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Digital twins benefits and challenges from intelligent motion control point of view

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***Abstract*—This paper analyses the digital twins' current status and future interests in the intelligent motion control domain based on the web survey conducted within a large European research project named IMOCO4.E. We aim to understand how the companies and institutions developing and utilizing digital twin technologies see the main benefits, challenges and next steps in their domain. We conclude, based on the survey, that digital twins are used, primarily in the design phase, to speed up the development of complex systems where utilizing physical prototypes is not feasible or even possible. The operational phase utilization is not yet seen as important, but it has great potential, especially when the development of digital twins has become more mature in relation to real-time interfacing, exact representation of real physical objects, and maintainability of implementation.**

***Index Terms*—intelligent motion control, digital twins, industry4.0**

I. Introduction

The rise of digital twins is fundamentally reshaping how industries design, operate, and maintain physical assets, processes, and systems. A digital twin, by providing a dynamic virtual representation of its real-world counterpart, enables engineers and operators to test hypothetical scenarios, predict potential failures, and optimize performance in a safe and cost-effective virtual environment. The profound benefits of digital twins extend across the entire product lifecycle, revolutionizing product development, streamlining manufacturing processes, enhancing installation procedures, providing immersive training experiences, boosting operational efficiency, and enabling proactive maintenance strategies [1], [2].

A digital twin is defined and characterized by a five-dimentional framework [3], as illustrated in Figure 1. Physical entity is the real-world asset or system being represented. Virtual Model is the digital representation that encompasses the physical entity's geometry, properties, behavior, and rules. Services comprises the functionalities the digital twin offers, such as simulations, diagnostics, or optimization. Data is the information flow between the physical entity and the virtual model, typically facilitated by sensors and internet-of-things (IoT) technology. Connection is the bidirectional link that enables real-time data exchange and control between the physical and virtual entities.

Recognized as a cornerstone of Industry 4.0, digital twins are a major focus of research and development initiatives worldwide. Strategic roadmaps highlight the pivotal role of digital twins in the industrial transformation and chart a trajectory for their further advancement [4]. This underscores the need for a comprehensive understanding of digital twins, not only in theoretical terms but also through practical insights into their application within specific domains.

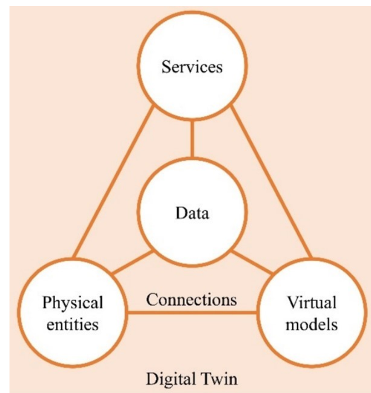

Fig. 1. Five-dimensional framework for digital twin.

Our aim is to understand the current status of digital twins in intelligent motion control, and also to better understand the challenges, benefits and future directions that industrial domains see as relevant to digital twins. In this paper, we explore the industrial case within IMOCO4.E [5], a large European project.

II. Intelligent motion control case

In the IMOCO4.E project (Intelligent Motion Control under Industry 4.E) [5], digital twins and Artificial Intelligence (AI) are used as a backbone for providing hardware and software building blocks for future European intelligent robotics.

The mission of the IMOCO4.E project is to provide distributed edge-to-cloud motion control intelligence for a wide range of human-in-the-loop cyber-physical systems involving actively controlled moving elements. [5] The aim is to deliver a reference framework consisting of architecture, data management and AI and digital twin toolchains and a set of building blocks for resilient manufacturing applications [5]–[7]. To validate the results, the IMOCO4.E has defined altogether 13 use cases, pilots, and demonstrations (henceforth use cases).

At first, we wanted to understand how IMOCO4.E use cases are positioned within the European industry roadmaps and analyzed needs and trends from different roadmaps and strategic agendas. Several European research roadmaps and strategic research agendas have been made for Industry 4.0 and other sectors that cover manufacturing and robotics research. As roadmaps are typically community efforts, they also reflect the interests of the specific community and, thus, differ somewhat from each other content-wise.

For the roadmap analysis, the following roadmaps and research agendas were analyzed: Electronics components and systems SRA [8], Manufuture 2030 SRIA [9], AI, data and robotics SRDIA [10], Made in Europe SRIA [11], national roadmap from the Netherlands [12], IMS 2020 [13], automotive industry roadmaps and technology trends related to electric drives [14]. More detailed analysis of the roadmaps is reported in the IMOCO4.E project deliverable [15].

Based on the analysis, several expectations for the digital twins were identified. Table I shows 13 main trends/needs for the digital twins that were collected from the roadmaps.

After the roadmap analysis, we wanted to understand which of the identified needs are relevant for the intelligent motion control use cases and which of the needs are seen as less relevant or obsolete. All use cases responded to identify which topics they see as either currently ongoing (X) or relevant in the near future, i.e. 2025 and beyond (F). Answers were collected during workshops where technology providers, use case owners and research partners participated in forming a joint view per use case. Results can be seen in Table I, reproduced from the IMOCO4.E project deliverable [15].

The majority of the use cases found simulator-based design and digital twins on complex processes either relevant or likely to become relevant in the near future. More than one-third of use cases found autonomous capabilities development, physics and knowledge combination, development of AR/VR user experiences, and ease of use for digital twins relevant or likely to become relevant in the near future.

Interoperability of digital twins, tracking mode simulations, immersive telepresence and human and knowledge integration were seen as relevant only in a few use cases. "Single source of truth" was seen as possibly relevant in the future; however, further discussions raised some questions about whether it was even a realistic goal in industrial digital twins due to substancial efforts required. Sustainability and circular economy were not considered relevant from the digital twins' perspective in the use cases.

Use cases provided insights about relevant research needs within the intelligent motion control domain. Identified needs led to developing more detailed needs based on the use case requirements and standard requirements for a reference architecture and its building blocks.

TABLE I
TRENDS/NEEDS RELEVANCY

Trend/need	***X***	***F***
Simulator-based design: continuous design improvement utilizing digital twins and virtual models	8	1
Digital twins for complex processes	5	4
Autonomous capabilities development in digital environment	4	2
Integration of interactive simulation technology for digital twins into AR and VR user experiences	4	2
Development of digital twins that can be interpreted, used and operated by domain experts instead of only by data scientists or ICT experts	3	3
Digital twins as a combination of physics and knowledge-based models	3	2
Virtual commissioning to bring collaboration between different disciplines and models in the same environment and interoperability to use applications across platforms	3	1
Heterogeneity of systems, interoperability of digital twins, information sharing and standards	1	3
Tracking mode simulation: model adoption based on measurements	1	2
Industrial robots immersive telepresence from design towards production lines and other operational scope	1	0
Humans and knowledge integration, human in the loop simulations and networked simulations	1	0
Future digital twins could be the "single source of truth" at any moment in time	0	5
Digital twins applied to sustainability and circular economy	0	1

III. RESEARCH QUESTION AND METHODOLOGY

Based on the roadmap analysis, we wanted to discuss the main identified topics in more detail and clarify the factors behind the trends and needs. The study's main research question is: "What are the benefits, challenges, and next steps of digital twins in intelligent motion control?"

The research methodology used in this study was a web survey conducted between November and December 2023. The survey was sent to a project consortium consisting of 46 partners representing research institutes, universities, and companies from small to big enterprises. We received a total of 27 responses from this group.

The questions were set so that we could have a question on the benefits of each of the three phases: prototyping, manufacturing, installation, training, and operation and maintenance. One question was set to determine drivers for digital twin development, challenges, next steps, and the importance of sustainability. For each category, questions were defined based on findings from the literature and expert knowledge of the consortium. In some questions, we offered the option "other" to be able to fill in the information in addition to categories premade. Lastly, we had two open-field questions on internal/external skills and one open-field question for respondents to fill in any additional information concerning digital twins they would like to address.

IV. Digital twins study results

The first question was: “What are the most important drivers or motivators for digital twins’ development?”. We made classifications for each question beforehand, and in this question, five levels were used to estimate the importance (1 = most significant driver, 5 = least significant driver). Answers received are presented in Table II.

The most popular drivers were product development and prototyping, and simulations, both with more than 20 out of 27 responses. In product development and prototyping, nearly half, and in simulations, nearly two-thirds consider it the most important or second-most important driver.

The answers well reflect the respondents’ backgrounds, as the majority of them are dealing with research and development activities, where product development and prototyping are core activities and different simulation scenarios are used as part of the process. The operations phase, on the other hand, was not seen as important.

The second question dealt with benefits in the prototyping phase: “What kinds of benefits do you see that digital twins offer in the prototyping phase?” Responses are presented in Figure 2.

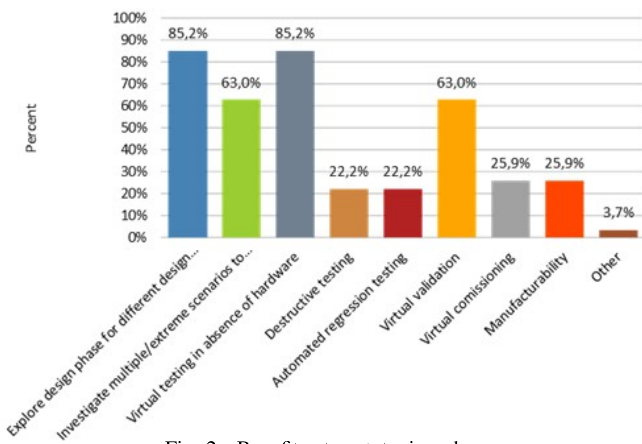

Fig. 2. Benefits at prototyping phase.

As the prototyping phase is the most common phase using digital twins among the IMOCO4.E project participants, it was interesting to see which use scenarios are most common. Design phase exploration and virtual testing in absence of hardware were highly used, over four fifths of respondents used digital twins for those. Investigation of scenarios and virtual validation were very common too, and two-thirds of the respondents used digital twins for those activities.

According to responses, digital twins offer benefits, especially when trying out different designs before the actual hardware is available. This may speed up the prototyping phase when actual hardware or physical copy is not needed to explore different solutions.

The third question was: “What kinds of benefits do you see that digital twins would offer in the manufacturing, installation, and training phase?” Responses are presented in Figure 3.

Training and avoiding the construction of expensive prototypes were seen as the highest benefits in this phase. More

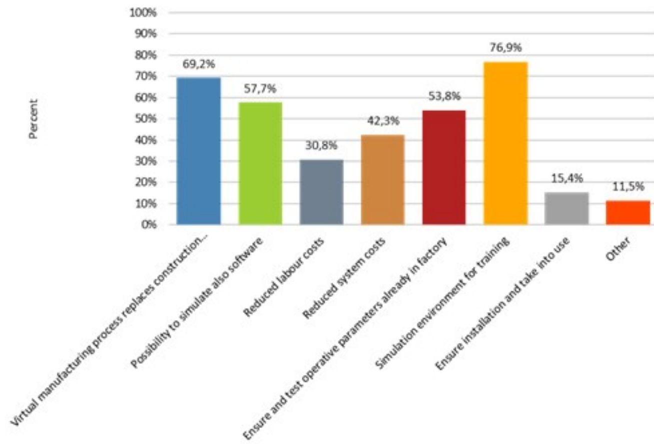

Fig. 3. Benefits at manufacturing, installation and training phase.

than half considered that also software simulation and operative parameters testing as a valid benefit. In other benefits, respondents raised the ability of digital twins to communicate with each other, safety increase and total cost savings in the long run as benefits.

Results are understandable as simulated environments for training purposes will make trainings more efficient as they are no longer tied to actual hardware and can be organized in different locations.

Fourth question was about benefits at operations and maintenance phase:. “What kinds of benefits do you see that digital twins would offer in the operations and maintenance phase?” Figure 4 presents the responses.

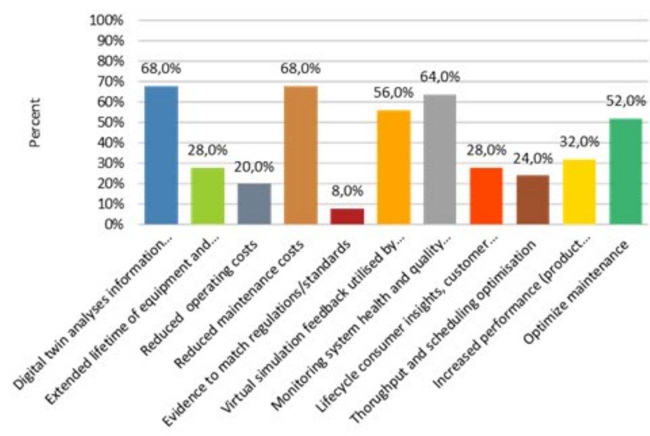

Fig. 4. Benefits at operations and maintenance phase.

Two-thirds of the respondents saw three benefits: the digital twin’s ability to analyze information from the physical twin, reduced maintenance costs, and system health and quality monitoring. More than half considered physical twin utilization of virtual simulation feedback and maintenance optimization valid benefits. In other benefits, one respondent named fault prediction.

In the operation phase, the benefits are mostly seen through maintenance aspects as digital twins can be used to analyze the information provided by the physical twins, e.g. monitoring

TABLE II
MOST IMPORTANT DRIVERS

Driver	Importance of drivers and number of responses					
	1	*2*	*3*	*4*	*5*	*N*
Concept evaluation	10,5%	21,1%	26,3%	26,3%	15,8%	19
Design visualisation	10,5%	21,1%	36,8%	21,1%	10,5%	19
Product development and prototyping	25,0%	20,8%	16,7%	20,8%	16,7%	24
Simulations	28,6%	38,1%	19,0%	14,3%	0,0%	21
Training	43,8%	18,8%	6,3%	12,5%	18,8%	16
Maintenance and services	6,7%	13,3%	26,7%	13,3%	40,0%	15
Operations	16,7%	0,0%	16,7%	33,3%	33,3%	6
Sales and marketing	25,0%	12,5%	12,5%	12,5%	12,5%	8

the system heath and optimising the maintenance. This will certainly have an effect on reducing maintenance costs.

Our fifth question moved from benefits to main challenges foreseen in developing and operating digital twins: "What kinds of challenges do you see in the digital twins in the future?" Figure 5 shows the responses.

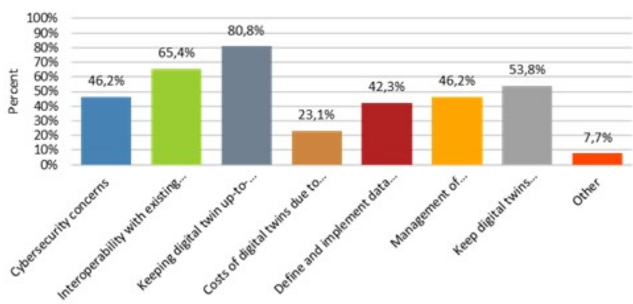

Fig. 5. Main challenges foreseen in developing and operating digital twins.

An overwhelming number of respondents saw how to keep digital twins up to date with new products and product variants as a main challenge. Also, interoperability issues were raised by nearly two-thirds of the respondents. More than half considered digital twins' compatibility with data sets and system settings as a challenge. However, the costs of digital twins were not seen as a big challenge. In other category, huge efforts developing digital twins and digital twins interoperability with other digital twins were raised as a challenge.

The following questions dealt with addressing the next steps in the respondent's organizations: "What are the next steps you are planning to do with digital twins?". The responses are shown in Figure 6.

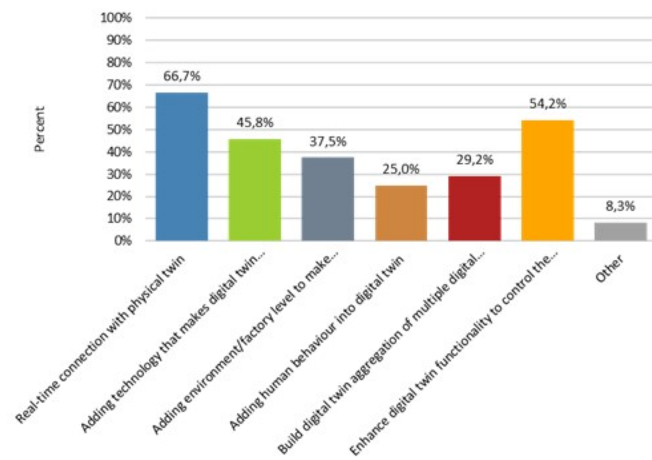

Fig. 6. Next steps with digital twins.

More than two-thirds of the respondents considered real-time connection to physical twin and more than half considered closing the loop as the next steps to be done with the digital twins. Also, increased accuracy and added complexity for operational processes were seen as important. Including human behavior was relevant only for one-fourth of respondents. In the other category, sensor latency, increased physics and unified data management for both digital and physical twins were mentioned.

Our seventh question dealt with sustainability issues, as importance of sustainability has risen a lot in recent years, we also wanted to understand how that is reflected in digital twins. The question was: "Do you foresee the importance of sustainability aspects to rise in forthcoming years in your digital twins?" Responses are presented in Figure 7.

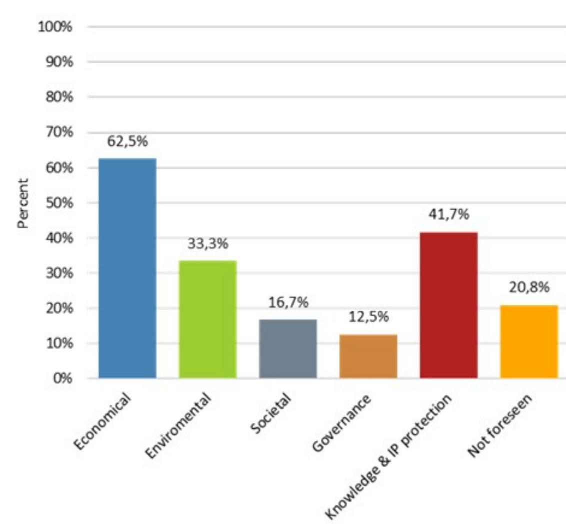

Fig. 7. Importance of sustainability aspects.

Rather surprisingly, mostly economic aspects of sustainability were seen as important, whereas environmental and societal aspects were not seen as that important for most of the respondents. Knowledge & IP protection was, however, seen as important by more than 40% of respondents.

In the final open questions, we focus on the required competences, both internal and external. For internal competences, such as systems engineering/modelling, data science, management and integration and AI and analytics skills, were seen by many as the most crucial skills. For external skills, many mentioned the following skills: modelling skills, especially physics modelling, sensor development, AI machine learning, digital twin interfaces, and VR and AR integration.

Finally, we had a question: "With regards to the study, would you like to add something regarding your digital twins development in the future?" Some issues were raised, such as: it is very expensive to develop full-scale digital twins that operate all aspects of products and their networks in collaboration and in real-time, digital twin lifecycle management is important and that it still requires work to make digital twins more accurate with their physical counterpart.

V. Limitations of the Study

During the research, digital twins were used more or less interchangeably with digital model and digital shadow [6], [15]. Therefore, some answers in the questionnaire might better reflect the status of the digital model/shadow instead of the digital twin. However, we still consider that the answers reflect the current status of the development and operations in this domain, even if we might sometimes deal with digital model/shadow instead of full-scale digital twin.

As the answers to the questionnaire were collected anonymously, there is no possibility for further categorization between the respondents.

VI. Conclusions

In this study, we identified the benefits, challenges and next steps when utilizing digital twins in intelligent motion control development and operations. The study revealed several key challenges that companies should address when developing digital twins and/or buying digital twin services.

On the basis of the survey conducted within the large European project named IMOCO4.E, digital twins are used, especially in the design phase, to speed up the development of complex systems where utilizing physical prototypes is not feasible or even possible. Although the operational phase utilization of digital twins is not yet seen as important, maintenance-related benefits were clearly identified.

Main challenges were identified related to product development and lifecycle management, as changes in products can challenge the maintainability of digital twins. Also, interoperability with existing systems was seen as challenging.

From the development point of view, the next steps are related to real-time operation, as the digital twins should be able to work in parallel with the physical twin. This is also a precondition for closed-loop control, which was also seen as a development target.

Sustainability aspects were not seen comprehensively, and economic aspects were seen as most relevant. It might be that the term sustainability in this target group was not understood in the same way as it may be defined in another context.

The results also offer the opportunity to further focus on aspects seen as relevant in this study when developing and operating digital twins. As IMOCO4.E project is at its last stage, the authors plan to do similar study in forthcoming large research projects and the results of the study will be used in the IMOCO4.E project when analysing experiences and benefits of the developed digital twins. More detailed research results and status of digital twins related technology and methodology advances during the IMOCO4.E will also be reported in several public deliverables made available later.

Acknowledgment

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