

Article

Navigating Digital Transformation in Asset-Intensive Companies: A Process Model Informed by Design Science

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Abstract

Companies in asset-intensive industries, such as aviation and railways, face unique digital transformation challenges due to the misalignment between the rapid evolution of digital technologies and decades-long asset lifecycles. Existing innovation frameworks are inadequate for managing this complexity, which in turn creates tensions between innovation requirements and operational reliability demands. This paper therefore investigates how asset-intensive companies can systematically integrate digital technologies, while fully complying with regulatory constraints and safety requirements. We employ a design science approach in a study of Nederlandse Spoorwegen (NS), the Dutch national railway operator, focusing specifically on the implementation of AI-driven CCTV systems within the operations of NS. Drawing on a literature review and participant-observer as well as interview data, we develop six design propositions that address the key digital transformation challenges of asset-intensive companies in the area of market readiness assessment, modular architecture, regulatory compliance, temporal coordination, ecosystem governance, and organizational capability development. Using these design propositions, we develop the Iterative Development & Adoption Model (IDAM) that operationalizes market maturity assessment through market readiness levels to guide make-or-buy transitions across four iterative phases: ideate, assess, realise, and review. This model includes a Development Reference Architecture for emerging technologies and an Integration Reference Architecture for more mature technologies, enabling concurrent sourcing strategies based on technological maturity. IDAM provides actionable guidance for decisions about technology adoption in asset-intensive contexts, thereby offering a systematic approach to innovation management in industries with very long asset lifecycles and huge regulatory constraints.

Keywords: design science; engineering design; technology adoption; digital transformation; product development; asset lifecycle; modular architecture; market readiness; operational reliability



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1. Introduction

Asset-intensive companies, such as those in the aviation and railway industry, face the fundamental challenge of temporally aligning the rapid development of digital innovations with decades-long physical asset lifecycles. *Digital transformation*, defined as the adoption and implementation of digital technology by a company to create new services (or products) or modify existing ones [1,2], is especially problematic for asset-intensive companies because they draw on expensive equipment (e.g., airplanes, trains) with an extended lifespan

and therefore traditionally rely on internal development strategies to fulfill very specific technological requirements [3,4]. Consequently, digital transformation creates a coordination challenge for asset-intensive companies which cannot be addressed by existing theories and tools (e.g., for technology sourcing) [5,6]; these theories and tools assume a substantial level of organizational flexibility that does not exist for capital-intensive physical assets that must also comply with strict regulatory requirements [7–9].

In other words, asset-intensive companies face *temporal alignment* tensions in their digital transformation efforts. But despite such tensions, these companies have to modernize their technological capabilities to remain competitive and meet evolving customer expectations [2], while operating under significant constraints arising from massive (past) capital investments, stringent regulatory requirements, and safety-critical operations. These constraints significantly limit their ability to adopt experimental approaches typically associated with digital innovation [10]. Moreover, asset-intensive companies have unique architectures [11] involving complex supply chains, long-term contracts, and specialized knowledge [3,12].

Railway operators exemplify these challenges in temporal alignment. That is, railway operators seek to integrate advanced technologies such as artificial intelligence (AI) and Internet of Things (IoT) in their operations, to meet the growing needs and expectations of their customers. But this must be done within the decades-long operational life of trains as well as strict safety standards [13,14]. Accordingly, the integration of digital technology by railway operators requires a careful temporal coordination effort across multiple factors, including legacy system compatibility, interoperability requirements, and continuous service delivery throughout the digital transformation process [15]. This paper therefore addresses the following research question: *can a market-driven technology sourcing process for asset-intensive companies be designed to effectively reduce the temporal misalignment between the rapid development of new digital technology and extended asset lifecycles?*

To address this question, we draw on a design science approach [16] that serves to bridge the gap between theoretical concepts and practical applications by developing solutions informed by design propositions. This approach covers four distinct phases: exploration, synthesis, creation, and evaluation [17,18]. The design propositions are defined in terms of context, agency, mechanism, and outcome dimensions [16,19]. The main result of this study is the Iterative Development & Adoption Model (IDAM), a process model for asset-intensive companies that need to temporally align their market-driven sourcing for digital technologies with very long asset life cycles. This model is grounded in a set of design propositions and offers a structured approach to sourcing digital technologies by asset-intensive companies.

Our main theoretical contribution involves the IDAM model for digital transformation by asset-intensive companies, grounded in a set of design propositions that are synthesized from various dispersed literatures [9,11,20–22]. IDAM also constitutes a practical contribution to the literature by providing guidelines to asset-intensive companies for navigating complex decisions about digital technology adoption. IDAM's emphasis on market readiness assessment and concurrent sourcing strategies enables these companies to balance innovation requirements with operational reliability demands [23,24].

The remainder of this paper is organized as follows. The next section reviews relevant theoretical perspectives from the literature on dynamic capabilities, digital innovation and transformation, institutional theory, industry architecture, and ambidexterity to identify the theoretical gap that motivates our research. The Methodology Section then details the design science approach, by describing the four-phase research cycle and the research setting of the Train Digitalization department of the Nederlandse Spoorwegen (NS). The Findings Section subsequently presents the results of each phase in the design science

process: the exploration of NS as an asset-intensive company, the synthesis of six design propositions from the literature, the creation of the IDAM model, and its subsequent evaluation. Finally, the concluding section serves to discuss the main contributions of our study, outline various limitations, and explore directions for future research on digital transformation in asset-intensive companies.

2. Background

In this section, we explore various theoretical perspectives that are relevant to digital transformation efforts in asset-intensive industries. First, the *dynamic capabilities* (DCs) theory [25,26] provides a generic framework for understanding how organizations adapt to technological discontinuities: DCs theory distinguishes between sensing, seizing, and reconfiguring capabilities [20]. Warner and Waeger [9] extend this framework specifically to digital transformation contexts, to demonstrate how firms must develop new capabilities for opportunity recognition, resource allocation, and organizational adaptation. However, asset-intensive industries face unique DC challenges, due to the temporal misalignment between asset development cycles and digital innovation cycles. While software-driven companies can rapidly develop new capabilities, asset-intensive sectors must build capabilities that align with decades-long asset lifecycles. This creates an inherent conflict between the rapid rise of new digital technology and the stability of operations in these industries [27].

Second, *digital innovation* theory [2,21] explains how the convergence of physical products with digital capabilities creates new innovation opportunities. More specifically, studies of layered modular architectures suggest that digital innovations are characterized by device, network, service, and content layers; these layers evolve independently while maintaining systemic coherence [28]. Nambisan et al. [22] therefore argue that digital innovation management requires new approaches, because traditional innovation frameworks assume stable product boundaries and clear innovation processes. Industry 4.0 frameworks [29,30] extend this convergence concept by emphasizing cyber-physical systems integration; physical and digital components interact in these systems through real-time data exchange and autonomous decision-making. In this respect, studies of cyber-physical systems explain how embedded computing and networking technologies transform physical systems into intelligent, adaptive entities [31]. Demeter et al. [32] illustrate how the digitalization of physical assets enables new forms of monitoring, optimization, and predictive maintenance. In asset-intensive industries, the (envisioned) convergence between physical and digital components creates major tensions in the area of product architecture and innovation timing when rapidly evolving digital layers have to be integrated in a slowly changing physical infrastructure.

Third, *institutional* theory [33,34] explains how regulatory and other institutions shape organizational behavior and innovation patterns. In asset-intensive industries, regulatory institutions create strong constraints on innovation by means of safety and reliability requirements that prioritize proven technologies over experimental approaches. The rise of Industry 4.0 technologies adds a layer of institutional complexity because existing regulatory frameworks are not (easily) applicable to cyber-physical systems that merge the conventional distinctions between the physical and digital realm [29]. The concept of institutional entrepreneurship [35] thus becomes relevant for understanding how firms can navigate and potentially reshape institutional constraints when engaging in digital transformation. For asset-intensive companies, however, the path-dependent nature of institutional development [36] creates inertial forces that resist rapid technological change, because regulatory frameworks largely focus on established technologies and therefore do not effectively accommodate digital transformation.

The fourth perspective outlined here is *industry architecture* theory [11] that provides insights into the complex value creation processes in an entire industry and how firms make decisions about new technologies in this broader setting. Especially the evolution from integrated to modular architectures [37] enables new forms of collaborative innovation, but also creates coordination challenges in managing a complex ecosystem with many suppliers. In asset-intensive industries, architectural choices are particularly critical because investments in physical assets constrain future technological options, implying that make-or-buy decisions become more consequential than in industries with shorter asset lifecycles. Here, Parmigiani's [23] concept of concurrent sourcing—simultaneously making and buying similar components—is especially relevant when firms must balance internal capabilities with external digital expertise, while maintaining operational control over their critical infrastructure.

Finally, *ambidexterity* theory [38,39] examines how a company balances two competing demands, that is, exploiting its existing capabilities while simultaneously exploring new opportunities. Asset-intensive industries face unique ambidexterity challenges in this regard. Exploitation in these industries involves decades-long commitments to physical assets. By contrast, exploration requires the flexibility to adapt to rapidly changing digital technologies [1,2]. This creates an inherent tension between long-term asset investments and short-term technological adaptability.

We can now define a clear theoretical gap at the intersection of these theoretical perspectives. For instance, DCs theory [9,20] emphasizes organizational agility and sensing mechanisms: it assumes a high level of organizational flexibility that asset-intensive companies do not have due to the temporal rigidity of decades-long asset lifecycles and regulatory compliance requirements. This rigidity creates a paradox in which the very capabilities needed for digital innovation [21,22] conflict with institutional demands for operational stability and regulatory compliance [33,34]. Another example is industry architecture theory [11] that was developed primarily for manufacturing settings in which architectural flexibility and shorter product cycles allow a rapid reconfiguration of the company's operations. In asset-intensive companies, architectural choices (made in the past) constrain future technological options, creating an inherent tension between the modular flexibility required for digital transformation and the strict reliability demands arising from safety-critical operations.

Table 1 outlines the five theoretical perspectives, explored in this section, to identify a fundamental *temporal alignment* problem that these perspectives have thus far failed to address: how can asset-intensive companies systematically navigate the intersection of rapid digital innovation cycles, extended asset lifecycles, regulatory constraints, and operational reliability requirements? This problem requires a novel approach that integrates and adapts temporal coordination mechanisms, institutional compliance strategies, (constrained) DC development, and modular architecture principles to the specific case of an asset-intensive company.

We already defined *digital transformation* in the previous section. In the remainder of this paper, we also frequently refer to *digital innovations*, the new digital (e.g., IoT or AI) technologies that an asset-intensive company can adopt and implement in its products and services. In other words, train operators and other asset-intensive companies draw on specific digital innovations, mostly developed elsewhere, to accomplish their digital transformation.

Table 1. Theoretical Gaps in Digital Transformation for Asset-Intensive Industries.

Theory	Description	Gap in Asset-Intensive Context	References
Dynamic Capabilities	Framework for organizational adaptation through sensing, seizing, and re-configuring capabilities	Assumes a level of organizational flexibility that does not apply to by decades-long asset lifecycles and regulatory requirements	[9,20,27]
Digital Innovation	Explains convergence of physical and digital capabilities through layered modular architectures	Focuses on software-driven contexts, and thus, inadequately addresses tensions between digital layers and a slowly changing physical infrastructure	[21,22,28]
Institutional Theory	Examines how regulatory institutions shape organizational behavior and innovation processes and their outcomes	Path-dependent regulatory frameworks resist rapid technological change and do not (effectively) accommodate the development of novel cyber-physical systems	[33–35]
Industry Architecture	Provides insights into make-or-buy decisions and modular sourcing strategies	Developed for manufacturing contexts with relatively short asset cycles; inadequate for path-dependent investments in physical assets with very long lifecycles, which constrain future options	[11,23,37]
Ambidexterity Theory	Examines balance between exploiting existing capabilities and exploring new opportunities	Assumes a substantial level of flexibility to adjust the exploration-exploitation balance; this assumption is inadequate when exploitation involves decades-long asset commitments	[1,38,39]

3. Methodology: Design Science

This research applies a Design Science (DS) approach to connect theory to practical solutions in the railway sector [17]. DS combines problem-solving with explanatory science to create and test artifacts [19]; it bridges theory and practice by generating design knowledge and principles to solve complex real-world issues [40]. In this DS study, we tackle the temporal alignment problem of railway operators and other asset-intensive companies, outlined earlier.

3.1. Design Science Approach: Four Phases

We adopted a DS approach consisting of four consecutive phases [18]: exploration, synthesis, creation, and evaluation, as shown in Figure 1. The DS cycle in this figure was combined with a process thinking perspective, to emphasize the temporal dimension of the problem and its potential solutions [41]. Each phase of the DS cycle in Figure 1 is explained below.

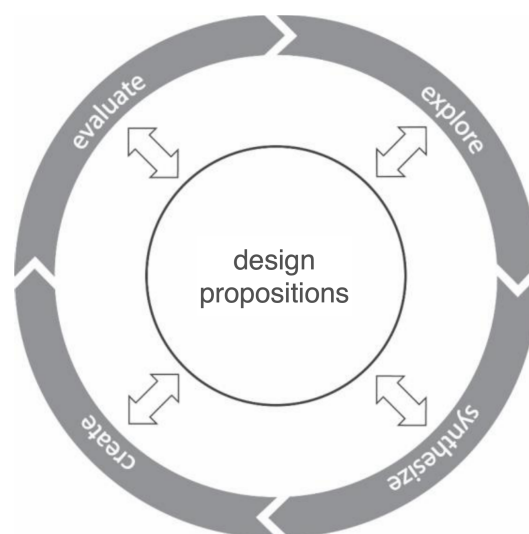


Figure 1. Design Science Cycle (source: Keskin and Romme [18]).

Exploration phase: In the exploration phase, we conducted a literature review, collected data as participant-observers in the NS, and conducted semi-structured interviews

with key stakeholders in the NS. This phase reflects Langley's [41] "tracing back" approach by examining how the NS as a railway operator currently deals with product and service innovations. In this phase, we thus assess the practical significance of the temporal alignment problem, as a foundation for subsequent phases of the design cycle [42].

Synthesis phase: In this phase, we applied Context–Agency–Mechanism–Outcome (CAMO) logic to define various design propositions that synthesize the existing body of knowledge in actionable design guidelines [16,19]. These design propositions are synthesized from both the literature reviewed and the practitioners interviewed in the previous phase. The synthesis phase thus transforms "nouns to verbs" [41] by focusing on the mechanisms of "innovating" and "strategizing" rather than innovation and strategy.

Creation phase: In the subsequent phase, we created a process model to guide railway operators through digital innovation processes. The design propositions developed in the preceding phase informed the creation of this model and, as such, provide prescriptive knowledge applicable to digital innovation in asset-intensive industries.

Evaluation phase: In this phase, we validated the model (created in previous phase) by examining its functionality, completeness, consistency, performance, usability, and organizational alignment. The external validity of the model was checked by means of additional discussions with the main stakeholders (also interviewed in the exploration phase). The model's internal validity was examined by assessing its consistency with the design propositions. In line with the standards for DS research formulated by Peffers et al. [40], this assessment ensures that the resulting model (as the main artifact arising from our study) not only has practical utility and impact but also has a strong theoretical foundation.

3.2. Research Setting

The research was conducted within Nederlandse Spoorwegen (NS), the principal railway operator in the Netherlands. The NS operates about 800 trains distributed across 8 different categories (called "series"), with a new Double Deck New Generation (DDNG) series being underway (<https://www.ns.nl/en/about-ns/trains-of-ns> (accessed on 29 September 2025)). For this study, we collaborated with the department of Train Digitalization of the NS. This department is structured into four distinct clusters: Software Development & Platforms, Safety & Security, Maintenance, and Transportation, with a strategic focus on developing digital technologies for the train fleet. More specifically, we focused on the Team Optic team that is responsible for the evaluation of AI-integrated CCTV systems on trains. AI-integrated CCTV systems provide a representative case of the digital transformation challenges faced by railway operators. As such, it was an ideal case for examining the complexities of integrating advanced digital technologies into safety-critical railway operations.

3.3. Data Collection and Analysis

The literature review conducted in the exploration phase started with searching the Scopus database, via "digital transformation" or "digital innovation" as key queries and filtering the resulting articles on the basis of title and abstract regarding their relevance for asset-intensive companies. We continued to add new sources to our literature base until reaching a saturation point, that is, when a set of theoretical perspectives was identified that apparently covers the entire literature on digital transformation. This resulted in the five theoretical perspectives outlined earlier in Section 2. The literature on these theoretical perspectives was also used in the exploration and synthesis phases, previously described.

This study draws on qualitative data collection via participant-observations, as well as interviews with key stakeholders [43] in the railway industry. This combined approach

enables the development of rich contextual insights into professional experiences and practices in digital transformation in railway operations.

The collection of participant-observer data [43,44] serves to overcome the limitations of desk research by directly observing operational environments and the practical use of technologies. The participant-observer data were collected during site visits, participatory sessions, and informal conversations, all documented in field notes. Table 2 summarizes the participant-observer data in terms of dates, observation types, context, and key insights. An example of the latter is the key insight arising from the visit to the Central Surveillance Center, exposing the researchers to the complexity of managing around 800 trains of ten highly different types (with the oldest trains dating back to 1980, and the most recent ones produced in 2023). Each train type needs specific software for footage retrieval, which, in turn, leads to major inefficiencies during incidents. Security officers in the Central Surveillance Center therefore have to use a distinct program for each train type, and if remote access fails, they have to collect the data by going to the train themselves.

Table 2. Participant Observations and Field Research Activities.

Date	Type of Observation	Participants/Context	Key Insights Documented
1 November 2023	Technical System Evaluation	Test engineer	CCTV system integration across train types, vendor collaboration challenges, data management via Network Video Recorder and operational design constraints
9 November 2023	Innovation Team Demonstration	Team Optic (CCTV Innovation Team)	AI-driven CCTV development process, risk assessment procedures, proof-of-concept limitations, and stakeholder requirement cycles
19 December 2023	Operational Site Visit	NS Central Surveillance Center (20 security officers, 1 manager)	Real-time monitoring of 8000+ cameras, emergency response procedures, technology heterogeneity challenges, and Genetec system integration
31 October 2023–15 February 2024	Informal Engineering Conversations	Various technical staff and engineers	Strategic technology adoption decisions, architectural documentation needs, supplier relationship dynamics, and certification challenges
Multiple sessions	Participatory Technology Assessments	Cross-functional development teams	System architecture evaluations, hardware-software integration testing, stakeholder alignment processes, and implementation barriers

We also conducted ten semi-structured interviews with key stakeholders from the NS and external consultancy firms. The interview participants, detailed in Table 3, represented diverse roles and forms of expertise to ensure a comprehensive coverage of perspectives on the digital transformation of railway operations. The interview protocol included open-ended questions about the interviewee’s perspective on digital transformation, railway innovation processes, and technology integration strategies. These questions addressed six primary themes:

- Current digital transformation initiatives and challenges;
- Stakeholder roles and relationships in innovation processes;
- Technology adoption decision-making processes;
- Safety and regulatory considerations;
- Supplier relationship management;
- Organizational change implications.

Each interview lasted between 60 and 90 min and was conducted between October 2023 and February 2024.

The qualitative data in the field notes (as participant-observers) and the interview transcripts were analyzed by means of a coding scheme. This coding scheme was inferred from the literature and contained key constructs such as temporal alignment, cyber-physical system, physical assets, reconfiguration, compliance, operational reliability, modular archi-

ture, and industry architecture. Sections 4.1 and 4.2 report the results of the analysis of the participant-observer and interview data.

Table 3. Interview Participants and Roles.

Role	Count
Business Consultants	2
Enterprise Architects	2
Project Leader	1
IT Consultant	1
Cluster Leaders	2
Technical Specialists	2
Total	10

In the evaluation phase, we presented a first version of IDAM to the same ten experts interviewed earlier, inviting them to assess its practical applicability. These sessions focused on completeness, logical consistency, and alignment with established processes within the NS. These sessions were more informal in nature, compared to the interviews conducted earlier. The conclusions of these sessions were thus only written down in short notes by the second author. We also discussed the IDAM model with senior management representatives and members of the CCTV project team. Section 4.4 describes the results of the evaluation phase.

4. Findings

Following the DS approach outlined in the previous section, this section reports the main results from the exploration, synthesis, creation, and evaluation phase. Notably, while the exploration phase (in Section 4.1) also draws on interview data, we only quote from these data in Section 4.2 about the synthesis phase because the latter provides a more deliberate structure (of design propositions) for doing so.

4.1. Exploration Phase: Train Operator as an Asset-Intensive Company

In this first phase, we explored the major constraints that arise from conventional requirements-driven procurement methods in companies with physical assets that have very long lifecycles [45].

These constraints are evident in the CCTV case of NS trains. Figure 2 provides an abstract representation of a typical onboard CCTV. There are two separate networks on any train. First, the safety and security network, in which the Train Management Control System (TCMS) for the driver is located; this safety domain also includes a separate Human–Computer Interface (HCI) for the driver to access extra info, like camera images (see the left side of Figure 2). The second network is for comfort and utility purposes, that is, managing front cameras, door cameras (to watch the safe entry of passengers), and cabin cameras. This network also contains the Onboard Information System (OBIS), Network Video Recorder (NVR) and modem connections to the shoreside CCTV management system.

The AI module is positioned next to OBIS and NVR in Figure 2. In this respect, cabin cameras are used for various purposes like passenger counting and empty train detecting, which are part of regular train operations; but these cameras can also be used for advanced AI-driven applications regarding social safety (e.g., aggression detection), lost luggage, or even weapon detection. By default, all indications generated from these applications need to be shared directly with the driver, who has the primary responsibility for safety on the train; on a secondary basis, all indications are also shared with shore-side systems. The

Train Digitalization department of NS is responsible for all systems on the train, including operations, partner management, interfaces, and standardization across all train series.

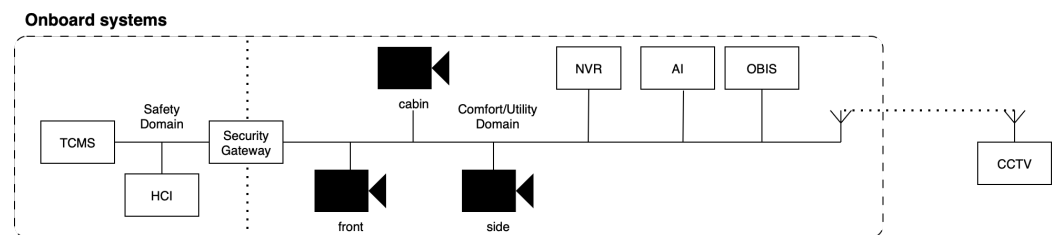


Figure 2. Abstract schematic of onboard cameras.

Our field notes as participant-observers also suggest that conventional tender processes, designed for mature technologies with established specifications, are inadequate for emerging digital technologies (e.g., applicable to the CCTV system in NS trains), characterized by rapid evolution and uncertain market readiness. That is, these digital technologies are temporally misaligned with train procurement cycles that take up to 10 years from the train’s initial conception to operational deployment. The case of the new DDNG train illustrates this timeline, as shown in Figure 3. This process began with its initial design in 2018 and then involved the development of a Reference Architecture (RA) until 2023. A critical design freeze then locks the train’s specifications, when these are handed over to the train builder. Operational deployment of the DDNG train is planned as of 2028.

This extended timeline creates two significant challenges. First, technologies specified during the early design phases may become obsolete by the time they are actually implemented. Digital innovations typically evolve in much shorter cycles, creating a mismatch between the procurement timeline and the speed of digital technology development. Second, another consequence of the extended procurement timeline is that any new digital technologies (becoming available after the design freeze) cannot be integrated in the new train, once the final RA specifications are sent to the train builder.

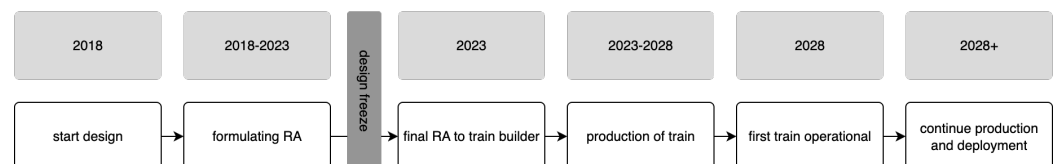


Figure 3. Design timeline of DDNG, the new NS train series.

This mismatch between procurement timelines and digital transformation cycles requires a novel process model that accommodates both traditional procurement requirements and dynamic innovation needs. Our data analysis in the first phase suggests that such a process model should integrate two pathways for technology development: in-house R&D capabilities for early-stage technologies and collaborative supplier development for market-ready solutions. This dual approach acknowledges that digital transformation requires flexible and iterative (in-house) processes that can adapt to technological uncertainty, while maintaining operational safety and regulatory compliance. It would also have to align the 10-year asset development cycle with rapid digital advancements. The design freeze phenomenon observed in the DDNG case, where specifications become immutable after five years, demonstrates the critical need for such a careful alignment.

4.2. Synthesis Phase: Design Propositions for Digital Transformation in Asset-Intensive Companies

The interview data and insights available in the literature were synthesized in six design propositions (DPs) that address the primary challenges of digital transformation in asset-intensive companies. These propositions arise from a systematic analysis of stakeholder

perspectives but also reflect theoretically grounded mechanisms for managing the complex interplay between technological dynamics and operational stability. Each DP addresses specific aspects of the innovation process, while contributing to an integrated approach that enables sustainable digital transformation within the constraints of asset-intensive operations. As explained in Section 3, the DPs are formulated in terms of the CAMO format.

DP1: Market Readiness Assessment

Asset-intensive companies need to evaluate both technological maturity and market availability in preparing and making strategic sourcing decisions about digital technologies. This involves assessing market readiness against internal capabilities to determine whether to pursue an early adoption strategy or only adopt proven market solutions. Our data suggest a nuanced approach to technology adoption within railway operations, as a cluster lead expressed: *“Travel information systems are now being developed in-house while standards are available in the open market.”* This reflects the complexity of decision-making processes that need to balance and switch between internal development and market procurement.

The technology integration strategy of the NS demonstrates a broad spectrum, spanning from internal development to “best-of-breed” market solutions, with collaboration as the central organizing principle. In moving across this spectrum, the NS oscillates between early adopter and smart follower roles, based on an evaluation process that considers both market maturity and the complexity of internal developments. An example of an internal development solution is the development of perception modules for recognizing (specifically Dutch) railway signage and signals, for which market solutions proved to be insufficient.

One of the enterprise architects highlighted the ongoing transition in the NS toward using commercial products. This transition marks the shift from a traditional build-centric to a purchase-centric approach. A systematic approach to evaluating market readiness would have to enable the NS (and other asset-intensive companies) to assess technology maturity before taking the decision about whether or not to implement the new technology, with the NS evaluating market readiness against internal capabilities to determine whether to pursue an early adoption strategy or implement a proven market solution. We synthesize these findings in the DP described in Table 4, which extends the literature on Technology Readiness Level frameworks [46,47] by incorporating market dynamics and supplier maturity [48,49] to bridge the gap between purely technical assessments and complex market realities.

Table 4. DP1: Market Readiness Assessment.

CAMO	Design Proposition
Context	In asset-intensive companies that seek to integrate new technologies in assets with very long lifecycles,
Agency	designers and developers need to assess the performance, reliability, and practical viability of these technologies,
Mechanism	applying a systematic evaluation of their market readiness and supplier maturity,
Outcome	which leads to well-informed decisions about technology integration and resource allocation.

DP1 extends DCs theory [9,20] by operationalizing DC’s sensing process specifically for asset-intensive contexts, in which traditional market sensing must be extended toward the evaluation of both technological maturity and supplier ecosystem readiness.

DP2: Modular Architecture and Standardization Strategy

A Reference Architecture (RA) can serve as an instrument for the modular integration of digital technologies, while maintaining system coherence across diverse asset portfolios. This integration would involve the creation of standardized interfaces that accommodate both current technologies and future innovations. Stakeholders interviewed consistently emphasized the strategic importance of modular approaches; for example, a cluster lead said: *"It is essential that this application be modularly integrated."* And an enterprise architect explained the procurement strategy shift: *"We adopt more of a 'buy before make' strategy,"* especially for passenger information systems for which the NS prefers to follow market standards rather than internally develop its own solutions.

The transition to this (preferred) "purchasing" model emphasizes the integration of off-the-shelf and Software as a Service solutions, requiring robust supplier and project management capabilities that are key in adapting third-party systems to specific operational needs. This represents a shift from development-centric to managerial and integrative organizational activities. But the enterprise architects as well as business consultants (interviewed) pointed at major challenges in implementing industry standards: that is, despite the suppliers' adherence to these standards, product functionalities continue to vary between suppliers, which necessitates custom-made integration work for each module delivered by suppliers.

Moreover, several enterprise architects highlighted the importance of the RA, which *"ensures that an NS train can also run on German or Belgian tracks,"* referring to interoperability requirements for cross-border European rail operations. The RA's development over time also reflects the need for adaptability to future technological changes, as a cluster leader noted: *"We try to look ahead and anticipate what might happen in the future."* This forward-looking approach ensures the RA accommodates current as well as anticipated future functionalities, while providing flexibility for modifications based on advancements in IT and operational technologies. Here, layered modular architecture theory [28,50] has to be extended to asset-intensive contexts in which physical constraints severely limit modularity options. Digital transformation in an asset-intensive company therefore requires a new approach to system architecture, one that accommodates both asset legacy issues and emerging digital capabilities.

A cluster leader also acknowledged the practical limitations of achieving true homogeneity, which reflects the variability in component availability from start to end [51,52] in the train production process of the NS. As also observed in Section 3, the NS currently operates approximately 800 trains across the Netherlands, comprising eight different series and a new type coming up; the oldest trains are from 1991 and the most recent one is from 2023. Each train type is equipped with distinct camera systems and IT layers, depending on the manufacturer and the period of construction. This diversity creates major challenges for replacing parts, as new components must fit into older spaces while meeting updated specifications to ensure correct configuration and compliance with international standards.

The design proposition in Table 5 synthesizes these insights in the area of modular architecture and standardization.

DP2 advances digital innovation theory's layered modular architecture framework [21,28] by dissecting how physical constraints in asset-intensive industries limit modularity options. This DP proposes a new approach to system architecture that accommodates both legacy asset integration and emerging digital capabilities, while maintaining operational coherence across diverse asset portfolios.

Table 5. DP2: Modular Architecture and Standardization Strategy.

CAMO	Design Proposition
Context	In asset-intensive companies exposed to an increasing complexity in software systems and technology requirements,
Agency	developers and system architects need to create systems that focus on specific functions and interact with others via well-defined interfaces,
Mechanism	drawing on modular systems that are rather easy to understand, develop, and maintain,
Outcome	which facilitates the integration of new technologies and the adaptation to evolving business needs.

DP3: Regulatory Compliance and Safety Integration

Safety and regulatory considerations represent essential constraints that must be systematically integrated into the digital transformation process, rather than being addressed as external barriers. This requires structural collaboration between technical teams, legal experts, and safety committees. Our data consistently highlight the paramount importance of safety considerations. For example, one cluster leader emphasized: *“There must always be attention to risk”*; this implies operational risk and safety considerations are central in all innovation decisions. This conservative stance with regard to novel technologies reflects the railway operator’s commitment to maintaining operational integrity while pursuing technological transformation. The challenge of incorporating new hardware components is also evident from the observation of a project leader: *“We’re only allowed to install RAIL-certified hardware.”* The RAIL certification process, governed by specific standards and EU regulations, tends to significantly delay the integration of advanced technologies into train operations, creating a tension between innovation speed and safety requirements.

An enterprise architect emphasized the critical balance *“in which the CCTV chain can embrace many innovations, especially in the area of digital security,”* while maintaining compliance with safety and operational protocols. Zhu [53] and Kieslich et al. [54] address the multifaceted challenges of integrating cyber-physical systems. Our data demonstrate how railway operators manage multiple constraints during technology adoption, by means of structural collaboration between developers, legal experts, and safety committees which implement risk mitigation and compliance mechanisms. DP3 thus integrates institutional theory (see Section 2) with innovation processes to specify how asset-intensive companies can foster risk mitigation and regulatory compliance (see Table 6).

Table 6. DP3: Regulatory Compliance and Safety Integration.

CAMO	Design Proposition
Context	In asset-intensive companies that adopt cyber-physical systems in safety-critical environments,
Agency	developers, legal experts, and ethics committees must collaborate to continually update legal regulations, craft ethical frameworks, and set safety standards,
Mechanism	fostering risk mitigation and regulatory compliance in a systematic manner,
Outcome	which ensures systems are deployed in ways that are legally sound and ethically responsible and adhere to safety and maturity standards.

DP3 integrates institutional theory [33,34] with digital innovation processes by demonstrating how regulatory constraints can be systematically embedded within innovation

frameworks rather than treated as external barriers. It thereby addresses the institutional complexity that arises when cyber-physical systems challenge existing regulatory boundaries in safety-critical industries.

DP4: Temporal Coordination and Flexibility Management

Asset-intensive companies must also develop capabilities to manage the misalignment between long development cycles and rapidly evolving technologies. This calls for adaptive governance structures and flexible implementation approaches, which balance long-term commitments with technological adaptability. For example, an NS project leader defined the following key challenge: *“Rapid technological developments make uniformity between trains challenging.”* In this respect, it is difficult to integrate the 10-year train development cycle (outlined earlier) with rapidly advancing digital technologies: once the final RA is submitted to train builders after five years, design modifications become problematic and the RA is potentially outdated by the time the new train is deployed.

The two interviewed cluster leaders both pointed at the financial implications of flexibility, noting that while adaptation to accommodate new technologies (sometimes) remains possible, it does incur huge costs due to investments in component redevelopment. In turn, this creates a financial risk that led the cluster leaders to argue that IT procurement should be decoupled from train tenders. This recommendation would imply that IT purchases are completely eliminated from train procurement tenders. One cluster leader also expected that there will be (a growing need for) more diversification of the train portfolio, with more train types but fewer units per type. This approach would promote innovation and accelerate the integration of new digital technologies, while reducing the risk of technological obsolescence.

More specifically, the transition to 5G networks and the increasing obsolescence of physical components (like network switches, modems and antennas) illustrate the difficulty of maintaining consistent technological standards across all train operations of the NS. The key challenge here is to reconcile the need for flexibility with the operational requirements of safety, reliability, and long-term asset management; in turn, this requires a novel approach to development processes that simultaneously accommodate stability and adaptability requirements (see Table 7). DP4 addresses these fundamental tensions between control and flexibility, which have also been identified in the literature on organization design [55,56].

Table 7. DP4: Temporal Coordination and Flexibility Management.

CAMO	Design Proposition
Context	In asset-intensive companies that operate on physical assets with very long lifecycles,
Agency	top managers should embrace continuous deployment and integration principles, as well as adaptive governance structures,
Mechanism	enabling dynamic adjustments to evolving requirements,
Outcome	which improves operational efficiency, enhances product innovation, and facilitates faster adaptation to technological and market changes.

In sum, DP4 addresses the core tension outlined in ambidexterity theory [38,39] by providing guidelines for balancing the exploration of rapidly evolving digital technologies with the exploitation of decades-long physical asset investments.

DP5: Ecosystem Governance and Partnership Strategy

Strategic sourcing decisions must account for the complex interplay between internal capabilities, external partnerships, and market dynamics. In other words, governance

structures should be instrumental in effectively managing concurrent strategies of buying, making, and partnering. The complexity of partnerships with suppliers is evident, for example, when a cluster leader highlighted that *“from our expertise, we can grow ourselves with the help of a supplier,”* thereby emphasizing that the current ownership model of NS may evolve in the future. This cluster leader referred to the example of the *“train as a service”* model, exemplified by Alstom’s services to Danish railways (which procures trains as a complete service from Alstom, including their deployment), which strongly contrasts with the current ownership model of NS. The same cluster leader pointed at the difficulties of collaborative innovation within tender processes in which *“you have to specify tenders in advance;”* this shows how procurement processes constrain collaboration (e.g., with external suppliers).

Nevertheless, our data underline that the NS is committed to creating and maintaining a balance between external collaborations and in-house R&D. The top managers of NS also acknowledges that the full ownership of its trains may limit its modification capabilities. They thus envision a new ownership model in which the NS gradually acquires ownership of newly acquired trains, aiming for full ownership 15 years after the initial procurement. The shared ownership with the train’s manufacturer would create stronger incentives for both the NS and the manufacturer to collaborate on upgrading the train with new (especially digital) innovations. This so-called vertical disintegration strategy [11,57] capitalizes on the train operator’s core competencies, while outsourcing activities related to non-core competencies. As such, railway operators would benefit from (partial) vertical disintegration via the novel train ownership model previously outlined. More generally speaking, DP 5 draws on the notion of concurrent sourcing in the industry architecture literature [11,23], as well as ecosystem governance theory [58], to provide guidelines for managing the unique challenges of digital innovation partnerships within asset-intensive companies (see Table 8).

Table 8. DP5: Ecosystem Governance and Partnership Strategy.

CAMO	Design Proposition
Context	In asset-intensive companies operating in competitive environments with complex supplier ecosystems,
Agency	top managers need to focus on core competencies, while strategically initiating and sustaining external partnerships,
Mechanism	exploiting the benefits from specialization, as well as innovation, without the full costs and risks arising from in-house development,
Outcome	which enhances organizational flexibility, as well as collaborative innovation with external partners.

DP5 therefore extends industry architecture theory [11] and its concurrent sourcing framework [23] by dissecting how strategic sourcing decisions must navigate the unique constraints of asset-intensive industries.

DP6: Organizational Capability Development

Finally, asset-intensive companies have to build dynamic capabilities for sensing opportunities, seizing resources, and reconfiguring operations to manage digital transformation effectively [9,15]. This requires a structured and sustained engagement with operational teams, external technology providers, academic institutions, and industry associations. In addition, it involves managing changes in organizational identity, while developing new competencies. Our data illustrate these challenges of digital transformation. Both cluster leaders noted major changes in the existing NS strategy for digital

transformation (launched two years earlier), implying a move from a make-strategy to a buy-strategy. One of the interviewed consultants explained the new strategic focus as follows: *“This strategy is about purchasing more digital products and responding to market trends, rather than developing its own solutions.”* This transformation requires role adjustments and potentially reduces the size of the R&D workforce, due to a decreased need for internal development. It also introduces ethical challenges among employees, particularly with respect to AI detection functions. The same consultant noted the personal impact of the digital transformation: *“A system engineer even dropped out because of personal concerns.”*

The transformation also causes an essential shift in the organizational identity of the NS, from a development-centric to an integrative railway operator. This shift implies NS managers need to carefully manage the technological, social and ethical dimensions of digital transformation. The study by Tripsas [59] analyzed how organizational identity serves both as a lens to evaluate technological opportunities and as a filter for strategic action. The last design proposition therefore integrates DCs theory [20] with organizational identity perspectives [60,61], to provide guidance in how an asset-intensive firm can build adaptive capabilities, while managing the challenges arising from digital transformation. This calls for a comprehensive approach to capability development, one that considers both technological and cultural dimensions (see Table 9).

Table 9. DP6: Organizational Capability Development.

CAMO	Design Proposition
Context	In asset-intensive companies facing technologies that challenge established organizational identities and capabilities,
Agency	top managers and their support staff need to acknowledge these challenges by
Mechanism	building new competencies within and outside the organization and breaking down old ones,
Outcome	which enables them to remain competitive and foster innovation while maintaining operational excellence.

The six design propositions, developed in this section, collectively address the theoretical gaps identified in Section 2. They integrate and adapt insights from the five theoretical perspectives outlined in Table 1 to the digital transformation challenges of asset-intensive companies.

4.3. Creation Phase: The Iterative Development & Adoption Model (IDAM)

The six design propositions, developed previously, informed the creation of a process tool, the so-called *Iterative Development & Adoption Model*. IDAM provides a systematic process for reducing the temporal misalignment between rapid cycles of digital innovation and the extended life-cycles of physical assets. It operationalizes the assessment of market maturity as the primary mechanism for managing make-to-buy transitions in digital transformation contexts. IDAM also integrates DCs theory [20,62] with the literature on industry architecture [11] and digital innovation [63]. Figure 4 provides a visual overview of IDAM.

Accordingly, IDAM provides structured guidance via four iterative phases for building organizational capabilities, while managing the temporal coordination challenges. It allows for early introductions of new (e.g., digital) technologies, also in areas where the market of suppliers has not fully evolved yet. As such, it differs from stage-gate processes that focus on whether or not to continue to invest in specific new products being developed [64]. The remainder of this section describes each key step (i.e., ideate, assess, realize, and review) in IDAM.

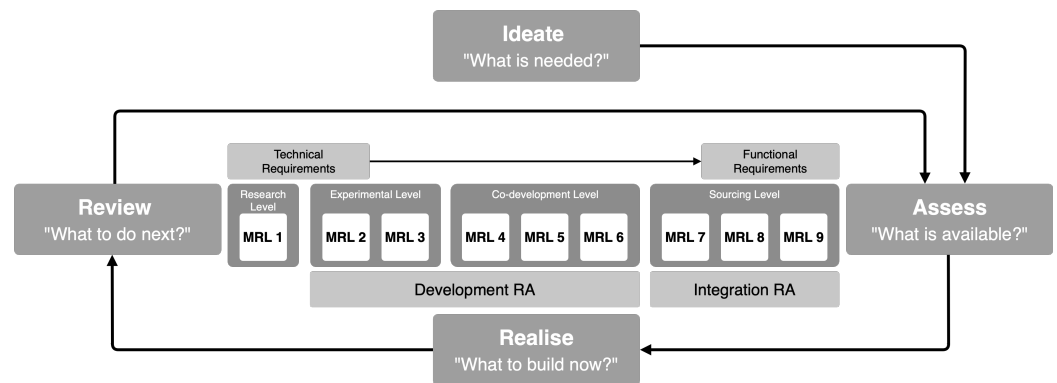


Figure 4. The Iterative Development & Adoption Model (IDAM).

Ideate: Collaborative Sensing and Opportunity Recognition—The ideation phase operationalizes DCs theory’s sensing dimension [20], by identifying digital innovation opportunities that are aligned with operational needs and strategic objectives. The key question “*What is needed?*” extends the company’s sensing capabilities beyond its organizational boundaries. DP6 on organizational capability development drives this phase by establishing systematic sensing routines that help the company identify innovation opportunities, through structured engagement with internal operations teams, external technology providers, academic institutions, and industry associations. DP4 implies that these opportunities need to be assessed from both the immediate operational requirements and the long-term implications for the asset lifecycle, to prevent any unsustainable misalignment. Here, collaborative innovation allows the company to draw on external expertise to identify promising opportunities at the intersection of digital technology and physical assets in heavily regulated environments.

Assess: Market Maturity Evaluation and Strategic Sourcing—The assessment phase serves as a critical decision point, in which the evaluation of market maturity determines the most effective sourcing strategies for the innovation opportunities identified. It addresses the question “*What is available?*” by means of structured evaluations of technological and market readiness. DP1 (Market-Technology Readiness Assessment) suggests that objective evaluation criteria need to be formulated for assessing both technological maturity and market availability, which, in turn, guide the digital transformation journey from “make” to “sourcing” decisions, as the market matures. The assessment in this phase employs four innovation levels, which are further detailed in a nine-level Market Readiness Level (MRL) scale; Table 10 outlines the full scale. The four levels are:

- *Research Level (MRL 1)*: Early-stage technologies (e.g., arising from internal R&D or academic research) that are not yet transformed into solutions. Such a technology typically entails a proof-of-concept, but is not adequately prototyped yet; this technology is therefore characterized by high levels of risk and requires substantial investments in its further development. These proofs-of-concept often provide promising opportunities to be explored for future adoption.
- *Experimental Level (MRL 2–3)*: Prototypes of new technologies in their experimental stages, which are not (yet) fully transformed into viable market solutions; they therefore require (further) internal R&D investments and substantial efforts in capability building.
- *Co-development Level (MRL 4–6)*: Technologies available as emerging market solutions with reliable suppliers as partners. These partnerships enable risk-sharing and collaborative capability development.

- *Sourcing Level (MRL 7–9)*: Increasingly mature market solutions with multiple suppliers, which enables a focus on integration rather than development. Functional requirements can be specified in a relatively straightforward manner.

The design of the assessment phase is especially informed by DP5 on ecosystem governance and partnership strategy and DP3 about regulatory compliance and safety integration. This phase guides make-or-buy decisions by creating and applying evaluation criteria that help to prevent temporal misalignment. Market maturity here is the primary determinant of the decision about whether or not to source (i.e., "buy") a new technology from external suppliers, moderated by institutional constraints.

Realize: Architecture Integration and Development Pathways. The realization phase focuses on the question "*What to build now?*" by implementing different development pathways aligned with market readiness levels, while maintaining system coherence through modular architecture principles. DP2 regarding modular architecture and standardization strategy provides the structural foundation for integrating components from different sourcing strategies within a coherent system architecture.

The realization phase distinguishes between two types of Reference Architecture (RA), based on technology maturity. The first type, called *Development RA*, is designed for emerging technologies that require flexibility and experimentation. This developmental approach establishes experimental platforms and research capabilities to accommodate the high level of technological uncertainty of emerging technologies. The second type, called the *Integration RA*, is designed for mature market solutions that prioritize standardization and reliability. This integration approach provides standardized interfaces and integration protocols for proven technologies. The distinction between the two types enables the asset-intensive company to apply different architectural strategies, acknowledging the market maturity level for the technology being integrated.

In addition to DP2, two other DPs informed the creation of the realization phase. DP5 structures the implementation complexity when multiple sourcing approaches are simultaneously used by establishing governance structures for co-development partnerships, supplier relationships, and internal R&D coordination. In addition, DP3 ensures consistent safety-oriented models that accommodate both experimental developments and mature external solutions. This creates distinct pathways: that is, internal R&D labs for low-maturity technologies, co-development facilities for medium-maturity solutions, and integration platforms for high-maturity market offerings.

Review: Organizational Learning and Iterative Refinement—Finally, the review phase addresses "*What to do next?*" by capturing the insights and learnings that arise from the experiences obtained in the realization phase and translating these insights into (proposed) improvements of future innovation cycles. In this respect, DP4 suggests these insights have to be incorporated into long-term planning and capability roadmaps, to ensure that experiences in short-term implementation work inform long-term strategic decisions. Moreover, DP6 recommends that one learns from implementation experiences by rigorously documenting successes, failures, and causal factors; such an organizational memory improves future decision-making. The review phase is thus fueled by structured feedback loops that improve the company's capability to navigate digital transformation while maintaining operational excellence.

Overall, the IDAM model integrates empirical findings and translates theoretical insights from multiple domains into practical guidelines for managing the digital transformation efforts in asset-intensive companies. By systematizing the assessment of market maturity as a key mechanism for managing temporal alignment, IDAM enables asset-intensive companies to pursue innovation across the full spectrum of technological maturity.

Table 10. Four Innovation Levels Aligned with Nine Market Readiness Levels.

Innovation Level	Requirement Level	MRL Level	Market Context		Description
Research level	-	MRL 1	Basic Innovation	Opportunity	Initial market need identified and basic digital solution concept formulated. In-house or academic research into emerging technologies and market gaps. No mature functional requirements and no proven business case yet.
Experimental level	Development RA	MRL 2	Concept	Validation	Digital concept tested through market research, user interviews, and basic prototyping. In-house development of minimum viable features to validate market assumptions.
		MRL 3	Market Proof of	Concept	Working prototype demonstrated to potential users/customers. Market feedback collected and business model hypotheses tested. In-house development with clear user validation.
Co-development level	Development RA	MRL 4	Technical	Partnership Ready	Solution architecture defined with detailed technical specifications. Ready for co-development with technology partners or suppliers based on technical requirements.
		MRL 5	Pilot	Market Testing	Beta version deployed with select customers or other users. Co-development partnerships established. Technical specifications proven in real market conditions with limited audience.
		MRL 6	Market	Validation Complete	Solution tested across multiple market segments. Partnership models validated. Technical specifications mature enough for broader implementation or supplier engagement.
Sourcing level	Integration RA	MRL 7	Commercial	Market Entry	Functional specifications defined for market-ready solution. Multiple suppliers can deliver based on functional requirements. Early commercial deployment beginning.
		MRL 8	Market-Proven	Solution	Solution commercially available from multiple suppliers based on functional specs. Proven market adoption (e.g., aviation or railway), certificates obtained, and clear ROI demonstrated across customer base.
		MRL 9	Market	Standard/Commodity	Mature market solution with established supplier ecosystem. Standardized functional specifications. Solution widely adopted and considered essential/standard practice in the market.

4.4. Evaluation Phase: Validating the Model

The evaluation of the IDAM model involved a two-step validation process, designed to ensure both theoretical rigor and practical applicability. The first evaluation step involved a formative assessment in the form of an alpha-test of the model [17,65]. In this alpha-test, we presented IDAM to the experts interviewed earlier, as well as to other NS stakeholders, including senior management representatives and members of the CCTV project team. These experts were especially invited to evaluate the completeness, logical consistency, and alignment of the IDAM with the requirements management process established within the NS. One general recommendation received as feedback in these meetings was to simplify the visual representation of the model, which initially was a bit more complex than the final version presented in Figure 4. Other major points of feedback are discussed below, where we evaluate the IDAM in terms of the design propositions.

In the second step, we evaluated the IDAM in terms of the six design propositions (formulated in Section 4.2), providing a more summative evaluation [65]. This last evaluation step served to assess to what extent the DPs are incorporated into the final model. In the remainder of this section, we, therefore, explore how each DP is instantiated in the final IDAM.

DP1 (Market-Technology Readiness Assessment): This proposition provides a core decision mechanism in IDAM in the form of clear evaluation criteria and decision pathways

through the nine levels of market readiness. All stakeholders in NS particularly valued this systematic approach to sourcing decisions, observing that it addresses the major challenges of NS in aligning decisions about the adoption of digital technologies with the long life-cycle of its physical assets.

DP2 (Modular Architecture and Standardization Strategy): The main thrust of this proposition is directly visible in the realization phase of IDAM in terms of the clear distinction between the Development and Integration reference architectures. Many experts praised this differentiation in two distinct RAs as it addresses the practical needs of managing experimental, as well as more mature technologies within the systems of an asset-intensive company. This modular approach also resonated strongly with technological experts within the NS, who recognized its value in managing the complexity of concurrent sourcing strategies.

DP3 (Regulatory Compliance and Safety Integration): This DP provides an essential constraint throughout all phases of the IDAM process, but several stakeholders noted that the requirements regarding regulatory compliance and safety integration are not explicitly visualized in Figure 4, although these are clearly presented in the written IDAM guidelines. Despite the lack of visual presence in the figure outlining IDAM, interviewees from the Safety and Compliance department of NS emphasized how IDAM's systematic approach improves their ability to evaluate and approve digital technologies by providing a structured process and clear criteria.

DP4 (Temporal Coordination and Flexibility Management): DP4 influenced IDAM's overall iterative structure and informed the distinction between the Development RA and Integration RA. Many NS stakeholders recognized how this proposition addresses one of their most pressing challenges: managing digital transformation within long-term commitments to physical assets. They particularly praised the iterative nature of IDAM for its ability to accommodate the continually changing technological landscape while sustaining the strategic coherence of the NS.

DP5 (Ecosystem Governance and Partnership Strategy): This proposition shaped multiple aspects of IDAM, particularly in the assessment and realization phases in which partnership evaluation and partnership management become critical. NS stakeholders noted how the model's explicit consideration of different sourcing strategies (i.e., make, buy, partner) aligns well with how the approach of the NS to collaborative innovation and supplier relationships has recently been evolving.

DP6 (Organizational Capability Development): The sixth DP informs the entire model through its emphasis on learning and capability building throughout all phases. Although not presented as a discrete component or step in IDAM, both experts and stakeholders recognized how the model's design helps to build an asset-intensive company's innovation capabilities through structured processes and iterative learning cycles.

5. Discussion and Conclusions

This study contributes to the literature on engineering design by addressing the unique challenges of digital transformation in asset-intensive industries. Our primary contribution is to operationalize the concept of temporal misalignment between digital innovation cycles and physical asset life-cycles, which extends previous work on digital transformation [8,66,67]. In the remainder of this section, we first explore in more detail how our findings extend various theories and then describe the main limitations of this study and the implications for future work in this area.

5.1. Theoretical and Practical Contributions

The IDAM approach extends dynamic capabilities theory [20,26] by introducing “temporally coordinating” as a fourth dimension to sensing, seizing, and reconfiguring. Al-

though conventional DC theory assumes that companies are inherently adaptive and flexible [62,68], our research indicates that companies relying heavily on physical assets must cultivate capabilities in temporal coordination, in order to effectively manage very long asset life-cycles that span several decades. This challenges the common assumption about adaptiveness and flexibility made in most DC studies [20,26] and provides a foundation for understanding capability development in asset-intensive environments, in which short-term technological adaptability must coexist with long-term infrastructure commitments.

Moreover, this study challenges digital innovation theory's [22,28] implicit assumption of architectural flexibility by demonstrating how the constraints of physical assets fundamentally alter digital transformation processes. In this respect, IDAM involves four innovation levels, aligned with a nine-point Market Readiness scale (defined in Section 4.3). The latter scale extends the widely used Technology Readiness Level scale [46,47] by integrating market dynamics, supplier ecosystem maturity, and institutional compatibility. This approach fills an important gap in the digital innovation literature that has thus far almost exclusively focused on software-driven advancements, which are not substantially constrained by physical assets and regulatory frameworks [67,69]. Here, the Development Reference Architecture and Integration Reference Architecture in IDAM offer a novel perspective on managing innovation and sourcing processes at varying stages of technological progress. These two complementary RA's especially also challenge the assumption that modular architectures [21] provide a universal type of flexibility. Instead, the IDAM approach shows how physical constraints require differentiated architectural strategies based on technological maturity and market conditions.

Our findings also demonstrate how industry architecture theory [11,70] and institutional theory [33,35] must be systematically integrated with the perspectives of digital transformation and DC in the specific context of asset-intensive companies. The IDAM model operationalizes this integration by showing how companies must simultaneously navigate multiple institutional logics: market efficiency pressures driving digital adoption, safety requirements constraining experimentation, and reliability demands prioritizing operational continuity. This integrated approach challenges the rather sequential applications of these theories prevailing in the literature [35,70], and instead advocates the concurrent management of technological, organizational, and institutional factors [1,4].

Finally, our research applies ambidexterity theory [38,39] by demonstrating how the exploration-exploitation balance becomes more structurally constrained in asset-intensive companies than in other companies. Traditional ambidexterity theory assumes that organizations can adjust their exploration–exploitation balance rather easily, but our findings show that massive capital investments in physical assets create a lock-in effect. Similarly, in a recent study of leadership capabilities in the metaverse industry, Mancuso et al. [71] concluded that capabilities aimed at managing digital assets (incl. IT infrastructure), as well as capabilities aimed at managing organizational factors are required, without specifying the constraints arising from the physical IT infrastructure. The six design propositions collectively address this type of constraint by providing mechanisms for managing exploration (of digital innovation opportunities) that fully respect exploitation commitments. In other words, this study extends ambidexterity theory to a specific industrial setting in which flexibility is structurally limited.

Overall, the concept of temporal misalignment serves as an integrative theoretical mechanism that connects insights from all five theoretical traditions examined in Section 2. Rather than treating these theories as competing explanations, our model and design propositions demonstrate how these theories converge around the central challenge of managing innovation with major temporal constraints. Dynamic capabilities provide the organizational foundation of IDAM, digital innovation theory explains the technological

opportunities, institutional theory especially defines the constraints as parameters, industry architecture theory guides the company's strategic choices, and ambidexterity theory helps to frame the tension being addressed. IDAM operationalizes this theoretical convergence of five perspectives in the form of a systematic process that addresses each theoretical dimension while maintaining coherence across the digital transformation process.

From a more practical point of view, IDAM provides actionable guidance for technology adoption decisions based on an analysis of market readiness. This allows managers of asset-intensive companies to assess digital innovation opportunities and mitigate their associated risks. IDAM also allows them to monitor the operational impact of a new technology in a controlled pilot setting before deciding to deploy it on a broader scale. We also found that the shift from co-development to supplier-buyer relationships requires effective management of expectations from both sides as well as a well-defined allocation of responsibilities among the partners involved. As the market of technology suppliers matures from co-development (at MRLs 4–6) to external sourcing (at MRLs 7–9), the partnership structure develops from a collaborative innovation arrangement to a more conventional buyer-supplier relationship. This results in requirements becoming more functionally specified. An asset-intensive company, as well as its suppliers, should be fully aware of these dynamics, and IDAM can help develop and deepen this awareness.

5.2. Limitations and Future Research

Our study has several limitations. The IDAM and its underlying design propositions were developed for a Dutch railway operator as an exemplary asset-intensive company. Future work will have to explore whether the IDAM approach can be generalized and applied to railway operators in other countries (e.g., with distinct institutional demands) and other types of asset-intensive companies (e.g., in the aviation and shipping industries).

Another limitation arises from the validation of the IDAM, which was primarily done via alpha tests with key stakeholders within the NS, as well as various external experts. A more substantial test would involve a longitudinal study of IDAM's application in navigating digital transformation, at the NS and other asset-intensive companies, across the life-cycle of a specific asset (e.g., a set of new trains ordered, manufactured, and employed). Such a test requires a field study of at least 10 years, given the extremely long life-cycle of this type of asset. This longitudinal test was not feasible in the context of the research reported in this article, but future work in this area should (ideally) draw on data collected over a much longer period of time.

A related limitation is that the validation of the main artifact developed (i.e., the IDAM) involved a relatively small number of experts. Subsequent work on IDAM will therefore have to draw on a much larger group of expert-users, also in other asset-intensive companies.

5.3. Concluding Remarks

Digital transformation in asset-intensive companies requires a novel approach, one that moves beyond the transformation lenses created for software-driven and other companies without durable physical assets. By extending and integrating theories in the area of dynamic capability, digital innovation, industry architecture, and institutional compliance, we developed a new model (IDAM) to help asset-intensive companies navigate the challenges of digital transformation while maintaining their operational integrity and regulatory compliance.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
CAMO	Context–Agency–Mechanism–Outcome
CCTV	Closed-Circuit Television
DC	Dynamic Capability
DDNG	Double Deck New Generation
DP	Design Proposition
DS	Design Science
HCI	Human–Computer Interface
IDAM	Iterative Development & Adoption Model
IoT	Internet of Things
MRL	Market Readiness Level
NS	Nederlandse Spoorwegen (Dutch Railways)
NVR	Network Video Recorder
OBIS	Onboard Information System
RA	Reference Architecture
TMCS	Train Management Control System
TRL	Technology Readiness Level

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