DIGITAL TWIN TECHNOLOGY IN THE RAIL INDUSTRY: A DUTCH QUALITATIVE CASE STUDY ON SUCCESS FACTORS, CHALLENGES, AND FUTURE USE CASES

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Assets in the rail industry are progressively being equipped with Internet of Things (IoT) technology. Digital Twins (DT) are increasingly being applied to manage those (critical) assets and the data they generate. One main problem area to which DTs could contribute is that of station management. However, few implementations are studied in-depth and empirically reported upon. This study focuses on qualitative exploratory research to uncover success factors, challenges, and future use cases regarding a DT implementation of a large station operated by a rail operator in the Netherlands. Results show that, in this case, most success factors and challenges are considered non-technical, i.e., most focus on internal and external collaboration within the project. We also identified consensus about how a DT would elevate station management maturity in the future, featuring (critical) asset monitoring, maintenance, crowd control, and safety management.

Keywords:
digital twin, success factors, challenges. implementation, case study

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1 Introduction

The term Digital Twin (DT) emerged in the early 2010s, but its concepts have roots dating back to the 1960s at NASA (Rajamurugu & Karthik, 2022). A DT is a virtual representation of an object or system throughout its lifecycle (Singh et al., 2021), leveraging real-time data, simulation, machine learning, and reasoning to inform decision-making (Goodwin et al., 2024). It can also influence the physical world based on changes in the virtual model. While there is no consensus on a definition of a DT, most research views it as a cyber-physical system that shares the concepts of a physical entity, a virtual model, and connections between both (Liu et al., 2022). This study aligns with the definition of a DT as "*a set of linked operation data artifacts and (simulation) models, which are of suitable granularity for their intended purpose and stakeholders and evolve throughout the product life-cycle*" (Boschert & Rosen, 2016). Nevertheless, this definition falls short of a true DT's requirement for bi-directional communication. (Fuller et al., 2020; Liu et al., 2022).

Digital Twin Technology (DTT) has expanded into various industries, including manufacturing, aerospace, aviation, and healthcare, due to its value in lifecycle data management, control, and monitoring (Uhlenkamp et al., 2022). In the rail sector, DTs can potentially aid in planning, design and engineering, construction and commissioning, and operations and maintenance. In this sector, we can differentiate between DTT for rolling stock (vehicles), rail infrastructure, and train stations. DTT promises to leverage innovation to improve design, enhance collaboration by visualizing (conflicting) stakeholder interests, and increase both asset reliability and performance (Botín-Sanabria et al., 2022). As Internet of Things (IoT) is increasingly implemented in the rail industry, there is an emerging need for infrastructure data management combined with proper approaches for visualization (Ghaboura et al., 2023). Also, because of IoT implementations, organizations in the rail industry are challenged with the integration of data from various sources, and processing of large volumes of data (Kaewunruen et al., 2021).

One of the primary purposes for using DTs in the rail industry is asset management. While asset management can relate to either rolling stock, rail infrastructure, or train stations, this study focuses solely on train stations. A relevant case study based on Kings Cross station in London (UK) focused on sustainability evaluation (Kaewunruen & Xu, 2018), although it relies heavily on Building Information

Modelling (BIM) instead of a true DT of a railway station. Dirnfeld et al. (2024) conducted a structured literature review of DTs in the rail industry which uncovered technical challenges applicable to DTs in practice, thus having a scoped focus on the technical perspective. The Asset Information Requirements (AIRs) studied by (Johnson et al., 2021) provide an inclusive approach to requirements gathering for the design and application of DTs in the rail industry. Still, recent literature suggests there is a lack of studies that focus on DTT for station management in the rail industry, which is also substantiated in the work of (Doubell et al., 2022; Ghaboura et al., 2023), for example stating: "*Considering digital twin adoption for public infrastructure, the rail industry is still at an early stage with few recorded implementations.*" (Doubell et al., 2022). Adoption is a broad term here as it refers to technical and non-technical aspects (Leso et al., 2023).

As train stations are critical assets in the rail industry, we argue that railway organizations could benefit from DTT (and relevant studies) to assist in the lifecycle management of these assets, especially if such studies present applicable knowledge about success factors and challenges to consider. Therefore, this paper aims to answer the following research question: *Which success factors and challenges regarding Digital Twin Technology for rail station management are relevant in the context of the Dutch Rail Industry?* The Dutch rail industry was selected based on an existing DT implementation for a major train station in The Netherlands. The selection of this case is further defined in the research method.

This paper is structured as follows: In section two, we provide an overview of the body of knowledge on DT implementations in the rail industry, with a focus on asset management. Within this scope, we identify success factors and challenges from the literature. This is followed by the research method used for this study in section three. Sections four and five describe the data collection and analysis applied in this study. The results follow in section six. We conclude the paper with a discussion and future research directions in section seven and conclusions in section eight.

2 Background and Related Work

Asset Lifecycle Management (ALM) in the rail industry, particularly for train stations, involves a systematic approach to managing station assets from planning, design, and construction to operation, maintenance, and eventual decommissioning. It comprises all systems, methods, procedures, and tools to optimize costs, performance, and risks for the complete rail infrastructure lifecycle (Liljenström et al., 2022).

DTs are increasingly applied to aid Application Lifecycle Manamagement (ALM) (Wilke, 2022), as is the case in the rail industry (Ghaboura et al., 2023). The recent contribution of Ghaboura et al. (2023) focused on providing a state-of-the-art overview of how DTs contribute towards digital transformation in the rail industry. Use cases most often discussed in the previous years in the body of knowledge are that of 1) maintenance and condition monitoring, 2) asset management, 3) damage detection, 4) predictive maintenance, 5) simulation modeling, and 6) optimization. These are all related to different or overlapping goals such as sustainability and safety.

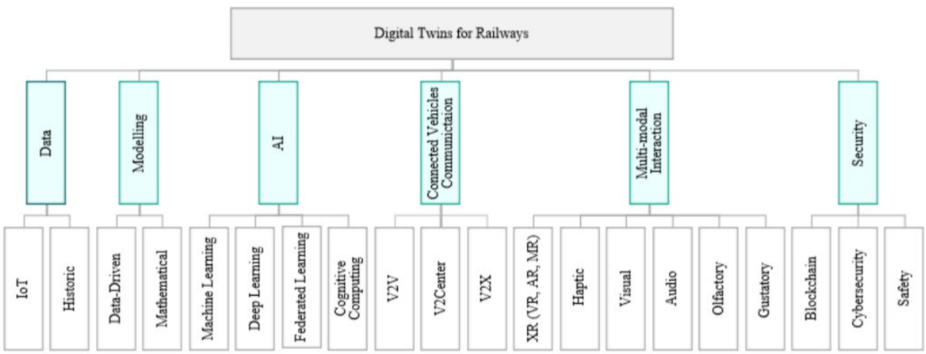

Figure 1: Digital Twins for Railways technology taxonomy
Source: (Ghaboura et al., 2023)

Furthermore, Ghaboura et al. (2023) identify key technologies regarding DTs in the rail industry from the extant body of knowledge, as summarized in Figure 1. These results encompass key technologies for all assets within the rail industry, of which train stations are a subset. We therefore include these key technologies in our gathering of empirical evidence for the case study.

Studies in the body of knowledge describe challenges regarding the design and implementation of DTs in the rail industry. For example, Dirnfeld et al. (2022) discuss the problem space of DTs and AI, concluding interoperability to be the most discussed challenge. Other papers (da Silva Mendonça et al., 2022; Dirnfeld et al., 2022; Zayed et al., 2023) with similar foci all mostly report on challenges from an IT perspective, and most do so from a meta-perspective without access to empirical data. Our study focuses on the identification of success factors and challenges in a more open setting similar to grounded theory (Packer-Muti, 2016), but more lenient in terms of mechanisms for protocol guidance. This case study attempts to identify success factors and challenges in a more holistic sense by not focusing solely on technical aspects or theoretical perspectives.

To provide a holistic overview of empirical evidence we zoom in on success factors that contribute to the adoption of technology at organizations, and the challenges that are faced. To ground the discussion about (critical) success factors, a definition of a success factor is provided, which is used in this paper and during the analysis: "*those few things that must go well to ensure success for a manager or an organization, and, therefore, they represent those managerial or enterprise areas that must be given special and continual attention to bring about high performance.*" (Boynton & Zmud, 1984). In the context of this definition, we explore organizational challenges and success factors in the rail industry. We emphasize the importance of examining both challenges and success factors, as solutions to challenges can reveal essential factors for success. This approach provides a more comprehensive understanding and aligns with in-depth case study methods.

3 Research Method

The goal of this study is to identify success factors and challenges regarding a DT initiative designed and implemented in the Dutch rail industry. As described earlier in this paper, the maturity of this research domain is limited; there is a lack of studies that address success factors and challenges derived from real DT cases in the rail industry.

In fields with limited maturity, an appropriate focus involves identifying new constructs and establishing relationships between identified constructs (Edmondson & Mcmanus, 2007). Examples are domain-specific concepts, processes, technologies, and cultural aspects, which are constructed, if defined, by Subject Matter Experts (SME's) but when they are not defined, they could be discovered as patterns in data and validated with SME's. Many researchers use explorative qualitative research methods to do so. We therefore conduct a qualitative study, using case study data collection and analysis to gather empirical evidence on success factors and challenges. A case study approach helps us develop context-based descriptions of the phenomenon studied (Myers, 1997).

4 Data Collection and Analysis

Data for this study was collected for two months; from January to February 2024. The case study features a dual-method approach, composed of 1) secondary data collection and analysis and 2) semi-structured interviews.

The selection of the participants in the case study should be based on the group of individuals, organizations, information technology, or communities that best represent the phenomenon studied (Packer-Muti, 2016). For this study, the phenomenon studied is represented by organizations and individuals who were involved with DT design and implementation for railway station management in the Dutch rail industry.

A large organization (hereafter referred to as Railorg) in the Dutch rail industry was selected for this research. Over the past three years, Railorg invested resources to design and prototype a DT for the largest train station in the Netherlands. These characteristics provided the best fit for selecting a DT project in the Dutch rail industry setting.

At Railorg, a case was defined as a single project that focused on the design and prototyping of a DT of a large railway station, with the goal of discovering whether DTT could help in providing comprehensive and complete 3D insights into the interior and exterior of the station in one integrated view. The interior and exterior were mapped using drone-mounted cameras and Lidar technology. Furthermore, the goal was to connect the 3D model of the station with real-time IoT data streams from elevators and escalators throughout the station. A screenshot of the DT is presented in Figure 2. Based on this project, a single-case design case study was adhered to (Yin, 2013).

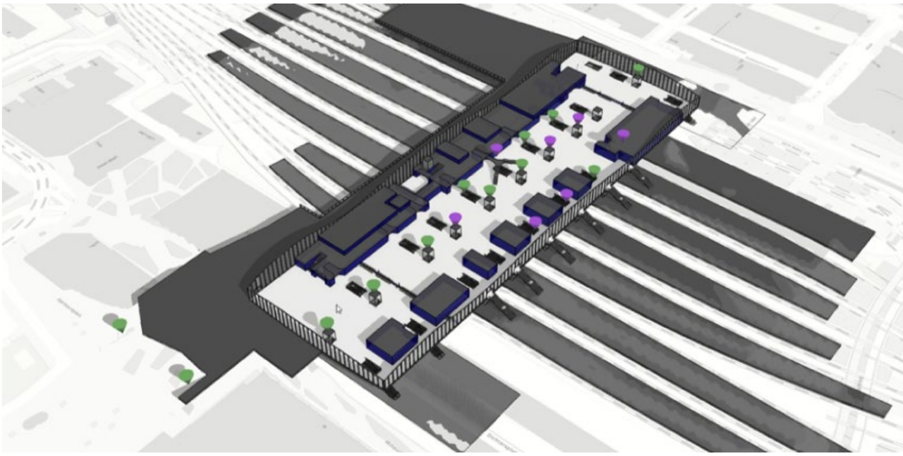

Figure 2: Railorg's largest train station in a DT
Source: Own

4.1 Secondary data collection

Secondary data collection was used as a supportive approach for the researchers to prepare the semi-structured interviews and provide the context of the selected case. Secondary data encompassed the documentation produced during the design and prototyping of the DT. The documents analyzed were mainly technical reports, advisory reports, and presentations that focused on the progression of the development during the project. The documents used in this study are produced by Railorg team members of the team responsible for the DT project, from different roles.

4.2 Semi-structured interviews

The main data collection consisted of semi-structured interviews. In total, seven interviews were conducted. Six interviewees represent distinct roles and departments within Railorg. One interviewee is an external DT consultant from an IT consultancy firm in the Netherlands that supported the Railorg team during the project. The following roles were interviewed: 1) IT Manager 2) Business Consultant 3) Data Management Product Owner 4) External DT Consultant 5) Station Manager 6) Real Estate Project Manager 7) Maintenance Manager. Each interview was conducted for one hour. Three researchers were present for each interview, with two researchers interviewing according to protocol and the third researcher taking notes. The interviews were conducted via MS Teams and recorded for reference purposes.

1. Role in the organization and relation to the DT project;
2. Examples of what did and did not work. What to repeat or avoid in the future;
3. Future of the project and how it should support Railorg;
4. Perspectives other than maintenance (e.g., sustainability, safety) the DT can support;
5. Which technologies could affect the future development of the DT in Railorg, and;
6. Other relevant sources to analyze or people to interview regarding this study.

4.3 Data analysis

The secondary data sources along with the transcriptions of the semi-structured interviews were coded using thematic coding. Thematic coding was done using the following coding categories: 1) success factors, 2) challenges, and 3) potential future applications of DTs and how technological advancements would impact these DTs at Railorg in the future. The first two categories refer to the empirical experiences of the interviewees. The third category refers to the perceived usefulness of DTs for other areas of application based on the empirical experience gained during the project. We applied the Toulminian's analysis approach of coding using claim-ground-warrant statements (Hitchcock, 2003). This allows us to deconstruct the practical reasoning in the context of the project to capture, analyze, and elicit patterns within the arguments the participants made about success factors and challenges.

In total, there were 57 claims-grounds combinations relating to success factors, 79 combinations relating to challenges, and 81 combinations relating to potential future applications and technological developments affecting the future of DTs at Railorg. The data was coded by four separate research team members of which one coded all interviews redundantly. Finally, an assessment of the intercoder agreement was made (average of 70,56% across all coders) and codes were merged. Two coders partook in a session where the codes were discussed, and consensus was reached where codes were different amongst the independent coders, also described by Campbell as a "negotiated agreement" (Campbell et al., 2013). Two researchers sorted the codes into three categories. An example of a claim-ground-warrant combination from our data is as follows: Category-*Challenge*, Claim- *Adding all information to our Digital Twin poses security challenges*, *Ground- Train stations have logistical hallways that should not be visible to all stakeholders because of security risks*, Warrant-*Expert source.*

The secondary data analysis was conducted on-site at Railorg due to security constraints. With open coding, one researcher coded secondary data related to the project, using the same approach as applied to the interview data.

5 Results

Data analysis was done according to the three categories: success factors, challenges, and potential future use cases. The success factors and challenges are clustered according to the topics they represent, starting with the topics that were most mentioned by the interviewees. This is followed by a description of potential future use cases as identified in the interviews.

5.1 Stakeholder collaboration

Stakeholder collaboration is complex in this case study because of the variety of roles and departments involved, as well as the necessary data, skills, and technologies required to realize a digital twin. On top of this, train stations are characterized by a fragmented ownership structure that includes the Railorg itself, municipalities, and local governments, as well as infrastructure owners. This resulted in the following success factors (SF) and challenges (C):

Success factors:

SF1. Involving only necessary stakeholders (in our case: IT and maintenance management) to reduce complexity and increase project velocity, while maintaining a balance with the necessary knowledge and skills to complete the project.
SF2. When including external partners, ensure that they have ample experience with DT technology from earlier projects.
SF3. A combination of agile and waterfall project management methodologies to suit the different phases of the project. For example, data collection using drones and point cloud processing was more suitable to a waterfall approach due to longer lead times.
SF4. In phases where agile project management is most suitable, deliver tangible results in clearly defined sprints to keep project sponsorship healthy.

Challenges:

C1. Stakeholders who were not initially involved in the project felt overlooked when they found out about the project at a later stage and were less willing to collaborate as a result.
C2. The fragmented ownership structure of train stations made it difficult to identify parties (fiscally) responsible for specific parts of the train station.
C3. Organizations involved in station ownership have differing organizational structures and siloed IT systems without a single point of truth for all assets. Inter-organizational collaboration was further hampered because organizations were reluctant to share data that would result in exposing these issues.

5.2 Business Involvement

The project was initiated by Railorg's IT department as a technical proof of concept, with limited involvement from business stakeholders or a clearly defined business case. It was performed mostly to gain experience in the technical aspects of developing a DT. This resulted in the following success factors and challenges.

Success factors:

SF5. The limited scope and number of stakeholders involved in the project allowed for a quick exploration of DTT and its application in a practical domain. This resulted in a short design phase.

Challenges:

C4. By not having all business stakeholders on board before initiating the project, alignment with their business goals was lacking and this obstructed the implementation and adoption of the DT by the business departments.
C5. Because of its technological approach, some stakeholders deemed the DT 'a solution seeking a problem' which reduced their support of the project.
C6. The project did not have a clear business case, making it more difficult to clearly measure its success and value.
C7. The full capabilities of DTT could not be explored because certain business stakeholders who owned data necessary to enrich the DT were not involved. While there was a complete 3D model of the station, it was only enriched with a limited set of sensor data.
C8. The innovative nature of the project was seen as misaligned with the current organizational strategy to prioritize its critical business systems, resulting in reduced management support and negative sentiment towards investing resources into DTT.

5.3 3D visualization

The DT was delivered as a 3D model of the interior and exterior of the train station. The interviews in this case study resulted in discussions on the effectiveness and usefulness of a 3D model vs. a 2D model or other types of visual representation. The following success factors and challenges regarding this topic were identified:

Success factors:

SF6. A 3D model can more easily convey information regarding dimensions and proportionality compared to other visualization methods. It also makes it easier to gain insight into multi-floored stations.

SF7. A 3D model is innovative and visually impressive and aids in marketing the project to stakeholders and project sponsors.

Challenges:

C9. A 3D model is sometimes considered superfluous when the information presented to the end user is just as easily conveyed through a 2D map or other dashboard, for example, binary status information of an object (in operation / out of order).
C10. The differing information requirements of departments within Railorg make it difficult to reach a consensus on the type of visualization, thereby obstructing collaboration between departments and the adoption of the DT.
C11. The design, maintenance, and usage of a 3D model may necessitate the use of more powerful and costly hardware when compared to other visualization methods.
C12. Current business processes rely heavily on on-site inspections and do not yet integrate dashboards or 3D models, which may challenge the adoption of DTT.
C13. Using LIDAR and drone technology to create a 3D model of the train station does not identify areas or installations that are obscured from view (hidden being ceilings or walls). The 3D model therefore does not satisfy the information needs of some stakeholders.

5.4 IT and data maturity

Interviewees mentioned that IT and data maturity (or lack thereof) influences the successful implementation of DT. We identify the following success factors and challenges for this topic.

Success factors:

SF8. The presence of sensors in the physical train station that can provide data to the DT model.
SF9. Real-time and continuous availability of such data via an IoT platform to enrich the DT with information, enabling it to be used in an operational environment.

Challenges:

C14. IoT data is currently not centralized and sometimes managed by external vendors, making it difficult to gather and present all such data in the DT.

C15. Experience with and maturity of IoT is limited, meaning that more IoT systems and data streams should be implemented before the insights provided by such systems can be leveraged in the DT.

C16. Building information management is implemented only to a limited extent within Railorg. Because BIM can function as an important data source for a DT, the lack of BIM makes it more difficult to achieve an accurate and up-to-date Digital Twin. Departments within Railorg are not yet familiar with using BIM in their processes and suppliers/contractors are unable to sufficiently supply such information, except for a few technical installations.

C17. Railorg is dealing with an aging workforce, negatively affecting the adoption of new technologies. IT-savviness of personnel is deemed insufficient by the interviewees. Processes that could be (partly) performed remotely through a DT instead rely on physical, on-site inspection. Automation sometimes does not extend beyond the use of basic office applications. The conservative way of working makes it difficult for the organization to get up to speed with new and advanced technologies such as DT.

C18. The lack of a 'Single Point of Truth' in regard to assets within the train station that are managed by different organizations makes it difficult to pinpoint a leading data source as input for the DT, while also complicating the inter-organizational exchange of data and keeping the data systems consistently up-to-date with changes in the physical environment.

5.5 Potential use cases (and technologies leveraging the implementation and use) of DTs at Railorg

Besides success factors and challenges, the interviews explored other potential use cases for DTT in the organization. The following were mentioned consistently among the interviewees:

DTs for (remote) monitoring: Unlike station managers responsible for large train stations who mostly work onsite, station managers in rural areas often manage several train stations that are geographically spread apart. Using DTT a station manager could get remote information based on sensor data at those stations. This information should be translated into actionable messages about what is happening and show predictions for the next best actions.

DTs for maintenance & asset management: Sensor data from (critical) assets within train stations could be used to further improve the maintenance process. Such assets include elevators, escalators, HVAC installations, and energy meters. Enabling predictive maintenance of these assets is desired by Railorg. Also, monitoring their performance helps to underpin contractual obligations between Railorg and external suppliers. Additionally, a DT could help direct external contractors to the relevant assets for repairs, cleaning, or resupplying activities. Calculations for the work to be carried out can be made beforehand, for example by measuring the total surface area of windows to be cleaned within the DT. This will speed up the process of directing external contractors. To properly execute maintenance and asset management within the DT, Railorg as well as external organizations responsible for (architectural) changes within the changes should commit these changes to the DT, possibly via BIM. Finally, a DT may help Railorg keep track of sustainability goals by measuring real-time energy consumption.

DTs for crowd control & safety management. Major train stations deal with large crowds, especially during peak hours or events. a DT could be used to monitor passenger flows in real time or allow station managers to simulate passenger flows during maintenance or disruptions. The impact of changes within the train station can then be tested before the work is carried out, or different configurations of assets can be compared before rollout. Another possible use case mentioned is social safety, where sensors could identify brewing trouble based on images and sounds and convey this to the DT so that action can be taken to mitigate potential security risks.

6 Discussion

Our study has limitations that should be noted. Firstly, the small size of the team constructing the Digital Twin (DT) at Railorg may affect the generalizability of the results to larger teams with different compositions. Collaboration is important as it was identified as both the most influential success factor and the biggest challenge. However, the small sample size makes the study more susceptible to cognitive biases such as social desirability, false consensus, and response bias. Additionally, confidentiality restrictions limited one researcher to review relevant documents on-site only, meaning that these documents cannot be reproduced for validation purposes.

The project's focus on collaboration suggests that the cultural characteristics of the project team, such as its autonomy, and its task-oriented and individualistic approach, may affect its generalizability to other teams in different cultural settings. While our case description supports the generalizability to similar settings, it's important to note that train stations (and the organizations managing them) vary greatly in scope and complexity, both within the Netherlands and globally.

This project's limited scope suggests that future research should explore relating success factors and challenges of DT design and implementation in the rail industry to IS/IT frameworks. Using ontological foundations such as the extended information systems framework (Strong and Volkoff, 2010) could help identify hot spots and best practices, as our study identified success factors and challenges using a more explorative approach. It is also important to gather more evidence from other cases and use quantitative data collection to improve generalizability and effective analysis of success factors and challenges. Furthermore, we identified the most significant success factors and challenges in this study, however, an important direction for future research would be to establish how these factors and challenges relate to each other.

Our study involved interviews with stakeholders from various domains including IT, maintenance, asset management, and innovation. Despite the varying terminologies used by the respondents, there is a significant degree of consensus within the organization regarding the desired attributes of digital twin technology. This suggests that future research should include these different viewpoints and preserve the varying terminologies where possible, to gain a broad and diverse understanding of the topic.

7 Conclusion

To conclude this paper, we revisit our main research question: Which success factors and challenges regarding Digital Twin Technology for rail station management are relevant in the context of the Dutch Rail Industry? Based on an in-depth case study featuring the design and implementation of a DT at Railorg, we identified (contextual) success factors, challenges, and future use cases of DTs relevant to the rail industry. While we identified several DT and general IS/IT-related success factors and challenges, most are related to the organizational culture, organizational structure, responsibility management, and how different stakeholders collaborate and inform each other, which is in line with other studies in the IS/IT research field (Leso et al., 2023).

This paper provides valuable empirical insights into a real Digital Twin (DT) case, adding to the body of knowledge especially in the context of the rail industry. While the findings may have limited generalizability, they contribute to understanding the importance of human factors in DT projects, opening avenues for further research. From a practical standpoint, the paper helps organizations, such as Railorg, in avoiding common pitfalls in DT projects and raising awareness of organizational culture and collaboration. The results are readily applicable in practice and can improve the efficiency and effectiveness of future DT projects.

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