

Digital Twin Stakeholder Communication: Characteristics, Challenges, and Best Practices

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ABSTRACT

Digital Twins (DT) encompass virtual models interconnected with a physical system through data links. Although DTs hold significant potential for positive organisational impact, their successful adoption in industrial practice remains limited. Whereas existing research predominantly focuses on technical challenges, more recent studies underscore the importance of addressing organisational and human factors to overcome implementation barriers. One central aspect in this context is stakeholder communication, especially given the ambiguous nature of the term DT in academic and industrial discussions. To expand the limited understanding of the factors causing challenging DT stakeholder communications, this article presents findings from an extensive exploratory study. It involves 27 in-depth interviews and two focus groups with highly experienced DT professionals. By employing grounded theory and the Gioia methodology, a grounded model for DT stakeholder communication challenges is derived. This model reveals the complex communication dynamics within DT projects, emphasising the emergence of novel stakeholder communication patterns that heavily rely on multi-disciplinary collaboration. In total, 28 communication challenges were identified, grouped into eight theoretical themes and categorised into two aggregate dimensions: human- and organisation-centric challenges. Additionally, the study identified 15 practices, e.g., defining clear objectives, and starting small and building gradually, that organisations are following to mitigate these challenges. As a result, this article provides the theoretical groundwork for a comprehensive understanding of DT stakeholder communication and its associated challenges by revealing distinctive features and offering practical guidance to overcome critical challenges in DT projects.

1. Introduction

In recent years, enhancing cost-effectiveness, sustainability, and flexibility has become essential to stay competitive. Digitalisation is a crucial enabler among the strategies embraced for achieving these goals. Digital transformation refers to the general integration of digital technology into all business areas, resulting in fundamental changes to how businesses operate and deliver value to customers (Gökalp and Martinez, 2022). In this context, Industry 4.0, known as the Fourth Industrial Revolution, refers to integrating digital technologies into manufacturing and other industrial processes, thereby intelligently connecting industrial hardware. It involves using digital technologies to create smart factories that are more efficient, flexible, and responsive to customer needs (Osterrieder et al., 2020). Another emerging concept that builds on Industry 4.0 is Industry 5.0, which

emphasises the importance of human-machine collaboration. It envisions a future where humans and machines work together in a more integrated and collaborative way (Xu et al., 2021).

A key concept of digital transformation that provides capabilities to enable new business models and decision support systems is the Digital Twin (DT) (VanDerHorn, 2021; Tao et al., 2019). DTs have rapidly increased in popularity in the last few years (Liu et al., 2021). Initially coined in the context of rocket development and control, the term DT has expanded its scope to encompass a wide range of applications (Benfer et al., 2021). While digital transformation is a broad organisational strategy, DTs have gained prominence in specific applications, combining elements of simulation, industrial Internet of things (IIoT), big data, artificial intelligence (AI), cyber-physical systems (CPS), cloud computing, and automation (Qi et al., 2021). At its core, the term

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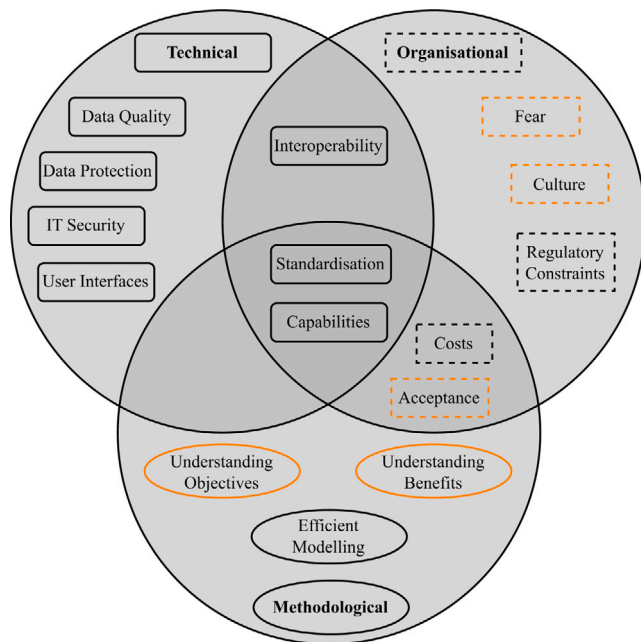


Fig. 1. Challenges of Digital Twin application.
Source: Adapted from Kober et al. (2022b).

DT describes the use of digital models interconnected with the modelled system. This interconnectivity allows models to be used in novel ways, as the effort and time delay associated with model parametrisation is eliminated. The increasing prevalence of sensors in the context of Industry 4.0 and the sharp cost decline and miniaturisation of computing hardware have enabled the use of live data throughout numerous applications.

Potential benefits of utilising DTs include reducing costs, risk, complexity, and design time or improving decision-making and efficiency (Jones et al., 2020; VanDerHorn, 2021). High-value industries like aerospace and automotive have been at the forefront of incorporating DTs into their digital transformation strategy (Psarommatis and May, 2023).

Although DTs theoretically offer much improvement potential, not much of this potential has yet been proven to reach industrial practice. Consequently, DT maturity in organisations is still low (Medina et al., 2021; Mourtzis, 2019). Paradoxically, this low maturity stands in contrast to continuously high investments in DTs involving millions of Euros (Trauer et al., 2022).

While the adoption of DTs in various industries is slowly growing, multiple open challenges still need to be addressed to improve the effectiveness of DTs in practical applications (Liu et al., 2022). Existing literature discusses multiple reasons for the apparent discrepancy between the enthusiasm expressed for DTs and the actual implementation maturity. Most studies investigating this topic focus on technical challenges of DTs, like interoperability, standardisation, real-time capabilities, and data quality (Hu et al., 2021; Bordeleau et al., 2020; Semeraro et al., 2021; Michael et al., 2022). However, recent empirical studies show that organisational, methodological, and human aspects are becoming more important to enable beneficial application scenarios.

Consequently, Fig. 1 summarises 15 key challenges identified by Kober et al. (2022b) from which human-related challenges are highlighted. These human-related aspects like understanding of objectives, understanding of benefits, fear of job loss and acceptance of change are identified as crucial challenges to the success of DTs (Kober et al., 2022b). Organisations struggle with achieving an optimum balance between how much they invest in DTs and how much they gain as benefits

(Kober et al., 2023a). DT fidelity is a critical factor that highly influences this relation (Kober et al., 2022a, 2023b). In Saporiti et al. (2023), similar results have been presented. They conducted a literature review and a delphi study to identify 18 challenges, which they structured into four categories: organisational, technological, data-related, and human-related. Following the lack of necessary skills, the second most relevant challenge was identified as the need to set realistic expectations, trust, and value propositions. Similarly, another study based on recent empirical data reveals that non-technical challenges like identifying a clear value proposition, setting realistic expectations, and building trust are more likely to cause issues in DT implementation (Trauer et al., 2022). Perno et al. (2022) also discuss the need to involve multiple stakeholders in DT projects and to set realistic expectations and trust, examining both technical and organisational challenges.

Besides merely identifying challenges, some studies also propose possible countermeasures to overcome human-related DT challenges. The study of Kober et al. (2022b) proposes clear communication among stakeholders about DT definition, measurable objectives, and evaluating benefits as crucial measures to overcome DT challenges. Similarly, clear communication about responsibilities, competencies, and common goals was found to be the most important countermeasure to overcome DT challenges, as it reached the highest relevance score and the highest agreement among experts in a Delphi study by Saporiti et al. (2023).

Since most available articles focus on technical aspects, a more in-depth understanding is required of how human-related and organisational DT challenges arise and develop. Although multiple authors superficially highlighted the importance of stakeholder communication in DT projects, little is known about the detailed characteristics and dynamics inside DT projects that cause challenging stakeholder communication. Moreover, there are no insights into detailed DT communication challenges and their countermeasures that support scholars and practitioners with solving these issues.

Thus, there is a risk that DT remains a hype phenomenon with no true benefits, which severely threatens the success of an organisation's digital transformation. Notably, the specificities of DTs render communication challenges more pertinent compared to the higher-level digital transformation theme, which lacks the direct operational connection that gives rise to communication challenges in distinct scenarios. Stakeholders in an organisation contribute to its digital transformation through individual projects, such as DT initiatives. Moreover, while the purpose and benefits of digital transformation are well-established, DT face ongoing scrutiny and questioning. Consequently, this article contributes to the targeted and value-oriented development and utilisation of DTs by answering the following research questions (RQs):

- RQ1: What communication challenges do DT stakeholders face?
- RQ2: What practices are applied to overcome these challenges?

To contextualise the RQs within the broader landscape of stakeholder communication research, it is imperative to acknowledge that stakeholder communication is an ongoing area of research across various domains (Unterhitzberger et al., 2021). Effective stakeholder communication is also recognised as pivotal to succeed in the realm of IT projects (Alsulaimi and Abdullah, 2020). However, despite the existing research in these areas, there is a noticeable gap pertaining to the specific challenges encountered in stakeholder communication within the context of DT projects. To date, there is a scarcity of literature addressing the nuanced aspects of communication challenges unique to DT initiatives. This gap is particularly crucial given the nature of DTs, where the interplay between human, organisational, and technical factors adds a layer of complexity to communication dynamics.

In summary, this paper seeks to contribute to the existing body of knowledge by shedding light on the communication challenges stakeholders face in DT projects, a domain where comprehensive literature

is yet to be developed. By addressing this gap, the findings aim to provide valuable insights for researchers and practitioners involved in DT initiatives.

As a brief note upfront, Section 2 presents an overview of the latest developments in DT research. Section 3 then presents the methodology used to approach these RQs. The following sections summarise the characteristics of DT projects (Section 4), the identified DT stakeholder communication challenges (Section 5), and the practices to overcome them (Section 6). Section 7 discusses the theoretical and practical contributions of these findings. Ultimately, Section 8 concludes the key messages of this article.

2. Current trends in DT research

Building on the foundational concepts and challenges outlined in the previous section, it becomes evident that the field of DTs is dynamic and multifaceted. This section provides an overview of the latest trends in DT research, offering insights into the diverse definitions, emerging applications, and technological advancements shaping the future of DTs. By examining these trends, we can better understand how DTs are positioned to drive innovation.

The popularity across applications has led to increasing confusion regarding the definition of DTs. Popular definitions are from [Kritzinger et al. \(2018\)](#), [Glaessgen and Stargel \(2012\)](#), and [Stark et al. \(2017\)](#). Nevertheless, there is still low consensus about the definition of DTs, e.g., if and how exactly DTs differ from related concepts and technologies, like simulation and model-based control. This confusion has resulted in a situation where almost every organisation seems to formulate its own interpretation of DTs, leading to a multitude of definitions and a lack of conceptual clarity ([Spoor and Weber, 2023](#)). Efforts have been made to synthesise these definitions, as demonstrated by [VanDerHorn \(2021\)](#) analysis of 46 existing definitions, mapping out DT's basic components being a physical environment and a virtual environment with its systems and processes and their physical to virtual and virtual to physical data links.

Despite all the previously mentioned challenges around DTs, the field has experienced significant research advancements and applications in recent years, profoundly influencing the landscape of smart manufacturing and industrial processes ([Sun et al., 2024](#)). Researchers and industry experts have investigated various facets of DTs, leading to an improving understanding of their potential and impact across different sectors. [Lattanzi et al. \(2021\)](#) have documented the progression of DT research, underscoring the pivotal technologies and concepts driving its practical implementation. This progression, categorised into formation, incubation, and growth stages by [Tao et al. \(2019\)](#), highlights the critical role of DT modelling, simulation, verification, validation, and accreditation (VV&A). Additionally, [Soori et al. \(2023\)](#) delve into the transformative potential of DTs in smart manufacturing, showcasing their ability to optimise decision-making processes across industries.

Concurrently, although being comparably slow, the industrial sector has adopted DT technologies to revolutionise traditional manufacturing practices and embrace the era of smart manufacturing. The synergy between DTs and Industry 4.0 technologies, as discussed by [Lu et al. \(2020\)](#), is driving innovations in product design, process optimisation, and real-time monitoring, thereby enhancing overall productivity and competitiveness. Moreover, [Kamble et al. \(2022\)](#) highlight the application of DTs in sustainable manufacturing supply chains, illustrating how DTs can streamline production processes, enhance resource utilisation, and promote environmental sustainability.

These trends underscore a shift towards data-driven decision-making, predictive analytics, and digital transformation, positioning DTs as a central enabler of agility, flexibility, and efficiency in modern industrial settings. Current trends in DT developments underscore the interdisciplinary nature of research and industry collaborations, emphasising the necessity for continuous innovation and exploration to fully harness the potential of DTs in driving digital transformation and smart manufacturing practices across diverse sectors.

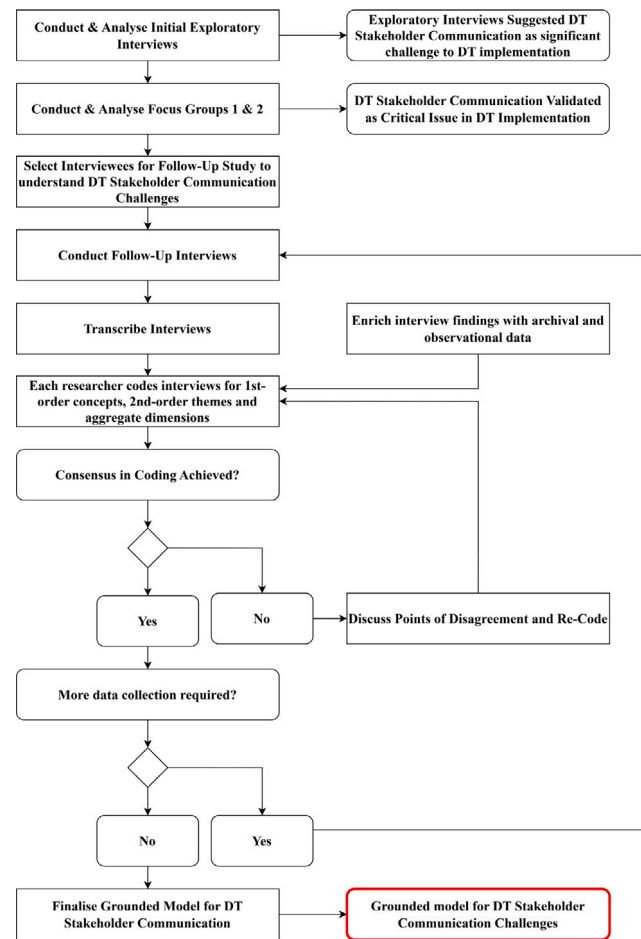


Fig. 2. Full research process and methodology.

3. Methodology

This section presents which methodology has been used to answer the RQs defined in the previous section. Section 3.1 generally explains the research design from a top level perspective. Then, Section 3.2 elaborates on how data was collected. Ultimately, Section 3.3 gives an overview about how data analysis was conducted.

3.1. Research design

Our research protocol first involved an in-depth exploration of general DT implementation challenges. We began by conducting 21 exploratory interviews with carefully selected, well-acknowledged industry professionals associated with DT development and utilisation to understand the challenges they faced when implementing DTs. The full results of this initial study can be found in [Kober et al. \(2022b\)](#). During these interviews, one of the main findings was that communication challenges were a significant barrier to DT implementation and usage. To further evaluate these insights, we conducted two focus groups with 11 experienced key stakeholders from multiple leading organisations to identify the main challenges faced by industry professionals who work in DT projects. Again, we selected the most important key stakeholders within several leading multi national enterprises (MNE). Throughout both workshops, we validated that stakeholder communication was one of the most pressing issues when conducting DT projects.

To further explore the DT stakeholder communication challenges in more detail, we conducted another set of focused interviews (see Section 3.2) with highly experienced professionals from the aerospace and

Table 1
List of study participants.

Nb.	Job title	Industry	Size [k]	Experience [years]	Interviews	Focus groups
1	Specialist Virtual Commissioning	Automotive	>100	7	1; 3	2
2	Product Owner Process Digitalisation	Aerospace	>100	18	1; 3	1
3	Senior Principal Digital Twin Manufacturing	Automation	>250	33	3	2
4	Industrial Digital Twin Project Manager	Aerospace	>100	17	1; 3	
5	Industrial Digital Twin Lead	Aerospace	>100	21	3	
6	Head of Site & Plant	Aerospace	>100	26	1	2
7	Head of Portfolio Development	Automation	>250	23		2
8	Senior Research Associate	Academia	>5	7		2
9	Research Associate	Academia	>1	3		2
10	Project Leader Product Development	Automotive	>100	11	1	1
11	Manufacturing & Industrial System Engineer	Aerospace	>100	5	1	1
12	Data Governance Production Logistics	Automotive	>80	11	1	1
13	Research Group Leader	Academia	>1	7		1
14	Research Vice President, Manufacturing Service	Consulting	>15	40	1; 2	
15	Business Architect Digitalisation	Automotive	>50	13	1	
16	Head of New Development Programme	Aerospace	>100	26	1	
17	Partner	Consulting	>30	9	1	
18	Industrial Modelling and Simulation Engineer	Aerospace	>100	10	1	
19	Head of Engineering Data Management	Automotive	>200	10	1	
20	Head of Development Controlling	Aerospace	>100	18	1	
21	Head of Digital Transformation	Aerospace	>100	24	1	
22	Senior Aircraft Architect Research & Technology	Aerospace	>100	22	1	
23	Partner	Consulting	>40	23	1	
24	Head of Site & Plant	Aerospace	>100	32	1	
25	Lead Industrial Digitalisation	Aerospace	>100	6	1	
26	Fast Track Leader Industry	Aerospace	>100	15	1	
27	Senior Vice President Engineering	Aerospace	>100	23	1	
				$\mu = 16.9$	$\Sigma = 27$	$\Sigma = 11$

automotive industries who were directly involved in developing and exploiting DTs in their organisations. We chose to focus on these two industries because previous literature has identified them as frontrunners in implementing DTs (Psarommatis and May, 2023). Therefore, conducting interviews with professionals in these industries provides the most comprehensive perspective on DT stakeholder communication issues. More details about how data collection and analysis were done follow in Sections 3.2 and 3.3. An overview of the full research process is illustrated in Fig. 2.

3.2. Data collection

We conducted a total of 27 in-depth, semi-structured interviews with a length of 0.5 to 1.5 h per interview over a period of 15 months (April 2022 to June 2023). In these interviews, we explored the communication challenges experienced by DT stakeholders and the approaches followed to mitigate these challenges. Additionally, common characteristics of DT projects that distinguish them from regular projects were identified. A full list detailing the interview and focus group participants is presented in Table 1. The numbers in the “Interviews” and “Focus Groups” columns indicate in which of the 3 interview iterations, respectively the 2 focus groups, the experts participated. The last row sums up the total number of interviews, respectively the total number of focus group participants. To ensure our data collection was comprehensive, we chose highly experienced interviewees with a mean of $\mu = 16.9$ years of relevant working experience.

An interview guide (see Appendix) was developed to explore the characteristics of the communication challenges experienced by DT stakeholders and the mitigating approaches adopted. This was developed by drawing from the interviewing approaches followed by previous literature exploring communication challenges in contexts such as management, global software development, and crisis management (Hedman and Valo, 2015; Holmström et al., 2006; Hale et al., 2005). We conducted interviews and secondary data collection until no new insights were obtained from the data and theoretical saturation was reached, as per the Gioia methodology (see next section).

Interviews were recorded where permission was granted and transcribed by the authors. Extensive notes were taken during or directly after the interviews to ensure fresh insights obtained by the researchers were not lost. We complemented our interview data with archival data, multiple informal conversations, and observational data.

3.3. Data analysis

We followed a grounded theory methodology for our data analysis. It is well suited to generate theory about phenomena when there is a lack of existing theory describing them (Cassell and Symon, 2004; Corbin and Strauss, 1990). Grounded theory involves an iterative data collection and analysis process as the grounded theory is developed. Data collection typically comprises observations, interviews, surveys, and archival research, whereas data analysis consists of the development of 1st-order concepts, 2nd-order themes, and the identification of dynamic relationships between them (Gioia, 2021).

To improve the rigour of our research, we additionally followed the Gioia methodology (Gioia, 2021). The Gioia methodology requires that data analysis begins with identifying 1st-order, informant-centric concepts. The identification of 1st-order concepts was conducted by analysing the raw data, in our case, interview transcriptions, notes, and observations, and applying codes to relevant text passages. In several iterations, these 1st-order concepts were then grouped into higher-level 2nd-order, theory-centric themes and theoretical dimensions. These concepts, themes, and dimensions were grouped into a data structure, allowing other researchers to backtrack the origin of the higher-level themes. The dynamic relationships between the 2nd-order themes and theoretical dimensions were then articulated and compared with existing literature to refine and create the grounded theory model of the phenomenon under study. The coding process was done using MaxQDA 2022, a qualitative data analysis tool. For our 1st-order concepts, we searched for instances of DT communication. Subsequently, for each DT communication instance, we identified:

- The special characteristics of DT projects.
- The challenges experienced in these communication instances.
- The measures and practices adopted to mitigate each communication challenge.

Table 2
Characteristics of DT projects.

Category	Characteristics	Description
Human	Lots of stakeholders	DT projects involve numerous participants from business and IT sectors.
	Multidisciplinary experts	DT projects rely on diverse teams of experts due to their complex nature.
	Lots of data sources	DT projects source data from diverse systems.
	Lots of technologies	DT projects often incorporate diverse technologies for data collection, analysis, and visualisation.
Technical	Multiple IT tools	DTs combine multiple software tools, including legacy tools.
	Long lifetime of DT models along the life cycle	Model reusability is common in DT projects, extending their lifetimes beyond traditional projects.
	Development of new DT models	Model development requires often missing expertise.
	Derivation from existing models	New DT models are often built from existing ones and can be augmented with real-time data features as needed.
	Continuous updating of DT models	DT models must ensure they remain up to date with the asset they are representing, unlike traditional models that may become outdated.
Organisational	Low DT maturity	DT projects are often characterised by a limited level of maturity and knowledge within project teams.

To increase the reliability of the findings, independent coding was conducted by the different co-authors. The co-authors compared and discussed 1st-order concepts, 2nd-order themes, and theoretical dimensions and their dynamic relationships until consensus was reached on the most suitable grounded theory model that described the data.

In the following sections, we present the results arising from following the Gioia methodology. We provide the full coding structure and illustrate quotes and detailed explanations of the different 2nd-order themes and their interrelationships.

4. Characteristics of DT projects

This section presents how DT projects differ from conventional improvement initiatives in manufacturing organisations, shedding light on their unique defining characteristics.

Projects that include the development or the utilisation of DTs tend to have certain special characteristics that, based on our analysis, are presented in this section. These characteristics include different aspects that lead to a certain complexity in DT projects. The following sections are structured into three categories: human, technical, and organisational perspective.

From a human perspective, DT projects usually involve many stakeholders from the operative business side and the IT side. Due to the thematic complexity, no single DT “super user” exists who is capable of developing and using all systems and tools based on DTs. Instead, DT projects require multiple experts who may only know parts of the DT in detail. This results in a high number and variety of experts involved.

From a technical perspective, data in DT projects can originate from many different systems. Another observed characteristic of DT projects is the necessity to incorporate different technologies for data collection, analysis, and visualisation. DT can be based on multiple software tools, ultimately comprising the DT application. These can be legacy tools that were used individually before DTs emerged. To allow the creation of DTs, these tools usually have to be combined and connected, e.g., in the form of co-simulations. Model reuse is common in DT projects, as they span across the life cycle of the twinned assets and its virtual models. In some areas, new models have to be developed that fit the purpose of the DT. However, most of these models are derived from already existing models. If necessary, these models are then extended with real-time capabilities. As DTs represent the physical reality, the DT models have to be kept up to date. While typical models that were, e.g., used in simulation projects become outdated, DT models should always represent reality as accurately as necessary.

From an organisational perspective, DT projects are currently characterised by a low level of expertise inside the organisation due to its innovative character. Organisations are still mostly in proof of concept

phases of their individual digitalisation initiatives. This adds further complexity to the deployment and adoption of DTs in organisations. Table 2 summarises the different facets characterising DT projects.

5. DT stakeholder communication challenges

As the previous sections demonstrated, stakeholder communication is one of the biggest barriers to DT adoption and implementation as a result of DT project’s complexity. In this section, we delve into the various stakeholder communication challenges encountered during the development and utilisation of DTs, obtained by conducting and analysing the studies explained in Section 3. These challenges can be categorised into two aggregate dimensions: those mainly arising from human factors (Section 5.1) and those mainly originating from organisational factors (Section 5.2). Fig. 3 depicts how challenges (1st-order concepts), abstract categories (2nd-order themes), and aggregate dimensions relate to each other, following Gioia’s approach (Gioia et al., 2013). This section’s entire structure follows Fig. 3. For all 2nd-order themes, we illustrate at least one representative quote from the study at the beginning of each paragraph, as recommended in Rockmann and Vough (2023).

5.1. Human-centric DT communication challenges

Benefits understanding. Table 3 summarises the communication challenges related to the understanding of DT benefits, which are discussed below.

“So for me, it [DT] is a product or solution, so it should be able to allow making decisions. But also, we need to identify who the customers are for such solutions and also, what will be the main advantages [of] using twin[s] for these businesses. And it is sometimes not so easy to align, because there’s this kind of translation between what it can do for specific use cases”. - Industrial Digital Twin Lead

General understanding of DT value proposition. Benefits are difficult to understand as the DT and its implications tend to be complex to grasp. Another factor is that it usually takes longer time periods to realise benefits, which makes it difficult to trace back the effects of DTs and separate them from other effects. There is also a lack of methods that support humans with estimating benefits.

Convincing DT stakeholders of benefits. The more abstract the DT benefits are, the more difficult it is to convince stakeholders, especially on an operative level. That is why DT examples sometimes aim to be

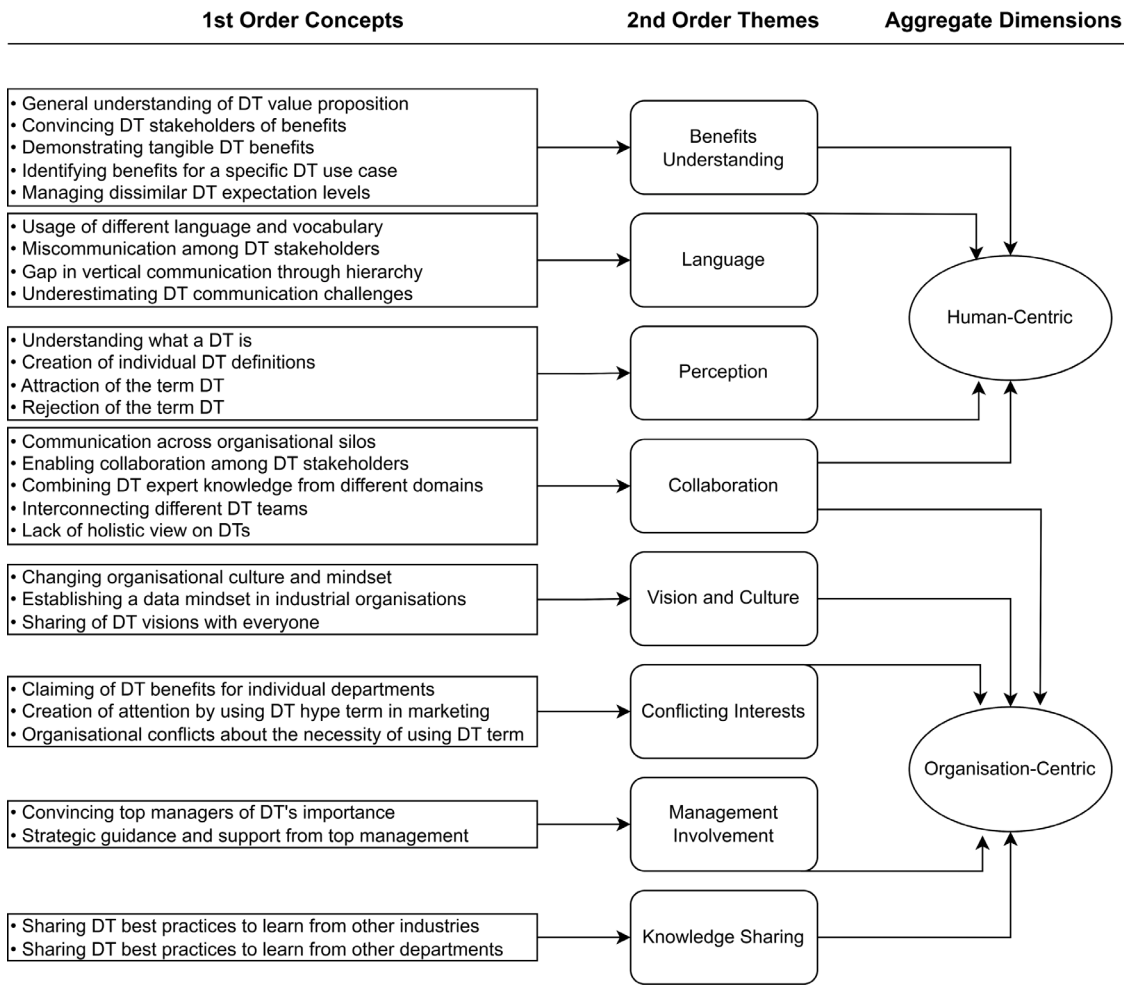


Fig. 3. Digital Twin stakeholder communications challenges data structure.

Table 3
Human-Centric Communication Challenges: Benefits Understanding.

Category	Description
General understanding of DT value proposition	DT benefits are difficult to grasp due to complexity of the system. Challenges in tracing and distinguishing DT's influence. Lack of methods to help estimate DT benefits.
Convincing DT stakeholders of benefits	Abstract benefits are challenging to sell to stakeholders, particularly at operational levels. DTs tend to be valued based on non-value adding features, such as 3D photorealism, over their practical benefits.
Demonstrating tangible DT benefits	Clearly demonstrating DT benefits to onboard people is difficult. Proving DT's value is crucial due to low maturity and belief in the success of implementations. Failure to verify DT benefits could lead to prioritising other initiatives. Communicating benefits is difficult, and quantification remains a challenge.
Identifying benefits for a specific DT use case	Identifying and isolating specific use case benefits is challenging. DT benefits are mostly abstract, like quality and efficiency improvements. Concrete translation of general benefits into measurable use case improvements is necessary. Complexities arise due to model reusability across cases.
Managing dissimilar DT expectation levels	Main challenge emerges from DT hype. High expectations set due to innovation claims, but limited industrial application. Bridging the gap between enthusiastic and pessimistic stakeholders is required.

more photorealistic than necessary to visually demonstrate potential benefits, e.g., by using 3D models.

Demonstrating tangible DT benefits. Onboarding people by clearly demonstrating DT's benefits is another major challenge. As most organisations currently have a low maturity level regarding DT implementation, verifying that applying DTs can lead to improvements is crucial to their success. Otherwise, priorities will likely be set in other, supposedly

more promising improvement initiatives. However, it is difficult to identify and communicate all direct and indirect effects that lead to benefits for an organisation. Quantifying these benefits is still difficult and not done sufficiently.

Identifying benefits for a specific DT use case. Another challenge is identifying concrete benefits achieved within a specific use case. DT benefits are mostly communicated abstractly in categories like quality

Table 4
Human-Centric Communication Challenges: Language.

Category	Description
Usage of different language and vocabulary	Heterogeneous team members from diverse functional and hierarchical domains lack unified DT language. No unified vocabulary for effective communication due to ambiguity. Particularly difficult to bridge the language gap between IT and operational stakeholders.
Miscommunication among DT stakeholders	Stakeholders lack shared understanding when discussing DT. Clearing up the exact meaning demands time and effort. Time constraints often lead to insufficient alignment on the term DT. Unnoticed miscommunication endangers DT projects.
Gap in vertical communication through the hierarchy	DT term gains attention in higher hierarchy levels, but less at the operative level due to high abstraction. Difficult to bridge the gap in communication between the abstract term and practical tools and models. Middle management faces difficulty in translating DT metaphor to operational reality.
Underestimating DT communication challenges	Some stakeholders, especially technical, lack critical awareness of communication. Multinational teams in MNEs increase the complexity of communication. Adapting information requirements to stakeholder needs becomes more difficult in DT projects. Low communication efficiency leads to wasted time aligning stakeholders on DTs. Newly formed interdisciplinary teams lack a shared context as basis for DT. Ambiguity of DT term further complicates communication.

improvement, efficiency improvement, risk mitigation, etc. However, these general benefits must be translated into tangible, measurable improvements within a specific use case, since otherwise it remains unclear whether the DT achieved desired outcomes. Additionally, the benefit assessment needs to consider the reusability of the models for other use cases, which makes their specification even more complicated.

Managing dissimilar DT expectation levels. This challenge mainly results from the hype around the term DT. Since many people and organisations use DTs to appear innovative, high expectations were set initially. However, not much has yet reached industrial practice, which is why some stakeholders, especially on an operative level, do not believe in DTs anymore. Bridging this gap between fully convinced stakeholders who see DTs as the next industrial revolution and stakeholders who are extremely pessimistic is a crucial communication challenge concerning DTs.

Language. Table 4 summarises the communication challenges related to the used language within DT projects that follow below.

“Then one [person] talks about the Digital Twin and the other about the Digital Shadow and as long as they don’t become concrete and don’t explain themselves, so to speak, and describe with examples what they mean concretely, they can wonderfully talk past each other”. - Senior Principal Digital Twin Manufacturing (translated)

“And in the worst case, you might even leave the conversation with the feeling that you had a good time. That’s the real worst-case scenario because you don’t have a chance to react, because you didn’t even register the miscommunication”. - Senior Principal Digital Twin Manufacturing (translated)

Usage of different language and vocabulary. The heterogeneous team members from different functional and hierarchical domains do not use the same language regarding DTs. They neither speak about the same targets nor technologies, even though they supposedly talk about DTs. One challenge is to find a common vocabulary that builds the basis for communication. Bridging the gap between the IT and the operative business stakeholders is perceived as particularly difficult.

Miscommunication among DT stakeholders. Frequently, stakeholders subconsciously refer to different aspects of DTs in their communication. However, they often do not realise it as it takes time and extra effort to clarify the exact meaning. Time constraints are usually a reason why an adequate alignment on the term DT is neglected. As a result, miscommunication is often not registered at all, putting DT projects at high risk. Miscommunication regarding DT can result from a person’s DT interpretation or the organisation’s DT understanding.

Gap in vertical communication through the hierarchy. Whereas the term DT creates attention in higher hierarchy levels, it is less common on

an operative level due to its high abstraction level. Bridging this gap from the supposedly concrete DT metaphor to the actual operative tools and models used to enable DTs is a difficult challenge for middle management.

Underestimating DT communication challenges. While communication is nowadays at least partially taught at university, it has not been such a relevant factor in technical studies in the past, according to the study participants. Thus, some stakeholders’ awareness of communication issues appears relatively low. Regarding DTs in MNEs, communication is especially challenging since multiple cultures work together in heterogeneous teams. Knowing and adapting the information abstraction level to different stakeholders’ information requirements in DT projects thus becomes more complex. Another important factor that is being underestimated is the efficiency of communication. Limited, valuable time in DT projects is wasted trying to align all stakeholders on what DT means. In the past, the well established context of communication facilitated this alignment and made it more efficient, which initially in DT projects is more difficult with newly formed interdisciplinary teams that do not speak the same technical language. Another issue is that the term appears self-explanatory while it carries much ambiguity.

Perception. Table 5 summarises the communication challenges related to the individual perception of DTs that follow below.

“When it comes to the term [DT], it is quite obvious that we find that our customers have a very different understanding of what they personally or in their work environment mean by the term Digital Twin”. - Senior Principal Digital Twin Manufacturing (translated)

Understanding what a DT is. Currently, it is difficult and time-consuming to explain the essence of the DT concept to all stakeholders at the required abstraction level. Much experience is needed to find an efficient and effective way of communication. Due to the inflationary and diverse usage of the term, communicators sometimes struggle with wrong expectations about what the DT is and which benefits it can deliver. While some people believe there is nothing new about DTs, others are overwhelmed by the alleged complexity of high-fidelity DTs. Since DT is such an unspecific, vague umbrella term, using it without any further clarification does add no or only little value. The communication lacks concrete, tangible examples of DTs. Moreover, stakeholders struggle to know which problems can be solved using DTs.

Creation of individual DT definitions. Many individuals and almost every organisation have created their own DT definitions, even though they are aware of other existing definitions. Sometimes, this happens for personal or organisational marketing reasons to appear innovative, which dilutes people’s perception of the term DT. DT definitions vary depending on the organisation’s and sometimes even the person’s

Table 5
Human-Centric Communication Challenges: Perception.

Category	Description
Understanding what a DT is	Explaining the DT concept is time-consuming due to the different levels of required abstraction. Much experience required for efficient communication. Inflationary usage of DT leads to incorrect understanding. Diverse opinions: Some people see nothing new in DTs, others find the perceived novelty overwhelming. Using the vague DT term without clarification is not beneficial. Lack of tangible examples and uncertainty about which problems can be solved with DT.
Creation of individual DT definitions	Most organisations create their own DT definitions. Multiple definitions within a single organisation add confusion and risk of miscommunication. DT's diverse concepts and technologies make establishing a common definition difficult.
Attraction of the term DT	Limited comprehension, yet widespread discussion of DT. The DT concept especially attracts tech enthusiasts. The “twins” metaphor within DT adds appeal and contributes to wide discussions.
Rejection of the term DT	DT term can lead to disillusionment due to unmet expectations. Perceived complexity and distance from real applications discourage stakeholders, especially on the operative level. Stakeholders sometimes avoid the term, jeopardising DT adoption.

perception using the term. There is a high chance that even inside a single organisation, multiple definitions exist and are used in parallel. Creating all these various definitions adds to the confusion of what DTs are by diluting the concept's meaning and enforces the risk of miscommunication. The alignment on a single, common definition is often seen as a challenging task rarely completed successfully as DT covers many different concepts and technologies.

Attraction of the term DT. Although only few people have enough knowledge and experience to fully cope with the complexity of DTs, it seems as if many like to talk about it. In particular, tech-enthusiastic stakeholders often find the term and the concept attractive. There is also the human touch of “twins” inside DT, which supports the hype around the term by creating an appealing metaphor that is, in contrast to reality, being perceived as easily comprehensible.

Rejection of the term DT. The concept appears too complex and far from reality, limiting its acceptance and true adoption in operative production. Consequently, stakeholders adapt and start avoiding the term, putting the success of DT adoption at risk. Perceived complexity of DTs also discourages some stakeholders who lose interest after a certain time.

Collaboration. Table 6 summarises the communication challenges related to the dynamics of collaboration in DT projects that follow below. Although this 2nd-order theme is located under 5.1, it covers both human and organisational aspects as depicted in Fig. 3.

“It’s a question of capabilities, of tools. You typically don’t find a tool that can do everything, because there has been no reason to develop such a tool so far. Admittedly, the tool would also be too complex for an individual person who uses it, because modelling the behaviour of technical systems, regardless of whether it is a mechanical behaviour or a complex mechatronic or automation behaviour, requires an expert. They must understand how their modelling tool works and have great knowledge of the subject matter. And when several disciplines come together, you won’t find the one “super user” who can do everything and is a master of everything, which means that you basically bring together partial models that are simulated in different solvers, and these tools then encapsulate the complexity, if you like. This means that once the model has been created, I no longer have to be an expert to use the model. And then I am the one who perhaps uses the combination of these models, but the actual modelling work is still very problem-specific, with very problem-specific tools, and for that, I need the experts”. - Senior Principal Digital Twin Manufacturing (translated)

Communication across organisational silos. Collaboration still has its limits at the edges of individual departments. Data flows in DTs through digital threads are continuous, though, and require the inputs and outputs of each silo. Thus, inter-silo communication becomes more important to successfully applying DTs in manufacturing organisations. This increased complexity of communication is challenging.

Enabling collaboration among DT stakeholders. Enabling collective thinking of stakeholders towards contributing to the organisation's goals is also challenging with DTs, even though impacts are immediately made transparent. The effects of actions inside silos are now visible in other silos and vice-versa. Nonetheless, this increased transparency does not automatically lead to an entire organisation collectively working on the same objectives.

Combining DT expert knowledge from different domains. As described in Section 4, DTs are multidisciplinary and often too complex to be understood by only one individual expert. Therefore, various engineers, e.g., production planners, IoT specialists, and modelling and simulation experts, work together to develop and utilise DTs, increasing the complexity of knowledge integration and communication. Making sure these experts understand each other work on the same targets is difficult since communication interfaces still require considerably manual alignment.

Interconnecting different DT teams. In DT development and utilisation, heterogeneous and interdisciplinary teams are working together in new constellations that have not been present before. As DT is a concept affecting the whole organisation, it concerns not only the engineering domains, but also different functional domains and hierarchy levels. Sometimes, teams do not realise this interconnection and thus do not communicate adequately.

Lack of holistic view on DTs. Specialised teams in their silos tend to get lost in technical details since they are not used to thinking holistically. This leads to further challenges, e.g., in connecting teams and understanding all benefits of developing and utilising DTs. By adopting DTs in organisations, this narrowed-focused view is inevitably being eliminated, facilitating holistic thinking. It can be challenging for stakeholders who need to cope with this change towards holistic thinking.

5.2. Organisation-centric DT communication challenges

Vision and culture. Table 7 summarises the communication challenges related to the organisation's DT vision and culture that follow below.

Table 6
Human-Centric Communication Challenges: Collaboration.

Category	Description
Communication across organisational silos	Collaboration in DT projects still has boundaries at departmental edges. DT's digital thread exposes silo inputs and outputs and demands real holistic collaboration. Inter-silo communication is crucial for DT success in manufacturing, but is often still implemented ineffectively.
Enabling collaboration among DT stakeholders	Challenge in promoting collective thinking among DT stakeholders. Increased transparency of interconnected effects through DT yields conflict potential.
Combining DT expert knowledge from different domains	DT requires collaboration across many disciplines. Multidisciplinary teams of engineers develop and use DTs, adding complexity. Ensuring shared understanding among experts is challenging due to complex alignment.
Interconnecting different DT teams	DT utilisation and development requires diverse interdisciplinary teams in novel configurations. DT's impact span various functional domains and hierarchy levels. Interconnections can be failed to notice, leading to inadequate communication.
Lack of holistic view on DTs	Specialised teams in silos often focus on technical details, lacking holistic thinking. DT adoption in organisations facilitates a single source of truth, promoting integrated ways of working.

Table 7
Organisation-Centric Communication Challenges: Vision and Culture.

Category	Description
Changing organisational culture and mindset	DT demands a shift in organisational culture and mindset. Existing priorities may downplay DT's adoption priority. Not all stakeholders equally recognise the need for DT to secure future competitiveness.
Establishing a data mindset in industrial organisations	Manufacturing organisations traditionally focus on hardware, less on IT and digitalisation. Establishing a digital mindset and embracing quick failure is challenging. Transitioning from a 'get it right the first time' approach appears difficult.
Sharing of DT visions with everyone	Sharing the DT vision inside the organisation is a challenge. All stakeholders should grasp why and how DTs align with the organisation's goals. Prioritisation of DTs often falls short of effective vision dissemination. Single individuals or departments spread the DT vision, facing scepticism and difficulties in convincing the full organisation.

"I think in our minds, when we hear automation, we still think maybe of robots that automatically drill, rivet, etc. But ultimately, we can also automate data flows and information flows. (...) I don't think that's in people's heads yet. It's somehow not really imaginable for many people, for whatever reason". - Product Owner Process Digitalisation (translated)

"And if we want to be efficient in usage, we really need to have a clear vision of what we could expect from that in the company. That doesn't mean we should do it. I just say we should have a clear vision in the company, saying 'Do we need to do Digital Twins or not?' And if we are doing twins 'where are we doing that?' And this should come from the top managers". - Industrial Digital Twin Lead

Changing organisational culture and mindset. DT requires a strategic change in organisational culture and mindset. Many regular operative tasks in manufacturing organisations are managed well today, even without DTs. Consequently, adopting DTs is sometimes not a priority, even though it promises substantial improvements. Successfully implementing DTs without propagating an organisation-wide need to do so is a major challenge. Although being a prerequisite, the need to secure future competitiveness by utilising DTs is not yet equally seen by all relevant stakeholders.

Establishing a data mindset in industrial organisations. Manufacturing organisations are used to being hardware-centric and thus are less familiar with digitalisation. With DTs, many experiments can be done in a risk-free, digital environment that allows multiple failures at low costs, whereas a hardware-centric organisation cannot afford to waste many resources on physical prototypes. Fully establishing this digital mindset and trust in quick failure compared to doing everything right the first time is challenging. DT's adoption calls for a continuation of this shift towards a data mindset, that emerged with the rise of simulations and similar technologies in industrial organisations.

Sharing of DT visions with everyone. Another challenge is sharing the organisational vision of DTs. Every stakeholder in the organisational

ecosystem should understand why DTs are being developed and applied and how these fit into their operative and strategic goals. However, it can be observed that DTs are not prioritised as required to spread the vision across the organisation with all necessary stakeholders. The vision of interconnected DTs is usually propagated by single people or departments who often face scepticism and struggle to convince their ecosystem.

Conflicting interests. Table 8 summarises the communication challenges resulting from conflicting organisational interests regarding the DT that follow below.

"The first challenge is a political one. This is the first one. Because everyone did a great job, they have done great projects. And everyone fears to have someone coming who says 'the benefit is for me'. No... it's all together!" - Industrial Digital Twin Project Manager

"My sales argument is actually 'with my Digital Twin, you get transparency.' And then the hairs on the back of their necks stand up, and they say 'eww, transparency. But I don't want you to create transparency here' (laughing), something like that". - Product Owner Process Digitalisation (translated)

Claiming of DT benefits for individual departments. This is a political challenge that becomes especially apparent when DTs are considered. Since DTs create transparency and neglect the traditional borders of departments, they can reveal unwanted facts that cannot be hidden anymore. It is a known challenge that an organisation's departments do not always behave in the best way to achieve overall organisational goals, but prefer to act in a way their departments benefit the most. Departments that are oriented towards acting in a way that their department is benefited the most may resist DT adoption, actively preventing the creation of transparency.

While stakeholders need to work together to enable the transformation towards DTs, some will try to block the development to

Table 8
Organisation-Centric Communication Challenges: Conflicting Interests.

Category	Description
Claiming of DT benefits for individual departments	Political challenges arise with DTs due to newly established transparency. DTs expose informal structures beyond departmental borders that were previously actively hidden. Departments still prioritise their own benefits over organisational goals. Some stakeholders aim to maintain departmental intransparency.
Creation of attention by using DT hype term in marketing	Marketing departments sometimes exploit the DT term for products without real innovation. Short-term benefits from DT hype, but long-term sustainability concerns arise. Over time, customers will recognise the lack of true novelty. DT marketing strategy is often driven by competitive pressure to seem innovative.
Organisational conflicts about the necessity of using DT term	Using DT as a general catch-all solution lacks true customer value. Labelling old products as DTs leads to confusion. Internal debates on the necessity of using the DT term emerge.

Table 9
Organisation-Centric Communication Challenges: Management Involvement.

Category	Description
Convincing top managers of DT's importance	Some organisations' top managers disregard the necessity of using DTs. Belief and support for DT initiatives from top managers are not always guaranteed. Top managers face challenges due to uncertainty about pursuing DTs.
Strategic guidance and support from top management	Top managers struggle with leading organisation's digital transformation with DTs. Complexity of implementing successful DTs is often not acknowledged. Lack of clear guidance on DT priority due to uncertain benefits. Top managers' uncertainty reflects across the organisation's DT goals and success.

keep the benefits of intransparency for their department. Another issue influencing how stakeholders communicate in DT projects is that the departments with the additional workload often do not directly benefit from the extra work. Instead, the Key Performance Indicators (KPI) of the receiving departments are improving, whereas the executing department's KPIs are becoming worse. Thus, extra work in one department can lead to benefits in other departments, which is another reason why benefits are not seen directly without applying collective thinking. This lack of understanding cross-departmental effects is a major communication challenge.

Creation of attention by using DT hype term in marketing. Organisations' marketing departments often use the term DT to advertise products related to DTs, which, however, do not have any true new features. Nevertheless, organisations still benefit from this increased attention by using the hype around the term. It is questionable whether this strategy is sustainable, since study participants mentioned the hype may flatten eventually and customers could eventually expect true innovation with genuinely novel features. Still, organisations decide to pursue this strategy as they may appear less innovative than their competitors if they do not use the term DT.

Organisational conflicts about the necessity of using DT term. In contrast to high-level marketing employees, more technical stakeholders better understand the nuances of all DT variations and thus claim that using the term DT as a general solution for all problems does not add any value to the customer. Nonetheless, sometimes old products are marketed as DTs, adding confusion rather than clarity inside an organisation. As a result, lengthy discussions arise about whether it is even necessary to use the term DT.

Management involvement. Table 9 summarises the communication challenges related to the top management's level of involvement in DT projects that follow below.

"I can quote some people who were saying that top managers should lead the digital transformation via Digital Twins. But if we want to have the full benefits of that, they should embrace the complexity of using Digital Twins. Otherwise, if we don't have this, we will have more local Digital Twins, and it's really different". - Industrial Digital Twin Lead

Convincing top managers of DT's importance. In some organisations, top managers have not recognised the importance of developing and

utilising DTs. Thus, top managers trust and support for these initiatives' success is not guaranteed. It is currently difficult for top managers to provide precise guidance on whether to pursue DTs or not due to the uncertainty around the concept and its benefits. Convincing these managers is difficult.

Strategic guidance and support from top management. Top managers struggle with leading the digital transformation of their organisations. The complexity of doing that is often not acknowledged sufficiently. Also, clear guidance is sometimes lacking about with which priority DTs should be pursued. This is partially because top managers are also unsure about the achievable benefits and, thus, the necessity of utilising DTs. This uncertainty affects whole organisations and poses a critical communication challenge to DT adoption.

Knowledge sharing. Table 10 summarises the communication challenges related to the organisation's ability to share knowledge that follow below.

"That's why there's a learning phase for everybody, for me, for the others. And that's why examples from the other industries, that's why your work, it's quite important. I think it's key also to say 'they succeeded by doing that.' And that's why we have lots of exchanges with the other industries to share lessons learned and failures and successes. (...) So we need to learn from the others. And we need to share it, and that's the challenge of twins". - Industrial Digital Twin Lead

Sharing DT best practices to learn from other industries. Missing knowledge sharing among different organisations and industries is another issue currently preventing DTs' widespread and effective utilisation. While sharing best practices is already difficult inside organisations, external knowledge sharing poses further risks. Organisations fear losing competitive advantages and are thus rarely willing to share their experiences. Additionally, interfaces for knowledge sharing often incorporate administrative hurdles, e.g., related to non-disclosure agreements. Sometimes, organisations also lack a realistic assessment of their expertise's value with DTs, which can quickly be overestimated in the current low maturity stages of DT. Due to increased reluctance to exchanging knowledge, the progression of digital transformation through DTs is jeopardised.

Sharing DT best practices to learn from other departments. The knowledge transfer between different departments inside an organisation is

Table 10
Organisation-Centric Communication Challenges: Knowledge Sharing.

Category	Description
Sharing DT best practices to learn from other industries	Missing intra-organisational and industry knowledge sharing impedes DT adoption. Organisations are reluctant to share knowledge due to competitive concerns. Administrative hurdles, like non-disclosure agreements, further complicate knowledge sharing.
Sharing DT best practices to learn from other departments	Knowledge transfer inside departments and organisations is challenging. Learning from others is vital for DT development and utilisation. Silos hinder collaboration, with multiple teams eventually tackling similar problems in early maturity stages.

another communication challenge. Learning from other people, departments, areas, etc., is crucial to facilitate the development and utilisation of DTs. At the moment, there are still many silos that independently work on the same challenges without knowing about each other and struggle with solving them.

6. Practices to overcome DT stakeholder communication challenges

This section summarises all relevant practices mentioned by the experts who participated in this study. The practices are based on the expert's experiences and were successfully employed and refined in industrial practice over multiple years. They are meant to serve as a means to overcome the DT stakeholder communication challenges from the previous section. As they are based on individual experiences, the practices do not serve as strict instruction of how to overcome the associated challenges. They rather serve as qualitative guidance, meaning that in some use cases it might be beneficial to deviate from the practices described in this section. The following section is structured similarly to Section 5, presenting practices related to human-centric challenges in Section 6.1 and practices related to organisation-centric challenges in Section 6.2. Table 11 summarises all mentioned practices and groups them into the best matching 2nd-order themes. While only grouped in one category, certain practices can impact multiple categories. This study did not specifically elaborate on the exact links, so a direct mapping of practices to 1st-order concepts was not done.

6.1. Practices to overcome human-centric DT communication challenges

Benefits understanding. One of the most important practices frequently mentioned by experts is to always start DT projects with a clear definition of the objectives. Clarifying why a DT shall be used to solve a problem or to leverage an improvement potential is crucial to all the following steps. This also includes selecting methods and tools to be used within the DT. Another important aspect is assessing the necessity for DTs, as sometimes other concepts can be more suitable or cost efficient. The question “do we need a DT, and if yes, what are the benefits of that?” must be answered as precisely as possible. Rather than aiming for complex high-fidelity DTs, the targeted DT must be as close as possible to the end user's needs. Project results are improved if empathy for the DT customer is shown and the customer's perspective is considered in all process steps. It is usually better to start with a limited set of objectives which may be reasonably covered by one solution instead of assuming that DTs will solve every stakeholder's problem. Moreover, the DT solution should be tested in production as proof of concept (PoC) to ensure that desired benefits are achieved considering all real-world constraints. While having a vision of where to go is good, it is really important to start simple. Small step introduction of DTs is crucial to avoid critical issues related to complexity, particularly in terms of change management. Organisations with limited DT experience often make the mistake of striving for high-fidelity DTs that never translate into practical operations, leading to a high risk of stakeholder resistance to DT solutions. Instead, organisations that establish straightforward solutions can then expand and connect DT use cases. Demonstrating tangible benefits becomes more manageable

with smaller use cases, making it easier to gain support. Additionally, learning from the experiences of other organisations can be valuable in avoiding common pitfalls. Another best practice is linking the higher-level organisational goals and the smaller-scale DT use cases. It helps to understand how smaller initiatives contribute to the bigger picture and thus increase the organisation's competitiveness. Most importantly, the exact benefit of utilising DTs should be assessed and communicated.

Language. Ideally, stakeholders have the awareness and time to prepare for every DT discussion and carefully assess what and how much they must explain in advance to ensure their conversation partner fully understands the arguments. This decision mostly depends on the conversation partner's DT knowledge depth and the discussion subject's complexity. The more DT knowledge is available, the fewer explanations and clarifications are needed. However, stakeholders must ensure they are not talking past each other. Choosing the right communication abstraction level is crucial to ensure messages are well received. A CTO requires more abstract and aggregated information on DTs than a modelling expert, who needs more details. Another factor is how much time is available for detailed explanations. Thus, communication efficiency is another important factor to consider, as meeting time and human attention are limited. However, evaluating the right abstraction level is difficult if limited time is taken for this task and the conversation partners' knowledge depth is unknown in advance. In these cases, finding a common denominator for all following communication is important. The question “how detailed information do my conversation partners need so that the information becomes valuable for them?” has to be answered before and during the communication.

Perception. Using the term DT can help to create a basic, high-level understanding of what is required as a solution. It guides in a certain direction known to everyone familiar with the term. If people are unsure or their understanding is heterogeneous, clarifying what DT means to them is always necessary. This step is always required when new teams are formed. Being as precise as possible with the terminology to avoid ambiguity is crucial, especially on an operational level. If the term DT appears too generic and further understanding has already been established, potentially even with an alternative term, then this term should be used throughout the project. Once attention is gained, the intermediate term DT becomes redundant, and more specific terms should be used depending on the solution. If attention is already there, the term DT is often not very useful anymore as it is too generic and carries much ambiguity. Already established solutions are preferably named more specifically, e.g., virtual commissioning, to avoid confusion. Especially when communicating with the operational teams, the term DT should be avoided in the long run. DT itself as an umbrella term is often too imprecise and vague. Moreover, starting with something to show helps to make the concept more comprehensible. It can also support gaining people's attention. Once attention is gained, it is crucial to find a common denominator that can be used to start building a conversation. This common denominator is a baseline and varies based on the target audience. Another aspect are visual elements, like drawings or videos, that can be used instead of presentation slides to overcome communication barriers, especially in MNEs. Visual elements can also prevent endless discussions about the concept by adding tangibility and leaving less room for individual interpretations.

Table 11
Practices to Overcome Digital Twin Stakeholder Communication Challenges.

Challenge	Practice	Description
Benefits Understanding	Defining clear objectives for DT projects	Commencing DT projects with defined objectives and determining suitable methods and tools within DT.
	Prioritising user-centricity and practicality	Prioritising DT alignment with user needs. Avoiding a one-size-fits-all DT approach.
	Starting with small DTs and building gradually	Beginning with small, manageable DT steps to mitigate complexity and change management related issues.
	Aligning organisational goals with smaller-scale DT initiatives	Highlighting contributions to overall goals and communicating the exact benefits.
Language	Effective DT information abstraction	Choosing the appropriate level of abstraction in communication and balancing information requirements for different stakeholders.
Perception	Effective communication and clarity	Using precise terminology and visuals to avoid ambiguity and overcome language barriers.
	Strategic use of the term DT to gain attention	Employing DT term for attention in specific situations.
	Transitioning from generic to specific DT terminology	Moving from DT to more precise terms to specify established solutions.
Collaboration	Improving data integration and transparency through DTs	Enhancing data transparency and interdepartmental data sharing for better decision-making.
Vision and Culture	Culturally empowering stakeholders for data-driven decision-making	Shifting mindset and culture towards data-driven decisions.
	Aligning DT actions with organisational vision	Ensuring alignment of DT actions with the bigger vision and facilitating understanding of individual contributions.
Conflicting Interests	Leveraging the term DT for high-level stakeholder engagement	Convincing high-level stakeholders through the term's perceived importance. Clarifying for those with in-depth DT knowledge or interest.
Management Involvement	Clear DT top management directions	Embracing complexity for transformation and facilitating a well-defined and manageable journey.
	Top management support as a critical basis	Starting DT initiatives from the operational level, but ensuring top management belief and support.
Knowledge Sharing	Promoting DT knowledge sharing	Knowledge sharing through factory visits, roadshows, and key user involvement with tangible, practical demonstrations.

The more concrete the explanations are, the better the anticipated understanding of the stakeholders will be. Under certain circumstances, e.g., if stakeholders personally like the term DT, it can be useful to temporarily mislabel specific solutions as DT to create attention. However, the details of what DT means must be clarified immediately to avoid confusion. Applying this procedure requires special rigour to ensure all stakeholders are aligned.

Collaboration. One best practice is breaking silos by explaining the need for data inputs from other departments to improve decision-making. Data flows should become more transparent so that the inputs and outputs of all silos are known. The question of “who delivers what to whom?” is formalised by creating this data map. Increased understanding through data continuity and standardisation of processes allows for better collaboration. Appointing dedicated roles to facilitate the communication between IT and operations is crucial to the success of DT projects. It is necessary to be sure that the communication gap between IT and operations is bridged by people who understand both sides.

6.2. Practices to overcome organisation-centric DT communication challenges

Vision and culture. Stakeholders must also understand and drive the change to data-driven decisions and automation in their organisations. This requires a change in mindset and culture that is a prerequisite for successfully applying DTs in manufacturing organisations, which still tend to stick to their old, less data-driven routines that have worked for the last years. Organisations should define for themselves which ultimate goal they want to reach. If they want to achieve the Industrial Metaverse, e.g., everyone needs to understand how their actions contribute to this bigger vision. Without this clarity, reaching such ambitious, disruptive objectives is difficult.

Conflicting interests. Using the term DT can be beneficial when projects have to be sold to high-level stakeholders. They can be convinced by the perceived attention around the term DT, without being interested in further details. However, immediate clarification is needed if the conversation partner has more in-depth knowledge or is interested in details. In these cases, stakeholders cannot appear innovative just by using the term DT.

Management involvement. Moreover, top management should provide clear guidance on which DT maturity level is targeted within the organisation. Based on their decision, they should also embrace the complexity of this transformation initiative to allow incremental, sustainable change. DTs should be introduced bottom-up. However, DT initiatives are in most cases only successful if they are supported by convinced top managers. In contrast to operative stakeholders, top managers do not need to know how exactly DTs can improve their organisation's business. Rather, they must understand that digitalisation is a necessary step in their organisation's transformation and that DTs are key enablers to achieve this.

Knowledge sharing. Knowledge sharing can be done by factory visits and roadshows where successful solutions and use cases are presented. Key users can then serve as knowledge multipliers, supporting these events and explaining existing solutions. Having already working DT examples available also helps to facilitate the DT understanding across organisations.

7. Discussion

The theoretical implications of this study are significant, as our article presents a grounded theory model on DT stakeholder communication not previously documented in the literature. This model addresses a critical gap by providing a nuanced and in-depth exploration of the communication challenges in DT projects, augmenting

existing knowledge and enhancing our comprehension of the human and organisational aspects contributing to solving these challenges. While existing studies of DT challenges only superficially describe human and organisational challenges, this article presents detailed insights into the DT stakeholder communication challenges that were not available before. Beyond the identification of single challenges, our study delves into the specifics of human and organisational aspects, presenting a comprehensive model (Fig. 3) that encapsulates these intricate dynamics into higher-level themes, e.g., benefits understanding, language, perception, and knowledge sharing. These themes, when analysed in the context of Fig. 3, emerge as pivotal components feeding into the broader aggregate dimensions, thereby establishing novel microfoundations for DT communication theory. Our research not only fills a critical depth gap in understanding communication challenges in DT projects but also establishes a unified grounded theory model, laying the groundwork for DT communication theory.

Traditional stakeholder communication theories do not fully account for the extended timelines and the evolving nature of collaborations in DT projects. Our findings suggest that these projects demand a more dynamic and adaptive communication approach which is more resilient to the changing landscapes of technology and stakeholder diversity. Our model also challenges the normative approaches to stakeholder communication by emphasising the need for a mindset shift towards embracing experimentation and learning from failures in contrast to the traditional strive for perfection. This insight is particularly relevant in the context of digital innovation in traditional manufacturing organisations, where communication and workflow patterns are often misaligned with the demands of DT development and utilisation. The absence of consensus in DT definition also offers an opportunity for theoretical advancements, as it prompts a reassessment of how definitions and conceptual clarity influence stakeholder communication dynamics. By integrating these specific challenges into our grounded theory model, this article not only fills a critical gap in understanding the unique dynamics of DT projects but also sets a new direction for future research in stakeholder communication theory (Parmar et al., 2010), especially in contexts marked by rapid technological advancements and multidisciplinary collaboration.

While this article identified communication challenges not only exclusive to DT projects, it underscored the unique effects of these challenges in influencing the success of DT adoption discussed in this section. Some challenges, like managing stakeholders' expectation levels or strategic guidance from top management, may also apply to regular projects unrelated to DTs, yet they were proven to be particularly influential within the context of DTs. DT projects are not totally dissimilar from other digitalisation projects and there are overlaps with findings for those in general, but they are distinguished in their need for the combination of modelling and data acquisition, requiring different stakeholders to interact. The following list highlights some of the facts that make DT stakeholder communication unique:

- In DT projects, multidisciplinary teams often collaborate in new ways, facing the challenge of extended project timelines and longer-lasting models. One of the key difficulties in these projects is tailoring the information to suit the diverse needs of various stakeholders, especially when these stakeholders with different backgrounds are collaborating for the first time and thus lack common ground which can lead to misunderstandings and inefficiencies in the project's execution.
- Moreover, industrial organisations struggle to foster a data-centric mindset that values quick, virtual experimentation and learning from failures, as opposed to the traditional approach of striving for perfection on the first try. Therefore, traditional communication and work flows are less suitable for digital innovation in manufacturing organisations.
- Since the benefits of DTs are rarely concrete, stakeholders often develop expectations based on unrealistic beliefs. This disparity in expectations can lead to significant barriers in effectively managing stakeholder perceptions and may result in underutilisation or misalignment of DT capabilities within the organisation.
- Furthermore, although DT is a compelling and seemingly straightforward concept, their oversimplified interpretation often results in unnoticed miscommunications. This hidden complexity can turn DT into a "nightmare in disguise", leading to significant hurdles in project implementation and collaboration, despite its approachable and engaging facade.
- Another critical hurdle in the field of DT is the lack of a universally accepted definition. Despite numerous efforts over recent years, there has been no success in establishing a widely accepted definition. This lack of consensus adds to the complexity of understanding DTs and prevents their effective implementation.

On a practical note, our research highlighted DT stakeholder communication as a pivotal issue with profound implications for DT development and utilisation. Neglecting these communication challenges can lead to DT initiatives remaining at low maturity levels, with limited benefits and the risk of abandonment due to dwindling confidence in their added-value. Among all mentioned practices, defining clear objectives for DT projects, starting small and building gradually, and effective communication by using precise terminology have been revealed as particularly effective to overcome human-centric DT stakeholder communication challenges. Furthermore, culturally empowering stakeholders for data-driven decision-making, aligning actions with organisational vision, and clear top management directions and support have been found to be crucial with regard to overcoming organisation-centric DT stakeholder communication challenges.

While some of the best practices identified might appear rudimentary, experienced DT experts still require several years of experience to reach these conclusions, increasing the relative value of these insights. This overview of challenges and best practices provides valuable decision support, assisting organisations in their DT endeavours and thereby increasing the chances of successful adoption.

Nonetheless, there are some limitations of this study. It is based on qualitative analysis with a limited number of participants, albeit achieving theoretical saturation and revealing a substantial overlap in responses among participants. However, this may constrain our findings' generalisability, primarily to organisations at similar DT maturity stages, particularly within the high-value manufacturing sector. Additionally, the investigated organisations only consist of MNEs, with most study participants having a central European background. However, the organisation's size and people's cultural backgrounds could be important factors influencing the communication and its challenges.

Thus, further research should investigate whether DT communication challenges differ in small and medium-sized enterprises and different cultural backgrounds. Moreover, researchers should explore the connections between DT characteristics and the identified communication challenges in more detail, e.g., by investigating direct links between the challenges and the characteristics that cause these challenges. Additionally, effective models and tools are needed to support the implementation of best practices for overcoming these challenges, particularly focusing on issues related to the benefits understanding, language, and perception. Notably, not all challenges appear to have equal relevance, calling for a quantitative follow-up study to determine which challenges have a higher influence on DT initiatives, providing essential guidance for organisations embarking on DT projects.

Overall, the study provides profound insights into the complex landscape of DT stakeholder communication challenges, offering substantial theoretical and practical implications. It provides crucial guidance for organisations striving to enhance the success of their DT projects and highlights the importance of addressing these challenges in the evolving area of DT adoption.

8. Conclusion

This article presents the unique characteristics distinguishing Digital Twin (DT) development and utilisation projects from common improvement projects in manufacturing organisations. It has been shown that DT projects are usually characterised by a high level of complexity caused by the involvement of many different stakeholders and technologies while simultaneously being limited by a low level of maturity. These characteristics underpin the relevance of human-centric and organisation-centric challenges, from which stakeholder communication has been identified as particularly critical. Thus, this article's main contribution is detailed insights about DT stakeholder communication challenges arising in these projects. The article presents findings from a novel study focusing on the human-related aspects of DT adoption in manufacturing organisations, recently gaining increasing attention in literature and practice. Knowing about these challenges is critical to the success or failure of DT initiatives. The results were obtained by conducting in-depth, semi-structured interviews and focus groups with DT experts enriched by archival data that were analysed using a grounded theory approach. 28 detailed challenges were identified and grouped into eight theoretical themes and two aggregate dimensions using Gioia's approach. Human-centric DT stakeholder communication challenges include benefits understanding, language, perception, and collaboration, while organisation-centric DT stakeholder communication challenges consist of vision and culture, conflicting interests, management involvement, and knowledge sharing.

The article elaborates on the DT stakeholder communication challenges and presents 15 practices to overcome them. These practices were extracted from the expert's experiences dealing with these challenges. Several best practices, e.g., defining clear objectives for DT projects, effective communication by using precise terminology, and aligning actions with organisational vision have been identified to effectively overcome human-centric and organisation-centric DT stakeholder communication challenges. By providing these insights, this article offers relevant practical and theoretical contributions and thus helps to prevent the risk of failure in DT projects. The article introduces a unique grounded theory model on DT stakeholder communication that fills a significant gap in existing literature by focusing on the nuances and complexities of human and organisational aspects in DT stakeholder communication dynamics. The findings also serve as foundational elements for a unified DT communication theory and thus contribute to the theoretical understanding of DT communication dynamics. Consequently, this article builds a key pillar of successful DT adoption in manufacturing organisations and supports increasing the chances of achieving benefits by applying DTs. It also helps managers to guide their efforts for DT implementation by considering a more dynamic and adaptive approach to communication in DT projects.

CRedit authorship contribution statement

Christian Kober: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francisco Gomez Medina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Martin Benfer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Jens Peter Wulfsberg:** Supervision, Resources, Funding acquisition. **Veronica Martinez:** Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition. **Gisela Lanza:** Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix

Interview Guide

1. What is your role regarding DT development and utilisation?
2. What do you understand by a DT project?
3. What DT projects exist within your organisation? What type of DT projects are you involved in?
4. What stakeholders are involved in DT projects in your organisation?
5. Who do you work with in the context of DT projects?
6. Who do you communicate with for DT related matters? What is the communication about?
7. What challenges do you experience when you communicate with these stakeholders?
 - (a) What have you done to resolve them?
 - (b) How much do these challenges hinder communication?
 - (c) Is there any critical type of communication?

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