) transformation programs and projects to ensure their delivery, overall coherence and rationalisation of involved technological landscapes [Op09]. As DTs are fundamentally information systems, they are a natural part of an enterprise's broader landscape of information systems, and should as such be managed and their development governed from this broader context. Nevertheless, current DT initiatives do not take this account, which results in important challenges to materialise the value of DT, justify required investments, and defend socio-economic sustainability of this novel technology.

The remainder of this paper is structured as follows. Sect. 2 explores some of the key planning challenges regarding the socio-economic sustainability of DTs. Subsequently, Sect. 3 highlights the value of adopting a broader EAM perspective to effectively address these challenges, while suggesting several research topics to further this research.

2 Planning challenges for Digital Twins

The socio-economically sustainable development and evolution of DTs involves several key planning challenges, some of which are discussed below.

Ad-hoc and isolated development – DTs are often introduced due to a technology-push, with significant focus on infrastructure, IoT and data collection [Op24; RSK20]. At the same time, the design and implementation of DTs often stays limited to specific needs of an isolated scenario [KC24]. Yet, DTs are embedded in the broader data, information system, and technology landscape of socio-technical system subject to twinning. These should be considered not only to avoid scalability, integration and maintainability issues of the designed DT, but the very planning, design and evolution of DT should be done within this broader context. This would allow for a strategic vision, identification of business value of DT, roadmapping of DT developments and would thus facilitate justification of considerable investments in DT technology.

Lack of user engagement – The use of DTs still revolves around basic functionalities, e.g. static visualisation and monitoring of (nearly) real-time data, with only modest application for informed decision-making [Qi21]. The involved technological complexity inevitably acts as a barrier for decision-making stakeholders [Op24; RSK20], while black-box nature of predictive models and ML/AI manipulations adds to the scepticism from domain experts, negatively affecting the use of e.g. simulation results as a basis for decisions [BS20]. The overly techno-centric approach to the development of DTs needs to be balanced to involve domain experts and other stakeholders at many levels, in order to e.g. clarify decision-making requirements and respective value of DT functionalities, incorporate domain knowledge from relevant domains and help establish transparency and trust.

Fragmented data ecosystems – DTs are 'hungry for data'. Indeed, sensing systems offer the possibility to continuously collect data, and monitor the behaviour of the systems. However, the value of collecting endless data must be clear: large amounts of data collected in different time frames, of differing collection frequencies, in different formats and abstraction levels, increase the challenge of data integration and interpretation, exacerbating pre-existing fragmented data landscapes [BS20]. This further emphasises the importance of a proper data management strategy in the context of DT development. Additionally, for DTs that aim to twin complex social-technical systems (e.g. supply chains [LPB24], real estate management [DMK21], urban planning [De20]), technical challenges involved in data ecosystems play second fiddle to the challenges of data ownership and willingness to share data with potential competitors, regulators, etc [OL18; SK22; TMR17].

Synergies in the IT landscape – At the heart of a DT, we find a *virtual model* of the twinned entity, which is created, and kept up-to-date, based on different data sources (including, but not limited to, sensor data) concerning the twinned entity [Jo20]. This does not differ fundamentally from a traditional information systems: the database underlying any (computerised) information system [IS87], is essentially a model of the state of affairs (with historical data) of the domain of interest of the information system. Contemporary DTs add to this AI-powered functions, which enable monitoring, simulations, optimisation (and eventually also actuation).

Therefore, it can easily be argued that a DT is 'just' a special kind of information system. Just as one expects a modern day information (systems) architecture to be integrated and synergetic landscape of applications and IT infrastructures, one would expect DTs to be an integral part of this. Some work into such a direction has e.g. been reported in [Li24]. More fundamentally, this requires a shift in considering DTs not as of a 'monolithic notion' and self-sufficient technology, but rather as a collection of components with complementary functionality that can be combined, and integrated with, existing information (systems) architectures. In line with [SI23], it would open up scenarios to, for instance, start with functionality of traditional (decision-support) information systems, and gradually – needs driven – add more data sources, richer virtual models and more advanced simulation and optimisation functionality to gradually evolve to a full-fledged DT functionality for a respective domain and decision-making challenge.

3 Architectural coordination for DT development and deployment

We argue that a socio-economically sustainable introduction, development and evolution of DTs can be achieved most effectively when taking holistically into account the informational, technological, organisational and strategic concerns of an ecosystem that DT is intended for.

The discipline of Enterprise Architecture Management (EAM) [Op09] aims to provide the approaches need to systematically take these considerations into account. Inspired by engineering and building architecture, EAM has established the use of architectural models [La17] as a major instrument to (1) manage, ensure coherence and coordinate structural planning challenges in (digital) transformation of organisations (refs), as well as to (2) specify high-level design of IS/IT solutions to business needs and manage their overall coherence within the IS/IT landscapes, and (3) coordinate among relevant stakeholdersand ensure overall coherence and alignment of initiatives [Pr18; PWB23].

When, indeed, including DTs as an integral part of the information systems landscape of enterprises, then this leads to a range of research challenges involving potential extensions of existing EAM frameworks and modelling languages. Below, we discuss some of these challenges.

Capturing the business case for DTs – Ultimately, the business case for any DT needs to be based on the added value it provides towards decision-making, monitoring, and learning about the twinned entity. Existing EAM related languages and frameworks would need to be extended to both capture the context of such usage of the DT, as well as ways to capture the actual added value of the DTs functionality towards these. Starting points could, e.g. be existing work on the economics of DTs [Th24], as well as work on dimensions to define the value of data [HMP24] (data *in use* actually), or more fundamentally, the economics of/behind decision-making [Mc92].

Capturing the fabric of the data ecosystem surrounding a DT – As discussed earlier, the risk of fragmented data ecosystems [OL18; SK22; TMR17] are likely to hamper the development and deployment of DTs. Therefore, it will be important to better understand the fabric of data ecosystems. In particular the different goals, interests and concerns of the different parties involved in these ecosystems.

Enabling the exploration of the informational landscape – As DTs are fundamentally information systems in support of decision-making, monitoring, and learning, about the domains they ‘twin’, it would be good for potential users of DTs to be able to explore, and discover the information that could be provided to them. Letting existing, and potential, users of a DT discover the potential information they may obtain from the DT, and the value this may bring towards their own decision-making/monitoring/learning goals, would add to the further development/growth of the business case for the DT.

Architectural roadmaps/best-practices to grow DTs – In line with work as, e.g. reported in [SI23] regarding an agile way to ‘grow’ digital twins, reference architectural roadmaps can be defined. Such roadmaps would capture possible strategies to gradually grow DT functionality, based on the needs of their users (in relation to the added value to them), and embedded in the larger data ecosystem.

4 Conclusion

In this *novel directions* paper, we have argued the need to make the development, deployment, and evolution of DTs, subject of *architectural coordination* within the broader frame of EAM. We also argued that DTs should not be seen as monolithic systems, but rather as a collection of components/chunks of functionality that should be integrated into the larger (inter-organisational) IT landscape.

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