Reliability-by-design for Digital Twins: Value Creation and Trust Throughout the Whole Lifecycle

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Abstract

Digital twins are reshaping the way systems are operating across various domains, seamlessly integrating the physical and digital realms, yet their full potential is often hindered by foundational challenges. This paper proposes a "Reliability-by-Design" approach, which is essential not just as a feature, but as a cornerstone in the lifecycle of Digital twin applications. By embedding reliability from the outset, Digital twins become reliable assets that enhance operational effectiveness and unleash their true value to the organization in question. We emphasize the necessity of reliability for ensuring Digital twins are effective, efficient, and valuable. Through exploring the alignment of Reliability-by-Design with organizational objectives such as improved risk management, alignment with users and organisation's needs, and adaptability to changes, this paper highlights its role in supporting decision-making and achieving resilience while reducing costs. Emphasizing a value-driven approach, we advocate for the adoption of Reliability-by-Design to elevate the impact and sustainability of Digital twin technologies across various domains.

Keywords

Digital Twin, Digital Twinning, Reliability-by-Design, Life-cycle Management, Operational Effectiveness, System of Systems, Strategic Advantage

1. Introduction

In the rapidly evolving landscape of technology, Digital twins are proving essential in a wide range of industries including manufacturing, healthcare, and urban planning. These innovative systems bridge the gap between real-world entities and their digital counterparts, enhancing decision-making and operational efficiency. Traditional approaches to Digital twin development often focus on technological capabilities without fully addressing reliability concerns. Common reliability issues include data integrity challenges, insufficient system integration, cybersecurity vulnerabilities, and the complexities of maintaining real-time synchronization between the physical and digital counterparts. These issues can lead to operational disruptions, increased costs, and reduced trust in Digital twin systems.

This paper proposes a Reliability-by-Design approach, advocating for the integration of reliability from the initial stages of Digital twin development. By doing so, Digital twins can evolve from being mere technological innovations into robust assets that enhance operational effectiveness. We examine how aligning this approach with organizational objectives such as improved risk management, better alignment with user and organizational needs, and increased adaptability can support decision-making, strengthen resilience, and minimize operational costs. Ultimately, we demonstrate that adopting a Reliability-by-Design approach is essential for maximizing the value and maintaining the sustainability of Digital twin technologies across various domains.

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2. Related work

Since Digital Twins represent its physical counterparts, they have quite a long lifecycle. In general, they have the same lifespan as the Physical twins. The research on operations and maintenance of cyber-physical systems has quite a history. After the introduction of the cyber-physical systems a lot of attention was paid to the major maintenance principles and approaches previously applied to complex systems[1]. The majority of research studies related to reliability were performed on fault-tolerant design[2] and failure analysis[3]. When the IoT devices started to appear, some research focused on the Internet-of-Things and the evolution of such IoT-based systems[4]. IoT devices brought the concept of distributed Digital Twins with them. It became evident that distributed character of complex systems of systems poses new challenges related to reliability in terms of synchronization and consistency between the distributed elements[5]. The research on distributed components related mostly to solving the issues of awareness upon current situation and solving the problems at stake at that specific moment of time.

The research on handling modern distributed Digital twins properly through their whole lifecycle has started quite recently. It was mentioned in the future directions for research for Digital twins[6]. Pileggi et al. have introduced the Double Helix model related to the intertwining of two lifecycles handling: both of Physical and Digital Twins. The mutual dependencies between lifecycles were discussed and the necessity of handling lifecycle was pinpointed[7]. However, paper misses the crucial point for Digital twins handling: reliability. Since modern Digital twins provide not only monitoring functionality, but also predictive capacities[8] and controlling power regarding its physical counterpart[9] including even handling failures[10], it is important that Digital twins are reliable through their whole lifecycle. The new trend on using AI helps to introduce Machine Learning methods for the predictions and failure handling[8],but it does not allows yet the structural approach to reliability leading to providing requested quality level of service.

Reliability as a qualitative aspect of physical assets is a widely known topic for research. From the beginning of cyber-physical systems research there was a tight attention paid to design related to reliability and safety. Lee et al. have defined as main challenges for the design of complex cyber-physical system safety and reliability. They claimed that to realize the full potential of CPS, experts will have to rebuild computing and networking abstractions, which will have to embrace physical dynamics and computation in a unified way[11]. Meanwhile, model-based engineering helped to define the necessary abstractions on telecom[12] and software levels[13]. It improved the connection between Digital and Physical twins, but it didn't solved the whole reliability challenge for Digital twins.

As a follow up, some authors have concentrated mostly upon security and dependability aspects regarding the reliability. They claim that the construction of complex CPS with respect to security and dependability (S and D) properties is necessary to avoid system vulnerabilities at design level[14]. Some others dedicate their research to the semantic aspects to make Digital twins more interoperable[15]. Enforcement of GDPR[16] on the EU level has brought research on privacy aspects still connected to the reliability of service[17]. The rise of the Service-oriented computing has introduced the use of SOA architectures[18] and service orchestration methods for complex interdependent systems of systems[19].

In general, there is a structured approach missing in all the previous research to the different stages of lifecycle for Digital Twins and diverse understanding of reliability aspect according to these stages of life. In this paper we propose such an approach.

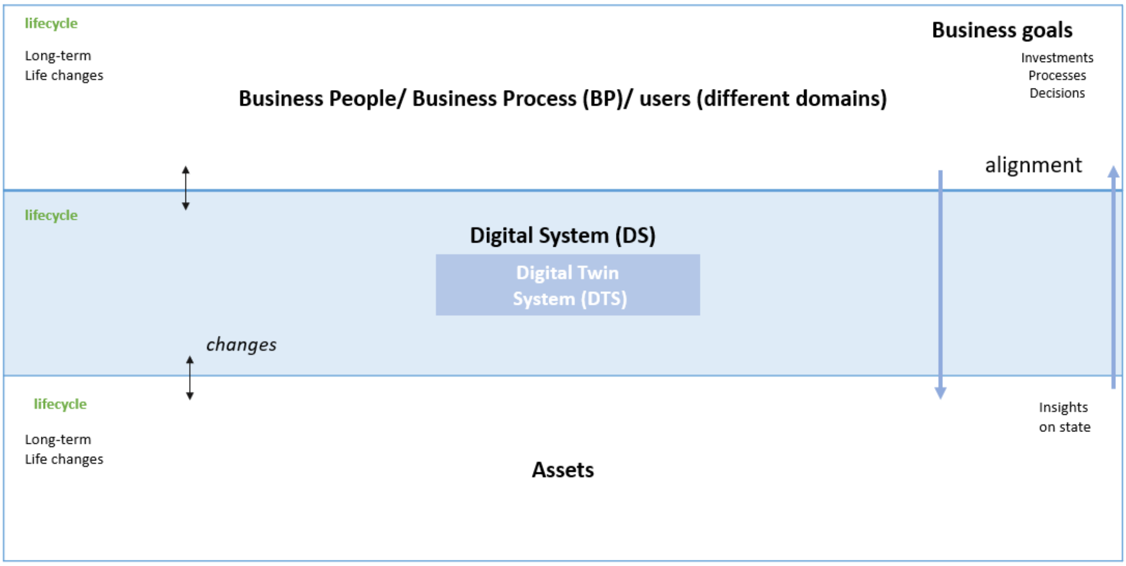

Figure 1: Integration of Digital System, Assets, and Business Processes

3. Why Reliability-by-Design?

Before discussing the structured approach to the different phases of the Digital Twin lifecycle, it is important to explain why reliability is a crucial aspect to address.

3.1. Challenges in Traditional Systems

Systems need to align with the continuously evolving business goals, assets, and personnel within organizations. To enable this alignment, Digital systems, assets, and business processes are integrated and dynamically synchronized as seen in Fig. 1. As systems of systems undergo changes—whether due to shifts in market conditions, regulatory updates, or technological advancements, the models supporting them can become outdated or misaligned. This misalignment can lead to reduced effectiveness, erroneous outputs, and ultimately, a loss of trust in the system's reliability. Digital twins are often implemented to dynamically reflect and adapt to these changes, but doing so reliably poses its own set of challenges. Throughout their lifecycle, the Digital Twins are dynamically and continuously synchronized to meet the business purpose and the users needs. Therefore, Digital twins need to evolve (consistently) well with the physical world. Reliability-by-Design systematically addresses these challenges by ensuring that Digital twins are not only reflective of the current state or are static representation of an asset but also ensuring that the digital system can accurately foresee and adapt to long-term changes or future shifts in all connected elements, be it the assets they represent, the business processes they support, or the users they serve.

3.2. Strategic Alignment with Organizational Objectives

Organizations operate in a state of continuous evolution, with strategic objectives that shift and expand over time. Digital twins, when designed with reliability at their core, become dynamic systems capable of evolving. They provide critical insights that align with and inform business goals, such

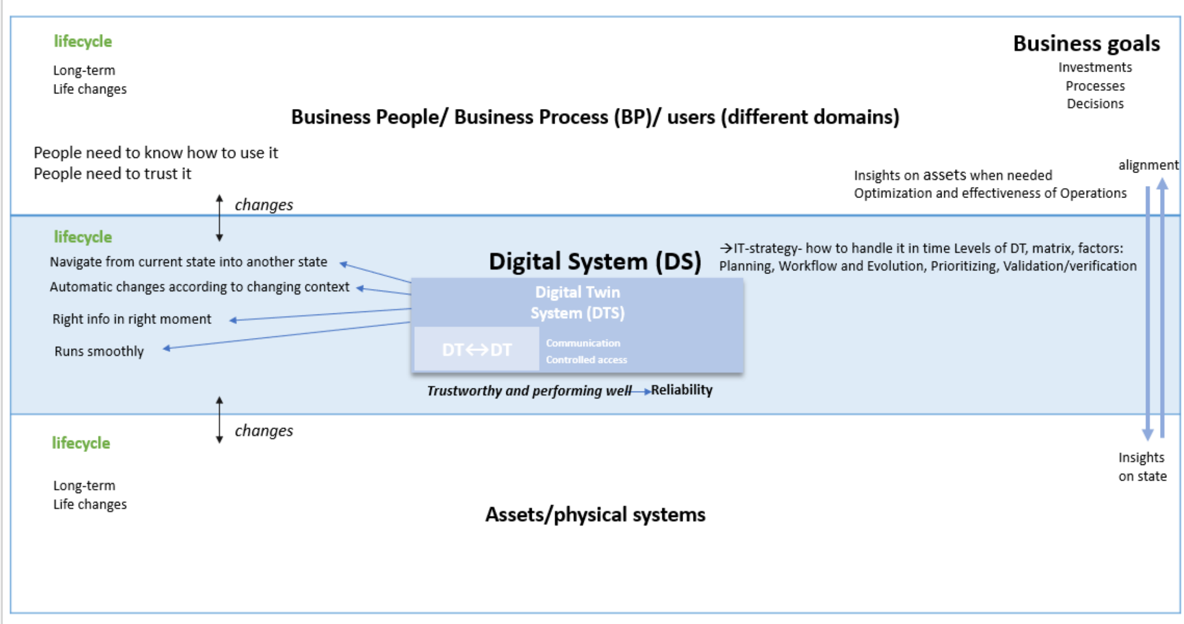

Figure 2: Integration and alignment of Digital Twins with Business Processes and Physical Assets

as optimizing operations, making informed decisions, and ensuring the effectiveness of ongoing processes. The strategic importance of Reliability-by-Design lies in its capacity to consistently align digital systems with organizational objectives, even within the dynamic context of evolving business environments. Fig. 2 illustrates the strategic alignment of Digital twins with business processes and physical assets, emphasizing the continuous adaptation to changes in organizational goals. By embedding reliability into Digital twins from the design phase, organizations can ensure that these systems continuously perform well and remain trustworthy. This reliability supports critical strategic goals such as risk mitigation, by predicting and managing potential failures; regulatory compliance, by maintaining accurate and current data; and sustainable competitive advantage, by enabling swift adaptation to changes. Moreover, reliable Digital twins cultivate stakeholder trust by consistently meeting or surpassing operational and strategic expectations.

3.2.1. Navigating and Adapting to Changes

As organizations and assets evolve, digital twins must not only capture the current state but also adapt to an anticipated or desired future state. This requires integrating real-time data and contextual changes, adjusting seamlessly to maintain performance and reliability. The process involves meticulous planning, workflow evolution, prioritization, validation, and verification—all carefully coordinated to ensure the digital twin remains reliable over time.

3.2.2. Building and Maintaining Trust

The ultimate goal of Reliability-by-Design is to foster and sustain trust within the system. For stakeholders to rely on the digital twin, they must trust not only the data it provides but also its capacity to perform consistently well over time. This trust is built through transparent communication, controlled access, and a strategy that accommodates changes in the system's lifecycle. Enhancing trust-

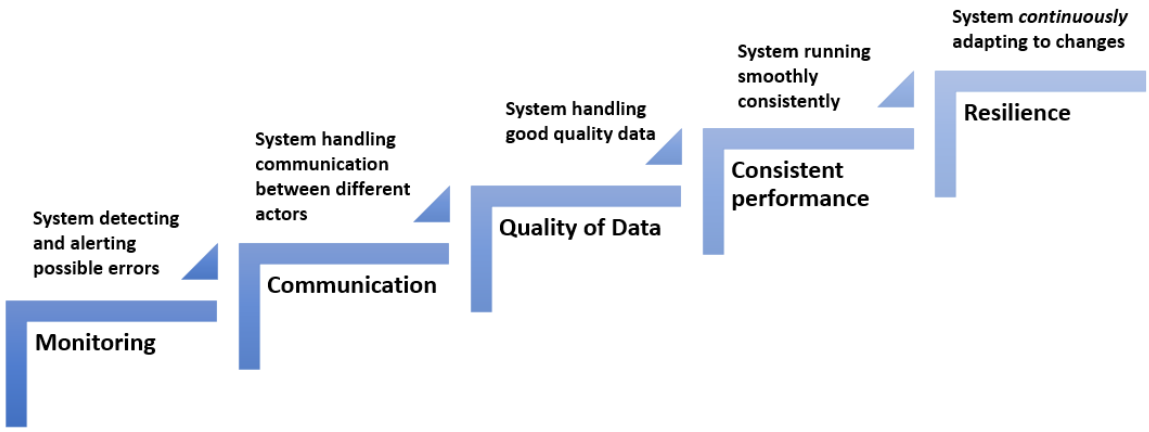

Figure 3: Operational Reliability technical considerations

worthiness involves rigorous testing, continuous improvement, and an unwavering commitment to data integrity.

3.2.3. The Threefold Path to Reliability

To achieve and maintain reliability in a digital twin, organizations must concentrate on three key aspects: how to achieve it, how to maintain it, and what needs to be mitigated to ensure consistency. This involves creating a Digital twin that is dynamically synchronized with live data in response to evolving conditions, delivering the right information at the right moment, and operating smoothly and efficiently. The reliability of this system supports informed decision-making, enhances operational resilience, and ultimately leads to cost-effectiveness.

4. What Does Reliability-by-Design Involve?

Reliability-by-Design in the context of Digital twins involves both technical and organizational considerations to ensure that Digital twin systems are not only operationally dependable but also consistently aligned with the strategic goals of the organization. Technically, it encompasses the integration of robust technical frameworks to maintain data integrity and system accuracy. Simultaneously, it requires effective organizational governance to ensure these systems are consistently aligned with strategic business objectives.

4.1. Technical Operational Reliability

Key constraints and components necessary to achieve operational reliability from a technical standpoint are illustrated in Fig. 3:

- **Monitoring:** Integral to Reliability-by-Design is the capability for systems to self-monitor. This means the Digital twin must have embedded mechanisms to detect and alert operators about potential errors in real-time.

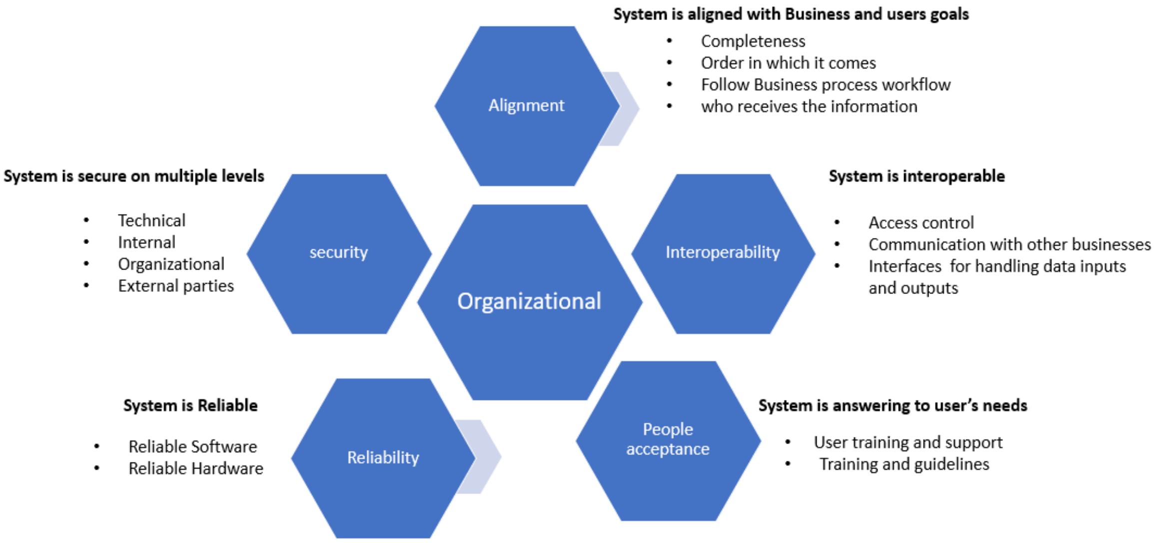

Figure 4: Operational Reliability organizational considerations

- **Communication:** Ensuring fluid and error-free communication between various actors within the system is crucial. This includes not only internal components of the Digital twin but also external interfaces with other business systems.
- **Quality of Data:** The reliability of a Digital twin is only as good as the quality of data it handles. Ensuring the twin utilizes high-quality, accurate data is fundamental to its operational reliability.
- **Consistent Performance:** To be reliable, the system must perform consistently under a variety of conditions and workloads, maintaining smooth operations without interruption.
- **Resilience:** The system's architecture must be designed for resilience, with the ability to adapt continuously to changes and potential disruptions in both the digital and physical environments.

4.2. Operational Organizational Constraints

Operational reliability also hinges on several organizational constraints that must be aligned as seen in Fig. 4:

- **Alignment:** The Digital twin must be completely aligned with business and user goals. This means ensuring that the data and insights it provides are complete, timely, and follow the workflow of business processes.
- **Interoperability:** It must also be interoperable within the organizational ecosystem, which includes access control, communication with other businesses, and managing data inputs and outputs effectively.
- **Security:** Security for Digital twins extends from the technical aspects of cybersecurity to internal organizational processes and the governance of interactions with external parties. Given

the sensitive nature of data handled by Digital twins, robust security measures are essential to maintaining system reliability.

- **Reliability:** At its core, the system demands reliable software and hardware. This is a prerequisite for trust in the system's outputs and long-term sustainability.
- **People Acceptance:** Finally, the system must be designed with user needs in mind, providing necessary training and support to ensure ease of use and enhance user acceptance. It should have clear guidelines to facilitate ease of use and enhance user acceptance.

Integrating these technical and organizational components into the design of Digital twins leads to systems that are not only robust but also trusted and integral to the decision-making processes within organizations. These components work jointly to ensure that Digital twins are reliable, thereby enhancing their value as strategic business tools.

5. How Is Value Created? (Realizing Tangible Benefits through Use Cases)

Value creation in the context of Reliability-by-Design in digital twinning occurs when reliability evolves from a mere technical feature to a driver of tangible business outcomes. This is demonstrated through several use cases where Digital twins, built with this approach, lead to measurable improvements in operational efficiency and strategic decision-making.

5.1. Tangible Benefits of Integrated Reliability

The value of integrating Reliability-by-Design in Digital twins can be seen across various dimensions:

- **Enhanced Efficiency:** Reliable Digital twins streamline operations by predicting bottlenecks, optimizing resource allocation, and reducing waste, thereby increasing efficiency. For instance, a study by D'Amico et al. demonstrated how the integration of predictive maintenance models in Digital twins led to a significant reduction in unexpected machinery breakdowns in manufacturing plants, resulting in a 20% increase in operational efficiency[10].
- **Increased Asset Up-time:** Predictive maintenance models within Digital twins can forecast equipment failure, allowing for proactive repairs that minimize downtime and extend asset life. Lei et al. highlighted how Digital twins of DC-DC converters in power systems enabled timely maintenance, resulting in a 15% reduction in downtime[9].
- **Quality Assurance:** By simulating production processes, Digital twins help maintain high-quality standards and consistency in output, which is critical for customer satisfaction and retention. Research by D'Amico et al. showed that Digital twins in material handling systems improved quality assurance metrics[10].

5.1.1. Examples of Use Cases

The value achieved through the application of Reliability-by-Design is illustrated in the following examples:

- Manufacturing: In a manufacturing plant, a Digital twin used for predictive maintenance ensures operational parameters for the machines, significantly reducing unexpected breakdowns and maintenance costs[20].
- Healthcare: Digital twins in healthcare, can optimize resource utilization, directly improving patient care through real-time data integration, predictive analytics, and personalized treatment plans. This approach enhances diagnostic accuracy, reduces errors, and enables early intervention, leading to more effective and targeted treatments[21].
- Urban Planning: Cities make use of Digital twins to simulate traffic patterns, which informs infrastructure development and helps reduce congestion, enhancing quality of life for residents[22].
- Energy Sector: Energy companies deploy Digital twins to model wind farms, optimizing turbine placement for maximal energy production and longer-term reliability in energy supply. Digital twins help in predicting maintenance needs and optimizing performance, leading to more efficient and reliable energy production[23].

5.2. Operational value creation

The process of embedding Reliability-by-Design principles for value creation involves:

- Clear Definition of Value: Organizations must define what constitutes value according to their needs and goals. For example cost savings, enhanced customer experiences, or improved product quality are examples of targeted values in many organisations. Organisations must ensure that the Digital twin in place is geared towards these goals.
- Metrics and key performance indicators (KPIs): Establishing clear metrics and KPIs allows organizations to measure the impact of their Digital twins against desired outcomes.
- feedback loop: The feedback loops integral to Digital twins inform continuous improvements, making the system ever more reliable and increasing its value to the organization.

5.3. Organizational value creation

Realizing value from Digital twins is an active process that involves:

- User Engagement: Encouraging user engagement with Digital twins through training, guidance and continuous support ensures that the insights provided are utilized effectively to drive value.
- Value-focused Development: The development of Digital twins needs to prioritize features and functionalities that contribute to the organization's value creation goals.
- Cross-Domain Collaboration: By working together across different domains, Digital twins help uncover new opportunities for value that are often missed when operations are kept separate. This approach breaks down barriers between different organisations, allowing for more efficient and innovative solutions.

6. Challenges and Mitigation Strategies

The integration of Reliability-by-Design into Digital twin initiatives is often faced with various challenges such as the complexity of the systems and their inter-dependencies, development costs and security and privacy concerns. As Digital twins grow in complexity, it becomes challenging to capture all system inter-dependencies without the models becoming too cumbersome. Establishing these sophisticated systems requires significant upfront investment, which may be financially challenging for some organizations. Ensuring consistent access to high-quality data is difficult, especially when integrating legacy systems or external data sources. As organizations expand, their Digital twins must scale effectively while maintaining reliability, even as the scope and volume of data increase. Given that Digital twins often handle sensitive data, maintaining security and privacy without compromising functionality is a critical ongoing concern.

To effectively tackle the challenges associated with complex Digital twins, organizations can deploy several strategic measures. Modular design simplifies the management of complex systems and enhances adaptability. Conducting detailed cost-benefit analyses helps justify initial investments by highlighting long-term savings and operational efficiencies. Comprehensive data management frameworks ensure consistent data quality and solve problems related to data silos and accessibility. Building Digital twins on scalable architectures from the start facilitates the addition of new functionalities and the management of larger data sets without the need for a complete system overhaul. Moreover, establishing stringent security protocols and adhering to privacy standards are essential to maintain the integrity and trustworthiness of the Digital twin.

Beyond these technical strategies, it is crucial to cultivate an organizational culture that emphasizes reliability. This includes regularly updating the skill sets of personnel involved in developing and maintaining Digital twins to meet evolving requirements. Implementing continuous performance monitoring to swiftly identify and rectify any issues with reliability is also key. Additionally, developing adaptive governance models that can respond to changes in technology and business practices while keeping a focus on reliability is important. By proactively implementing these strategies, organizations can harness the benefits of Reliability-by-Design, not only enhancing current operations but also positioning themselves to effectively navigate future technological and market developments.

7. Conclusion and Future Directions

This paper emphasizes the importance of integrating Reliability-by-Design into Digital twinning practices, exploring the interplay between data fidelity, operational efficiency, and complex system inter-dependencies. Through this exploration, reliability has emerged as fundamental, not only for maintaining the integrity of Digital twins but also for enhancing their value across various sectors.

The paper further highlights that reliability is more than a technical feature: it is an operational necessity that transforms Digital twins from static digital replicas into dynamic, reactive assets. As organizations increasingly rely on these sophisticated models for critical decision-making, reliability builds confidence and trust—vital attributes in today's data-driven marketplace.

Looking ahead, the landscape of Digital twinning technology is broad and continuously expanding, with advancements in Artificial intelligence, machine learning, and cloud computing pushing the capabilities of Digital twins. As these technologies evolve, the adoption of Reliability-by-Design becomes increasingly essential to ensure that Digital twins remain accurate, secure, and seamlessly integrated within fast-evolving industrial and infrastructural ecosystems.

Emerging technologies introduce new challenges, including the need for real-time data processing and integration with decentralized systems of systems. Innovations in computational power and data storage are expanding what Digital twins can achieve. In response, Reliability-by-Design must evolve, integrating cutting-edge security measures, advanced analytics, and innovative architectural solutions to maintain the reliability of Digital twins as vital decision-making tools. Reliability-by-Design is set to become a standard practice in Digital twin development, being not only part of technological solutions but also the frameworks within which businesses operate, compete, and innovate. By ensuring that Digital twins are dependable, adaptable, and secure, we enable organizations to thrive amid the complexities of the modern era.

In conclusion, this paper emphasizes that the principles of Reliability-by-Design are crucial for both the present and future of Digital twinning. It serves as a call to industry leaders, technologists, and strategists to learn these principles, nurture a future where Digital twins are associated with trust, excellence, and innovation. As the conversation around Digital twins evolves, the necessity for reliability becomes increasingly clear.

References

[1] S. Ruiz Arenas, I. Horvath, R. Mejia-Gutierrez, E. Opiyo, Towards the maintenance principles of cyber-physical systems, Strojniski Vestnik 60 (2014) 815–831. doi:10.5545/sv-jme.2013.1556.

[2] E. Dubrova, Fault-Tolerant Design, Springer New York, 2013. URL: https://books.google.nl/books?id=FRs_AAAAQBAJ.

[3] S. Sierla, B. O'Halloran, T. Karhela, N. Papakonstantinou, I. Tumer, Common cause failure analysis of cyber–physical systems situated in constructed environments, Research in Engineering Design 24 (2013). doi:10.1007/s00163-013-0156-2.

[4] P. Li, Q. xu, N. Wang, Evolution course and analysis of internet of things, Lecture Notes in Electrical Engineering 219 (2013) 221–228. doi:10.1007/978-1-4471-4853-1_29.

[5] M. Jahromi, S. M. Hosseini Bamakan, Q. Qu, H. Tabbakhian, The capability of distributed generation in digital twin platform, Procedia Computer Science 221 (2023) 1208–1215. doi:10.1016/j.procs.2023.08.108.

[6] T. Y. Melesse, V. Di Pasquale, S. Riemma, Digital twin models in industrial operations: State-of-the-art and future research directions, IET Collaborative Intelligent Manufacturing 3 (2021) 37–47. doi:https://doi.org/10.1049/cim2.12010.

[7] P. Pileggi, E. Lazovik, J. Broekhuijsen, M. Borth, J. Verriet, Lifecycle governance for effective digital twins: A joint systems engineering and it perspective, in: 2020 IEEE International Systems Conference (SysCon), 2020, pp. 1–8. doi:10.1109/SysCon47679.2020.9275662.

[8] A Lesson on Operationalizing Machine Learning for Predictive Maintenance of Gas Turbines, volume Volume 4: Controls, Diagnostics, and Instrumentation; Cycle Innovations; Cycle Innovations: Energy Storage; Education; Electric Power of *Turbo Expo: Power for Land, Sea, and Air*, 2021. doi:10.1115/GT2021-59249.

[9] Z. Lei, H. Zhou, X. Dai, W. Hu, G. Liu, Digital twin based monitoring and control for dc-dc converters, Nature Communications 14 (2023). doi:10.1038/s41467-023-41248-z.

[10] R. D'Amico, A. Sarkar, H. Karray, S. Addepalli, J. Erkoyuncu, Detecting failure of a material handling system through a cognitive twin, IFAC-PapersOnLine 55 (2022) 2725–2730. URL: https://www.sciencedirect.com/science/article/pii/S2405896322021383. doi:https://doi.org/10.1016/j.ifacol.2022.10.128, 10th IFAC Conference on Manufacturing Modelling, Management and Control MIM 2022.

[11] E. A. Lee, Cyber physical systems: Design challenges, in: 2008 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC), 2008, pp. 363–369. doi:10.1109/ISORC.2008.25.

[12] D. C. Schmidt, Guest editor's introduction: Model-driven engineering, Computer 39 (2006) 25–31. URL: https://doi.org/10.1109/MC.2006.58. doi:10.1109/MC.2006.58.

[13] P. Derler, E. A. Lee, A. Sangiovanni Vincentelli, Modeling cyber–physical systems, Proceedings of the IEEE 100 (2012) 13–28. doi:10.1109/JPROC.2011.2160929.

[14] N. E. Petroulakis, G. Spanoudakis, I. G. Askoxylakis, A. Miaoudakis, A. Traganitis, A pattern-based approach for designing reliable cyber-physical systems, in: 2015 IEEE Global Communications Conference (GLOBECOM), IEEE, 2016. URL: https://openaccess.city.ac.uk/id/eprint/17217/. doi:10.1109/GLOCOM.2015.7417794, © 2016 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other users, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works for resale or redistribution to servers or lists, or reuse of any copyrighted components of this work in other works.

[15] J. Lin, S. Sedigh, A. Miller, Modeling cyber-physical systems with semantic agents, in: 2010 IEEE 34th Annual Computer Software and Applications Conference Workshops, 2010, pp. 13–18. doi:10.1109/COMPSACW.2010.13.

[16] GDPR, https://gdpr-info.eu/, 2010 (accessed April 4 2024).

[17] N. E. Petroulakis, I. G. Askoxylakis, A. Traganitis, G. Spanoudakis, A privacy-level model of user-centric cyber-physical systems, in: L. Marinos, I. Askoxylakis (Eds.), Human Aspects of Information Security, Privacy, and Trust, Springer Berlin Heidelberg, Berlin, Heidelberg, 2013, pp. 338–347.

[18] M. Sargolzaei, H. Afsarmanesh, Service Oriented Collaborative Network Architecture, in: L. M. Camarinha-Matos, H. Afsarmanesh, R. Fornasiero (Eds.), 18th Working Conference on Virtual Enterprises (PROVE), volume AICT-506 of *Collaboration in a Data-Rich World*, Springer International Publishing, Vicenza, Italy, 2017, pp. 381–394. URL: https://inria.hal.science/hal-01674860. doi:10.1007/978-3-319-65151-4_35, part 11: Service-Oriented Collaborative Networks.

[19] V. Degeler, L. I. L. Gonzalez, M. Leva, P. Shrubsole, S. Bonomi, O. Amft, A. Lazovik, Service-oriented architecture for smart environments (short paper), in: 2013 IEEE 6th International Conference on Service-Oriented Computing and Applications, 2013, pp. 99–104. doi:10.1109/SOCA.2013.26.

[20] N. H. Abd Wahab, K. Hasikin, K. Wee Lai, K. Xia, L. Bei, K. Huang, X. Wu, Systematic review of predictive maintenance and digital twin technologies challenges, opportunities, and best practices, PeerJ Computer Science 10 (2024) e1943. URL: https://doi.org/10.7717/peerj-cs.1943. doi:10.7717/peerj-cs.1943.

[21] K. Venkatesh, M. Raza, J. Kvedar, Health digital twins as tools for precision medicine: Considerations for computation, implementation, and regulation, npj Digital Medicine 5 (2022) 150. doi:10.1038/s41746-022-00694-7.

[22] S. Ruiz Arenas, I. Horvath, R. Mejia-Gutierrez, E. Opiyo, Towards the maintenance principles of cyber-physical systems, Strojniski Vestnik 60 (2014) 815–831. doi:10.5545/sv-jme.2013.1556.

[23] H. A. O. O. Haghshenas, Amirashkan, E. T. Mikalsen, Predictive digital twin for offshore wind farms, Energy Inform 6 (2023). doi:10.1186/s42162-023-00257-4.