PRINCIPLES FOR THE INDUSTRIALISATION OF THE INFRASTRUCTURE RENOVATION AND REPLACEMENT ASSIGNMENT

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Abstract

The Netherlands faces an unprecedented infrastructure renewal assignment that cannot be addressed through traditional project-based delivery. Although industrialisation is widely promoted as a solution, its adoption remains limited due to a lack of system-level understanding of the conditions required for scaling. This study positions industrialisation as a coordinated transformation of infrastructure asset management and develops a principles-based perspective to support this transition. Using thematic analysis of literature and expert validation, five principles are identified. Together, these principles clarify why isolated technological initiatives struggle to scale and establishes a foundation for developing action perspectives and policy directions to guide industrialisation.

Introduction

The Netherlands faces an urgent and complex challenge in the renewal (renovation and replacement) of its aging civil infrastructure (TNO, 2023). Approximately 40% of bridges and viaducts are approaching or have exceeded their intended service life, with annual renewal costs projected to rise from €1.1 billion in 2021 to €2.4 billion between 2021 and 2030, and further to €2.9 billion annually between 2031 and 2040 (TNO, 2023). Delivering this scale of intervention requires a significant increase in the pace and efficiency of infrastructure projects.

However, the Dutch construction sector, as currently organised, lacks the capacity and supporting ecosystem to respond effectively (Bletsis, 2020). The sector remains structured around bespoke, one-off projects, characterised by fragmented procurement practices, limited standardisation, and temporary supply chains. This “loosely coupled” structure limits knowledge transfer and learning across projects (Dubois and Gadde, 2002), constraining productivity improvements relative to the wider economy. As a result, existing delivery models remain heavily reliant on labour-intensive, on-site activities, which are associated with inefficiencies such as cost overruns, delays, and waste (Eriksson et al., 2014). At the same time, increasing pressures related to sustainability, resource efficiency, and a shrinking workforce further intensify the need for more productive ways of working (Pottachola, 2024).

Taken together, the scale and urgency of the renewal assignment render the prevailing one-to-one, project-based delivery model increasingly untenable. Without a fundamental shift in how infrastructure renewal is organised and coordinated, the sector will struggle to meet demand (TNO, 2023), making the search for scalable, efficient solutions, and the delivery models that enable them, not only necessary but inevitable.

In response to such systemic challenges, the construction sector has increasingly sought to adopt principles originating from manufacturing, such as standardisation, mechanisation, and automation (Lessing, 2015). These developments are collectively referred to as the industrialisation of construction. Initially, industrialisation in construction was primarily understood as the use of off-site manufacturing as technical means to relocate work away from the unpredictable construction site (Lessing, 2015). Over time, this interpretation has evolved into a more holistic perspective, where industrialisation is framed as a systematic, process-oriented approach characterised by standardisation, continuous improvement, and long-term supply chain integration (van Ee, 2022; van Groesen, 2022; Pottachola, 2024).

Within the Dutch infrastructure sector, industrialisation is widely regarded as a promising solution direction for addressing the renewal assignment. Initiatives such as Industrial, Flexible, and Demountable (IFD) bridge concepts illustrate this potential through reduced project lead times, faster on-site construction with less disruption, and designs that enable disassembly and long-term reuse (EIB, 2022). Feasibility studies in the Dutch context estimate a potential market for IFD of € 3.3 billion for decentralised asset owners between 2025 and 2035, with an associated economic benefit of approximately €300 million (EIB, 2022).

Despite this recognised potential and the availability of supporting technologies, the adoption of industrialised solutions in infrastructure renewal remains limited. This limited uptake cannot be attributed to technological immaturity, but rather to the fragmented way in which industrialisation is pursued, often through isolated instruments or technologies, without a coherent understanding of the organisational conditions required to support industrialised production (Bletsis, 2020). The infrastructure sector operates in an extremely demand-driven environment, reinforcing the central role of asset owners in enabling or constraining industrialised production. In the Dutch context alone, nearly 370 decentralised public authorities are responsible for infrastructure assets. While efforts on industrialisation heavily focuses on the market side, the role of asset management organisations in this transition is frequently overlooked. Yet, it is precisely the upstream decisions made by asset owners, such as structuring demand to create continuity, defining project requirements that support standardisation, and designing procurement frameworks that incentivise long-term investment, that largely shape the conditions under which industrialised solutions can emerge and scale (EIB, 2022).

The complex nature of infrastructure construction, coupled with the systemic and multifaceted character of industrialisation, requires supporting frameworks capable of structuring and coordinating action across diverse actors (Brouwer, 2024). Although frameworks for industrialised construction have been developed in the housing sector (e.g., Lessing, 2015), these are not fully transferable to the infrastructure domain due to differences in asset characteristics, governance structures, and demand dynamics (Eriksson et al., 2014). Moreover, these frameworks are grounded in an implicit assumption that enabling conditions for industrialised construction such as stable demand and aligned procurement and governance structures are already in place. However, this assumption does not hold in the infrastructure sector, which is characterised by its demand-driven nature and complex product systems. Here, the conditions required for industrialisation are not given, but must be actively created, particularly through asset management practices. Consequently, existing frameworks provide limited guidance for coordinating industrialisation efforts in the infrastructure sector, leaving actors without a shared perspective to align decisions, organise actions, and assess progress.

This study addresses this gap by developing a principles-based framework for the industrialisation of infrastructure asset management, derived through thematic analysis of literature and validated with expert input. By identifying the fundamental principles that characterise industrialised infrastructure systems, the study provides a foundation for aligning and coordinating industrialisation efforts across actors as a system-level transformation of infrastructure asset management.

The remainder of this paper is structured as follows. First, the paper builds its theoretical foundation by drawing on existing industrialisation literature mostly from the building context and adapting these insights to the specific context of infrastructure asset management. Next, the research is described that was conducted to derive principles. The findings section presents the five derived principles. This is followed by a discussion of the implications for asset owners, governance, and sector-wide coordination. Finally, the paper concludes with key insights, limitations, and directions for future research.

Theoretical Foundation – Industrialisation of Asset Management

Industrialisation of construction represents a shift from a traditional design-to-product mindset, where each project is treated as inherently unique, toward a product-to-design perspective that emphasises system-oriented thinking (van Ee, 2022). This shift aims to enable construction companies to achieve economies of scale through integrated value and supply chains across projects (van Groesen, 2022). This transition has been most visibly advanced in the housing sector, where industrially produced modular homes are increasingly regarded as a viable response to the European affordable housing crisis (van Ee, 2022). The growing adoption of prefabricated and modular housing solutions reflects an acceptance of industrial approaches as alternatives to so-called traditional construction methods.

The transition to a product-based mindset in infrastructure sector is not yet advanced. Infrastructure projects are frequently characterised as complex product systems (CoPS) that are unique in nature, which has contributed to a reluctance to adopt standardisation and platform-based approaches due to site-specific conditions and varying client requirements (Stout, 2016). As a result, industrialisation in infrastructure often manifests as isolated technological interventions rather than as a coordinated reorganisation of production and decision-making processes across the value chain. Recent studies, however, demonstrate that even complex civil engineering structures such as bridges can be decomposed into standardised modules and subsystems (EIB, 2022). This perspective is particularly relevant in the context of infrastructure renewal, where the dominant task is no longer greenfield construction but the large-scale renewal of existing assets.

To build on this shift in perspective, industrialisation of construction in this study is positioned not as the application of isolated methods or technologies, but as a coordinated transformation of infrastructure asset management that creates the conditions for the effective adoption and scaling of productivity-enhancing approaches across the value chain (Brouwer, 2024). The definition adopted in this study is synthesised from recurring elements in the literature and subsequently contextualised to the Dutch renewal assignment, where fragmented demand, temporary coalitions, and high transaction costs inhibit productivity improvement. The formulation deliberately emphasises organisational restructuring, scale creation, and the enabling of process-oriented technologies, as these dimensions repeatedly emerged as prerequisites for industrial performance (Lessing, 2015; Stout, 2016; Bletsis, 2020; EIB, 2022; Brouwer, 2024). In line with this perspective, and tailored to the specific dynamics of the Dutch infrastructure renewal assignment, we define industrialisation as:

‘The reorganisation of (specific parts of) the infrastructure sector, to reduce its inherent project-based and demand-driven nature, in order to implement and enhance process-oriented technologies, for the

purpose of achieving economies of scale and reducing transaction costs, and eventually to mitigate the productivity challenges in the renewal assignment.'

Industrialisation therefore implies a shift from a purely project-based logic toward a more project-independent or product-oriented approach, in which commonalities across projects are systematically identified and leveraged through product platforms and standardised solution spaces (van Groesen, 2022). Such a shift enables organisations to move from reactive forms of production towards more proactive forms, including mass customisation, where project-specific variation is accommodated within a stable, standardised system (van Groesen, 2022). By aligning supply and demand more effectively, industrialisation creates the conditions under which repetition, learning, and optimisation across projects become possible (Bletsis, 2020).

The reorganisation of the sector is also a prerequisite for the effective implementation of process-oriented technologies, which form the operational backbone of industrialisation (Lessing, 2015). Technologies such as automation, mechanisation, and digital configurators enable the transition from craft-based, labour-intensive practices to manufacturing-led production processes. However, without the process stability and organisational alignment provided by industrialisation, advanced technologies cannot be effectively deployed at scale (Pottachola, 2024). In this sense, industrialisation is not the result of technological adoption, but rather a necessary condition for technologies to deliver productivity gains.

Operationally, industrialisation aims to realise economies of scale and economies of repetition, which are currently difficult to achieve in the infrastructure sector due to fragmented and unpredictable demand (Brouwer, 2024). Standardisation and the aggregation of demand into programs or portfolios enable the production volumes required to justify investments in industrial facilities and tools, thereby reducing unit costs (EIB, 2022). In parallel, a shift from transactional, lowest-price procurement toward long-term supply chain partnerships reduces transaction costs associated with repeated tendering, coordination, and non-value-adding activities, resulting in a more economically viable and resilient value chain (Eriksson et al., 2014).

In this way, industrialisation offers the potential for a necessary productivity leap, enabling the sector to execute extensive renewal programmes within financial, temporal, and environmental constraints, while maintaining quality and safety standards. However, this conceptualisation implies that it cannot be operationalised through isolated methods, technologies, or best practices alone. Given the diversity of asset types, organisational settings, and institutional arrangements in the infrastructure sector, prescriptive solutions are unlikely to be transferable or scalable across contexts (Bletsis, 2020). Therefore, industrialisation requires a framework that articulates the fundamental conditions underpinning such a transition, while allowing for contextual interpretation and implementation.

In this study, these foundational conditions are expressed in the form of principles. Principles serve as high-level propositions that describe essential characteristics of industrialised asset management systems without prescribing specific solutions or technologies. As such, they provide a shared analytical lens for understanding industrialisation across different actors and contexts. They form the basis for systematically analysing how organisations enable or constrain the adoption of productivity-enhancing approaches.

Research Method

This study adopts a qualitative, exploratory research design aimed at defining foundational principles for the industrialisation of infrastructure asset management. The study uses thematic analysis as its primary analytical method to identify, synthesise, and abstract recurring values and patterns into a coherent set of industrialisation principles.

The research process began by formulating a working definition of industrialisation in the context of infrastructure asset management. Industrialisation was conceptualised as a systemic transformation that reduces the inherently project-based nature of infrastructure delivery with scalable, process-oriented approaches. Based on this definition, the purpose of the principles was defined. The principles were positioned as (1) fundamental propositions that provide an action-oriented perspective for stakeholders; (2) a conceptual foundation for defining and guiding industrialisation efforts and for informing policymakers; and (3) a basis for future maturity assessment models. This step established the analytical lens used throughout the study.

A targeted literature review was conducted to explore theoretical and empirical insights related to industrialisation. Search strings combined keywords such as industrialised construction, industrialised building systems, modular construction, prefabrication, and product platforms, together with related concepts including standardisation, DfMA, off-site manufacturing, process integration, supply chain integration, and construction productivity. The initial set of 84 identified publications were screened based on their relevance to the objectives of this study. The primary inclusion criterion concerned the extent to which a study provided insight into why industrialisation-related approaches were adopted and which organisational, institutional, or process conditions were associated with successful implementation and productivity improvement. Following this screening, 39 publications were retained for detailed analysis. Given the limited availability of systemic perspectives on industrialisation within infrastructure, many selected studies originated from the building sector.

Data from literature were analysed using thematic analysis. The analysis proceeded in four iterative steps. First, key concepts and terms related to industrialisation, productivity, and organisational change were identified across data sources. Then, related codes were grouped into broader themes representing recurring values and patterns. The focus during this analysis was understanding what the characteristics, enabling conditions, and motivations behind various implementation of industrialisation technologies were. The identified themes were further refined and abstracted to capture their underlying fundamentals, resulting in a set of higher-order principles. Each principle represents a necessary condition for enabling industrialised asset management.

The derived principles were subjected to expert validation through a series of semi-structured interviews with domain experts. In total, experts included asset managers, policy specialists, and engineers representing four decentralised authorities, one national agency, and four contractors. In these sessions, the five principles and their preliminary definitions were presented to each organisation individually. Participants were asked to reflect on the extent to which the principles corresponded with their current productivity ambitions, strategic directions, and practical experiences.

The interviews examined the relevance, clarity, and completeness of the principles, as well as their recognisability in ongoing initiatives. Feedback from these validation interviews was used to refine the formulation of the principles, sharpen definitions, and ensure their applicability across both demand- and supply-side contexts.

Findings

The thematic analysis resulted in five principles that characterise industrialisation in infrastructure asset management. A detailed overview of the coding structure linking codes with relevant sources, themes, and principles is provided as supplementary material to this paper (TNO, 2026). Each principle is discussed in detail in the following sections.

Principle 1: Continuity and Repeatability

In any industry, the market operates most efficiently when there is a steady flow of demand (EIB, 2022). In construction, however, a fragmented, project-based approach forces organisations to constantly (re)adjust their resources and operations, leading to inefficiencies, increased costs, and slower delivery (Dubois and Gadde, 2002). A continuous flow of standardised demand allows for a stable and predictable environment where workflows can be optimised and scaled over time (EIB, 2022).

The principle of Continuity and Repeatability describes the extent to which infrastructure renewal activities are organised to enable stable production flows, and reuse across projects. The analysis highlights a transition from fragmented, one-off project delivery towards process-based approaches in which production logic is decoupled from individual project contexts (Eriksson et al., 2014). Central to this principle is the aggregation of demand through programmatic and portfolio-based planning to create predictable workloads that sustain industrial operations (Eriksson et al., 2014; EIB, 2022; van Groesen, 2022). Long-term supply chain integration also emerged as a key theme, reflecting the importance of stable partnerships, team continuity, and synchronised off-site and on-site processes in maintaining steady production flows (Vrijhoef and Koskela, 2005; Söderholm, 2010; Lessing, 2015; Pottachola, 2024).

Along these lines, we define Continuity and Repeatability as *the principle of ensuring continuous operations over time in a way that supports the development of repeatable products and processes.*

In essence, this principle enables scalable and predictable processes, optimises resource allocation, reduces costs and project durations, and fosters innovations and reuse of data, and modular solutions across projects.

Principle 2: Specialisation

Continuity in processes enables organisations to simplify workflows by reducing portfolio diversity and complexity. This, in turn, creates the opportunity to structure operations around a more focused and narrowed scope of products or services, allowing organisations to concentrate their resources and expertise on these defined areas (Vrijhoef and Koskela, 2005). Specialisation refers to the deliberate narrowing of organisational scope to increase efficiency and performance through focused capabilities.

The thematic analysis indicates a shift from generalist, project-oriented organisations towards product- and process-oriented structures. This includes strategic limitation of the solution space (Stout, 2016), market segmentation, and the development of specialised offerings aligned with repeatable production processes (Vrijhoef and Koskela, 2005). At the organisational level, specialisation is supported by permanent, dedicated teams and the distinction between core and non-core competencies (Vrijhoef and Koskela, 2005; Lessing, 2015). At the supply chain level, the analysis points to a transition from project-based subcontracting towards system suppliers and long-term strategic partnerships, enabling cumulative learning and early integration of specialised knowledge (van Ee, 2022; van Groesen, 2022; Pottachola, 2024).

Along these lines, we define Specialisation as *the principle of focusing resources and expertise on a specific, narrowed scope of assets or services by simplifying workflows and reducing portfolio complexity.*

Specialisation enhances the organisation's technical proficiency, simplifies portfolio management, and enables the market to deliver high-quality, tailored solutions for specific assets or types of interventions.

Principle 3: Knowledge Codification

Continuous improvement is necessary in an industrial system (Lessing, 2015). In the fragmented and project-based nature of the construction sector, valuable knowledge is often lost when teams disband after projects (Dubois and Gadde, 2002). Most of this knowledge remains tacit, leading to missed opportunities for improvement and a failure to learn from mistakes (Pottachola, 2024). Furthermore, this knowledge is frequently lost as individuals retire or move to organisations (Pottachola, 2024).

Knowledge codification captures the transformation of tacit, individual expertise into explicit, reusable organisational assets. The analysis reveals recurring themes related to formalising decision logics, and solutions in order to avoid repeated reinvention (Stout, 2016; Andersson and Lessing, 2017). Structuring information for interoperability and machine readability emerged as a critical theme, including the use of standardised data formats, taxonomies, and shared information structures such that knowledge and information from multiple individuals can be aggregated (van Ee, 2022; Pottachola, 2024). Feedback loops for continuous learning and the use of digital tools, such as semantic models, BIM, and design configurators support the retention, application, and evolution of codified knowledge across projects (Cao et al., 2021; van Ee, 2022; Pottachola, 2024).

Along these lines, we define Knowledge Codification as *the principle of formalising and embedding tacit knowledge into structured systems to ensure it is retained, reused, and enables continuous improvement across organisations, projects, and individuals.*

Knowledge codification thus enables organisations to systematically build on past knowledge, improving decision-making, execution, and long-term planning. This ensures the retention of expertise as individuals leave, enables building on experience for better decision-making, facilitates faster onboarding, and prevents repeated errors or rediscovery of solutions.

Principle 4: Pre-Engineering

In the construction industry, resources are often allocated to create bespoke designs and solutions for individual projects (Dubois and Gadde, 2002). While uniqueness is an inherent characteristic of construction projects, many projects share commonalities that are often overlooked, particularly in the infrastructure sector (Bletsis, 2020; EIB, 2022). These overlooked commonalities prevent the industry from utilising standardisation, thereby limiting scalability.

Pre-engineering refers to shifting engineering effort upstream by resolving complexity early and systematically. The analysis highlights the decomposition of complex systems into modular components (Stout, 2016; van Groesen, 2022) and the development of product platforms (Knippenberg et al., 2019; van Ee, 2022) or kits of parts (Cao et al., 2021) as central mechanisms. This enables configuration-based solutions while isolating variability to specific modules.

Front-loading design decisions, including early design freezes and early integration of suppliers (Wuni and Shen, 2020), is identified as a key theme to reduce downstream uncertainty. Further themes include the integration of design and production through Design for Manufacture and Assembly (DfMA) principles and the gradual shift of production logic from on-site construction towards manufacturing-oriented processes, including off-site and hybrid production models (Eriksson et al., 2014; Pottachola, 2024).

Along these lines, we define pre-engineering as *the principle of developing reusable products and processes through standardisation and pre-definition, enabling scalability and reducing the reliance on bespoke, project-specific efforts.*

Pre-engineering accelerates project delivery by reducing bespoke efforts and thus shorter design/ planning lead times, enhances market productivity through reusable and optimised designs and processes, and supports the development of sustainable and circular methods and processes.

Principle 5: Socio-Technical Alignment

The construction industry is inherently fragmented vertically (across project phases), horizontally (across expertise), and longitudinally (across projects) (Adriaanse, 2014). This fragmentation leads to misalignment between social systems (people, contracts, organisations) and technical systems (processes, technologies, tools) (Pottachola, 2024). Industrialisation requires a collective effort toward common goals, and achieving alignment between these systems is important for a full-fledged industrial system.

Sociotechnical alignment captures this need to align contractual, organisational, cultural, and digital dimensions of industrialisation. The analysis shows that industrial objectives are difficult to realise without contractual frameworks that support collaboration, shared risk, and early stakeholder involvement (Vrijhoef and Koskela, 2005; Bletsis, 2020). Traditional transactional and lowest-price contracting approaches frequently conflict with industrialised modes of operation (Eriksson et al., 2014; Bletsis, 2020). Beyond formal arrangements, the analysis highlights the importance of network-centric cultures based on trust, transparency (Stout, 2016), and shared situational awareness (Bletsis, 2020; Pottachola, 2024). Aligning digital systems with organisational workflows also emerges as a theme (Pottachola, 2024), indicating the required social and organisational transformation as a technical one.

Along these lines, we define Sociotechnical alignment as *the principle of achieving the alignment between social systems and technical systems, ensuring that resources are coordinated to function cohesively within a larger operational framework.*

Sociotechnical alignment ensures stakeholder priorities and resources are aligned for effective collaboration on large assignments, such as the infrastructure renewal assignment. Furthermore, this enables the full utilisation of product platforms' potential.

Expert Validation Results

To evaluate these principles, validation interviews were conducted with senior asset managers and project managers from asset owners, contractors and engineering firms. The principles and their definitions were well received, with practitioners confirming that they represent not merely theoretical constructs but active levers they consider for addressing the productivity gap. They were widely recognised, prompting reflection on how they are already applied in practice while also revealing weaknesses in current approaches and opportunities for improvement.

Continuity & repeatability was consistently recognised as foundational to achieving industrialisation. Asset owners emphasised that creating continuity in demand is increasingly a strategic priority, as it enables more reliable collaboration with the market, lowers inherent variability in tender outcomes, and provides space for innovation. Contractors highlighted that continuity directly reduces transaction costs by allowing reuse of designs, processes, and supply-chain arrangements; several noted that repeatability enables significant learning effects that are currently lost in one-off projects.

Specialisation was seen as a means to allocate resources outside of the project scope and towards more continuous and repeatable operations. Specialisation is relevant at multiple scales within organisations and the sector. For example, on the team level specialisation was related to the ongoing shift of moving from project teams to expertise teams that works across multiple projects often resulting in higher productivity yields.

Knowledge codification was widely recognised by practitioners as essential, yet it remains a difficult principle to operationalise. While organisations acknowledge the need to retain and reuse knowledge, they struggle to translate tacit experience into structured, reusable assets. Challenges arise in transferring knowledge across projects. While lessons learned may be documented through evaluation at project closure, they are rarely converted into systematised and codified forms such as design rules, or configuration logics. In addition, underlying data is often fragmented, stored in inconsistent formats, or confined to individual projects. The experts linked this challenge back to specialisation, as a means to have coherent systems that enable knowledge capture across projects.

Practitioners mentioned a wide variety of activities in asset management where pre-engineering has benefits. Examples included pre-engineered parametric models for the reassessment of bridge typologies, development and use of IFD-standards to stimulate product-platforms for bridges, and detailed designs of specific modular bridge concepts that can be applied across projects. Across these applications, implementing this principle was seen to deliver clear added value.

Sociotechnical Alignment emerged as one of the most challenging and systemically important principles. Practitioners repeatedly noted that even when technical solutions exist (such as standards for IFD bridges) misalignment in contracts, governance structures, and organisational incentives prevents their adoption and potential. Examples included projects where standardisation was technically feasible but not contractually supported, resulting in bespoke solutions despite shared intentions to industrialise. Besides the variability in specifications across projects, current procurement practices often incentivise late-stage design changes thus hindering pre-engineering or the adoption of a pre-engineered concept.

Discussion

While extant literature has catalogued the barriers hindering industrialisation in construction a unified perspective explaining the foundational conditions required to enable this transition has remained largely absent, especially in the infrastructure sector. This study extends the existing body of knowledge by shifting the analytical focus away from individual enabling technologies toward the underlying conditions that shape industrialisation across the entire infrastructure value chain. The five principles identified through the thematic analysis collectively describe how industrialisation restructures the organisational, institutional, and production logic of infrastructure asset management. This supports the ongoing shift in the literature away from viewing industrialisation in construction as a production technique, toward understanding it as a broader organisational and system-level transformation of construction delivery (van Ee, 2022; Pottachola, 2024). The results help explain why the increasing maturity of individual enabling technologies has not translated into widespread adoption. The principles are not independent but forms an interdependent system of conditions. For example, Continuity and Repeatability create the essential market stability required for Specialisation. Without a predictable pipeline of aggregated demand, firms cannot justify the investments in specialised equipment or fixed process crews required for industrial efficiency (Vrijhoef and Koskela, 2005; EIB, 2022). Simultaneously, Knowledge Codification acts as the prerequisite for Pre-Engineering and configuration-based solutions. Shifting from tacit to explicit knowledge is critical for enabling digital configurators and product platforms that facilitate mass customisation (van Ee, 2022; Pottachola, 2024). Socio-Technical Alignment underpins the ability of organisations to sustain these industrialised practices over time by addressing the social gap where implementation fails due to a lack of cultural adaptation or workforce skills (Bletsis, 2020).

Partial implementation, such as adopting isolated technologies or methods without addressing their enabling conditions, is therefore unlikely to result in sustained productivity improvements. The interdependency of principles provides a plausible explanation for why many industrialisation initiatives remain confined to pilots rather than scaling across organisations and portfolios. By making these enabling conditions explicit, the principles offer a diagnostic lens for understanding where and why adoption stalls, and where targeted interventions are required.

These findings have important implications for infrastructure asset management organisations. Importantly, it challenges the implicit assumption that industrialisation is primarily a supply-side responsibility. Asset management activities can broadly be divided into demand-side led planning phases, and supply-side led realisation phases. In practice, industrialisation is frequently associated with the realisation phases through technologies such as prefabricated systems, with the locus of responsibility placed largely on contractors and manufacturers (EIB, 2022). While these technologies represent concrete applications of industrialisation, they are insufficient in isolation to deliver the required productivity gains. The principles highlight that without the bundling of demand and the harmonisation of technical standards across projects, the market lacks the continuity needed to invest in standardised, repeatable, and scalable solutions. Thus, industrialisation must be reconceptualised not just as a downstream construction tactic, but also as an upstream asset management strategy.

To support the formulation of such upstream strategies, the principles developed in this study provide an actionable reference for both individual asset owners and for coordination across asset owners within the wider infrastructure governance system. At the level of individual asset management organisations, the principles offer a structured way to translate industrialisation ambitions into concrete strategic choices. In practice, this may manifest in portfolio and programme bundling strategies that prioritise repetition and continuity, or in the selection of procurement and contract arrangements that incentivise long-term collaboration, data sharing, and knowledge reuse.

Beyond individual organisations, achieving industrialisation at scale requires coordination across asset owners. In the context of the polycentric Dutch infrastructure sector (Bletsis, 2020), industrialisation cannot be realised through top-down control or isolated organisational change alone. The principles provide a shared coordination mechanism that can support alignment across organisational boundaries. By articulating common conditions for industrialised project delivery, the principles offer a common language through which multiple asset owners can coordinate strategies. In practice, this may manifest in joint project bundling to create market continuity, as well as in the alignment of specifications and contract frameworks to enable standardisation and repeatability. In this sense, the principles enable coordination without centralisation, allowing asset owners to retain autonomy while contributing to a shared industrialisation trajectory.

The principles also complement existing maturity models and transition frameworks by shifting the focus from organisational capability to system-level suitability. Existing maturity models for industrialised construction, such as the Industrialised Construction Maturity Model which evaluates organisational enablers and outcomes (Wang et al., 2020), primarily assess how well an organisation is equipped to develop and deliver industrialised solutions. Implicitly, these models assume that the broader system conditions in which organisations operate are conducive to industrialisation. The principles proposed help to assess whether the foundational conditions across the value chain are aligned to enable industrialisation in the first place. For example, a contractor may develop a technically mature modular bridge concept that scores highly on existing maturity models yet fails to scale due to misalignment with demand-side practices and needs, procurement frameworks, or other sociotechnical conditions. By explicitly accounting for such system-level alignment, particularly between asset owners, market actors, and governance arrangements, the principles enable an assessment of whether organisations are operating within an appropriate playing field for industrialised infrastructure renewal. This system-oriented perspective is largely absent from existing maturity frameworks in the literature.

Conclusions

This study examined why industrialisation, despite recognised potential and technological maturity, has struggled to scale within the Dutch infrastructure renewal context. Through a thematic analysis of literature, complemented by expert validation, the study identified five foundational principles that characterise industrialised infrastructure asset management: Continuity and Repeatability, Specialisation, Knowledge Codification, Pre-engineering, and Sociotechnical Alignment. The findings illustrate that industrialisation cannot be realised through partial or isolated interventions. The principles are inherently interdependent, and this interdependence helps explain why many industrialisation initiatives remain confined to pilots, despite technological maturity. Importantly, the study highlights the decisive role of asset management organisations in shaping the conditions for industrialisation through upstream decisions related to portfolio planning, requirement setting, procurement, and long-term demand aggregation.

Through the principles, this study contributes a missing system-level perspective to the literature on industrialised construction. The principles provide a shared language for aligning stakeholders, structuring decision-making, and creating the conditions necessary for sustained productivity improvements. In doing so, it supports the transition of industrialisation from an abstract ambition to a structured, strategic approach capable of addressing the scale, urgency, and complexity of infrastructure renewal.

This study has several limitations that open avenues for future research. First, the framework is grounded in the Dutch infrastructure renewal context; its applicability to other construction domains with different governance and market structures remains to be tested. Second, the principles are primarily derived from literature and supported through expert validation rather than extensive empirical observation. Future work could therefore enrich the framework through case-based studies that examine how industrialisation conditions emerge and interact in practice. Third, the principles are currently treated as equally important. While their interdependencies are recognised, their relative weight, sequencing, and dominance remain unexplored. Further research could investigate these dynamics and translate the principles into maturity models for transition support.

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