THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Structuring Construction Projects for Integrated Delivery

A Spatio-Temporal BIM Framework Linking Design and Production Information and Teams

EFRAIM LJUNG

Department of Architecture and Civil Engineering

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Cover:
Icons representing categorised information structured within a spatio-Temporal Breakdown Structure (TBS)

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Motivational Context

I affirm that God is the creator of heaven and earth and that humanity is entrusted with the mandate to steward and govern creation in partnership with Him (Genesis 1:26–28).

In Genesis 11, the account of Babel illustrates the power of unified human action: “the people is one, and they have all one language… and now nothing will be restrained from them, which they have imagined to do.” This passage highlights how shared language, collective identity, and coordinated effort enable effective execution.

However, the project’s vision was misaligned with God’s intended purpose for creation. As a result, God confounded their language, disrupting their collaboration. The narrative thus demonstrates that while unity and coordination are powerful, they must be grounded in alignment with God’s purpose for mankind.

From a theological perspective, effective project management rests on unity, shared understanding, and coordinated action directed toward a purpose consistent with God’s design. This research explores how such principles can inform contemporary project management and contribute to more integrated and purposeful project execution.

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Abstract

The construction industry continues to struggle with low productivity, fragmented processes, and challenges in integrating design and production. While digitalisation efforts, particularly Building Information Modelling (BIM) have improved certain aspects of coordination, they have not fundamentally resolved the underlying structural fragmentation of project information. This thesis argues that the core issue lies not primarily in technology, but in how information is structured and understood across project stages. Current approaches operate at mismatched levels of abstraction: BIM provides an overarching representation of the built asset, while classification systems offer highly detailed coding schemes. Between these levels, a critical structuring gap remains largely unarticulated, making it difficult to identify, analyse, and ultimately resolve fragmentation in practice. To address this gap, the study adopts a Design Science Research approach to develop and evaluate a novel Spatio-Temporal Breakdown Structure (TBS) that integrates temporal (production-based) and spatial (location-based) dimensions into a unified information structure. By linking design information, production planning, and organisational responsibilities within a shared structure, the TBS enables a more explicit alignment between what is designed, how it is built, and who is responsible for delivery. Empirically grounded in two primary construction projects and drawing on practices like takt planning and BIM-based workflows, the research demonstrates how fragmentation emerges across information, organisation, and production logic. Rather than being a formal case study design, these project environments are used as testbeds for artefact development and evaluation within a Design Science Research approach. The findings show that existing structuring principles are insufficient for supporting flow-oriented production and interdisciplinary coordination. In contrast, the proposed framework introduces a more detailed yet coherent conceptualisation of project structure, making previously hidden interfaces and dependencies visible. The contribution of this thesis is twofold. Theoretically, it advances the understanding of construction information as a socio-technical system, bridging BIM, breakdown structures, and classification standards within a production-oriented paradigm. Practically, it provides a concrete and applicable structuring method that enables improved coordination, transparency, and predictability in project delivery. By positioning itself between high-level digital models and detailed classification systems, this research provides the industry with a practical way to identify and resolve fragmentation.

Keywords: Spatio-Temporal Breakdown Structure (TBS), Integrated Delivery, Building Information Modelling (BIM), Information Management, Takt Planning, Total BIM, Production.

Acknowledgements

This research is, at its core, driven by a persistent curiosity a need to understand how the construction industry truly works beneath its surface. What began as a professional interest gradually unfolded into something deeper: an exploration of the underlying logic, the hidden structures, and the flows of information, often hard to fully grasp, that shape the building process. The further I ventured, the more it felt like stepping into a kind of modern mythodrama where complexity, fragmentation, and coordination continuously interact, and where meaning must be actively uncovered.

I would like to express my sincere gratitude to Skanska, and in particular to Tobias Ekstedt and Peter Samuelsson, for giving me the opportunity throughout my professional career to explore and question the mechanisms of the construction process. Your openness made it possible to not only observe, but to truly investigate.

Patrik Johansson, thank you for your patience and for serving as a sounding board in the development of *Samläsningen*. What began as an idea in practice became the very entry point into this research journey.

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I am deeply grateful to everyone involved in the research through the case projects, and especially those in the primary design cases. Your patience during workshops, information analyses, and interviews has been invaluable. Thank you for believing in the ideas, for engaging openly, and for allowing the research access to the data needed to test its underlying theses.

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Finally, to my wife, thank you. For enduring walls covered in whiteboards, for the countless moments when my mind was elsewhere, immersed in processes and information structures. Thank you for believing in me, for your unwavering support, and for walking alongside me throughout this journey.

Gothenburg, April 2026

Efraim Ljung

Appended papers

Paper I:

Developing Support for BIM-based Takt-time Schedules for Production Control

Viklund Tallgren, M., Johansson, M., & Roupé, M., Ljung E. (2022). Developing support for BIM-based takt time schedules for production control. In Proceedings of the 22nd International Conference on Construction Applications of Virtual Reality Chung-Ang University, South Korea.

I contributed as a co-author through participation in empirical observations and discussions related to the Total BIM study visits, providing practice-based insights that informed the interpretation of findings and the development of the paper.

Paper II:

Identifying and Developing Prerequisites for Takt Planning in a BIM-based Construction Process

Ljung, E., Viklund Tallgren, M., Roupé, M., & Johansson, M. (2023). Identifying and developing prerequisites for takt planning in a BIM-based construction process. In CONVR 2023 – Proceedings of the 23rd International Conference on Construction Applications of Virtual Reality (pp. 574–584). Firenze University Press.

I am the main author and led the empirical work, including data collection and initial analysis, based on direct involvement in the Hovås Tak project and an associated internal development initiative. The analysis and interpretation were developed in collaboration with the co-authors, linking the empirical findings to the broader research context and existing literature.

Paper III:

The Significance of a Shared Breakdown Structure for Work Preparation Planning for a Predictable Execution

Ljung, E., & Viklund Tallgren, M. (2024). The significance of a shared breakdown structure for work preparation planning for a predictable execution. In Proceedings of the Creative Construction Conference. Prague, Czech Republic.

I am the main author and was responsible for the empirical data collection and analysis, including a second phase of data collection in Case 1 with additional interviews and recorded observations of roof assembly. The material was complemented with interviews and project data from Case 3, enabling comparative analysis across cases. The analysis and academic framing were developed in collaboration with a co-author.

Paper IV:

Can Interoperability between Disciplines be Improved by Adding Phasing Information Using Standardised Coding?

Ljung, E and Viklund Tallgren, M (2024) Can Interoperability Between Disciplines be Improved by Adding Phasing Information Using Standardised Coding? In: Thomson, C and Neilson, C J (Eds) Proceedings of the 40th Annual ARCOM Conference, 2-4 September 2024, London, UK, Association of Researchers in Construction Management, 111-120..

I am the main author and led the research and writing process, building on advanced literature studies in information structuring and construction standards. The work focuses on linking the empirically developed prototype to standardised information frameworks. The analysis and conceptual framing were developed in close collaboration with the supervisor.

Paper V:

BIM from Design to Production: Enabling Model-Based Construction Framework with Total BIM

Viklund Tallgren, M., Ljung, E., Disney, O., Johansson, M., & Roupé, M. (2025) In proceedings of the 25rd International Conference on Construction Applications of Virtual Reality (CONVR 2025).

I contributed as a co-author, participating in the development of the framework and the interpretation of results in collaboration with the co-authors. While the primary responsibility for writing lay with the supervisors, I contributed to discussions, analysis, and conceptual development, informed by ongoing work on the TBS artefact.

Additional publications

Digital Issue Reporting in Model-Based Construction Projects

Disney, O., Ljung, E., Roupé, M., & Johansson, M. (2024, November). Digital Issue Reporting in Model-Based Construction Projects. In International Conference on Construction Applications of Virtual Reality (pp. 99-111). Singapore: Springer Nature Singapore.

Terminology

In this research project, the following terms, definitions, and abbrevations are used:

Term	Definition
AMA (Allmän material- och arbetsbeskrivning)	Swedish standard for technical specifications and execution descriptions, based on BSAB classification.
Artefact	Designed construct, model, method, or system developed to address a problem.v
BAS-P	Building Work Environment Coordinator – Design stage. The party responsible for coordinating health and safety aspects during the design and planning stage of a construction project.
BAS-U	Building Work Environment Coordinator – Execution Phase. The party responsible for coordinating health and safety aspects during the execution stage of a construction project.
Breakdown structure	Hierarchical decomposition of project information, work, or systems.
BSAB 83 / BSAB 96	Swedish classification systems for structuring construction information and specifications.
Building Information Modelling (BIM)	Modelling technology and associated set of processes for producing, communicating, and analysing digital representations of built assets.
Certified inspector Kontrollansvarig (KA)	Certified third-party role in Swedish construction projects responsible for ensuring compliance with regulatory requirements and overseeing inspections and controls.
EN ISO 17412	Standard defining levels of information need (LOIN) for specifying required information content.
ISO 12006-2	Framework for structuring classification systems in construction.
ISO 16739 (IFC)	Open data standard enabling interoperable exchange of structured BIM information.
ISO 19650 series	International standards for information management using BIM across the asset lifecycle.
ISO 21511	Standard defining principles for structuring work breakdown structures (WBS).
ISO/IEC 81346 series	Standards for reference designation systems based on function, product, and location aspects.

Term	**Definition**
Level of information need (LOIN)	Specification of required information content, geometry, and documentation for a given use.
Production phase	A time-bounded unit of construction work defining a coherent scope, typically associated with a dedicated delivery team.
Production zone	A spatially bounded unit within a production phase that defines where work is performed, used in location-based planning and takt-based sequencing.
Project stage	Distinct lifecycle-level division of a project (e.g. design, construction, operation), distinguished from “phase”, which refers to subdivisions within production.
SBEF (Svensk Byggtjänst Elementförteckning)	Swedish classification structure for construction elements used in cost estimation and specification.
Semi-precast concrete elements	Hybrid concrete elements combining prefabricated components with in-situ casting.
Takt area / takt zone	Spatial unit in which work is completed within a takt interval.
Takt time	Defined production rhythm governing the pace of work.
Takt-time planning (TTP)	BIM-enabled operationalisation of takt planning in which production is structured into repetitive work sequences across defined locations and fixed time intervals. By linking takt time (production rhythm) with location-based planning, TTP enables coordinated visualisation and integration of design information with production control.
TBS (Spatio-temporal breakdown structure)	A structuring approach for organising construction information by integrating temporal (production phases) and spatial (production zones) dimensions as orthogonal principles.
Total BIM	Approach in which the BIM model serves as the primary and authoritative source of information across all project phases, replacing document-based practices and enabling a single source of information.

Table of Contents

1 My Point of Departure and Professional Background

Over the past twenty-five years in the construction industry, I have accumulated experience in a range of roles and from diverse perspectives on building projects. My professional trajectory has gradually shifted upstream from on-site construction work to design management generating a growing interest in how the entire construction process can be organised more efficiently. This section outlines the key professional experiences that motivated my transition to academia and shaped my research focus on improving productivity without sub-optimising or compromising quality, cost control, or the work environment.

1.1 Early Professional Experience: Foreman

After graduating as a structural engineer in 2000, I began my career as a foreman on a detached timber housing development consisting of multiple single-family homes in order to gain first-hand experience of construction practices and learn directly from skilled workers. My initial challenge was to understand how all the construction documents were connected. All available documentation was reviewed, and 2D drawings were overlayed, and sections and details were added to provide an overall understanding. Together with the skilled workers and colleagues at the site office, the planning of the construction process took on a work-breakdown structure that created shared understanding of the execution sequence. To provide the site manager with a reliable basis for labour-hour allocation, I reorganised the cost-estimation data in Excel so that it followed the actual execution process. This restructuring improved both resource planning and the follow-up of hours spent. As foreman I also led the site factory and the framing team. For prefabrication, I manually extracted information from design files to produce manufacturing drawings for load-bearing walls, façades, slabs, and roofs, and I managed factory logistics. The skilled workers were accustomed to hand made manufacturing drawings but by collaborating with designers, I obtained their digital DWG files and combined relevant layers into customised manufacturing drawings. These digital drawings were easier to revise and add details and comments to meet the needs of the skilled workers. The digital drawings demonstrated higher accuracy and greater reusability than the hand-made drawings in subsequent projects, an early confirmation of the productivity advantages of digital information management.

This practical knowledge, learning how to interpret the various project documents and reorganizing information to support the production process became a natural way of working on site. Although reviewing the full set of project documentation, including parts beyond one's immediate responsibility, is time-consuming it fosters a comprehensive understanding of the project. Over time, this approach came to be regarded as an established best practice. However, it also reflects a largely sequential, "waterfall-like" workflow, in which information is restructured downstream to support production, often making upstream verification and feedback difficult and cumbersome.

1.2 Leadership and Coordination: Site Manager

Advancing to the role of site manager in 2006, I became responsible for the full production process of a detached wooden-house development comprising one hundred houses. My leadership broadened from guiding a few teams to coordinating all trades/disciplines across multiple production phases. This provided a comprehensive view of how different phases are interlinked and the importance of having a common goal that connects all participants in the project. A common goal within a production phase improved collaboration and productivity within the phase but also needed to align with the overall project goal. Some disciplines delivered their work within a single phase, whereas others such as mechanical, electrical, and plumbing had sub-deliverables spanning several phases and needed to coordinate their work with different groups.

For example, in the wooden-slab factory, mechanical and plumbing components were partially installed before the beams were fixed in position, facilitating more efficient assembly. Structuring the project by production phases proved useful both for delegating responsibilities to foremen and for defining subcontractors' deliverables, as well as for planning site layout and logistics. In the detached woodhouse project, it was easy to follow the progress from phase to phase in each house. As I transitioned from detached housing projects to larger developments, such as apartment buildings and a school project, the overall production phases remained similar. However, due to the increased scale and complexity of the buildings, each production phase needed to be subdivided into smaller geographical areas, often referred to as production zones, aligned with the sequence of work. This type of spatial subdivision is inherently embedded in detached housing projects, where each unit naturally constitutes a discrete production zone.

The financial follow-up was often particularly challenging as budgets were often structured based on agreements and financial resource accounts that did not follow the actual workflow. Calculations had to be restructured so that production data could be sorted in phase and cost categories, allowing production reports to align with the budget structure while minimizing administrative effort.

At project completion, I was responsible for verifying that all sub-deliverables and production phases were properly integrated to meet client requirements and goals. Because construction documents had been re-organised into work preparations and manufacturing drawings, careful checking was required to ensure that functional intentions in the original design were not lost. This was also a time-consuming task that required long experience and understanding of the work process of production.

1.3 Design Management and Integration Challenges

My next position as design manager in 2015 revealed yet another critical dimension of the construction process. The design team's work-breakdown structure focused on the completed product and the technical systems that met client requirements, rather than on the production phases as I was used to. Knowledge of production processes within the design team was limited. Although early involvement of contractors and production personnel enabled the transfer of lessons learned from suboptimal design solutions, the traditional/established division into separate design and production teams continued to hinder the integration of information and workflows. In the production phase, disciplines are inherently aligned around a shared and tangible goal: the physical realisation of the building. This requires close coordination as different trades must integrate their work in space and time to assemble the building as a coherent whole. The interdependencies are explicit, and the need for collaboration is directly driven by the act of construction itself.

In contrast, the design phase is characterised by a division of responsibilities across technical systems, where each discipline develops its own subsystem (e.g., structural, plumbing). While these subsystems must ultimately be coordinated, their interfaces are often less clearly defined during design, making it difficult to delimit what information needs to be shared by whom and when. As a result, the unifying “common goal” present in production is less operational in design, where integration is more abstract and often deferred rather than continuously resolved.

To address this gap, I introduced a work process based on risk-assessment and logistics workshops, structured according to production phases and conducted during the design stage. For each phase, focus groups were formed, bringing together stakeholders from both design and production. These groups examined how planned construction sequences would impact technical systems, with the aim of improving constructability, optimising delivery logistics, and identifying risks that needed mitigation.

The approach evolved into a pilot project within the company to evaluate whether the work-breakdown structure of production phases could be embedded directly in construction documents. Such integration would enable the extraction of production-oriented features without laborious reorganisation, thereby significantly reducing the need for production teams to reinterpret and restructure design information. At the same time, the integrity of the original design structure would be preserved.

1.4 Transition to Research

This development project raised fundamental questions about how digital information structures can better support both design and production. These questions became the basis for my research proposal and the doctoral studies that followed. My practical background from on-site management to design coordination thus provided not only professional expertise but also a critical perspective on how improved digital integration can enhance productivity and predictability across the construction process.

2 Introduction

Although the construction industry plays a critical role for economic development and societal well-being, it still continues to face persistent challenges related to low productivity, fragmented processes, and inefficient information management. Despite technological advancements, productivity growth in construction has lagged behind other sectors, reflecting structural inefficiencies in how projects are organized and executed (Bühler et al., 2025; Hermansson & Song, 2024).

This productivity gap has been widely attributed to fragmented value chains, weak process standardization, and limited integration of digital technologies across project phases (Bühler et al., 2025; Samuelson & Stehn, 2023). The challenges indicate that the problem is not only technological, but also structural, relating to how information and processes are organised across the project lifecycle. A key manifestation of these structural challenges is the continued reliance on document-based information practices. In such approaches, project information is distributed among fragmented 2D drawings and documents.

This limits digital integration and contributes to inconsistencies, misinterpretations, and inefficiencies in project execution (Foroughi Sabzevar et al., 2024; Brooks et al., 2023). Construction projects are characterised by fragmentation across organisational, disciplinary, and lifecycle boundaries (Koskela & Howell, 2008; Samuelson & Stehn, 2023; Viklund Tallgren, 2021). As a result, project delivery involves multiple actors operating with partially disconnected information structures, leading to discontinuities between design and production. This structural fragmentation contributes to inefficiencies such as rework, delays, and coordination challenges. It also limits the ability to manage production as a continuous value flow, which is a central principle in Lean Construction. (Koskela & Howell, 2008; Samuelson & Stehn, 2023; Viklund Tallgren, 2021).

From an information perspective, these challenges result in insufficient integration and limited interoperability between systems and stakeholders. Although digital technologies such as BIM have been increasingly adopted, their implementation often remains limited to specific use cases and project phases. As a result, BIM supports disconnected information flows rather than integrated lifecycle systems (Sundquist et al., 2020; Samuelson & Stehn, 2023). Consequently, information generated during design stages is not effectively transferred or reused in production phases. At the same time, feedback from production is rarely structured in a way that supports systematic learning and continuous improvement across projects (Pishdad & Onungwa, 2024; Bühler et al., 2025; Disney et al., 2024).

Building Information Modelling (BIM) has been promoted as a key enabler for improving information management and integration in construction. Over time, BIM has evolved from a tool for 3D modelling into a broader paradigm for structured information management across the project lifecycle (Brooks, 2023; NBS, 2023). Standards such as ISO 19650 emphasize the importance of consistent information management processes and common data environments to support collaboration and information exchange (ISO 19650-2, 2019). However, despite increasing adoption, BIM implementation often remains limited to specific uses, such as design coordination, and does not fully support integration with production planning and execution (Royano et al, 2023; Rehman et al., 2025).

In parallel, Lean Construction has emerged as an alternative paradigm focusing on flow efficiency, waste reduction, and continuous improvement. Approaches such as the Last Planner System and Takt Planning aim to improve reliability and coordination in construction processes (Ballard & Howell, 1995; Prastyo & Wiguna, 2026). While these methods have demonstrated improvements in production performance, they are often implemented independently of digital information models, resulting in a disconnect between planning logic and the underlying project data (Bühler et al., 2025; Samuelson & Stehn, 2023).

Recent research highlights the need for more integrated approaches that combine product, process, and information perspectives. In particular, the lack of a unified information structure linking design models, planning entities, and production data has been identified as a critical barrier to achieving interoperability and seamless information flow (Gebremichael et al., 2022; Royano et al, 2023). Classification systems and breakdown structures provide a foundation for structuring information, but their application is often inconsistent and insufficiently connected to production processes (Royano et al, 2023, Kolarić, S 2022, ISO 12006-2, 2020; IEC 81346, 2023).
Addressing these challenges requires a shift towards integrative information structuring principles that can bridge the gap between design and production. Combining spatial (location-based) and temporal (process-based) dimensions has been identified as particularly important for supporting production-oriented planning and control (Bühler et al., 2025; Rehman et al., 2025). A unified project structure, in which both information and organisation are consistently structured, enables clearer interfaces, defined roles, and formalised information exchanges, thereby reducing fragmentation and supporting interdisciplinary integration (Sonnenwald, 1996).
Building on this background, the current study investigates how project information could be structured to support integrated project execution. The research is positioned within the field of construction management and digital construction, focusing on the intersection of BIM, Lean Construction, and information structuring. It adopts a Design Science Research (DSR) approach, in which an artefact is developed and evaluated to address identified problems in practice (Hevner, 2007).

The overarching research question guiding this study is:

How can project information be structured to reduce fragmentation between design and production and support an integrated and well-coordinated information flow throughout the project lifecycle?

To address this question, the study is organized around the following sub-questions:

1. What are the limitations of current project management and information structuring approaches for supporting integrated project execution?
2. How can integrative structuring principles, based on product and process perspectives, improve information consistency and interoperability?
3. Can a spatio-temporal breakdown structure be designed and implemented to support production planning and execution in construction projects?

To answer these questions, the study develops a Spatio-Temporal Breakdown Structure (TBS) as a conceptual and practical artefact. The TBS integrates spatial, product and process-oriented information with temporal-oriented dimensions to form a unified information structure, enabling the alignment of BIM-based design information with production planning and execution processes. By linking objects, locations, activities, and workflows within a coherent structure, the artefact aims to support designing, planning, control, validation, and knowledge transfer across project stages.

The contribution of this research is twofold:

- It advances the theoretical understanding of how integrated information structures can support construction project management by bridging BIM, breakdown structures, and classification systems.
- It provides a practical contribution through the design and evaluation of an artefact that can be applied in real-world projects to improve coordination, transparency, and production performance.

In this context, the core contribution is the development of TBS as a unified information structuring mechanism linking design and production. In doing so, the study responds to the need for more robust and scalable approaches to managing information in construction and contributes to the ongoing digital transformation of the industry (Samuelson & Stehn, 2023; Bühler et al., 2025).

3 Theoretical frame and related works

This chapter presents perspectives from both industry and academia on Building Information Modeling (BIM), focusing on how information in construction projects is categorized, structured, and standardized. It further examines how such information can be decomposed and organized to support project management throughout the lifecycle of a built asset. By synthesizing existing research and standards, the chapter builds a conceptual foundation for understanding information as a structured resource, which is essential for enabling integrated and production-oriented project delivery.

3.1 Information Required to Execute a Project

Building Information Modeling (BIM) has gained widespread recognition as a transformative development in the architecture, engineering, and construction (AEC) sector, enabling stakeholders to collaborate more accurately and efficiently compared to traditional processes (Azhar, 2011; Eastman et al., 2018). However, despite its well-documented potential, BIM adoption has consistently fallen short of expectations (Azhar, 2011; Ghaffarianhoseini et al., 2017; Walasek & Barszcz, 2017) and remains uneven across projects and organizations. Recent studies indicate continued growth yet also highlight persistent inconsistencies in how BIM is understood and implemented. For example, BIM adoption in the United Kingdom increased from 13% in 2011 to approximately 70% in 2023, although the interpretation of "adoption" varies significantly across respondents (National BIM Specification [NBS], 2023). Similarly, a survey of Swedish contractors reported a 58% adoption rate, but primarily associated to BIM us for visualization, communication, and coordination rather than fully for integrated information management (Bosch-Sijtsema et al., 2017). More recent research reinforces this pattern, showing that while BIM applications such as 4D and 5D provide clear benefits in terms of visualization, planning, and cost control, their use is often limited to specific project phases or isolated applications rather than fully integrated lifecycle processes (Pishdad & Onungwa, 2024; Rehman et al., 2025). This suggests that while BIM is increasingly used, its implementation often remains partial and limited in scope.

One underlying challenge is that BIM is defined in multiple, overlapping ways by researchers, industry bodies, and software providers (International Organization for Standardization [ISO], 2018a; Succar, 2009). The *BIM Handbook* defines BIM as "a modeling technology and associated set of processes to produce, communicate, and analyse building models" (Sacks et al., 2018, p. 14), whereas ISO 19650-1 characterizes it as the "use of a shared digital representation to facilitate design, construction and operation processes" (ISO, 2018a). Despite differences in emphasis, these definitions converge in highlighting BIM as more than a digital model or software application. Rather, BIM represents a structured approach to creating, managing, and exchanging information across the lifecycle of a built asset. Extending this perspective, recent research has introduced the concept of *Total BIM*, where the model is not only a shared representation but also the primary and authoritative source of information throughout all project phases, effectively replacing traditional document-based practices (Disney et al., 2024). This interpretation emphasizes BIM as a fully integrated information environment, where design, construction, and operational data are continuously developed and managed within a single digital framework.

Taken together, these perspectives indicate a shift from document-based to information-based processes, which is central to ongoing digital transformation efforts in the construction industry (Samuelson & Stehn, 2023).

As built assets become increasingly complex, project teams have become more specialized, reinforcing fragmentation in project delivery and information exchange (Fisher et al., 2017;

Nepal & Staub-French, 2016; Samuelson & Stehn, 2023). This fragmentation is further reinforced by the project-based nature of the industry, where temporary organizations and discipline-specific practices limit continuity and integration across lifecycle phases (Samuelson & Stehn, 2023). In parallel, technological adoption has often occurred in isolated silos, where digital tools are implemented within specific domains without full integration into project-wide workflows (Sacks et al., 2018). Addressing these challenges requires not only technological solutions but also a coherent strategy for integrating teams, processes, and information structures (Fisher et al., 2017). Consequently, the architecture and organization of information itself become a critical enabler for achieving integration.

BIM functionality fundamentally depends on systematically structured and classified information, which enables interoperability across diverse tools and data schemas, such as IFC-based or classification-based exchanges. It also underpins the integration of multidisciplinary information sources from design and planning through construction and operation via shared data models, controlled vocabularies, and governance mechanisms (Kiviniemi, 2005; Laakso & Kiviniemi, 2012; Succar, 2009). A structured information environment is therefore essential for coordinating contributions across professional domains and for maintaining data consistency and integrity throughout a building's lifecycle. Without such a structure, the potential of BIM to support integrated project delivery remains limited.

International standards such as ISO 19650 (ISO, 2018a), ISO 12006-2 (ISO, 2015), ISO 16739 (ISO, 2018b), ISO 21511 (2018c) and ISO 81346 (ISO, 2022) provide frameworks for organizing construction information, while the Industry Foundation Classes (IFC) support open and interoperable data exchange. Drawing upon these standards and extant scholarship, project information can be grouped into the following interrelated categories:

1. **Requirements and client objectives**: vision, purpose, organisational information requirements (OIR), functional objectives, and performance criteria
2. **Product information**: geometric and semantic attributes, including materials, components, and performance properties
3. **Process information**: plans and schedules, cost estimates, logistics, organisational structures, and governance mechanisms
4. **Operation and maintenance information**: facility management data, performance monitoring, and lifecycle analyses
5. **Competence and experiential information**: tacit knowledge, best practices, and lessons learned, and
6. **Regulations and guidelines**: statutory requirements, building codes, permits, certifications, and industry standards

These categories provide a structured basis for classifying and exchanging project-relevant information across lifecycle phases. They capture different but interrelated types of information required to support decision-making, coordination, and execution throughout the project (Tauriainen et al., 2016; Fisher et al., 2017; Gu & London, 2010; Kiviniemi, 2005; Nonaka, 1994; Sacks et al., 2018; Succar, 2009).

In parallel to such categorizations, alternative approaches have been developed to structure and operationalize project information within BIM-based processes. One widely adopted approach is the concept of nD BIM, where additional types of information are integrated into the model beyond 3D geometry. Typical extensions include 4D (time), 5D (cost), and higher dimensions such as 6D and 7D, often associated with sustainability and facility management. These extensions enable improved visualization, planning, and control of construction processes, as well as enhanced lifecycle-oriented information management (Chuck Eastman et al., 2011; Bilal Succar, 2009; Pishdad & Onungwa, 2024; Rehman et al., 2025).

In addition, the concept of BIM maturity levels has been introduced to describe the degree of integration and collaboration among project stakeholders. Levels range from fragmented, document-based practices to fully integrated and model-based environments, where information is consistently shared and managed across disciplines and lifecycle phases (Bilal Succar, 2009; Kamal Khosrowshahi & Yasaman Arayici, 2012).

While these approaches emphasize the integration of specific information types or levels of collaboration, the categorization adopted in this study instead provides a complementary perspective by explicitly structuring information in relation to project requirements, product, process, and lifecycle considerations.

Such structural clarity becomes particularly important in emergent approaches such as Total BIM, where the digital model functions as the single source of truth throughout design, construction, and operation. Research indicates that this approach requires rigorously structured and consistently maintained information, integration of legal and contractual frameworks, and seamless information transfer across lifecycle phases (Disney et al., 2024). These factors reinforce the notion that BIM's full value can only be realized when information is treated as a strategic asset, systematically structured, governed, and exchanged in standardized ways.

3.2 Integrated Breakdown Structures for Construction Project Management

To manage BIM-enabled processes in construction projects, information must be decomposed into manageable and interoperable units. Breakdown structures constitute a fundamental mechanism for structuring and integrating project information. According to the Project Management Body of Knowledge (PMBOK), a Work Breakdown Structure (WBS) is a hierarchical decomposition of the total project scope that ensures complete coverage of all work, commonly referred to as the "100% rule" (PMI, 2017; ISO, 2018c).

Originally developed for systematic project control in the U.S. defence industry in the 1960s, the WBS has evolved into a central structuring mechanism in BIM-based environments, providing a common reference for coordinating design, planning, and cost estimation (ISO, 2018c; Jung & Woo, 2004). In practice, it is complemented by additional breakdown structures representing different management perspectives, including the Cost Breakdown Structure (CBS), Risk Breakdown Structure (RBS), Information Breakdown Structure (IBS), and Location Breakdown Structure (LBS) (ISO, 2018c; Gebremichael et al., 2022).

The integration of these structures enables alignment between technical domains by linking work packages to cost accounts, spatial units, risk elements, and information requirements. For example, integrating WBS with CBS supports consistent cost and schedule control, while linking WBS and LBS enables location-based and takt-oriented planning. Empirical studies indicate that such integrated structures can improve coordination, reduce schedule deviations and support more reliable and controllable project execution (Cerezo-Narváez et al., 2020; Radman et al., 2025; Rehman et al., 2025).

Beyond their analytical role, breakdown structures also function as a shared communication framework, supporting responsibility mapping, information exchange, and performance tracking across project phases (Ballard & Howell, 2003). Despite these advantages, the integration of multiple breakdown structures is often constrained by heterogeneous classification systems and inconsistent structuring principles (Gebremichael et al., 2022; Pishdad & Onungwa, 2024). In practice, different project actors apply discipline-specific coding systems and decomposition logics, resulting in semantic inconsistencies and limited interoperability across lifecycle phases. These challenges are further amplified by the absence of standardized structuring and naming conventions within work breakdown structures and related planning artefacts such as schedules. As multiple valid WBS configurations can be constructed for the same project—reflecting different organisational perspectives, functional decompositions, or lifecycle orientations—no single dominant structuring logic emerges (Globerson, 1994). Consequently, parallel structuring practices develop across disciplines, where variations in terminology, coding, and levels of detail complicate the integration of schedules, cost structures, and information models. Without a shared decomposition language, this leads to inconsistencies in how work packages are defined and referenced, resulting in duplication, hidden interfaces, and reduced transparency in planning and control (Cretu, 2025).

International standards such as ISO 21511 (2018c) and the ISO 19650 (2018a) series address these challenges by defining principles for hierarchical decomposition, relationships to organisational and functional structures, and requirements for a Common Data Environment (CDE). However, these standards primarily provide high-level guidance but do not define a detailed mechanism for achieving consistent integration across breakdown structures.
From a theoretical perspective, further limitations arise from the underlying assumptions of breakdown structures. As argued by Koskela and Howell (2002), traditional structures are grounded in a transformation-based view of production, where projects are decomposed into discrete tasks. While effective for hierarchical control, this perspective does not adequately capture production flow, interdependencies, or the dynamic nature of project execution.
To address these limitations, Gebremichael et al. (2022) propose the concept of a Unified Breakdown Structure (UBS), which introduces two stable primary structures: the Physical Breakdown Structure (PBS), representing physical components, and the Functional Breakdown Structure (FBS), representing lifecycle activities. Secondary structures such as WBS, CBS, and LBS are then consistently referenced to these primary structures, enabling improved consistency and interoperability across disciplines and project phases.
The UBS framework aligns with the objectives outlined in ISO 21511 (2018c), particularly with respect to improving communication and control throughout the project lifecycle. In parallel, the ISO 19650 (2018a) framework introduces the concept of delivery teams as multi-disciplinary groups responsible for defined information. Together, these approaches emphasize the need to structure information in relation to both physical and functional systems, as well as organisational responsibilities. From a communication perspective, both early work on boundary-spanning roles (Sonnenwald, 1996) and more recent BIM research highlight the importance of structured mechanisms for integrating distributed knowledge across disciplines. In BIM environments, structured information artefacts, such as models and classification systems, provide a shared basis for coordination and information exchange (Sacks et al., 2018). Embedding PBS and FBS identifiers within a Common Data Environment (CDE), alongside clearly defined information responsibilities, supports the linkage between information containers and their physical and functional context. This improves traceability, reduces duplication, and contributes to a more coherent information environment for collaborative project execution (Gebremichael et al., 2022; ISO 21511, 2018c).

3.3 Standardization for Information Coding and Construction Process

Since the 1930s, when Sweden first began to systematize building information, the construction sector has continuously sought effective methods for classifying and structuring project data (Royano et al., 2023). This section traces the evolution of Swedish classification systems from BSAB to CoClass and positions ISO/IEC 81346 (2022) as an enabling framework for multi-aspect, lifecycle-oriented information coding. It further connects these structuring principles with the process and information management frameworks of ISO 19650 (2018a) and expands the perspective to the Norwegian concept of Systematic Completion and its associated maturity indices (MMI and FMI), which operationalize the development and verification of information and functional performance throughout the project lifecycle. (Prosjekt Norge, 2016; Prosjekt Norge, 2023; Entreprenørforeningen Bygg og Anlegg et al., 2022)

3.3.1 From BSAB to CoClass: Towards Lifecycle-Structured Information

In Swedish construction practice, a coding system, BSAB 96, which was refined and released in 1996, remains the dominant classification system, underpinning technical specifications through AMA, as well as procurement processes and quantity take-off. The Swedish National Board of Housing (Boverket, 2022) notes that BIM models are often structured according to BSAB 96, while estimations, climate declarations and life cycle assessment (LCA) practices still rely on earlier BSAB 83/SBEF logic (SBUF, 2013, Malmqvist et al., 2023).

However, the increasing use of BIM and digital workflows has exposed limitations in these legacy classification systems, particularly in terms of insufficient granularity and limited support for the consistent identification of building components across different project phases and information domains. As project information becomes more detailed and interconnected, there is a growing need for classification systems that enable precise, unambiguous, and machine-readable identification of components, systems, and their relationships.

In response to these challenges, CoClass was introduced in 2016 as a new Swedish classification system designed to support a higher level of detail and a more comprehensive representation of the built environment. CoClass represents a conceptual advancement by aligning with international standards such as ISO 12006-2 and ISO/IEC 81346, thereby enabling consistent identification of functional, spatial, and product-related aspects across the asset lifecycle (Svensk Byggtjänst, 2019). In this respect, CoClass supports a shift from document-based classification toward structured and machine-readable information environments, which are essential for digital project delivery and lifecycle information management.

The ISO/IEC 81346 series provide a Reference Designation System (RDS) in which any physical or logical object can be classified according to three primary aspects: Function (F), Product (P), and Location (L) (International Organization for Standardization [ISO], 2022). CoClass adopts and extends this multi-aspect logic into a comprehensive classification framework suitable for BIM, digital twins, and asset management. Ongoing developments within the ISO/IEC 81346 series, led by ISO/TC 10 (International Organization for Standardization, n.d.), including emerging parts addressing manufacturing systems and processes, further indicate a gradual extension of the standard towards supporting information structuring across both project execution and operational phases. This development reinforces the relevance of integrating temporal and production-related aspects into standardized information models.

Masterstudies of the Swedish construction industry (Alkawamleh & Vindevall, 2025; Kaimeh, 2024; Larsen, 2023) indicate that legacy classification structures, particularly BSAB, remain deeply embedded in tools, processes, and contractual practices, while newer systems such as CoClass have slower adoption. This suggests that the transition is not only a technical challenge but also an organisational and institutional one.

3.3.2 Lifecycle Information Maturity and Systematic Completion

Information in construction projects evolves progressively throughout the lifecycle, as formalized in the ISO 19650 series and further specified in EN 17412, which defines levels of information need. To operationalize these principles, the Norwegian construction sector has developed the concept of Systematic Completion, integrating the Model Maturity Index (MMI) and the Function Maturity Index (FMI) as structured approaches to managing digital and functional development (Prosjekt Norge, 2016; Prosjekt Norge, 2023; Entreprenørforeningen Bygg og Anlegg et al., 2022).

Systematic Completion provides a process-oriented framework to ensure that the delivered asset fulfils defined functional requirements by coordinating information maturity across design, construction, and commissioning. Conceptually, it aligns with systems engineering principles and the V-model, where requirements definition and system decomposition are systematically linked to verification and validation activities throughout the lifecycle.

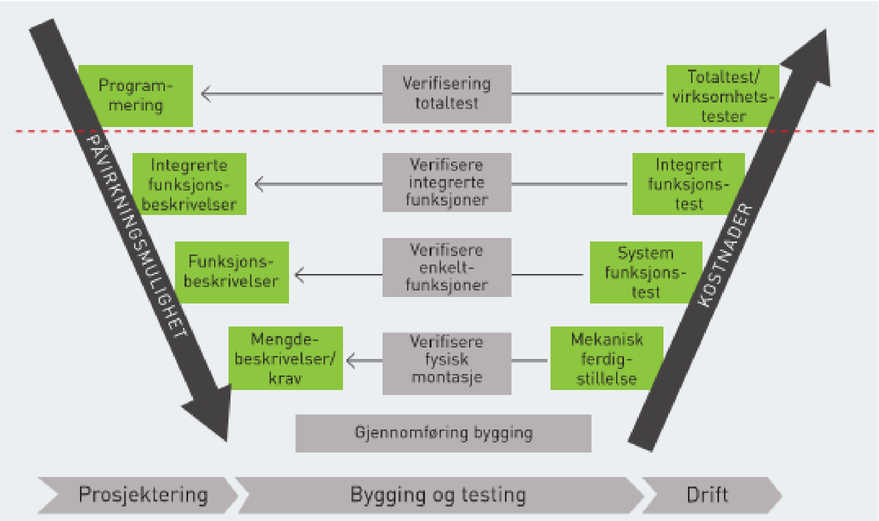

Figure 1 V-modell for Construction project, Prosjekt Norge, 2016, section 8

The MMI defines the maturity of digital models across standardized levels (MMI100–MMI500), while the FMI captures the progressive validation of system functionality (FMI100–FMI700). Together, they establish a dual-layered structure that synchronizes model development with functional performance, supporting traceability between requirements, design, and verification. In this way, Systematic Completion operationalizes ISO 19650 principles while aligning with the multi-aspect structuring logic of ISO/IEC 81346.

3.3.3 Linking Information Structure to Production Flow

Construction projects can be structured through two interrelated perspectives: system structures, which define the built asset and its components, and breakdown structures, which organize work, cost, and spatial information. Integrating these perspectives is essential for coherent digital information management and effective value creation in BIM and VDC environments (Seppänen et al., 2010; Kunz & Fischer, 2020).

While classification systems and maturity frameworks support the structuring and validation of information, they do not directly support the planning and control of production processes. In contrast, Lean-based approaches such as takt planning explicitly address production flow by structuring work in time and space. Takt planning is a Lean-based production methodology that organizes construction work into repetitive and synchronized cycles, aligning activities, resources, and spatial zones in time and space to achieve a continuous and balanced workflow (Ballard & Howell, 2003; Seppänen et al., 2010).

3.3.4 Classification Practices in an International Context

International classification systems for construction information have largely developed as national implementations of the ISO 12006-2 framework, resulting in structurally similar but context-specific systems. Examples include Uniclass 2015 in the UK, supporting process-oriented BIM workflows, Finland’s Talo system with a strong element-based approach for cost and production control, and Norwegian NS/TFM frameworks emphasizing lifecycle information management. Despite these similarities, no unified global system exists, and current practice remains fragmented across national standards, requiring mapping and adaptation in international projects. This highlights the importance of positioning Swedish CoClass within a broader interoperable yet heterogeneous classification landscape.

3.4 Summary and Implications for the Study

Taken together, the literature shows that the integration of information coding (ISO/IEC 81346 and CoClass), process structuring (ISO 19650 and EN 17412), and lifecycle maturity management (Systematic Completion, MMI, and FMI) defines a coherent framework for managing construction information. This integrated perspective positions information management not merely as a technical issue of classification, but as a socio-technical process of aligning systems, functions, and data maturity across the project lifecycle. At the same time, the emergence of flow-oriented production methods such as takt planning underscores the need to further connect information structures with the dynamics of construction execution. Despite these advances, a unified way of integrating spatial, temporal, and information structures across design and production is still lacking, highlighting the need for a structured approach to support integrated project execution. Hence, this thesis addresses this gap through the development of TBS, following a Design Science Research approach focused on the iterative development and evaluation of an artefact to address practical problems while contributing to scientific knowledge. (Johannesson, 2021, chapter 4). The research is grounded in a socio-technical systems perspective, where project performance emerges from the interaction between information structures, organisational arrangements, and production processes (Sonnenwald, 1996; Sacks et al., 2018; Samuelson & Stehn, 2023). Furthermore, it is complemented by production theory (Transformation–Flow–Value), which emphasises flow and the limitations of traditional task-based decomposition (Howell, 1994, Koskela & Howell, 2002; Koskela & Howell, 2008), which form the theoretical foundation for the methodological approach presented in the following chapter.

The review indicates that existing approaches address spatial and temporal aspects of construction separately, with limited support for structuring information in relation to both dimensions. This highlights the need for a more integrated approach to information structuring in the production phase. The TBS addresses this by introducing a spatio-temporal structuring logic that links activities to production zones and sequences, supporting coordination between design and production.

4 Research Design and Methodology

This chapter presents the research design, methodology, and processes used in this study. The research adopts a Design Science Research (DSR) approach to address the identified gap by developing and evaluating a structured artefact, the Spatio-Temporal Breakdown Structure (TBS), intended to support the integration of design and production information.

In this context, the artefact represents both a conceptual structure and an operational framework for organising information in construction projects. The chapter explains how the DSR approach guided the iterative development and evaluation of the TBS, and how the research process was structured to ensure both theoretical grounding and practical relevance. The research aims to address the long-standing problem of fragmented information structures between design and production phases in construction. This is done by taking a practice-oriented approach grounded in real project environments often seen in design science research-based projects.

The research is guided by a socio-technical systems perspective and production theory (Transformation–Flow–Value), which provide a conceptual lens for the design of the artefact and the interpretation of empirical findings (Sonnenwald, 1996; Sacks et al., 2018; Samuelson & Stehn, 2023; Koskela & Howell, 2008). In this context, using Design Science Research as the overarching framework enabled identification of prerequisites, the creation and evaluation of an artifact that would solve an identified problem while contributing to scientific knowledge. The methodology follows Alan R. Hevner's (2007) three-cycle view of DSR and integrates empirical data from case studies and collaborative research projects, several of which are documented in the appended papers.

4.1 Design Science Research as the Overarching Approach

Design Science Research (DSR) is a problem-solving approach aimed to generate scientific knowledge through a systematic building and evaluation of artifacts (Hevner, 2007; Gregor & Hevner, 2013). An artifact may take the form of a model, method, construct, or instantiation (March & Smith, 1995). Within construction management research, this approach has proven particularly suitable for bridging the gap between practical improvement and academic rigor (Cole et al., 2005; Iivari, 2007).

In this thesis, DSR provides a structured framework for exploring how digital information structures can be improved through iterative design and evaluation. The main contribution, the TBS, is conceptualised as a composite artefact comprising both a model and a method in line with Design Science Research (DSR) principles.

The TBS artefact consists of:

- **A spatio-temporal structuring model**, defining how project information is organised according to spatial (location-based) and temporal (process-based) dimensions
- **A multi-aspect coding and referencing logic**, linking product, process, and location aspects into a coherent and interoperable structure
- **A lifecycle-oriented method for structuring and managing information**, guiding how project information is progressively organised and aligned across design and production stages, and

- **A mapping mechanism to existing standards**, enabling integration with established classification systems and frameworks (e.g., ISO 19650, ISO 12006-2, ISO/IEC 81346, and CoClass)

From a DSR perspective, these components together enable the TBS to function as an integrative artefact that improves coordination, communication, and predictability between design and production Thereby TBS reduces information fragmentation and supports a consistent information flow.

4.2 The Three-Cycle View of Design Science Research

The study follows Alan R. Hevner's (2007) three interrelated cycles.

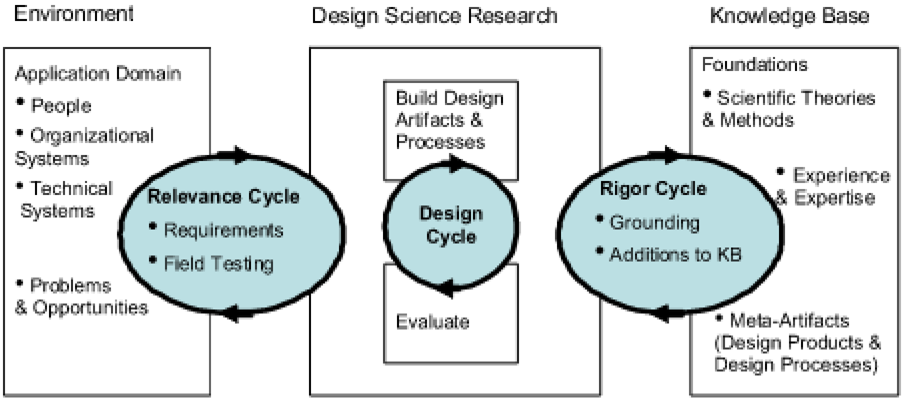

Figure 2 The Three-Cycle View of Design Science Research (adapted from Hevner, 2007, Figure 3.1).

The figure illustrates the three interrelated cycles that form the foundation of Design Science Research. Together, these cycles ensure that the research at hand maintains both practical relevance and scientific rigor.

- **The Relevance Cycle** connects the research to industry practice through case projects and empirical observations. It captures the practical challenges related to information fragmentation and incorporates empirical insights derived from the researcher's point of departure and the studied cases.
- **The Design Cycle** supports the iterative development and refinement of the TBS artefact. This cycle constitutes the core of the research process, where the TBS is progressively refined through successive design iterations.
- **The Rigor Cycle** ensures grounding in existing literature on BIM, classification systems, and production planning. Links the research to existing knowledge bases, including both academic literature and established practices within the construction industry, such as standardization efforts and project management methodologies. Relevant DSR literature ensures theoretical grounding and methodological rigor, while the study contributes new knowledge back to the field.

4.3 Research Process and Design Framework

The overall research process followed a structured progression aligned with the Design Science Research (DSR) framework proposed by Paul Johannesson and Erik Perjons (2021) (Figure 3). The process consisted of five main iterative phases: explicating the problem; defining requirements; designing and developing the artefact; demonstrating the artefact; and evaluating it in practice. Each phase informed subsequent iterations, enabling progressive refinement of both the artefact and the underlying problem understanding.

The process was initiated through an initial problem formulation, which was further refined through empirical investigation to identify the underlying causes of information fragmentation. Based on this, a set of design requirements was defined, forming the foundation for the development of the artefact. The artefact was then iteratively developed, demonstrated in real and simulated project environments, and evaluated in relation to its ability to address the identified problem.

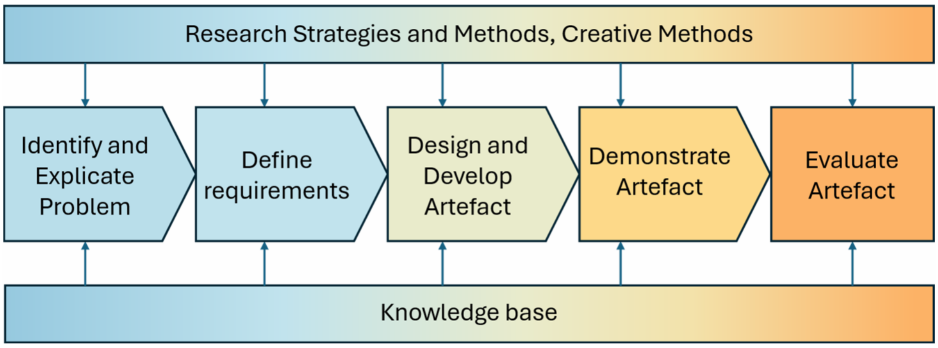

Figure 3 The method framework for Design Science Research with research strategies and knowledge base (adapted from Johannesson & Perjons, 2021).

4.4 Iterative Development of the Artefact

The TBS is developed as a generic structuring principle rather than a project-specific implementation. It is based on the integration of two orthogonal dimensions: a temporal dimension, represented by production phases, and a spatial dimension, represented by production zones. The development of the artefact followed an iterative design process consisting of two main cycles, resulting in two successive prototypes. Each cycle combined empirical investigation with theoretical refinement, contributing to both an improved understanding of the problem and the progressive development of the artefact.

4.4.1 Prototype 1 – Empirical Problem Exploration and Initial Design

The first prototype originated from an in-depth study of information flows in a real construction project, Hovås Tak (Project in Case 1). The study was initiated by recurring challenges observed in practice, particularly the need to rework design information to fit production processes. This reflects a sequential ‘waterfall’ logic, where design and production are weakly integrated, leading to inefficiencies and loss of information continuity.

The research strategy for this phase was exploratory and practice-based. A focus group consisting of 10 representatives from different disciplines within the project was formed and followed throughout the study. Data were collected through interviews, focus group workshops, and analysis of how information was created, transformed, and used across project phases. This enabled a nuanced understanding of the problem and its underlying causes.

The knowledge base in this phase was primarily empirical, consisting of:

- Experiences from participating stakeholders
- Observations from the Case 1, and
- The researcher's own professional experience

As described in Paper II, the analysis identified the need for a shared information structure, which became the central design principle for the first prototype.

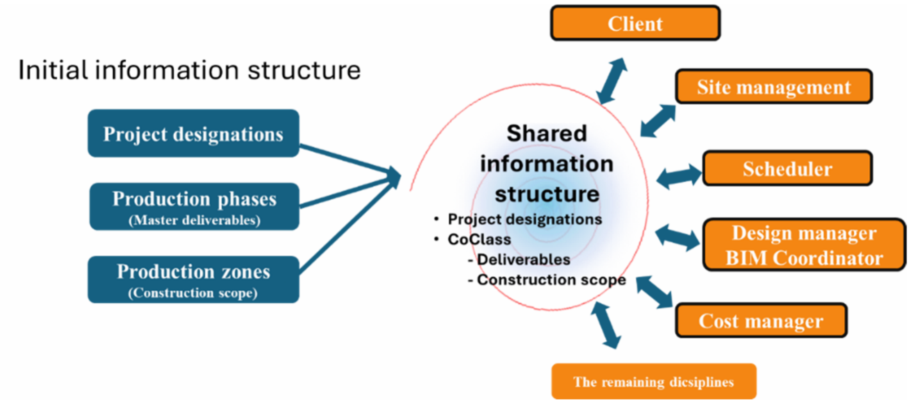

Figure 4 First prototype of the artefact and the establishment of a shared information structure from Paper II

The resulting information structure was partially implemented and guided the project's information management approach. However, full implementation was not achieved. The evaluation of the prototype revealed several critical challenges, including:

- Limitations in existing classification systems
- Constraints in software tools and interoperability
- Resistance related to established work practices

These findings, further elaborated in Papers II and III, demonstrated both the potential of the approach and the need for further development.

The initial prototype thus primarily contributed to explicating the problem and defining initial design requirements, while also providing a first instantiation of the artefact.

4.4.2 Prototype 2 – Theoretical Expansion and Artefact Refinement

The challenges identified in Prototype 1 formed the basis for a second, more comprehensive research cycle. This phase aimed to deepen the understanding of the problem and expand the knowledge base in order to refine the artefact and improve its applicability across different project contexts.

To achieve this, additional Case 2-4 were included in the study to investigate whether similar challenges related to information fragmentation and the integration of design and production could be identified. In Eriksberget (Project in Case 2), where the project started with insights gained from Hovås Tak, the research further developed the information structure of the first prototype.

The research strategy combined empirical and analytical approaches. Expert interviews and workshops with specialists in information management were conducted to identify requirements for robust and scalable information structures. As described in Paper IV, this work demonstrated how multi-aspect coding enables both discipline-specific detailing and cross-disciplinary integration.

In this phase, the knowledge base was significantly expanded and formalized. In addition to empirical insights, it included:

- Project management methodologies (e.g., Lean Construction, Takt-planning, VDC, Systematic Completion)
- Information management frameworks (e.g., classification systems, breakdown structures, information maturity concepts such as FMI and MMI), and
- Relevant standards and theoretical models described in chapter 3 Theoretical frame and related works.

To support experimentation and validation beyond individual project constraints, a testbed, the SIM House was developed as a subset of data from the Eriksberg project. This testbed enabled controlled testing of information structures and workflows, allowing the artefact to be developed and evaluated independently of specific project conditions. A detailed analysis of the empirical material resulted in a refined and more explicit set of design requirements for the artefact. Based on these requirements, the TBS was further developed and anchored in established industry standards and theoretical frameworks.

Building on these insights, the second prototype, presented in this thesis, formalizes the artefact through integration with:

- Integrated breakdown structures for construction project management
- Standardization of information coding and construction processes, and
- Information management frameworks required for project execution

Through this refinement, the artefact evolved into a more robust and generalizable conceptual model, providing a structured approach for integrating design and production information across project contexts, Figure 5 and Figure 6.

This iterative development process demonstrates how the artefact progressed from context-specific empirical insights to a theoretically grounded and transferable solution for model-based production planning and control.

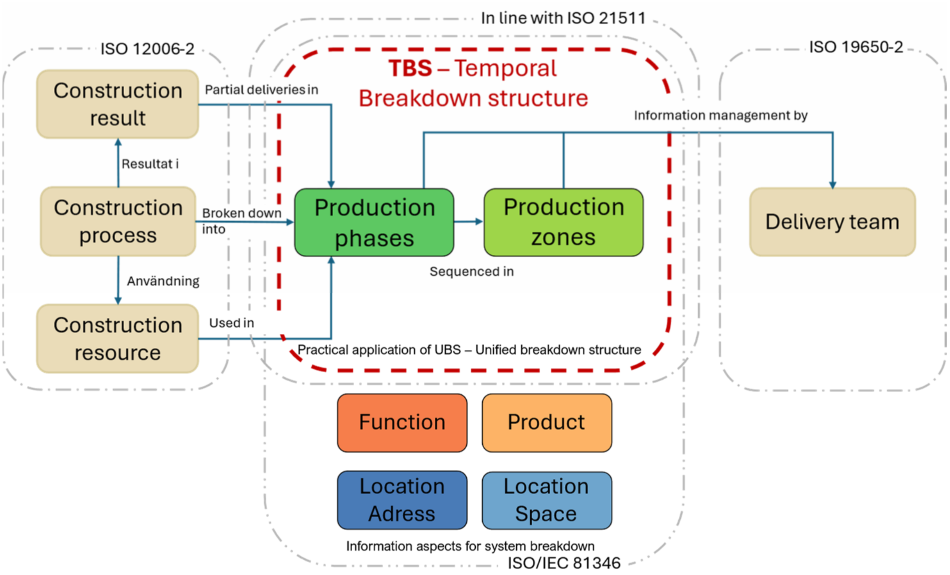

Figure 5 The TBS model artefact conceptualized in relation to ISO standards, illustrating the integration of the information model (structure).

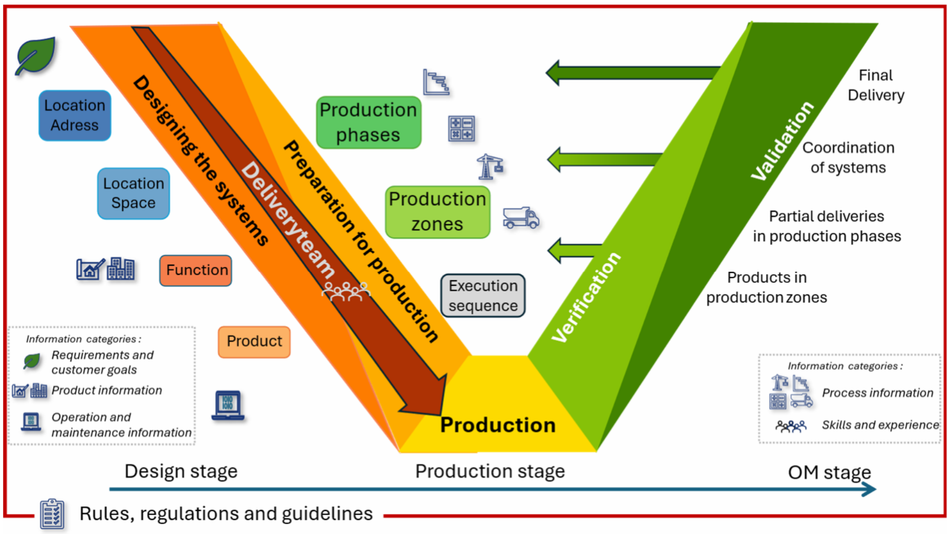

Figure 6 The TBS method artefact conceptualized in relation to project lifecycle, illustrating the information method (flow), aligned with systems engineering principles

4.5 Research Design and Data Collection

This study adopts a qualitative, design-oriented case study approach, with Design Science Research (DSR) serving as the overarching framework. The empirical work was conducted in close collaboration with ongoing industry projects, where the researcher was actively involved. This enabled a combination of participatory observation and cross-case comparison, supporting both artefact development and evaluation.

Data collection was structured to support the iterative development and validation of the TBS artefact. Multiple complementary methods were employed, allowing for comparison of data and insights across different project contexts.

The research process followed an iterative design logic, where empirical insights informed successive refinements of the artefact, and each iteration was evaluated through workshops, pilot implementations, and feedback sessions. To support this iterative design process, data collection was structured using multiple complementary methods, each contributing to different stages of artefact development and evaluation. The methods are presented below.

4.5.1 Workshops and Focus Groups (Artefact Development)

Workshops and focus groups constituted a primary method for artefact development and evaluation. These sessions involved project managers, site engineers, BIM coordinators, designers, and other relevant stakeholders, depending on the project phase and the type of information under investigation. Participants were selected based on their direct involvement in generating or using the information being studied, and were complemented, where relevant, by representatives from downstream disciplines responsible for applying that information in subsequent project phases. The workshops served multiple purposes, including identifying requirements, developing and testing emerging prototypes, and evaluating the usability and applicability of the TBS concept.

4.5.2 Focus Group – Hovås Tak (Shared Structuring Logic)

In the Hovås Tak project, I established a focus group to identify a shared structure for project information. The disciplines most influential in shaping design and construction information were identified and brought together in a group of ten participants.

The group included representatives from the client organisation, design management and BIM coordination, cost management, scheduling, and site management. Each participant contributed domain-specific perspectives on how information is structured, used, and transferred across project phases. The purpose of the focus group was to explore how a common structuring logic could be established across disciplines, forming the basis for the initial development of the artefact.

4.5.3 Focus Group – SIM House (Classification and System Structuring)

In the Eriksberget project, a focus group was established to analyse existing information coding structures and to explore how the TBS could support improved integration of project information. The group consisted of project representatives, including an estimator, scheduler, and structural engineer, as well as two representatives from the main contractor (a digital strategist and a process developer) and two external specialists in information management. The analysis focused on a selected dataset representing three interacting systems the load-bearing system, the plumbing system, and the spatial system in relation to the construction process. Two workshop sessions were conducted, facilitated by the external specialists, to support the evaluation of how classification structures interact with process-oriented information and how these could be aligned within the TBS framework.

4.5.4 Focus Group – Total BIM (Practice-Based Understanding)

Participation in an established industry focus group provided a practice-based perspective on digitalisation and changing work practices in construction. The focus group consisted of representatives from multiple organisations, including designers, project managers, digital leaders, and site management personnel, all with big interests in model-based delivery and integrated process strategies.

The group engaged with projects in Norway and Sweden that applied model-based workflows and, in several cases, takt planning methodologies. This provided an opportunity to observe how different project contexts approach the integration of design, planning, and production. The objective of the researcher's participation was to understand how structured processes support model-based delivery by analysing the interaction between digital tools, project organisation, and production planning. Particular attention was given to how information structures support or limit the implementation of takt-based planning approaches.

The focus group discussions served as a primary data source for identifying current practices and challenges in the industry. The researcher participated as an observer without facilitating the sessions, in order to maintain a practice-oriented perspective.

Site visits complemented the focus group discussions, enabling observation of how digital models were used in production, how coordination was achieved across disciplines, and how information was applied in practice.

4.5.5 Interviews

Semi-structured interviews were conducted with key project participants, typically lasting between 45 and 90 minutes. These interviews provided in-depth insights into how design and production teams experience coordination and information management challenges in practice. The interviews supported both the identification of problem areas and the evaluation of the artefact's relevance and applicability.

4.5.6 Document and Model Analysis

Document and model analysis was conducted to examine existing information structures in detail. In the first two case projects, full access was granted to project documentation, including internal data from the main contractor. The analysis covered multiple types of project information and was structured according to the information categories identified in section 3.1. These included product-related information (e.g., design documentation and BIM models), process-related information (e.g., schedules and cost estimations), and organisational and managerial information (e.g., contracts, quality and safety documentation, logistics planning, and project organisation structures). This categorisation enabled a systematic analysis of how different information types were structured, how they related to each other, and how they supported—or limited—the integration of planning and production processes. The analysis focused on identifying inconsistencies, overlaps, and gaps between information structures, particularly in relation to their ability to support coordinated and production-oriented workflows.

4.5.7 Project Observations

Project observations were conducted during both the design and production stages. In the design stage, observations focused on meetings and interactions between project participants, complemented by informal interviews to deepen understanding of coordination practices. In the production stage, observations included participation in planning meetings and site visits, allowing for analysis of how different disciplines coordinated work, how information was requested and used, and how logistics and production activities were managed. Particular attention was given to how information was interpreted and applied in practice, and how this related to the structuring principles underlying the artefact.

4.5.8 Monitoring of Execution (Detailed Process Analysis)

To analyse specific work operations in detail, selected construction activities were recorded on video. This enabled a comparison between planned sequences and actual execution. The recorded material was analysed together with participating workers, who contributed to interpreting deviations between planned and actual outcomes. This method provided detailed insights into how planning logic translates into production practice, supporting the evaluation of the artefact at an operational level.

4.6 Evaluation Strategy

Evaluation is a central part of Design Science Research, ensuring that the developed artefact is relevant, useful, and grounded in both theory and practice (Hevner et al., 2004). In this study, the evaluation was carried out iteratively throughout the design process, combining both conceptual assessments and empirical testing.

The artefact was evaluated based on three main aspects:
- **conceptual validity** (whether the structure is logically coherent and theoretically grounded),
- **practical applicability** (whether it can be used in real project contexts), and
- **integrative capability** (whether it supports the connection between product, process, spatial, and temporal information).

To address these aspects, three complementary evaluation approaches were used: observational, experimental, and analytical. These approaches reflect different stages of the research process and different levels of maturity of the artefact.

4.6.1 Evaluation Approaches

The evaluation can be categorized into three main approaches:

1. **Observational evaluation (case-based insights)**
   The artefact was studied in real project environments through case studies and participatory observation. This included workshops, coordination meetings, and ongoing interactions with practitioners, where the applicability and relevance of the TBS concept were assessed.
   These observations provided insights into how the artefact supports communication, coordination, and shared understanding across disciplines in practice.
2. **Experimental evaluation (test bed – SIM House)**
   To enable controlled experimentation beyond the constraints of live projects, a test environment the SIM House was developed. This testbed, allowed the researcher to:

   - Experiment with different information structures
   - Simulate information flows across project phases
   - Analyse the integration of product and process data

   The sanitary drainage system was used as a representative example to model and describe information flows in detail. This enabled a structured evaluation of how the artefact supports the continuity and traceability of information across design and production.
3. **Analytical and descriptive evaluation**
   The artefact was also evaluated conceptually through comparison with existing standards and frameworks, including classification systems and information management principles. In addition, informed reflections and scenario-based reasoning were used to examine how the artefact addresses identified challenges and supports improved integration of information across project phases.

4.6.2 Evaluation Criteria

The evaluation was guided by four main criteria:

1. **Utility** – The extent to which the TBS supports the integration of product and process information in BIM-based environments.
2. **Quality and consistency** – The alignment of the artefact with established standards (e.g., ISO/IEC 81346) and its ability to provide a coherent and scalable information structure.
3. **Efficacy** – The artefact’s ability to improve coordination, predictability, and communication between design and production.
4. **Adoption potential** – Stakeholders perceived value of the artefact and its feasibility for implementation in practice.

4.6.3 Empirical Evaluation and Current Limitations

The empirical evaluation of the artefact is primarily based on insights from case studies and workshops (Papers II–IV), observations of coordination and planning processes, and experimental studies conducted in the SIM House environment.

While the artefact has been partially applied in practice, particularly in relation to cost estimation and production planning within the author's organisation, it has not yet been fully implemented or systematically evaluated in a complete project setting.

This represents a limitation of the study. The evaluation should therefore be understood as exploratory and developmental in nature, focusing on demonstrating the potential, applicability, and relevance of the artefact, rather than providing comprehensive empirical validation.

Given the design-oriented and practice-based nature of the research, ensuring rigor has been an important consideration throughout the study. The researcher's dual role as both practitioner and academic observer has provided valuable domain insight and facilitated access to empirical contexts. At the same time, this position has influenced the framing of the research, the selection of cases, and the interpretation of results, with a tendency towards production-oriented perspectives.

To address this, reflexivity has been applied as an ongoing practice. Continuous reflection, together with discussions with supervisors and industry partners, has been used to critically examine assumptions, challenge interpretations, and reduce the risk of bias.

Despite these measures, the findings should be interpreted with an awareness of the study's context-dependent nature and the current level of artefact maturity.

4.7 Ethical Considerations

The research was conducted in accordance with established ethical principles for collaborative and industry-based research. All participants were informed about the purpose of the study, and informed consent was obtained prior to data collection. Participation was voluntary, and individuals were anonymized where possible, with personal data limited to role and experience.

The use of real projects as empirical material increased the relevance and credibility of the study but required careful handling to ensure confidentiality.

The study focuses on collaborative processes and information structures rather than individual performance, which limits ethical risks. At the same time, the proposed artefact may influence established roles and practices within project organizations. This is considered consistent with ongoing industry developments towards more collaborative and integrated ways of working.

4.8 Summary

This chapter has outlined the methodological foundation of the study. By adopting a Design Science Research approach, the research combines academic rigor with practical relevance to address challenges in information integration between design and production.

The TBS was developed through two iterative design cycles, combining empirical case studies with experimental evaluation in the SIM House test environment.

The following chapters build on this foundation. The summary of empirical material defines the problem context and design requirements, followed by the design and development of the artefact. Finally, the evaluation chapter presents the assessment of the artefact's performance and applicability.

5 Case description

This chapter presents the empirical case projects that form the basis for the development and evaluation of the TBS artefact. The projects provide the contextual grounding for identifying and formulating the derived design requirements, in line with the relevance cycle of Design Science Research.

The empirical material comprises five case projects with different characteristics, levels of access, and degrees of maturity in relation to BIM-based information management and production-oriented planning. Together, the cases provide an empirical material acquired through combining in-depth longitudinal engagement, focused comparison, exploratory observations, and contextual reference material.

The two **Primary Design Cases** constitute the core empirical setting for artefact development and evaluation. These cases provided extensive access to design and production processes, including documentation, interviews, workshops, focus groups, and meeting observations. This enabled iterative development, testing, and refinement of the TBS artefact in close interaction with practice.

The **Focused Comparative Case** complements the primary cases by providing a targeted analytical perspective on specific production activities and associated information flows. By comparing structuring practices with those observed in the primary cases, this case supports a more detailed examination of how information structures influence work preparation, coordination, traceability, and production planning.

The **Exploratory Case-Inspired Empirical Material** represents two projects at an early stage of implementing takt planning. These cases contribute insights into the practical challenges, adaptations, and prerequisites associated with introducing flow- and location-based planning methods in Swedish construction projects. As such, they inform the problem space and support the formulation of design requirements.

Taken together, the type of cases differs in scope, maturity, and level of engagement, but complement each other by providing both depth and variation. This combination enables a comprehensive understanding of the relationship between information structures, organisational arrangements, and production processes, thereby supporting both the development and evaluation of the TBS artefact. The empirical material includes both data reported in the appended papers and additional unpublished material collected during the research project, as summarised in Table 1 Overview of the case projects, their characteristics, data sources, and their respective roles in the research design.

Table 1 Overview of the case projects, their characteristics, data sources, and their respective roles in the research design.

	Case 1	**Case 2**	**Case 3**	**Case 4**
Type of case	Primary Design Case	Primary Design Case	Focused Comparative Case	Exploratory Case-Inspired Empirical Material
Project	Hovås Tak	Eriksberget (and SIM House)	Klassrummet	Office in Lund, Residential building in Gothenburg
Type of project	Residential	Residential	Residential	Office and lab / Residential
Size	59 apartments, 5170 m2	130 apartments 15793 m2	135 apartments, 11399 m2	24,000 m^2, 5 floors / 90 apartments, 9252 m2
Data collected	Project documentation (design and production data); 12 interviews; >5 workshops; documentation from five focus group meetings (design stage); continuous observations and meeting notes (design and production); video recordings of penthouse framework assembly.	Project documentation (design data); 14 interviews; 5 workshops; observations and meeting notes from the design stage; detailed analysis of information structures.	Project documentation (roof assembly, production phase); 5 interviews; 2 site visits with on-site observations.	5 interviews; 1 workshop; 3 site visits (Lund and Björlanda); exploratory observations for project understanding.
Related papers	Paper II, III, Part of additional paper	Paper IV	Paper III	

5.1 Case 1: Hovås Tak – Residential Apartment Project

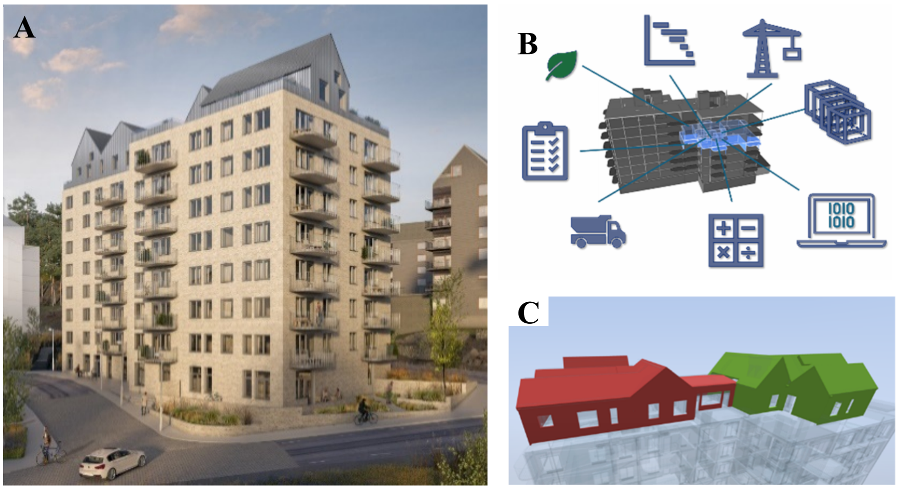

Figure 7. (A): The project case 1, Hovås Tak (Nordr, 2022), (B) Illustrating the common denominator providing interoperability opportunities between disciplines (C): The rooftop penthouses 1 and 2, coloured for sequencing according to production zones.

5.1.1 Project overview and empirical context

The Hovås Tak project is a residential apartment development in southern Gothenburg, Sweden, studied as a Primary Design Case. The case forms one of the core empirical settings for the development and evaluation of the TBS artefact, providing longitudinal access to both design and production processes. The project consists of two joined tower blocks forming a single building structure. Each stairwell contains four apartments per floor, resulting in 59 apartments and a gross floor area of approximately 5,170 m^2. The structural system consists of semi-precast concrete elements, complemented by lightweight steel infill walls and a non-load-bearing brick façade. The penthouses are constructed using prefabricated timber frames with metal-clad roofs and façades.

5.1.2 Data collection and research involvement

The project was studied longitudinally from the detailed design stage through to project completion. As an industrial PhD candidate employed by the main contractor, the researcher had extensive access to project documentation, meetings, and stakeholders. This enabled in-depth analysis of information flows across design and production.

Data collection included:

- **Focus group material:** Documentation and observations from the project-based focus group working on the development, implementation, and evaluation of a shared information structure. The focus group was active from the design stage through detailed design and into production, providing empirical input for defining requirements and evaluating the first prototype.
- **Project documentation:** Analysis of design and production documentation to examine how different categories of information are structured and represented across project phases.
- **Interviews:** Semi-structured interviews with 12 participants during the production phase, including project manager, site manager, three foremen, project engineer, scheduler, estimator, subcontractors (mechanical and electrical), and workers involved in roof assembly.
- **Workshops:** Multiple workshops conducted in both design and production stages to evaluate and refine the proposed information structure. These included:
    - workshops with site management and foremen focusing on the application of the structure for takt planning
    - workshops with project management exploring integration with production control software
    - workshops with scheduler, estimator, and digital coordinator examining integration between 3D models, scheduling, and cost estimation
- **Observations and meeting records:** Continuous documentation of meetings, discussions, and project activities throughout the design and production phases.
- **Knowledge-sharing workshop:** A workshop involving site management, cost engineers, schedulers, and digital coordinators to capture experiences and challenges related to the implementation of the proposed information structure.

In addition, production data in the form of issue logs and verification data were analysed, contributing to further empirical insights.

5.1.3 Relation to appended papers

The Hovås Tak project forms a primary empirical case in several appended papers. The development of a shared information structure and coding system is reported in Paper II. The detailed analysis of roof assembly and production-related processes is reported in Paper III. Production data and issue-reporting material also contributed to the additional publication.

5.1.4 Additional empirical data

Beyond the findings reported in the appended papers, the case revealed several critical challenges related to information management in model-based construction.

A key observation was the variation in digital maturity and understanding of model-based workflows across stakeholders. Although digital requirements were formally defined, their practical implementation was hindered by limited understanding of how information should be structured, filtered, and used by different actors.

For example, subcontractors described the need to manually identify and mark elements in drawings, such as components to be cast into concrete, to ensure completeness during production. This task, traditionally performed through manual quantity take-off and visual marking of drawings, could instead be supported through structured filtering of BIM data, where objects are coded according to production phases.

Site management also described challenges in assembling information for work preparation, as relevant data had to be retrieved from multiple sources. When information shared a consistent structure and naming convention, both preparation and follow-up processes were facilitated.

Overall, the case highlighted the need for:

- Shared information structures across disciplines
- Improved alignment between design and production information
- Mechanisms for filtering and grouping model data according to production needs, and
- Increased understanding of user-specific information requirements across the project lifecycle.

5.2 Case 2: Eriksberget – Residential Apartment Project

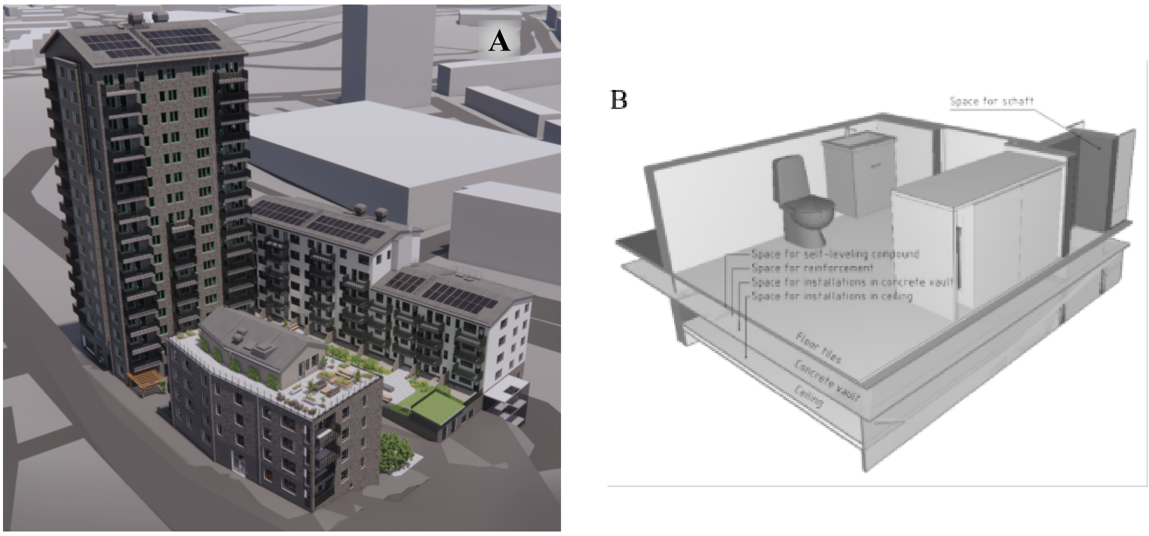

Figure 8 (A)The project Eriksberget - Case 2 (Egnahemsbolaget, 2023), (B): The bathroom studied to form basis for an informationstructure

5.2.1 Project overview and empirical context

The Eriksberget project is a residential apartment development studied as a Primary Design Case. The case provided detailed insight into the development of information structures during design and early production planning and supported the evaluation of how structured information can be prepared for production-oriented use.

The project consists of three buildings with a total of 132 apartments and an underground garage. The total gross floor area is approximately 15,872 m². The buildings vary in height, including one five-storey building, one sixteen-storey building, and one building divided into a lower section of seven floors and an upper section of nine floors.

5.2.2 SIM House test bed

A subset of the project data was extracted and used to develop a test environment, referred to as the SIM House. This test bed enabled detailed exploration of how the TBS structure could be implemented across different information categories and how information from multiple disciplines could be integrated within a shared framework. By decoupling the analysis from the live project context, the SIM House supported iterative testing and refinement of the proposed information structure together with the disciplines responsible for generating the original data

5.2.3 Data collection and research involvement

The The project was studied during the detailed design stage and the initial phase of production planning. Due to an appeal of the building permit, the production stage could not be followed within this research. Nevertheless, the early project stages provided extensive insight into the development of information structures and planning processes. As the main contractor was the same as in Case 1, the researcher had extensive access to project documentation, meetings, and stakeholders.

Data collection included:

- **Focus group material:** Documentation and observations from a project-based focus group established to analyse limitations in existing classification and information structuring approaches identified in Prototype 1. The focus group was active during the detailed design stage and contributed to defining requirements for the information structure developed in Prototype 2.
- **Interviews:** Semi-structured interviews with 12 participants from different disciplines, including architects, structural engineers, MEP engineers, cost engineers, schedulers, project managers, site managers, and digitalisation coordinators.
- **Workshops:** Multiple workshops conducted to evaluate and refine the proposed information structure. These included:
    - workshops with site management, scheduler, and structural engineer to explore sequencing and simulation of structural assembly
    - workshops with contractor support functions (e.g. procurement, project management, district management) to identify information requirements related to the structural framework phase
    - workshops and unstructured interviews conducted as part of the development of the SIM House test environment, involving representatives from structural engineering, architecture, plumbing, and HVAC, who provided and validated project information

- **Observations and meetings:** Participation in design coordination and production planning meetings, supported by continuous observation of project activities during design stage.
- **Project documentation:** Analysis of design-phase documentation to examine how different categories of information are structured and represented.

In addition, coordination activities between key roles such as project management, structural engineering, and scheduling were observed to understand how information structures were developed and applied in practice.

5.2.4 Relation to appended papers

The Eriksberget project is primarily reported in Paper IV. In addition, parts of the empirical material were used to develop and evaluate the SIM House test environment, which supports experimentation with information structures and the proposed artifact outside the project setting.

5.2.5 Additional empirical data

The case provided detailed insights into how information structures are developed and adapted to support sequential production processes, particularly in the framing phase.

A key observation was the need to group and restructure information to support production sequencing. This was studied through:

- Workshops with experienced framing experts focusing on information flows and structuring needs
- Analysis of how information is prepared for sequential execution in structural assembly, and
- Observations of coordination between structural engineers, project managers, and schedulers

In one observed workshop with three participants, the assembly sequence of the structural system was simulated and optimized. This involved re-coding building elements according to production zones and synchronizing information between logistics planning, structural models, and scheduling. The structural engineer ensured compliance with structural requirements, while project management, site manager and scheduler optimized material flow and execution sequencing.

These observations highlight the importance of:

- Dynamic restructuring of information to match production logic
- Alignment between design models and production planning structures, and
- Integration of logistics, scheduling, and technical design information

The case also demonstrates the value of separating the development and evaluation of information structures from the live project environment. The SIM House testbed enabled iterative testing and refinement of structures together with the disciplines responsible for creating the original information.

Overall, the findings emphasize the need for flexible yet standardized information structures that support both design coordination and production execution.

5.3 Case 3: Klassrummet – Residential appartement Project

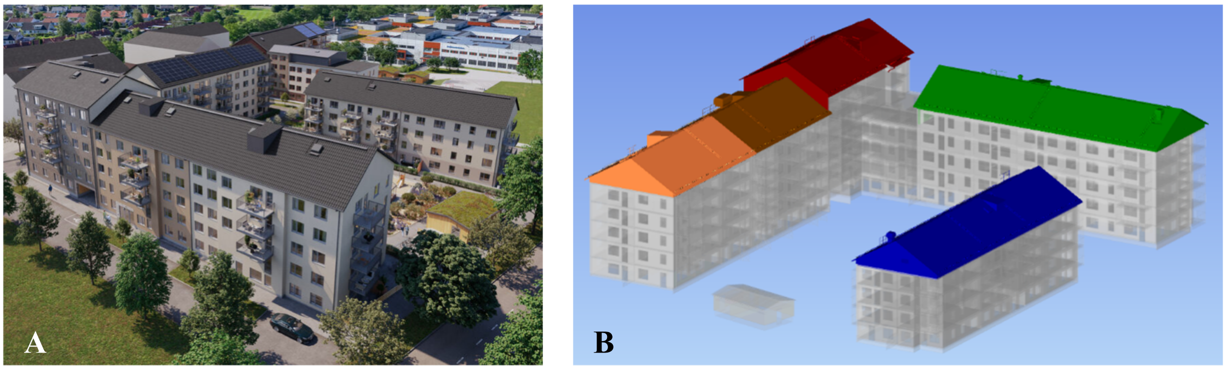

Figure 9 (A): The project Klassrummet – Case S1, (B): The rooftops 1-5, coloured for sequencing according to production zones (construction scope).

5.3.1 Project overview and empirical role

The Klassrummet project is a residential apartment development studied as a Focused Comparative Case. The case complements the primary design cases by enabling targeted analysis of work preparation planning and information structuring in a production context. By focusing on specific production activities and their associated information flows, the case enables comparison with the primary cases. This supports a more detailed examination of how variations in structuring practices influence coordination, traceability, and production planning

5.3.2 Data sources and research involvement

The empirical material consists of project documentation, observations of work preparation activities and five separate interviews conducted with key project participants: the project manager, the site manager, the project engineer, who also acted as information coordinator, and two foremen. The case was also analysed in relation to how breakdown structures were applied in practical work preparation.

5.3.3 Relation to appended papers

The research has mainly focused on the analysis of the information flow for the roof assembly that is reported in Paper III.

5.3.4 Additional empirical data

The project was part of a pilot project for the development of software for detailed information coordination. As a result, high demands were placed on the project´s information structure, as also reported in Paper III. The case demonstrated the importance of a shared breakdown structure for enabeling traceability between planning, cost estimation, and execution. When such structures were applied consistently, improved predictability and coordination between disciplines were observed. The project engineer highlighted challenges in aligning detailed design documentation with practical work preparation on-site. Foremen who were accustomed to performing their own quantity take-off from drawings needed support to become comfortable filtering information from the model-based software. The software made it possible to retrieve information such as estimated quantities, hours, start and end dates, and cost data linked to specific work tasks. By using the software for both work preparation and reporting, the project demonstrated how information could flow seamlessly from design to completed execution. Deviations could be identified, followed up, and corrected more efficiently. This case therefore illustrates how detailed and consistently applied breakdown structures can strengthen traceability and support more predictable production execution.

5.4 Case 4: Introduction of Takt Planning in two Swedish Construction Projects

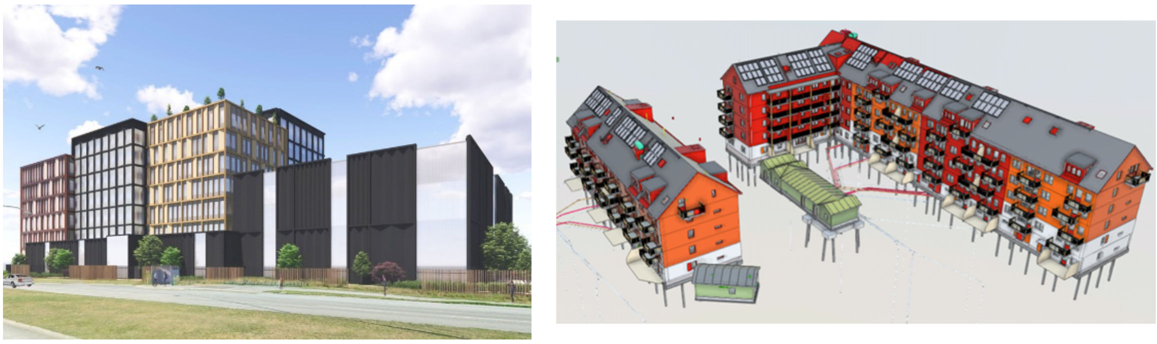

Figure 10 Two supplementary projects studied for takt planning implementation in Sweden

5.4.1 Project overview and empirical context

This Exploratory Case-Inspired Empirical Material is based on observations from two construction projects in which takt planning was implemented for the first time within the contractor’s project organisations in Sweden. The projects comprise an office building in Lund and a multi-family housing development in Gothenburg, both delivered as design–build contracts by the same main contractor. By capturing early-stage implementation experiences within a consistent organisational context, these cases provide insights into the initial challenges, adaptations, and prerequisites associated with introducing takt planning in practice.

The office building comprises approximately 24,000 m² distributed over five floors, including laboratory and workshop facilities on the ground floor. The residential project consists of two buildings with five and six storeys respectively, comprising a total of 70 apartments distributed across six stairwells, with a total gross floor area of approximately 9,252 m².

In both projects, traditional design approaches based on drawings and specifications were used during the design phase. takt planning was introduced during the production phase, specifically for interior finishing works.

5.4.2 Data sources and research involvement

The empirical material was collected through site visits, five interviews, one evaluation session, and observations of planning and follow-up activities, including short team meetings where status updates were discussed and clarifying questions addressed.

In the office project, interviews were conducted with the scheduler and site manager at two stages: prior to the start of production and during ongoing production. In addition, a site visit included participation in a weekly takt planning follow-up meeting with approximately 15 participants, followed by a reflective evaluation session with project stakeholders.

In the residential project, interviews were conducted with the project manager, site manager, and project engineer during a site visit. Observations focused on how takt planning was visualized and communicated within the project.

5.4.3 Main empirical data from Introduction of new work practices

Both projects were implementing takt planning for the first time, which required changes in established work practices across the project organizations. The shift implied a transition from activity-based planning towards a more flow- and location-based approach. At an early stage, it became evident that a shared understanding of takt planning principles was necessary. Differences in how participants interpreted sequencing, zone definitions, and the importance of maintaining a stable production pace created initial challenges. Additional effort was therefore required to communicate the structure of the takt plan and the expectations associated with it. Although the scheduler and site manager in both projects had prior experience with sequenced work, the introduction of takt planning made this sequencing more explicit and systematically structured. This contributed to a clearer overall production logic but also required adjustments in how sequencing was communicated and followed within the project. The experiences indicate that the introduction of takt planning involves not only a new planning method, but also adjustments in roles, collaboration, and ways of working.

5.4.3.1 Increased requirements on planning, logistics and preparation

A clear observation in both projects was that takt planning increased the demands on early-stage planning, particularly in relation to material quantification, procurement, and logistics. Since production is governed by a fixed rhythm, resources and materials need to be available at the right time and in the right sequence.

For example, a plumbing subcontractor in the office project highlighted the need to quantify material requirements in advance for each takt zone. This required more effort during the planning phase compared to previous practices but resulted in more clearly defined and prepared work tasks.

During production, this contributed to fewer interruptions related to missing materials or unclear scope. Overall, the projects indicate that takt planning requires more preparation upfront, which supports a more stable execution phase.

5.4.3.2 Improved coordination and transparency in production

Both projects showed that takt planning improved coordination between trades and increased transparency in the production process. By structuring work into zones and a defined sequence, dependencies between different actors became more visible.

In the office project, this facilitated coordination of handovers between trades. In the residential project, the visualization of takt zones and associated start and end dates provided a shared understanding of the production pace. This made communication within the project more straightforward and supported follow-up of progress, as all participants could relate to a common plan.

5.4.3.3 Role of visualization and structured information

Visual representations of takt zones and schedules were important in both projects. These supported a clearer understanding of the work sequence, responsibilities, and timing among project participants.

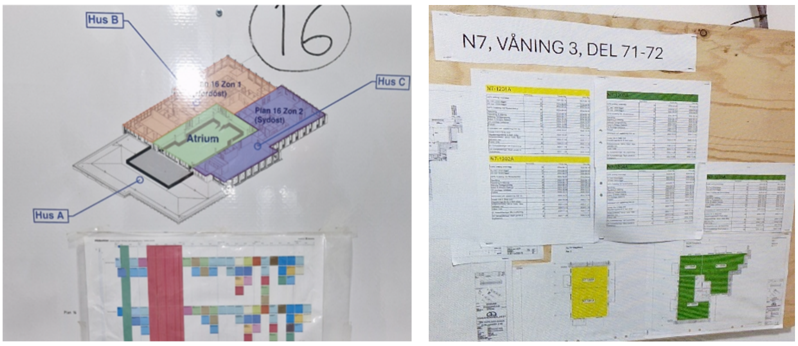

Figure 11 Takt planning board for Takt control in each takt zone

In the residential project, the procurement engineer noted that the takt plan facilitated material planning by clearly indicating quantities and delivery timing for each takt. This contributed to a more structured procurement and logistics process.

At the same time, the usefulness of these visualizations depended on the availability of well-structured information. When project data was not aligned with the takt structure, additional effort was required to make it applicable.

5.4.3.4 Implications for information structuring

In both projects, the introduction of takt planning revealed limitations in existing information structures. While the takt plan itself provided a clear production logic, supporting information such as drawings and quantities was not always organized accordingly. This required project teams to adapt and restructure information, for example by aligning it with takt zones and sequences.

The experiences suggest that information needs to be more closely aligned with the production setup in order to effectively support takt planning.

6 Additional empirical data

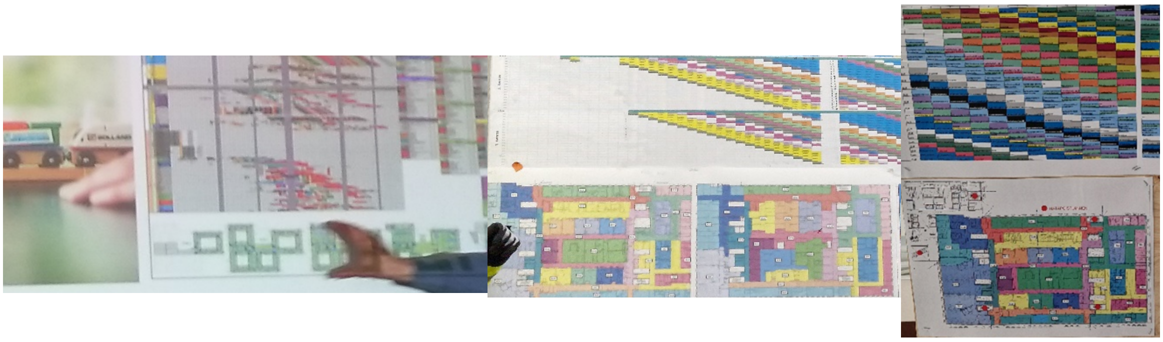

Figure 12 Visualisation of Takt-planning structure from different projects in the Nordic.

6.1 Nordic perspective on Takt-planning

This This empirical material provides a Nordic perspective on takt-time planning based on four study trips conducted in Norway, Finland, and Sweden. The material represents projects with a higher level of maturity in both takt planning and model-based processes and therefore serves as a reference point for more advanced practices.

The purpose of this material is to broaden the empirical foundation by capturing how structured approaches to production planning and information integration are applied across different national and organisational contexts.

Three of the study trips were organised in collaboration with the Total BIM focus group and included eight site visits to projects in Norway and Stockholm, Sweden. These visits also comprised a total of eleven seminars addressing key challenges and practical experiences related to digitalisation and the implementation of Total BIM management. In particular, the discussions highlighted how takt planning is implemented within model-based project environments, including how production planning, information structuring, and coordination practices are adapted to support flow-oriented and location-based execution.

One of the visited projects demonstrated a particularly high level of digital maturity. In this context, two semi-structured interviews were conducted to gain deeper insight into how information is structured and linked to takt planning for production control. The interviews were carried out with the client's project manager and a mechanical subcontractor working with highly detailed, model-based work preparation.

The fourth study trip was conducted in Finland and included visits to three projects across multiple locations. This visit was carried out together with representatives from an internal Lean Construction interest group within the author's organisation. The primary focus was to study projects with a high level of maturity in takt planning and to better understand its practical implementation and perceived benefits. In addition, one takt planning specialist was interviewed to provide further insight into implementation practices and how different levels of takt maturity influence project coordination and control.

Overall, the study trips enabled interaction with practitioners in various roles and provided insights into how takt planning contributes to improved structure in construction projects, both in terms of information management and organisational coordination.

6.2 Data sources and research involvement

The empirical material consists of unstructured interviews and on-site observations conducted during study visits and notes from seminars, complemented by three of follow-up semi-structured interviews to enable a more in-depth understanding. The interviews primarily targeted practitioners responsible for developing and managing takt plans, including roles such as project managers, site managers, and planning specialists.

The data collection focused on:

- Information needs related to takt planning
- Structuring of information to support location-based and sequential production
- Practical implementation of takt planning in ongoing projects

Given the exploratory and contextual nature of this material, the data are less detailed than in the primary design cases. However, they provide valuable comparative insights across multiple projects and organisational contexts.

6.3 Main insights from practitioners with higher maturity in takt planning

The projects studied in Norway and Finland generally demonstrated a higher level of maturity in takt planning compared to the Swedish cases. These project organizations showed more experience in applying location-based planning approaches, where activities are systematically structured into takt sequences, often referred to as takt trains.
In these cases, takt planning was not treated as a standalone scheduling tool, but as an integrated part of the production setup. This was reflected in more consistent use of takt logic across planning, coordination, and follow-up.

The observations suggest that repeated application of takt planning contributes to the gradual development of organisational capabilities, including improved coordination practices, clearer role definitions, and more stable production processes.

6.3.1 Focus on location-based structuring in takt planning

Across the studied projects, takt planning was primarily implemented as a production planning methodology, with a strong focus on sequencing and coordination of on-site activities. A common approach was to define shared takt zones, which formed the basis for coordinating work across disciplines and structuring production into takt sequences.
Within this setup, subcontractors and project teams adapted their detailed planning and quantity take-off practices to the predefined takt zones. In some cases, 3D models were used to support this work by coding building elements according to takt zones, enabling model-based quantity take-off.
These practices indicate that location-based structuring was well established in production planning and, in some cases, partially supported by digital models. However, BIM was generally used as a supporting tool rather than being fully integrated with the takt planning methodology.

6.3.2 Challenges in integrating design information with takt planning

A recurring observation across the cases was the limited integration between design information and takt-based production planning. Takt plans provided a clear structure for execution, typically represented in schedules where each phase corresponded to a group of takt sequences. However, this logic was not consistently reflected in design documentation or model organisation. As a result, a gap emerged between the production setup and the underlying information structure.
The interviews further highlighted the challenges associated with this transformation. Aligning technical design data with production logic, including zoning, sequencing, and

coordination between trades required additional effort and often project-specific solutions. Although this process was facilitated when information structuring was addressed early in the design phase, the lack of standardized approaches led to variations in how effectively design information could support takt-based planning and execution.

6.3.3 Implications for model-based construction and Total BIM

As three of the study visits were conducted together with the Total BIM group, the observed practices were also reflected on in relation to model-based construction and the concept of a single source of truth in the seminars. The observations align with research on model-based construction, where BIM is increasingly positioned as a central information carrier across project phases. In this context, there is clear potential to integrate production planning methods such as takt planning directly into structured model information. However, the studied projects also demonstrate that current practices remain fragmented. There was limited alignment between BIM structures developed during design and the information structures needed for production planning and execution. This indicates a gap between the ambition of integrated information and how information is currently structured and used in practice, particularly in relation to supporting both design and production.

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7 Summary of the papers

This chapter synthesises the main aims, data collection methods, findings, and contributions from each of the five papers. Taken together, the results demonstrate that BIM-based information must be systematically categorised and decomposed to support a standardised, traceable, and lifecycle-oriented information flow across project phases.

- **Categorisation by type of information** – Paper IV proves how ISO/IEC 81346's functional, locational, product, and process aspects create a multi-layered classification that supports interoperability.
- **Breakdown into work packages** – Papers II and III show how shared WBS and production phase–based structures allow predictable takt-time planning, cost/schedule traceability, and cross-project benchmarking.
- **Process integration and quality assurance** – Papers I, IV and V illustrate how BIM-based takt planning, Model Maturity Index, and Systematic Completion can jointly secure structured, standardised, and production-ready information delivery.

7.1 Paper I. Developing Support for BIM-based Takt-time Schedules for Production Control

Viklund Tallgren, M., Johansson, M., & Roupé, M. Ljung, E, (2022). Developing support for BIM-based takt time schedules for production control. In Proceedings of the 22nd International Conference on Construction Applications of Virtual Reality Chung-Ang University, South Korea.

7.1.1 Purpose

To explore how Building Information Modelling (BIM) can be directly connected to takt-time planning (TTP), understood here as a BIM-enabled operationalisation of takt planning that structures production into repetitive work sequences across defined locations and fixed time intervals. By linking takt time (the defined production rhythm) with location-based planning, TTP provides a framework for coordinating design information with production control. The study addresses the limited integration between BIM-based design information and production-oriented planning, aiming to support more stable, predictable, and coordinated construction flows.

7.1.2 Method

A comprehensive literature review on Lean Construction, location-based planning, and collaborative planning was combined with three empirical cases (hospital, office/laboratory, airport terminal) where TTP was applied in BIM-based projects. Data were collected through site visits, recorded presentations, and unstructured interviews with site managers.

7.1.3 Findings

The study shows that a 4D collaborative planning process (Virtual Production Planning, VPP) enables BIM objects to be disassembled and reassembled into takt-time sequences, linking design information directly to production planning. This process supports early constructability review and facilitates the identification of design issues prior to execution. The findings further demonstrate that active engagement of subcontractors in BIM-based planning workshops enables the articulation of tacit knowledge related to construction sequencing, material handling, and site-specific problem-solving. Through interaction with the model, this experience-based knowledge is formalised into explicit planning information, enriching both the takt-time schedule and the 4D model.

By integrating subcontractors' practical insights into the planning process, the resulting schedules exhibit increased robustness and resilience to site variability, while also strengthening collaborative plan development and improving the predictability of short-term production control.

7.1.4 Contributions

This paper establishes a conceptual and practical bridge between BIM and Lean takt-time methods, offering evidence that the combination provides a robust basis for categorising and sequencing BIM information by location and production flow. By embedding experiential know-how in the BIM-based takt schedule, the work moves beyond purely geometric or contractual data to include practical construction intelligence. This provides a strong foundation for the thesis's argument on how BIM information should be categorised and decomposed to include both formal digital objects and the informal knowledge that drives reliable production.

7.2 Paper II. Identifying and Developing Prerequisites for Takt Planning in a BIM-based Construction Process

Ljung, E., Viklund Tallgren, M., Roupé, M., & Johansson, M. (2023). Identifying and developing prerequisites for takt planning in a BIM-based construction process. In CONVR 2023 – Proceedings of the 23rd International Conference on Construction Applications of Virtual Reality (pp. 574–584). Firenze University Press

7.2.1 Purpose

To identify and develop the prerequisites required for implementing takt planning within a BIM-based construction process. In particular, the study examines how information structures, work breakdown principles, and data integration across design and production phases can support the operationalisation of takt planning, enabling consistent coordination, traceability, and flow-oriented production control.

7.2.2 Method

A three-stage qualitative study was carried out on the Hovås Tak apartment project:

- focus-group workshops with client, design manager/BIM coordinator, cost manager, scheduler, and site management to define a shared coding and Work Breakdown Structure (WBS);
- implementation of the agreed structure in design documentation and cost control;
- evaluation of its impact on scheduling, site management and production.

7.2.3 Findings

The paper shows that establishing a shared WBS enriched with production phases (previously referred to as "deliverables") and production zones (previously "construction scope"), provides a uniform project language that enables traceability from design through construction and into operations. By directly linking the main contractor's cost and scheduling structures to BIM objects, the study demonstrates how integrated datasets can support cross-project analysis of key performance indicators (KPIs), including productivity and schedule adherence.

Furthermore, the structured information enables automated extraction of construction-relevant deliverables for procurement and facilitates dynamic schedule visualisation. This, in turn, supports the implementation of takt planning by providing a consistent and production-oriented information basis across project phases.

7.2.4 Contributions

This paper contributes by identifying the lack of a shared WBS and coding structure as a key barrier to integrated construction planning, and by proposing an empirically grounded prototype of a shared, deliverable-based information structure that enables cross-disciplinary coordination without replacing existing systems. The study further demonstrates how such a structure, combined with BIM-based visualization and collaborative processes, improves communication, supports production planning, and enables new forms of data-driven analysis in construction projects.

7.3 Paper III. The Significance of a Shared Breakdown Structure for Work Preparation Planning for a Predictable Execution

Ljung, E., & Viklund Tallgren, M. (2024). The significance of a shared breakdown structure for work preparation planning for a predictable execution. In Proceedings of the Creative Creative Construction Conference. Prague, Czech Republic.

7.3.1 Purpose

To test the hypothesis that a shared breakdown structure across disciplines improves traceability and predictability in work preparation planning and execution.

7.3.2 Method

Two rooftop assembly projects were analysed using a qualitative, deductive approach. Semi-structured interviews with managers, engineers, foremen and skilled workers were combined with a detailed comparison of planned WBS structures and actual site execution.

7.3.3 Findings

The Case Project 3, described in Chapter 5.3 that fully detailed and consistently applied the shared WBS achieved interoperability between costing, scheduling, and documentation. This ensured that costs and schedules could be traced directly to work packages and that deviations were quickly identified. In contrast, the Case Project 1, described in Chapter 5.1 lacking this detailed WBS showed gaps between planned and executed work and weaker cost–time traceability. The study thus confirms that shared, detailed WBS structures are critical for predictable execution and for capturing lessons learned for future projects.

7.3.4 Contributions

This paper strengthens the argument that a harmonised breakdown structure is not only a planning tool but also a mechanism for continuous improvement and knowledge transfer. It underscores that BIM information must be decomposed into granular, standardised work packages to achieve the predictability and traceability needed for industrialised, takt-driven production.

7.4 Paper IV. Can Interoperability between Disciplines be Improved by Adding Phasing Information Using Standardised Coding?

Ljung, E and Viklund Tallgren, M (2024) Can Interoperability Between Disciplines be Improved by Adding Phasing Information Using Standardised Coding? In: Thomson, C and Neilson, C J (Eds) Proceedings of the 40th Annual ARCOM Conference, 2-4 September 2024, London, UK, Association of Researchers in Construction Management, 111-120.

7.4.1 Purpose

To investigate whether interoperability between disciplines can be improved by incorporating phasing information into standardised classification systems, enabling the integration of design and construction process data. The study examines how multi-aspect coding based on ISO/IEC 81346 can reduce ambiguity in cross-disciplinary communication and support more consistent data exchange across project phases.

7.4.2 Method

A two-stage qualitative design was employed: (1) in-depth interviews with twelve practitioners from key design and construction disciplines, and (2) a workshop with classification experts.

The empirical focus was a specific construction detail, referred to as the bathroom floor assembly, selected to delimit the study while maintaining relevance across multiple project phases. As a multi-layered and cross-disciplinary assembly, ranging from the structural slab to the ceiling below it integrates structural, technical, and finishing components. This made it a suitable unit of analysis for examining how information is structured, coordinated, and translated between design and production contexts.

7.4.3 Findings

The research revealed persistent incompatibilities among existing classification systems and a lack of documented agreements on levels of detail and information exchange. By applying ISO/IEC 81346's functional, locational, product, and process aspects, the findings demonstrated how phasing information can be codified to create a common vocabulary and to support platform-neutral data exchange. The exercise showed how multi-aspect coding allows both discipline-specific detailing and cross-disciplinary integration.

7.4.4 Contributions

This paper provides concrete evidence that ISO/IEC 81346 offers the semantic and structural foundation required to systematise BIM data across disciplines and project phases. It extends current understanding of how to achieve true interoperability and paves the way for structured, life-cycle information flows in line with ISO 19650.

Importantly, it also clarifies how each ISO/IEC 81346 aspect aligns with established work breakdown structure (WBS) principles. By showing these correspondences, the study demonstrates how ISO/IEC 81346 can serve as a unifying backbone that links WBS thinking with digital classification, enabling predictable, standardised information flow and enhancing interoperability throughout design and construction.

7.5 Paper V. BIM from Design to Production: Enabling Model-Based Construction Framework with Total BIM

Viklund Tallgren, M., Ljung, E., Disney, O., Johansson, M., & Roupé, M. In proceedings *of the 25rd International Conference on Construction Applications of Virtual Reality (CONVR 2025)*

7.5.1 Purpose

To develop a framework for model-based construction (Total BIM) that integrates BIM with Lean Construction, takt-time planning, and Total Quality Management (TQM), positioning the model as a legally binding, production-ready source of truth. The study further explores how structured information, aligned with control zones and phased production processes, can support the integration of design and construction in a coherent delivery framework.

7.5.2 Method

A multiple-case study of a Norwegian hospital and a Swedish office project was conducted using focus groups, site observations, and semi-structured interviews. Analytical focus was placed on the Model Maturity Index (MMI), Level of Information Need (LOIN), and Systematic Completion (SC) processes.

7.5.3 Findings

The hospital project demonstrated how SC-based quality gates and weekly 17–0 checkpoints enabled progressive model maturity while aligning BIM development with procurement, control zones, and takt-time planning. This created a structured link between design information and production execution, supporting predictable workflows and early issue resolution.

In contrast, the office project, operating under a more fragmented procurement structure, revealed limitations when early contractor involvement and structured quality assurance were lacking, resulting in weaker alignment between model development and production needs.

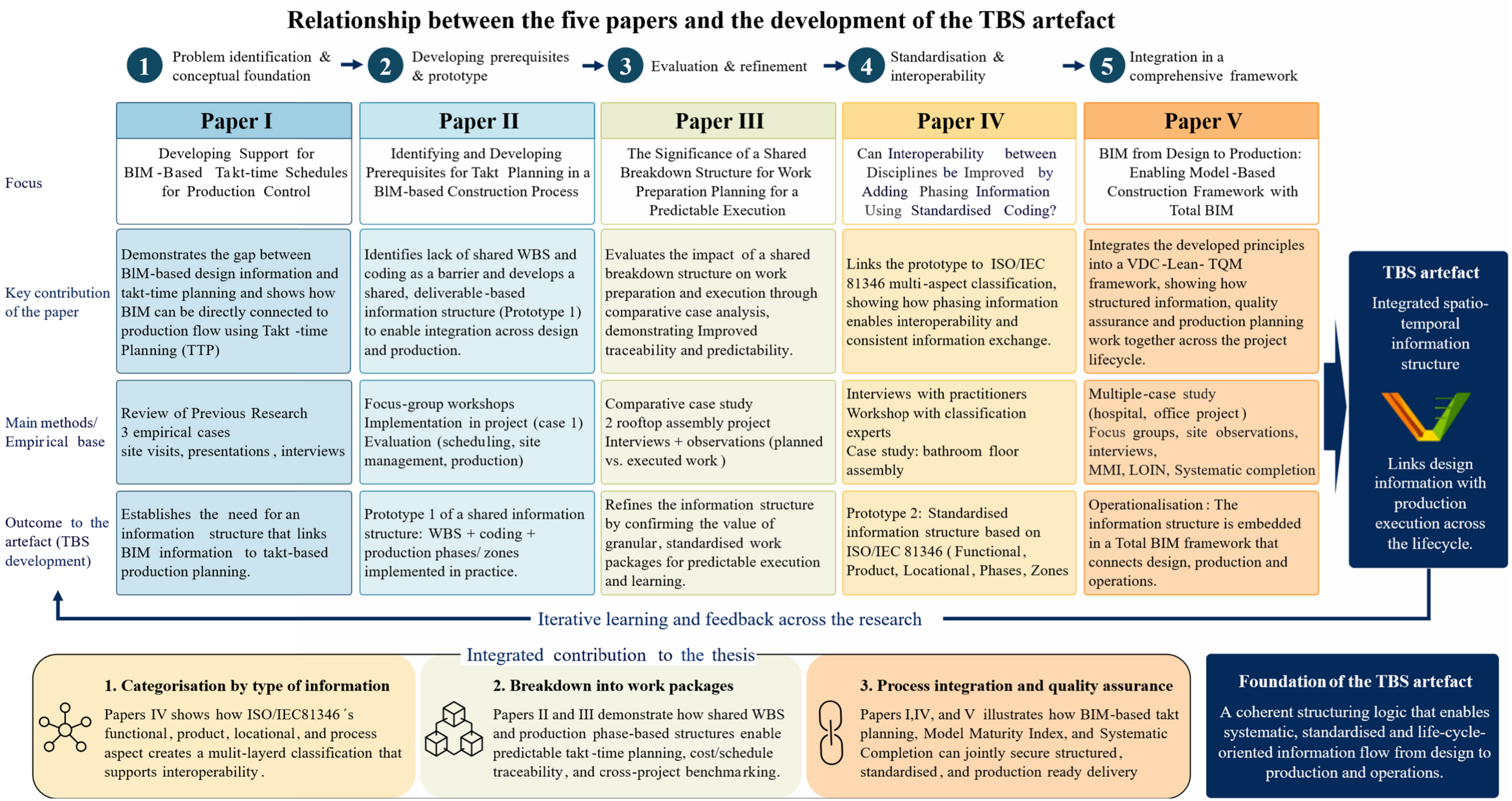
Across cases, the findings show that when model maturity, quality assurance, and production planning are systematically aligned, Total BIM reduces rework, shortens schedules, improves cost predictability, and enables a transparent, lifecycle-oriented digital twin. These results highlight the importance of structuring information in relation to production phases and control zones to support consistent information flow from design to execution.

7.5.4 Contributions

This paper operationalises an integrated VDC–Lean–TQM framework for Total BIM, demonstrating how structured quality assurance, model maturity assessment, and phased production alignment can govern information flows from design through construction to operations. The study shows how linking model development to control zones and takt-based production sequences enables a more coherent integration of design and execution, supporting production-oriented planning and control. In doing so, it provides empirical grounding for how model-based workflows can function as a reliable interface between design information and construction processes, contributing to more integrated and predictable project delivery models.

7.6 Integrated Contribution: From Individual Studies to a Coherent Artefact

This section synthesises the contributions of the five papers and presents their integration into the TBS artefact. Figure 13 illustrates the progression from problem identification to artefact development, evaluation, standardisation, and integration within a model-based construction framework.



Relationship between the five papers and the development of the TBS artefact

1 Problem identification & conceptual foundation → 2 Developing prerequisites & prototype → 3 Evaluation & refinement → 4 Standardisation & interoperability → 5 Integration in a comprehensive framework

	Paper I	**Paper II**	**Paper III**	**Paper IV**	**Paper V**
Focus	Developing Support for BIM-Based Takt-time Schedules for Production Control	Identifying and Developing Prerequisites for Takt Planning in a BIM-based Construction Process	The Significance of a Shared Breakdown Structure for Work Preparation Planning for a Predictable Execution	Can Interoperability between Disciplines be Improved by Adding Phasing Information Using Standardised Coding?	BIM from Design to Production: Enabling Model-Based Construction Framework with Total BIM
Key contribution of the paper	Demonstrates the gap between BIM-based design information and takt-time planning and shows how BIM can be directly connected to production flow using Takt-time Planning (TTP)	Identifies lack of shared WBS and coding as a barrier and develops a shared, deliverable-based information structure (Prototype 1) to enable integration across design and production.	Evaluates the impact of a shared breakdown structure on work preparation and execution through comparative case analysis, demonstrating Improved traceability and predictability.	Links the prototype to ISO/IEC 81346 multi-aspect classification, showing how phasing information enables interoperability and consistent information exchange.	Integrates the developed principles into a VDC-Lean-TQM framework, showing how structured information, quality assurance and production planning work together across the project lifecycle.
Main methods/ Empirical base	Review of Previous Research 3 empirical cases site visits, presentations, interviews	Focus-group workshops Implementation in project (case 1) Evaluation (scheduling, site management, production)	Comparative case study 2 rooftop assembly project Interviews + observations (planned vs. executed work)	Interviews with practitioners Workshop with classification experts Case study: bathroom floor assembly	Multiple-case study (hospital, office project) Focus groups, site observations, interviews, MMI, LOIN, Systematic completion
Outcome to the artefact (TBS development)	Establishes the need for an information structure that links BIM information to takt-based production planning.	Prototype 1 of a shared information structure: WBS + coding + production phases/ zones implemented in practice.	Refines the information structure by confirming the value of granular, standardised work packages for predictable execution and learning.	Prototype 2: Standardised information structure based on ISO/IEC 81346 (Functional, Product, Locational, Phases, Zones	Operationalisation: The information structure is embedded in a Total BIM framework that connects design, production and operations.

TBS artefact

Integrated spatio-temporal information structure

Links design information with production execution across the lifecycle.

Iterative learning and feedback across the research

Integrated contribution to the thesis

1. Categorisation by type of information

Papers IV shows how ISO/IEC81346´s functional, product, locational, and process aspect creates a mulit-layerd classification that supports interoperability.

2. Breakdown into work packages

Papers II and III demonstrate how shared WBS and production phase-based structures enable predictable takt-time planning, cost/schedule traceability, and cross-project benchmarking.

3. Process integration and quality assurance

Papers I,IV, and V illustrates how BIM-based takt planning, Model Maturity Index, and Systematic Completion can jointly secure structured, standardised, and production ready delivery

Foundation of the TBS artefact

A coherent structuring logic that enables systematic, standardised and life-cycle-oriented information flow from design to production and operations.

Figure 13 Relationship between the five papers and the development of the TBS artefact

8 Problem contextualisation: From Information Categories to Information Use in Practice

The six information categories presented in Section 3.1 describe *what information is required* across the lifecycle of a construction project. While this categorisation provides a structured, content-oriented understanding of project information, it does not explain how information is created, transformed, and applied in practice. To address this limitation, empirical material from Case 1 and Case 2 was analysed with a focus on how information is used in design and production contexts. The analysis operates at the same conceptual level as the information categories but reinterprets them from a use-oriented perspective. This enables a more nuanced understanding of project information beyond the static representations typically associated with BIM, thereby supporting a shift from content-oriented categorisation to a use-oriented interpretation that better reflects how information is applied in production processes.

This perspective distinguishes between two dimensions:

(1) the lifecycle domain (design vs. production), and

(2) the information logic (product-oriented vs. process-oriented).

The 'lifecycle domain' reflects the temporal and organisational structure of projects, while the latter captures the distinction between defining *what is built* and *how it is built*.
This distinction is particularly relevant in construction, where a persistent fragmentation exists between design and production. As discussed in Section 3.1, project information is often structured according to disciplinary and lifecycle-based categories. However, the separation between design and production stages, reinforced by project-based organisational structures, limits effective information integration and digital transformation (Samuelson & Stehn, 2023). As a result, design information is frequently developed independently of production needs, while planning, estimation and control systems are established separately, leading to discontinuities and inefficiencies.
Rather than redefining the information types introduced earlier, this section reinterprets them through the lens of product-oriented and process-oriented logic. Product-oriented information primarily defines the building as an artefact, while process-oriented information defines how the building is realised. Although the integration of these perspectives is partially addressed through model-based approaches such as 4D and 5D BIM (see Section 3.1), these integrations remain limited and often require manual restructuring (Pishdad & Onungwa, 2024; Rehman et al., 2025).
As illustrated in Figure 14, design information is primarily product-oriented, while production information is primarily process-oriented. Although elements of process information are introduced during design, such as early cost estimation and constructability considerations in the management of design these remain loosely coupled to the underlying product model. In production, product information becomes an essential input but must be reinterpreted and reorganised to support the production process, such as planning, estimation for production, logistics, and execution, often resulting in duplication and fragmentation.
The transition from design to production therefore represents a transformation problem rather than a simple handover. Design information, structured according to product-oriented and disciplinary principles, must be translated into process-oriented representations suitable for planning and control. This transformation is rarely standardised as noted in Case 1-5 both for work preparation in detail in paper III, Case 1 and restructuring for takt in Case 4, which contributes to fragmented schedules, cost structures, and work preparation data. As highlighted in previous research, the lack of standardised integration across lifecycle stages

limits automation, traceability, and data-driven decision-making in BIM-based processes (Pishdad & Onungwa, 2024).

Rather than viewing design and production as separate domains, this study conceptualises them as an integration problem. The artefact developed in this research addresses this challenge by linking product-oriented and process-oriented information within a shared structure. By doing so, it enables a continuous and traceable information flow from design to production, thereby supporting more coordinated and production-oriented project delivery.

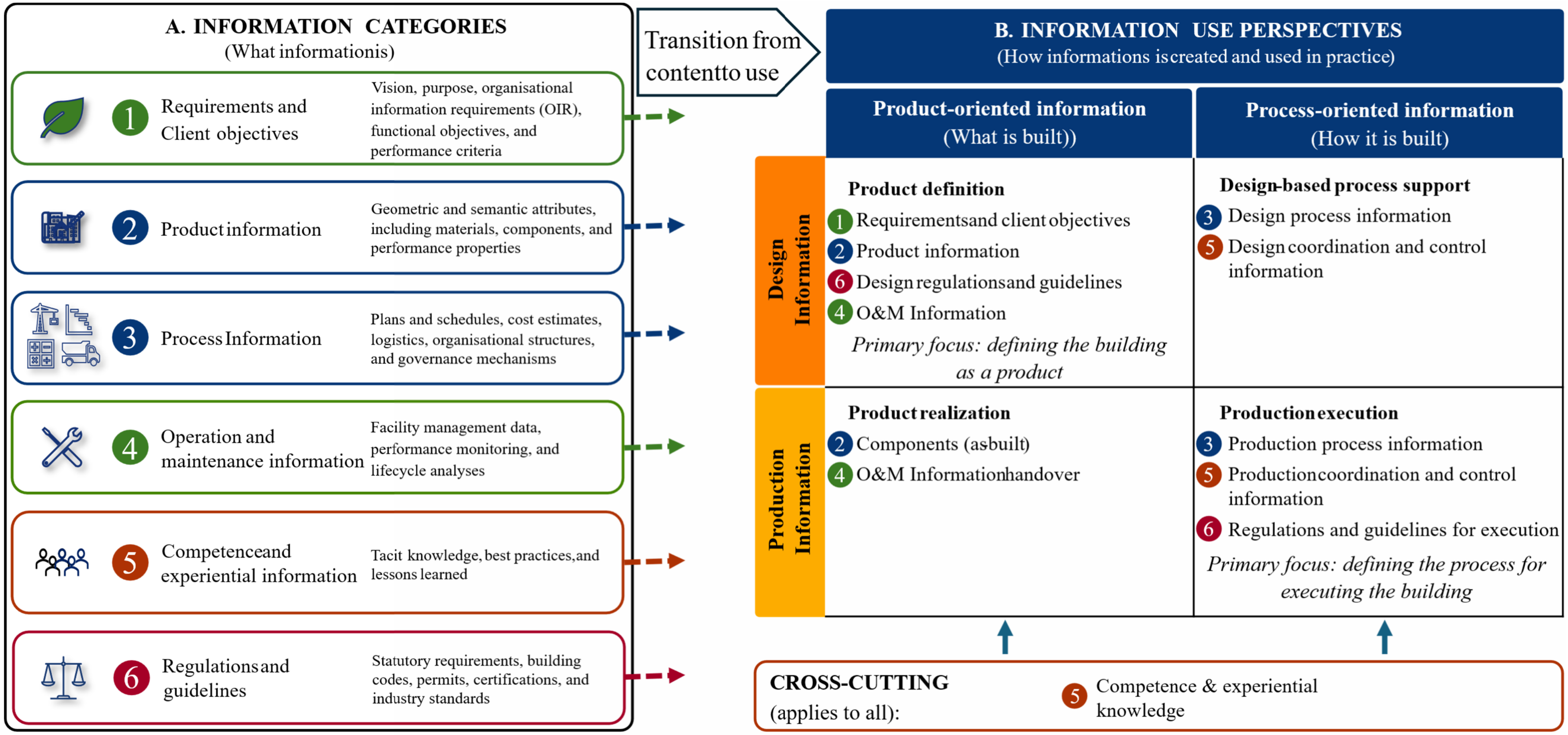


Figure 14 The figure illustrates the structuring of BIM along product- and process-oriented dimensions across design and production phases.

9 Problem formulation: From Empirical Synthesis to Information Structuring for Design–Production Integration

Across the empirical material including the author's point of departure, the Case 1-4 studies, the additional empirical data and the five appended papers a consistent pattern emerges: the construction industry is undergoing a digital transition toward model-based, production-oriented processes, yet this transition remains incomplete and fragmented.
A central observation is the persistent disconnect between design and production, despite the increasing adoption of BIM. While BIM enables a shared digital representation of the building as it matures along the project stages, its use is still limited to design coordination and visualization, rather than being fully integrated into production planning and control. This results in parallel information flows, where design documentation (model, drawings, descriptions, etc) and production process documentation (estimation, schedule, logistics etc) coexist without full alignment.

Across the cases and papers, four recurring empirical themes can be identified:

1. Fragmentation of information and processes
Construction projects are characterised by fragmented organisations, discipline-specific tools, and disconnected information structures, a pattern consistently observed across all case studies and reinforced by insights from the Total BIM focus group. This fragmentation leads to inefficiencies, rework, and difficulties in coordinating production.
Even in BIM-enabled projects, the coexistence of drawings (documents) and models (digital information) that does not follow the shared information structure (Hybrid BIM) limits the potential of digital workflows and undermines trust in the model as a single source of truth.

2. Lack of shared structures linking design and production
Several studies (Paper II, III, IV) highlight the absence of a shared breakdown structure or coding logic that connects:

- Design information structure (product-oriented information, classification structure section 3.3)
- Estimation, logistics, and budgeting structures (company-specific hybrid structures integrating product- and process-oriented information)
- Production planning structures (process-oriented information, breakdown structures, section 3.2)

This lack of alignment leads to poor traceability, weak communication, and a limited ability to connect design with execution. Conversely, locally implemented shared structures (Cases 1–4; Papers II–IV), linking selected information domains or workflows, are associated with improved predictability, coordination, and learning across sequences and projects, despite limited overall integration.

3. Need for production-oriented use of BIM
A recurring insight is that BIM must shift from a product-oriented information representation to a product- and process-oriented information carrier.

Empirical findings show that when product-oriented information is integrated with:

- collaborative planning processes for example takt planning
- on-site information flows for example planning and visualisation of material logistics and site layout

It enables better communication, earlier detection of constructability issues, and increased engagement from production actors as shown in Paper III and in the interviews in Case 4, and from the Total BIM focus group.
Emerging approaches such as Total BIM further illustrate this shift, where the model becomes the legally binding and operational backbone of the project (Paper V).

4. Socio-technical challenges in implementation
Across the interviews and observations in the cases, (Case 1-4, Total BIM focus group) and the papers specially paper III, it is evident that the challenge is not purely technical.
The adoption of BIM-based design and production depend on:

- user involvement and collaborative processes
- alignment with existing work practices
- organisational culture and roles

This confirms the importance of a socio-technical perspective, where artefacts must integrate people, processes, and technology.

9.1 Cross-case interpretation

Taken together, the appended papers (Paper 1-5) complemented with material from Case (Case 1-4) and the Total BIM focusgroup in this study suggests that the core problem is not the absence of digital tools, but rather the absence of integrated information structures and methods that connect product and process-oriented information with Design and Production.
The cases collectively demonstrate that:

- BIM has high potential but limited operational integration
- planning methods (e.g., takt planning) require better information structure support
- collaboration improves when information is visual, structured, and shared
- current practices lack a unified way of structuring and linking information across product- and process-oriented information.

This positions the research problem within Design Science Research as the need to develop a prescriptive artefact that addresses these gaps, aligning with the notion that DSR contributes through artefacts that prescribe “how to do something”.

9.2 Derived design requirements for the artefact

Based on the cross-case synthesis, the artefact (model + method) should fulfil the following requirements:

R1. Establish a shared information structure across product- and process-oriented information
The artefact must enable a common information structure that links:

- Product-oriented information
- Process-oriented information

→ This addresses fragmentation and supports traceability.

R2. Integrate design and production information
The artefact should bridge the gap between design and construction by enabling:

- direct connection between product-oriented content and production planning
- continuity of information from design to execution

→ This supports a model-based production process.

R3. Support production-oriented planning (takt and flow)
The artefact must enable:

- representation of production sequences in relation to space (location-based logic)
- integration of takt planning principles with BIM

→ This enables flow, predictability, and control in production.

R4. Enable collaborative and visual planning processes
The artefact should:

- support multi-stakeholder collaboration
- provide visual and model-based representations of BIM as it matures throughout project lifecycle
- facilitate shared understanding across disciplines

→ This improves communication and engagement.

R5. Ensure usability in a socio-technical context
The artefact must be:

- aligned with existing work practices
- usable by both design and production actors
- adaptable to different project contexts

→ This supports adoption and practical relevance.

R6. Enable structured data for feedback and learning
The artefact should:

- support structured data generation during production
- allow linking of issues, progress, and outcomes to model elements

→ This enables continuous improvement and knowledge reuse.

10 Design and Development of the Artifact

The TBS is developed as a response to the requirements derived from the cross-case synthesis (R1–R6), section 9.2. These requirements highlight the need for a unified information structure that integrates design, planning, and production within a model-based construction process.

In line with Design Science Research, the TBS is conceived as a prescriptive artifact that defines how information should be structured, linked, and operationalized across project stages. The primary design objective is to bridge the gap between design-oriented BIM models and production-oriented planning and control, thereby enabling continuity of information from design to execution.

The artefact introduces a spatio-temporal structuring logic that complements existing information structures (e.g., breakdown structures and classification systems). By doing so, it enables a coherent and traceable flow of information across disciplines, roles, and project stages.

10.1 Design Principles

Based on the derived requirements (R1–R6), five design principles guide the development of the artefact:

- **DP1 – Shared information structure:** Information shall be organized within a common information structure that links design and production (product- and process-oriented information).
- **DP2 – Design–production integration:** The artefact shall establish explicit connections between BIM-based design information and production planning and execution.
- **DP3 – Production-oriented structuring:** Information shall be structured to support production flow, sequencing, and takt-based planning.
- **DP4 – Collaborative and visual accessibility:** The artefact shall enable shared understanding through visual representations and role-based filtering and access to information.
- **DP5 – Socio-technical usability and learning:** The artefact shall align with existing practices while supporting feedback, learning, and continuous improvement.

These principles operationalize the identified requirements and define the conceptual foundation of the TBS. Together, they guide the translation of empirical findings into a structured artefact that is both theoretically grounded and practically applicable.

10.2 Artifact Overview: The Spatio-Temporal Breakdown Structure (TBS)

The core structuring logic of the TBS is based on two orthogonal and complementary dimensions: a temporal dimension (production phases) and a spatial dimension (production zones). As illustrated in Figure 15, these dimensions provide the primary structure for organising construction work across time and space, while simultaneously enabling the integration of four interrelated information dimensions: what is built (product), when it is executed (process), where it is performed (location), and who is responsible (organisation).

The dimensions are orthogonal in the sense that they represent independent structuring principles—time and space—allowing each to be defined without constraining the other. At the same time, they are complementary, as meaningful production planning and control emerge only when both dimensions are combined to represent the flow of work through space over time.

Together, these dimensions form a spatio-temporal structure that enables coordinated planning, execution, and analysis of construction processes, while operationalising a socio-technical perspective in which product, process, location, and organisational responsibilities are integrated within a unified information structure.

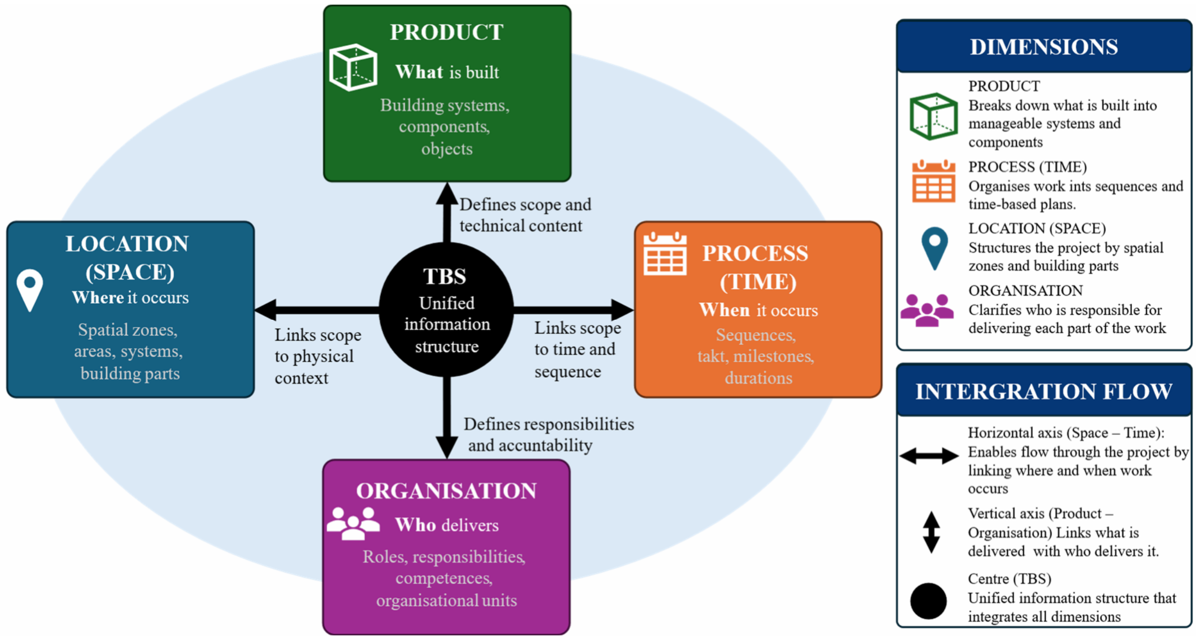


Figure 15 The Spatio-Temporal Breakdown Structure (TBS) as a socio-technical integration framework.

10.2.1 Production phases (temporal–organisational dimension)

Production phases represent time-bounded partial deliveries of the project, defining *when* work is performed and coordinated. Each phase constitutes a coherent scope of work that can be planned, executed, and validated as a unit, based on interdependent systems, disciplines, and stakeholders.

Each phase is assigned to a dedicated delivery team, establishing a temporal–organisational structure that explicitly links *when* work is performed with *who* is responsible. This clarifies responsibilities, interfaces, and information dependencies across phases.

As a result, information can be managed in terms of completeness, consistency, and accountability over time, enabling structured handovers and coordinated progression between phases.

10.2.2 Production zones (spatial–operational dimension)

Production zones represent the spatial subdivision of the project within each production phase, defining *where* work is performed. Zones are geographically bounded units, such as areas, building parts, or systems that structure the physical context of production.

This spatial–operational structure enables location-based planning, takt-based sequencing, and coordination of trades within shared workspaces. By organising work according to spatial context, zones support the alignment of activities with physical constraints and dependencies.

As a result, work can be synchronised and controlled based on *where* it occurs, enabling improved coordination, flow, and situational awareness on site

10.2.3 Spatio-temporal integration

The integration of production phases and production zones forms a spatio-temporal production structure, where each unit of work is defined by both a temporal scope (*when*) and a spatial context (*where*).

Within this structure, product and process information are integrated by linking *what* is to be built with *when* and *where* it is executed, while organisational responsibilities define *who* delivers each part of the work.

This unified structuring enables alignment between design, planning, and execution, supporting coordination across disciplines and trades. It further establishes a continuous and traceable flow of information across both time and space.

As a result, information is structured according to how work is sequenced and executed in practice, rather than being separated by project stages or disciplinary boundaries, thereby operationalising an integrated and production-oriented information logic.

10.3 TBS as a breakdown structure

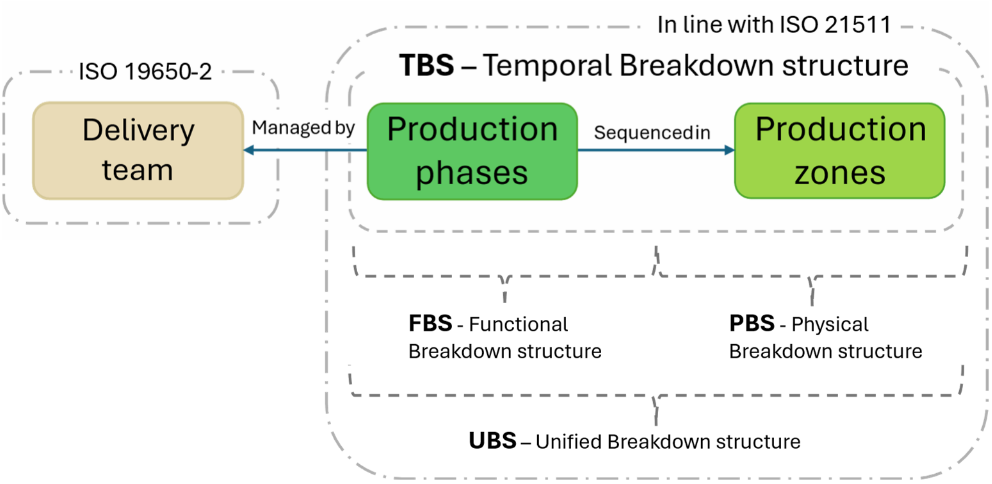


Figure 16 How TBS as model artifact adapts the UBS-Unified Breakdown Structure in line with ISO 21511 and is conceptually connected to ISO 19650-2

A recurring challenge identified in both the literature (Gebremichael et al., 2022) and the empirical material, as shown in section 7 is the fragmentation of breakdown structures across disciplines, lifecycle stages, and information domains. Existing approaches to structuring project information are often developed in isolation, cost breakdowns, work breakdowns, location breakdowns resulting in weak interoperability and limited traceability across systems. This fragmentation has been identified as a key barrier to effective information integration and digitalisation in construction (Gebremichael et al., 2022).

Conceptually, the TBS addresses this problem by building on the integrative principles proposed in the Unified Breakdown Structure (UBS) seen in Figure 16, which emphasises the need for a consistent structuring logic across information domains. Rather than introducing additional parallel structures, the TBS operationalises this principle through a unified spatio-temporal framework, consisting of a temporal–organisational dimension (production phases) and a spatial–operational dimension (production zones).

Within this framework, production phases constitute the primary structuring mechanism for when work is performed and who is responsible. Each phase defines a coherent, time-bounded scope of work assigned to a dedicated delivery team, thereby directly addressing identified requirements related to responsibility allocation, coordination, and information ownership. By structuring all project information according to explicitly defined phases, the TBS satisfies fundamental breakdown structure principles, such as completeness and non-overlap (e.g. the

"100% rule" in ISO 21511), while simultaneously enabling accountability and coordination of interdependencies across the project lifecycle.

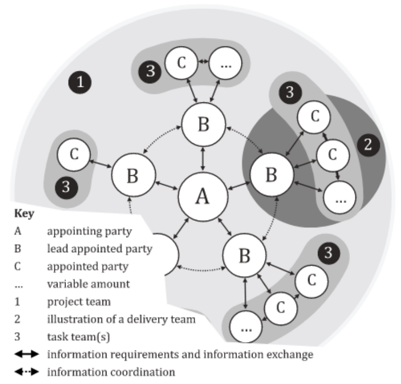


Figure 17 Illustration from ISO 19650-2 page 12 Interfaces between parties and teams for the purpose of information management,

This explicit coupling of temporal scope and organisational responsibility aligns with the principles of information management defined in ISO 19650-2, seen in Figure 16 where the definition of delivery teams, responsibilities, and information interfaces is central. However, in contrast to treating these as procedural or contractual requirements, the TBS embeds them directly into the production structure, thereby translating information management principles into an operational planning logic.

Complementing this, production zones constitute the spatial–operational dimension, defining where work is performed. These zones enable a location-based structuring of activities, which directly addresses empirically observed coordination challenges related to trade interdependencies, workspace conflicts, and spatial constraints. By organising work according to geographically bounded units, the TBS reduces coordination complexity and supports the sequencing and synchronisation of work in space.

The integration of production phases and zones further enables the alignment of product and process information, ensuring that what is to be built is consistently linked to when and where it is executed, as well as who is responsible. This integrated structuring directly supports flow-oriented production planning by enabling the application of takt planning principles, where spatial subdivision and temporal sequencing are combined to achieve balanced and continuous production flow. In doing so, the TBS addresses recurring empirical challenges related to variability, interruptions, and lack of flow in construction production.

Finally, by ensuring that each information object, whether related to cost, schedule, or risk is linked to a consistent temporal identifier (phase) and, where relevant, a spatial identifier (zone), the TBS establishes a unified structuring logic across traditionally separate breakdown structures. This creates a shared reference system that enables consistent information exchange, improved interoperability, and traceability across disciplines and project stages.

In this way, the TBS can be understood as a design response to the fragmentation problem not by replacing existing breakdown structures, but by integrating them through a common spatio-temporal framework. This represents a shift from parallel and discipline-specific decomposition towards a coordinated and production-oriented structuring logic, supporting decision-making, coordination, and continuous information flow throughout the project lifecycle.

10.4 TBS in classification structure

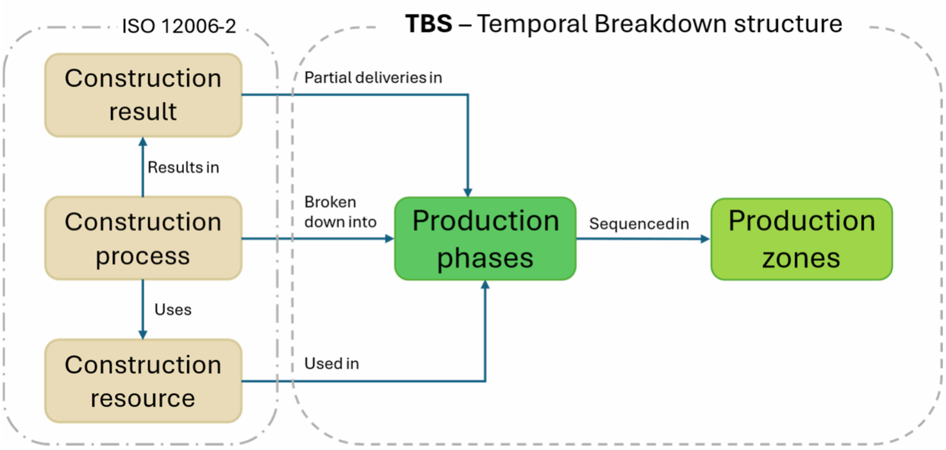


Figure 18 Conceptual how TBS as model artifact connects to ISO 12006-2

A recurring issue identified in both the literature, and the empirical material is that classification systems provide well-defined taxonomies for construction information yet remain weakly connected to the logic of production. Standards based on ISO 12006-2 establish principles for structuring information into classes and tables, but they do not prescribe how this information should be grouped, sequenced, or managed in relation to project execution.

The TBS addresses this limitation by introducing production phases as a production-oriented structuring principle, Figure 18. Rather than organising information solely according to what it represents (e.g. building elements or systems), the TBS enables information to be structured according to when it is produced and by whom. This directly responds to empirically identified challenges related to fragmented information handovers, unclear responsibility boundaries, and the difficulty of linking design information to production activities. By associating each information object with a defined production phase, the TBS makes it possible to consistently identify the resources, actors, and information required at each phase of execution.

In this sense, a standardised structure for production phases becomes a prerequisite for integrating design and production information beyond project-specific implementations. While building components can be consistently defined at an industry-wide level through national implementations of ISO 12006-2, such as CoClass, ensuring semantic consistency across projects, the sequencing and dependency relationships between production phases remain project-dependent. However, by applying a shared structuring logic for phases, these variations can be systematically analysed, compared, and improved over time.

In this way, the TBS complements classification systems by adding a production dimension that enables their practical application in planning and execution, rather than limiting them to static categorisation.

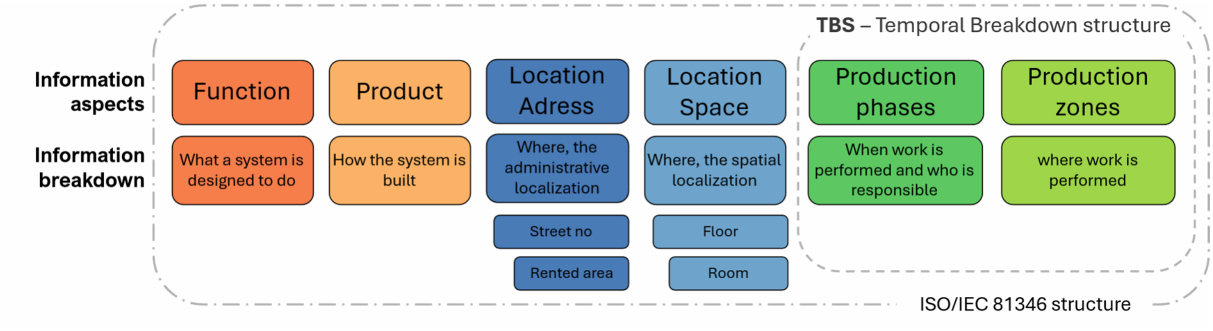


Figure 19 Conceptual how TBS as model artifact complements ISO 81346

While ISO 12006-2 provides a framework for categorising construction information, it does not define how individual information objects should be uniquely identified across multiple perspectives. This limitation is addressed by the ISO 81346 series, which enables information to be described simultaneously from different aspects, including function (what the object does), product (the physical component), and location (where it is situated). This multi-aspect structuring reflects a fundamental requirement to represent construction information in a way that supports multiple interpretations without loss of consistency. However, while ISO 81346 provides a robust framework for describing what an object is and where it belongs, it does not explicitly capture when information is generated or how it relates to the sequence of production.

The TBS extends this multi-aspect logic by introducing a temporal–organisational dimension (production phases) and a spatial–operational dimension (production zones) see Figure 19, thereby enabling information to be consistently linked to responsibility, location, and execution over time. In contrast to classification and reference designation systems, which primarily describe objects and their relationships, the TBS provides a structuring logic for how information is used and coordinated in the production process.

While the present study focuses on the conceptual integration of these dimensions, their implementation can be formalised through established classification and reference designation systems, such as ISO 81346 and ISO 12006-2–based schemas (e.g. CoClass). This enables production-related information to be coded alongside functional, product, and spatial identifiers, supporting consistent information exchange across systems and lifecycle stages. Ongoing developments within the ISO/IEC 81346 series, including emerging parts addressing processes and production systems, further reinforce the relevance of integrating temporal aspects into standardised information models.

The combination of ISO 12006-2, ISO 81346, and the TBS thus establishes a coherent structuring logic in which classification, reference designation, and production are integrated rather than treated as separate domains. Functional, spatial, and product-related information can thereby be consistently defined and linked to when and by whom it is produced.

In this way, the TBS acts as an integrating layer that connects established classification principles with the operational logic of construction production. Rather than introducing a new classification system, it provides a mechanism through which existing standards can be operationalised in a production-oriented, model-based environment, enabling traceability, coordination, and continuous information flow across the project lifecycle.

10.5 TBS as a method artefact: Managing information maturity across the lifecycle

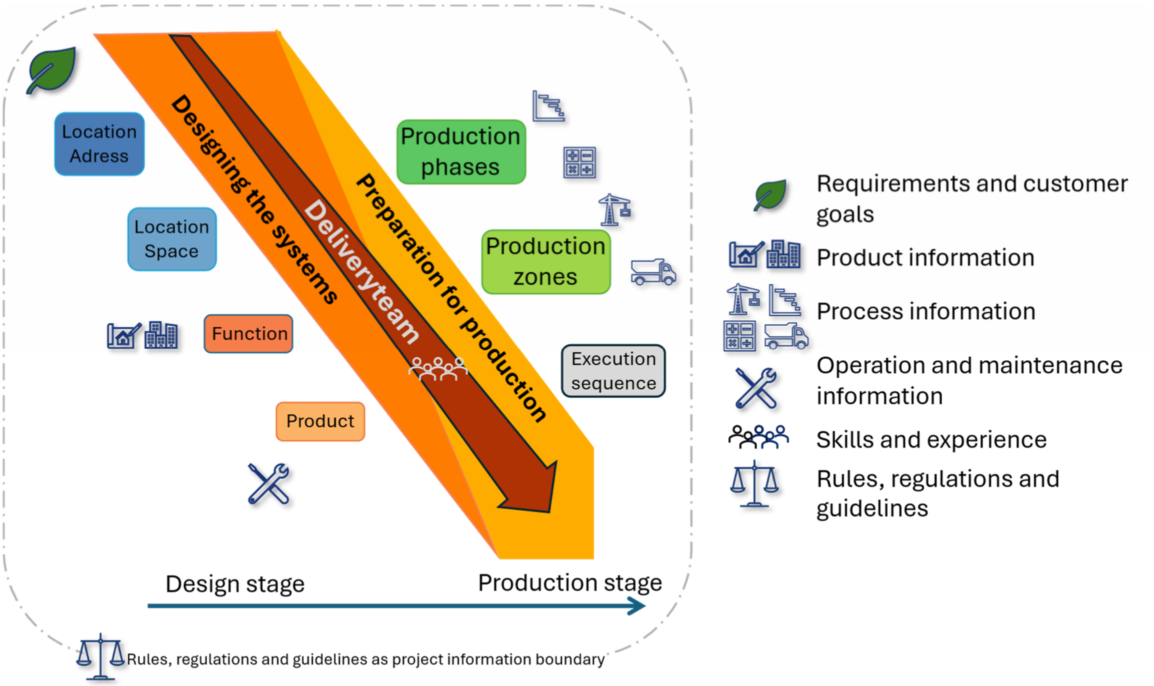


Figure 20 TBS as method visualising progress of information delivery team development.

While the TBS model artefact defines how project information is structured and interrelated, described in 9.3 and 9.4, this section focuses on the method artefact, describing how information is progressively generated, refined, and validated within that structure throughout the project lifecycle.

The method artefact operationalises the spatio-temporal structure by linking information development to lifecycle progression. In doing so, it provides a structured mechanism for managing information maturity across design, production, and operation, addressing a recurring challenge identified in both the literature (Pishdad & Onungwa, 2024; Rehman et al., 2025) and the empirical material synthesised in section 8: the fragmented coordination of how project information evolves across disciplines, over time, and in relation to production.

Building on the information categories introduced in Section 3.1 and reinterpreted in Section 8 through a design–production and product–process perspective, project information is progressively elaborated across core domains, see Figure 20, including requirements and client objectives, product information, process information, operation and maintenance information, and experiential knowledge. These domains evolve within a framework defined by regulatory requirements and project-specific constraints, but are coordinated through the spatio-temporal structure of the TBS.

During the design stage, project requirements and client objectives are translated into a buildable system through progressively developed product and process information. At this stage, production phases provide a temporal–organisational structure for coordinating information development (when and by whom), while production zones introduce a spatial–operational structure (where) that anticipates how work will be executed. Together, these structuring principles enable design information to be developed in alignment with the intended production flow, rather than as an isolated representation of the product.

This approach reflects empirically observed needs for earlier integration of production knowledge, as delivery teams are progressively expanded from design disciplines to include production and process-related competences. By linking information development to production phases, the TBS ensures that information maturity is aligned with execution requirements, reducing discontinuities between design and production.

Towards the end of the design stage, see Figure 20, the information required for execution within each production phase reaches a level of maturity sufficient to enable coordinated work across production zones. At a detailed level, activities within each zone can be sequenced to establish a structured production rhythm, commonly referred to as takt-based workflow, where work progresses systematically across zones.

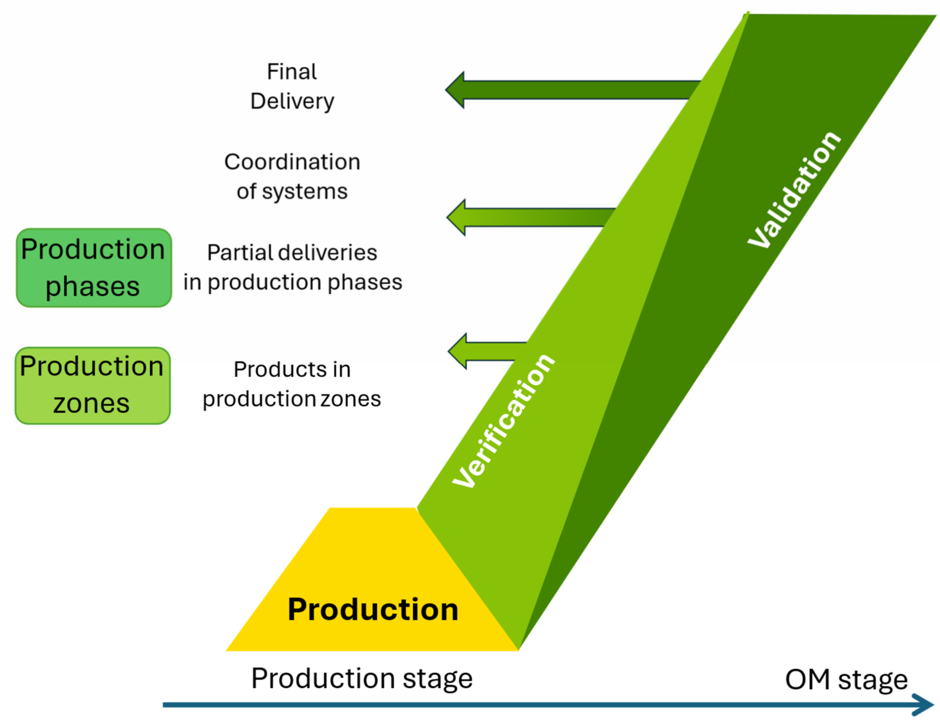


Figure 21 TBS as method visualising feedback on completed deliveries.

When the production stage is initiated, production phases and zones provide a consistent framework for organising and controlling the production system. Planned work can be directly compared to executed work at the level of zones, enabling verification of sequencing, resource availability, and execution conditions. Deviations can be identified early and addressed to maintain production flow as seen in Case 4 and Total BIM focus group with project using takt planning methodology.

As production progresses, the focus shifts from local execution within zones to completed deliveries at the level of production phases and technical systems. This reflects the upward leg of the V-model, where executed work is evaluated against design intent, enabling a transition from verification of performed activities to validation of functional outcomes. This transition has been identified as a recurring challenge in both the initial problem formulation and the empirical material (Cases 1–4; Papers II–V), particularly in relation to systematic verification, self-control processes, and the alignment between planned and executed work.

At project handover, all partial deliveries can be systematically validated against project requirements and client objectives, supporting a controlled transition to the operation and maintenance phase. In this context, the TBS provides a structured linkage between design intent, production execution, and asset performance.

This progression aligns with the principles described in ISO 19650, where information evolves from Organisational Information Requirements (OIR) to the Project Information Model (PIM) and ultimately the Asset Information Model (AIM). The TBS method artefact complements this framework by linking information maturity directly to production flow and verification processes, thereby operationalising lifecycle-based information management.

The composition of delivery teams evolves throughout the lifecycle as actors enter and exit the project in response to shifting responsibilities. The TBS mitigates the resulting coordination challenges by linking contractual responsibilities to a shared spatio-temporal context. Actors can identify what they are responsible for, when and where their work is performed, and with whom coordination is required.

By making these relationships explicit, the TBS reduces reliance on implicit knowledge and ad hoc coordination, enabling more efficient onboarding, improved continuity, and a more consistent flow of information across the project lifecycle.

10.6 Synthesis of the TBS artefact

The results presented in this chapter describe the TBS as a unified artefact comprising both a model and a method, which together address the identified fragmentation between design and production (see Section 8).

As a model, the TBS defines a spatio-temporal information structure based on production phases and production zones. This structure establishes a shared breakdown logic in which product-oriented and process-oriented information are integrated across design and production, enabling coordinated planning, execution, and analysis of construction processes.

In relation to existing frameworks, the TBS complements established classification and reference designation systems by introducing a production-oriented structuring logic. By linking product definitions to sequencing, location, and execution contexts, the TBS enables a flow-oriented representation of work, where design intent can be consistently traced through planning and realised in production.

As a method, the TBS describes how information is progressively generated, structured, and validated within this framework throughout the project lifecycle. By linking information development to production phases and zones, and aligning with a V-model representation, it enables the continuous coordination of information maturity across interconnected domains, including requirements, product, process, and operational information. This establishes a structured relationship between design intent, execution, and asset requirements.

The artefact further supports collaborative interpretation and coordination by providing a shared and visually interpretable structure through which different actors can relate their contributions to both product and process perspectives. In addition, the integration of feedback from production into the information structure enables iterative learning and the incorporation of experiential knowledge across project phases.

Taken together, the model and method artefacts establish a structured yet adaptable framework for integrating design and production information. This enables consistent information flow, improved traceability, and enhanced coordination across project contexts, while supporting a shift towards a more production-oriented and integrated approach to information management in construction.

The two figures, originally presented in Section 4 (Figure 5, Figure 6) and reproduced here as Figure 22 and Figure 23, illustrate this duality: the first positions the TBS in relation to classification and information structuring frameworks, while the second demonstrates how the

TBS method supports the progressive development and validation of information within a lifecycle perspective.

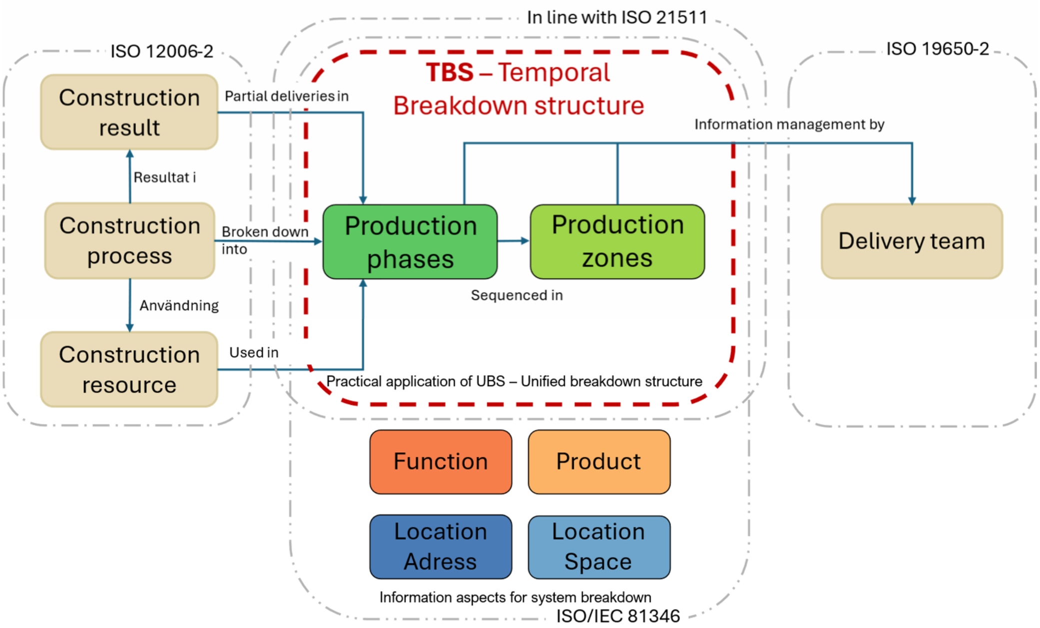


Figure 22 The TBS model artefact conceptualized in relation to ISO standards, illustrating the integration of the information model (structure)

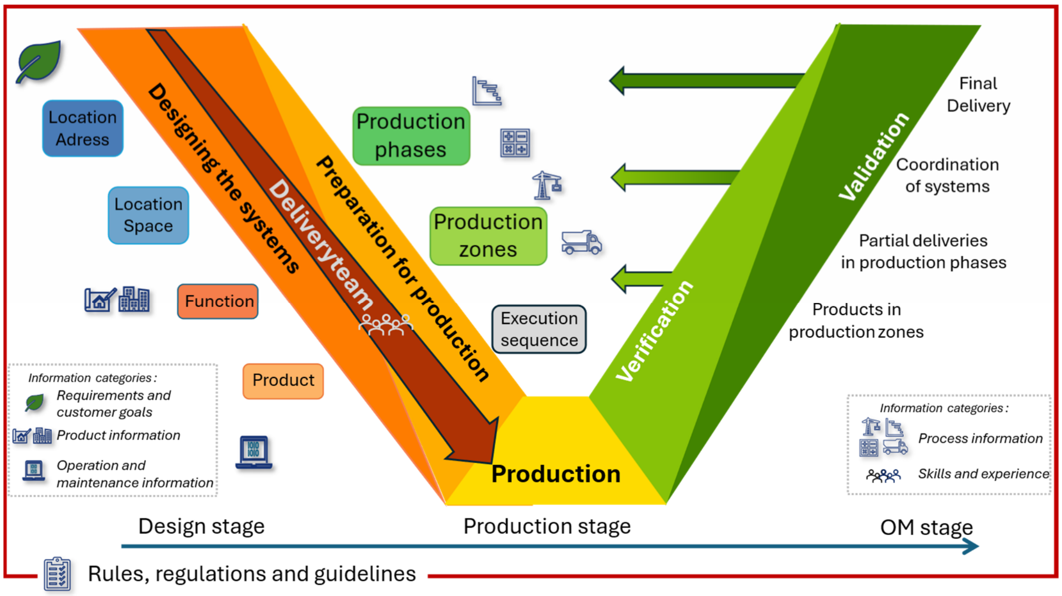


Figure 23 The TBS method artefact conceptualized in relation to project lifecycle, illustrating the information method (flow), aligned with systems engineering principles

10.7 Evaluation through a testbed, the SIM House

The SIM House serves as an experimental testbed for developing and evaluating the proposed TBS within a controlled yet empirically grounded context. It is derived from the real construction project Eriksberget, representing one of three residential buildings, and reflects a multi-actor project environment managing project information.

Building on the problem contextualisation in Chapter 8 and the problem formulation in Chapter 9, the SIM House provides a setting for examining how project information can be structured and integrated across lifecycle stages. This is explored through the instantiation of the TBS artefact, comprising both the conceptual model and the associated method, as developed in Sections 10.2–10.5. While the preceding sections establish the artefact through its alignment with classification principles, standards, and information maturity frameworks, the SIM House enables an evaluation of how this model–method combination performs when applied to the integration of design and production information within a bounded project context.

Rather than replicating the full complexity of the real project, the SIM House abstracts and reconstructs a subset of the project's information environment. The focus is placed on a limited set of interrelated building systems and their associated spatial context, enabling a controlled examination of how the TBS supports systematic information structuring and alignment between design and production, while maintaining traceability to real project conditions.

Within this scope, the sanitary drainage system is used as the primary evaluation case. The system is inherently structured into sub-deliveries aligned with different production phases, requiring coordination between disciplines over time. At the same time, its relatively limited number of components makes it suitable for illustrating how the TBS model and method operate in practice.

To provide contextual grounding, the evaluation also includes complementary information domains that interact with the sanitary drainage system (Figure 23):

(i) the address and room system for spatial localisation,
(ii) the wall and slab system as part of the structural context, and
(iii) the ventilation system, and
(iv) the sanitary drainage system

Together, these domains constitute a bounded yet representative subset of the project's information, capturing key spatial, structural, and building services relationships relevant for design–production integration.

Applying the TBS artefact to this subset enables an examination of how structured system representations can function as reusable templates, supporting a more consistent interpretation of requirements compared to experience-based practices. It further allows sub-deliveries to be coordinated within their respective production phases, verified against planned outcomes, and validated against project-specific requirements and applicable standards, as described in Section 10.4.

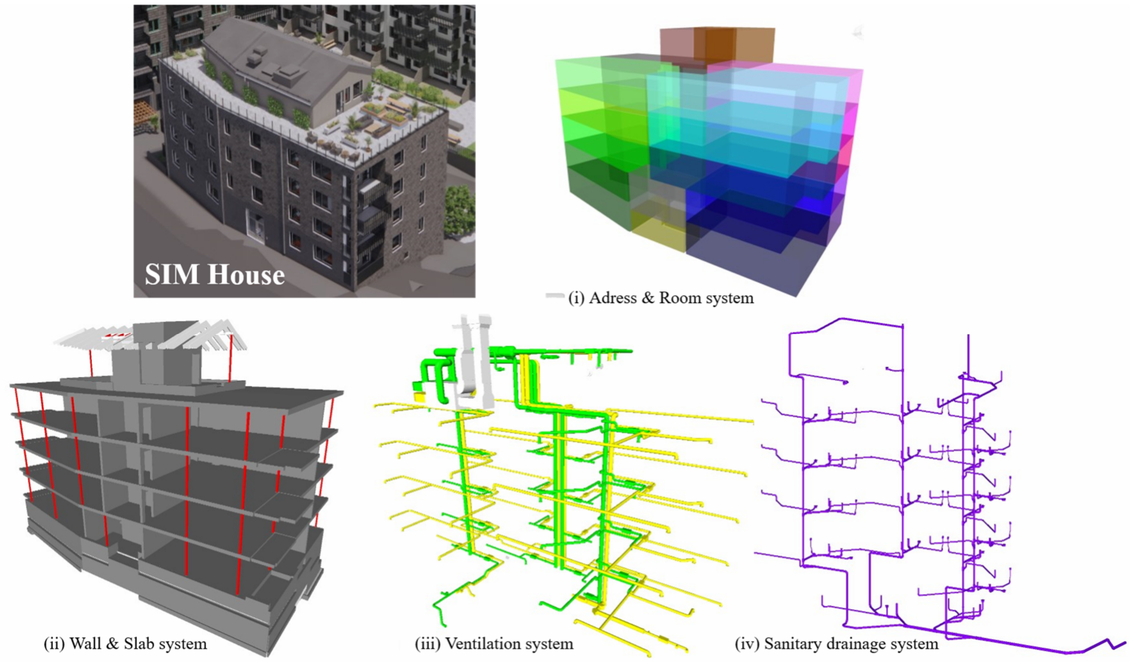


Figure 24 Visualization of the SIM House and the four systems included in the evaluation

10.7.1 Production Phases in SIM House

The production phase structure applied in the Eriksberget (Case 2) project builds on a company-specific breakdown originally developed in the Hovås Tak project (Case 1). While the overall phase structure remains consistent, the Eriksberget project required a more detailed decomposition to support planning and execution.

In the SIM House evaluation, the analysis is scoped to the Framework phase and a specific spatial unit, Production Zone 2, enabling a focused examination of how the TBS artefact structures and integrates information at an operational level. To capture the interfaces and dependencies that influence this structuring, adjacent phases (Groundwork and Interior Work) and neighbouring zones are also considered. These provide the necessary context for analysing how boundaries are defined and how delivery teams establish shared understanding and coordination across phases and zones.

Within this bounded scope, the evaluation illustrates how the conceptual information structure (model artefact) is instantiated in the Framework phase, and how the associated method supports the grouping, sequencing, and allocation of responsibilities across both temporal (phases) and spatial (zones) dimensions.

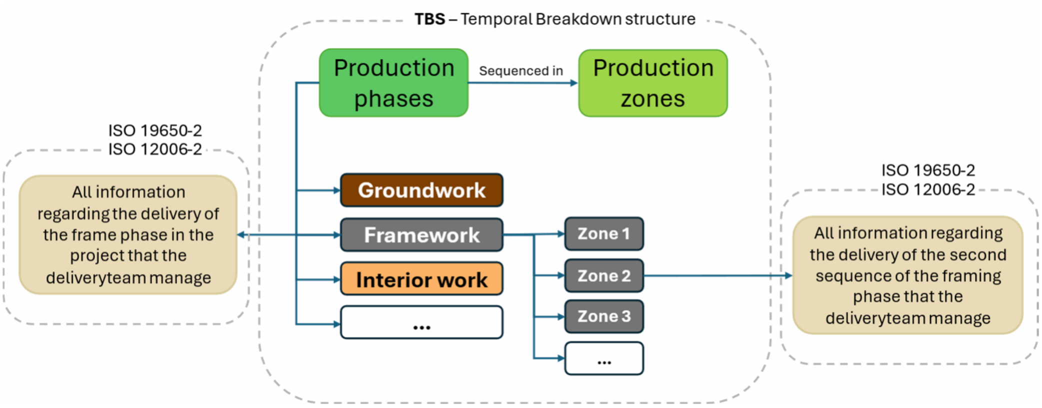


Figure 25 TBS illustrating a bounded breakdown of production phases and production zones, including clarification of information content and responsibility.

10.7.2 Evaluation Framework: A Systems Engineering Perspective

The evaluation examines how the TBS artefact structures and integrates information within the defined scope of the SIM House, with particular focus on the Framework phase and Production Zone 2. Rather than assessing individual design principles in isolation, the evaluation considers how these principles are manifested in combination through the application of the artefact within a deliberately bounded context. Although limited to a subset of information and a specific production phase, this scope captures key relationships between design and production, enabling the combined effects of the design principles to be analysed in context.

From a systems engineering perspective, the evaluation illustrates how project information evolves through successive levels of structuring, from client objectives to system design, coordinated deliveries, and execution. Within this progression, the TBS artefact is examined in terms of how it:

- structures information across temporal (production phases) and spatial (production zones) dimensions,
- supports the definition and coordination of sub-deliveries, and
- links structured information to verification and validation activities.

In this way, the SIM House provides a setting for analysing how the artefact contributes to information maturity, coordination, and execution within a design–production context..

10.7.3 From Client Objectives to Technical Systems

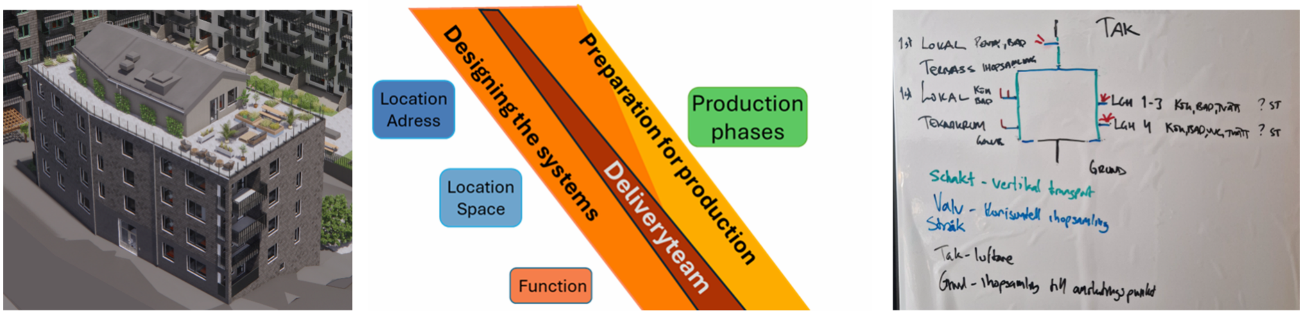


Figure 26 External representation of SIM House illustrating client objectives translated into requirements for technical systems, including a conceptual functional diagram of the sanitary drainage system.

At the early stage of the project, client objectives are translated into functional requirements for technical systems, marking the initiation of the system design process. For the sanitary drainage system, the plumbing designer interprets these objectives and defines system-level functions related to the collection, transport, and disposal of wastewater.

Within the TBS framework, production phases are introduced as a structuring principle already at this stage, enabling the early formation of delivery teams, as illustrated in Figure 27. This allows system requirements to be related to specific production contexts, where interdependencies between technical systems can be identified and coordinated. As a result, requirements are not only defined at the system level but are progressively specified in relation to sub-deliveries across production phases.

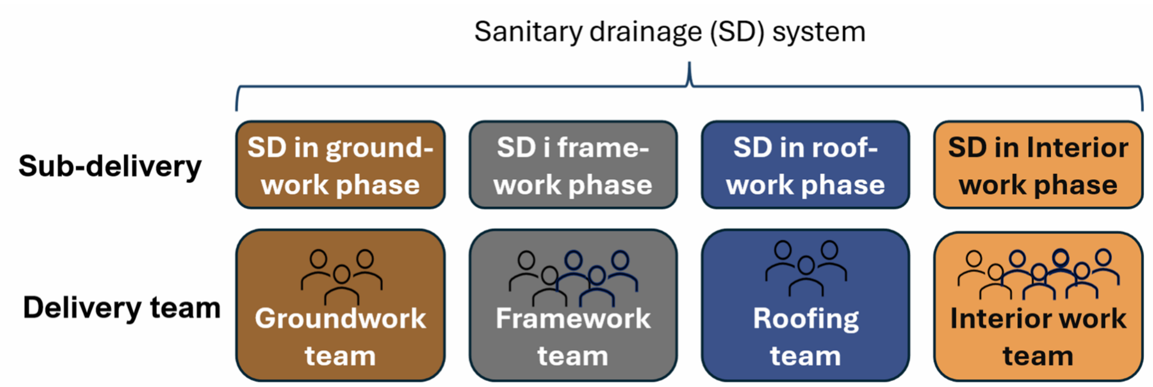


Figure 27 TBS structuring principle of organisation and deliveries

Through participation in different delivery teams, the plumbing designer refines system requirements based on inputs from other disciplines and their respective sub-systems within each phase:

- **Groundwork phase**: defines boundary conditions for the collection and conveyance of the sanitary drainage system to the municipal connection point, as well as constraints related to foundation methods and overall drainage configuration.
- **Framework phase**: structural systems constrain routing possibilities, influencing spatial requirements such as slopes and vertical distribution.
- **Roofwork phase**: introduces requirements for drainage and ventilation routing through the roof level.
- **Interior work phase**: establishes demand by defining the number of apartments and sanitary spaces, forming the basis for system capacity and performance requirements.

This phase-based structuring enables system requirements to be formulated in a way that anticipates downstream integration and execution, supporting coordination across disciplines and reducing the need for later reinterpretation.

10.7.4 From Technical Systems to Product Systems

Once the functional requirements of the sanitary drainage system have been defined for each sub-delivery (Figure 27), the system is further developed into product systems. At this stage, the design transitions from functional descriptions to concrete specifications of components, materials, and assembly principles.

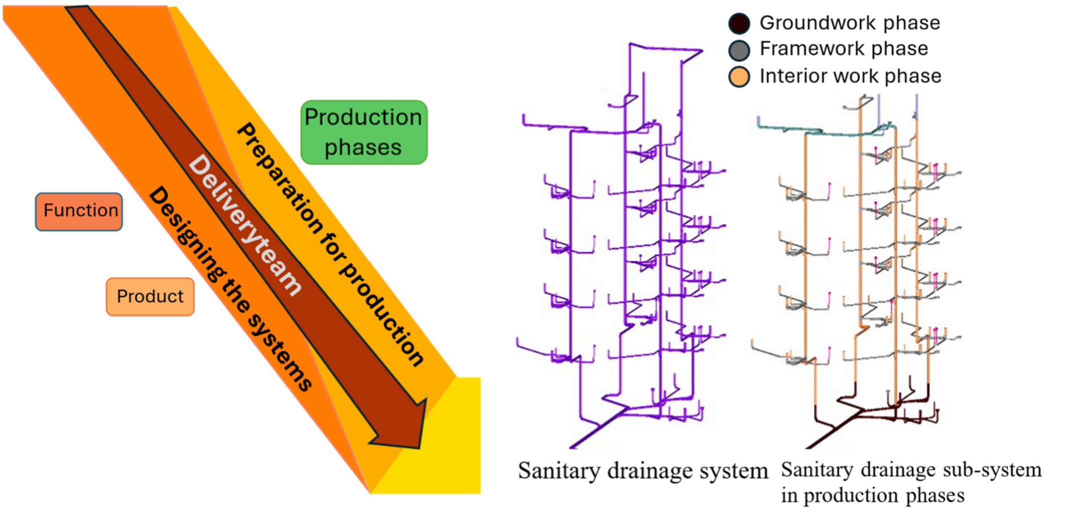


Figure 28 Increasing maturity from functional descriptions to product systems, including increased detailing of production preparation and clarification of scope through production phases.

The introduction of the TBS enables a clearer definition of boundaries between production phases and sub-deliveries, making scope and responsibilities more explicit, Figure 28. By structuring system requirements in relation to specific production phases, responsible designers can identify which technical systems must be coordinated within each phase, Figure 29.

This phase-based contextualisation supports the selection of product systems that not only fulfil functional requirements but are also compatible with interfacing systems and their associated constraints. For example, when sanitary drainage is coordinated within the structural framework phase, integration with the structural system influences product selection, including requirements related to embedding pipes within slabs, tolerances, and installation sequences. The demarcation between production phases further clarifies the scope of work within each phase and supports resource planning and material logistics. For instance, if hollow-core slabs are used, sanitary drainage may need to be installed as suspended systems in a later production phase.

By enabling coordination of system requirements and product choices within delivery teams at this stage, potential integration issues can be identified and addressed earlier in the process. The integration of product systems with other technical systems generates process information required for production planning and execution, including assembly sequences, resource and time requirements, logistics flows, and risk considerations. For the sanitary drainage system, integration with the structural system influences installation strategies, such as embedding components within slabs and coordinating installation floor by floor.

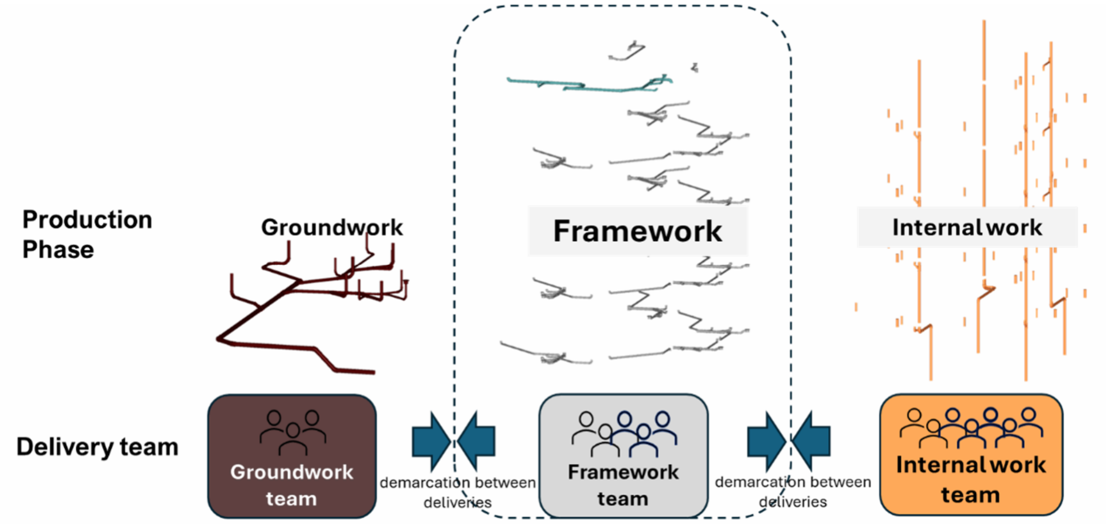


Figure 29 Visualization of how delivery teams structure and group information within production phases, including clarification of boundaries between phases, here exemplified through the sanitary drainage system.

As product maturity increases, both product and process information are progressively refined within each production phase. Where structured information from previous projects is available, this can be related to the current phase and sub-deliveries, providing a basis for identifying risks and constraints. This phase-based structuring allows such information to be considered within delivery teams in relation to specific execution contexts, supporting more informed work preparation, planning, and production control. The resulting information also contributes to documentation required for operation and maintenance.

Within this structured context, the transition from design to production becomes more explicit. The phase-based structuring provides a basis for coordinated handover from the construction work environment coordinator in design (BAS-P) to the coordinator in production (BAS-U). Prior to the start of each production phase, BAS-U can verify that relevant information is available, that work preparation has been carried out, and that work environment requirements have been addressed.

The structuring of information by production phases also supports the development of phase-specific work environment plans and site layout plans (APD plans). These can be coordinated across adjacent phases, reducing interface risks between delivery teams. When each team is responsible for its phase-based planning, while coordination is maintained across teams, a shared understanding of site conditions can be established.

10.7.5 From System Deliveries to Coordinated Execution in Production Zones

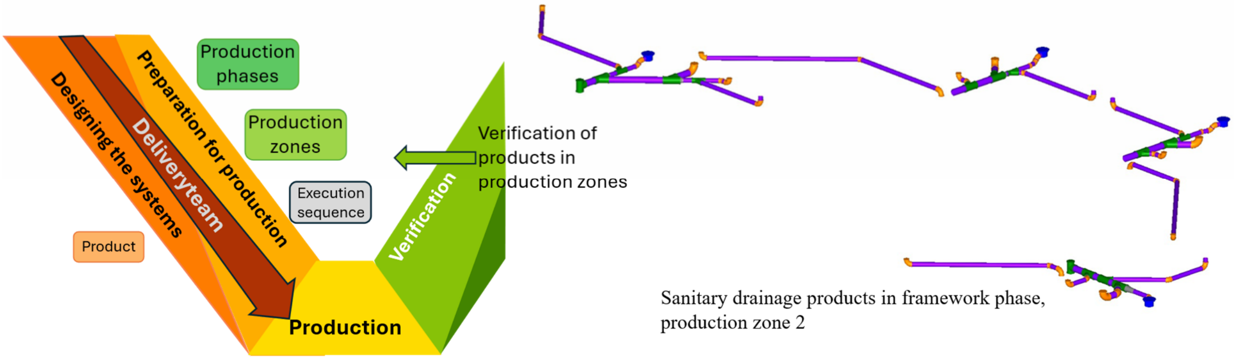


Figure 30 Increased detailing of production preparation and decomposition of product phases into execution sequences through production zone structuring, clarifying the scope of work and associated product installations.

As the project transitions from design to production, the focus shifts to coordinating execution in time and space. Within the TBS framework, sub-system deliveries are structured into production zones, Figure 30, where work is planned, executed, and verified as bounded work packages. These zones provide a shared spatial reference, establishing a common spatial logic that aligns disciplines and facilitates coordination within and across delivery teams.

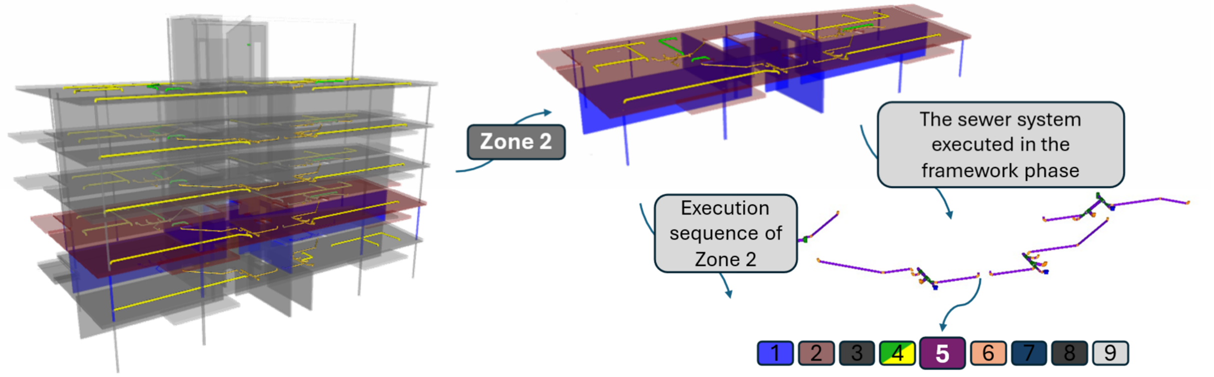


Figure 31 Sub-delivery of the sanitary drainage system in the framework phase, illustrated in relation to the structural system (walls and slabs) and the ventilation system, including grouping within a production zone and sequencing of work across disciplines.

Within each zone, delivery teams coordinate the sequence of work across disciplines, Figure 31. By defining scope, responsibilities, and dependencies at the level of sub-deliveries, a shared sequencing logic can be established that reflects both system interdependencies and practical constraints. For the sanitary drainage system, this implies that certain installations can be executed as continuous operations within a zone, while others require staged execution in coordination with structural and reinforcement activities. Such dependencies can be made explicit and negotiated within delivery teams, supporting alignment between trades regarding sequencing and handovers.

This structured basis enables the development of recurring work sequences across zones, for example inspired by takt planning principles, where stable execution patterns can be established and adapted to project conditions. While not prescriptive, this creates conditions for more synchronised workflows, where actors gain a clearer understanding of preceding and subsequent tasks, as well as their own role within the sequence.

Observations from previous projects (Case 4) indicate that while takt-based production logic can provide a clear structure for execution, supporting information is often not aligned with the same zoning and sequencing principles, requiring additional effort during planning. The SIM House evaluation demonstrates how information can instead be aligned with production zones already during the integrated design stage, enabling delivery teams to focus on coordination and refinement during execution.

10.7.6 Validation of Deliveries, Systems, and Final Approval

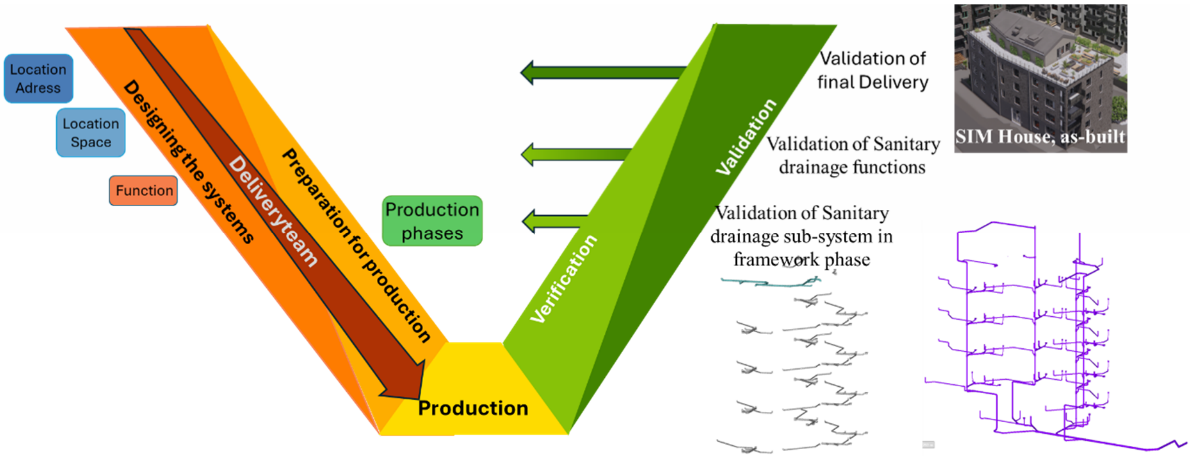


Figure 32 Verification of sub-system in production phases, validation of completed systems and validation of final delivery.

When a production phase is completed, the corresponding delivery team consolidates its sub-deliveries and prepares the associated information for handover. This includes both product-related information and process documentation required for subsequent use in operation and maintenance. Within the TBS structure, verification is integrated with the completion of sub-deliveries and production phases, Figure 32. Completed work is assessed against defined scope, location, and quality requirements, with relevant actors confirming that intended deliveries have been fulfilled. This phase-based approach enables progressive verification, reducing reliance on a single end-stage assessment.

As sub-deliveries are completed, the structured approach also supports the capture and reuse of project experience. Lessons learned can be discussed within delivery teams and incorporated into a structured knowledge base, supporting continuous improvement across projects.

When all sub-deliveries related to a technical system have been completed, the focus shifts from verification of individual components to validation of system performance. At this stage, involved disciplines collectively assess whether the system fulfils its intended function, supported by consistent and structured documentation. This also enables the finalisation of information required for operation and maintenance, ensuring continuity beyond the production stage.

The decomposition provided by the TBS further allows inspection activities to be aligned with the completion of production phases and systems. Partial inspections can be carried out progressively, enabling earlier identification and resolution of issues and reducing the need for late-stage corrections. Within this structure, representatives such as municipal building inspectors and certified inspectors can review completed sub-deliveries together with the relevant disciplines at the end of each phase, Figure 32.

By linking inspection and verification activities to phase-based deliveries, the TBS establishes a clearer basis for coordination between project actors and regulatory functions, contributing to transparency and traceability throughout the production process. Final approval consolidates the outcomes of phase-based verification, system-level validation, and progressive inspections, providing a structured basis for assessing whether the building meets defined requirements and fulfils its intended function.

11 Discussion; From Fragmented Practices to Integrated Production Logic

This research set out to investigate how construction project planning and production control can be supported through a more integrated use of information across the project lifecycle, with a particular focus on the relationship between design information and production-oriented planning. Rather than viewing Building Information Modelling (BIM) as a solution in itself, the study is based on the premise that current construction practices are characterised by a fundamental misalignment between product-oriented information, developed in design, and process-oriented information, required for planning and execution. This misalignment contributes to persistent fragmentation in both information structures and organisational arrangements, limiting the potential of digital technologies to improve project performance. (Bühler et al., 2025; Foroughi Sabzevar et al., 2024, Koskela & Howell, 2008 Samuelson & Stehn, 2023 and section 8).

In response, the research developed and evaluated the TBS as a design artefact. The TBS integrates spatial decomposition, temporal sequencing, and production logic into a shared information structure intended to support coordination across design, planning, and production as presented in section 10. Rather than representing a stand-alone technical solution, the artefact should be understood as both an operational tool and an analytical lens through which existing practices can be reinterpreted.

The discussion therefore moves beyond a description of the artefact itself and instead focuses on what the development and evaluation of TBS reveal about the underlying challenges of construction project delivery. In particular, the findings point towards a need to reconsider how information is structured and used across the project lifecycle.

While BIM has introduced new possibilities for information integration, its application remains largely aligned with discipline-specific design practices. As such, BIM primarily supports the development and coordination of product-oriented information, representing building elements, systems, and technical solutions.

However, the findings indicate that this information is only partially structured to support process-oriented uses, such as production planning, sequencing, and control. As a result, additional effort is required to transform design information into forms that are usable for execution, reinforcing fragmentation across project phases. (Royano et al., 2023; Rehman et al., 2025). This pattern is also reflected in the empirical material (Cases 1–4) and consistently observed across Papers I–V. This observation aligns with broader research indicating that the construction industry continues to be characterised by fragmented value chains, weak process integration, and limited realisation of digitalisation benefits (Bühler et al., 2025; Samuelson & Stehn, 2023; Koskela & Howell, 2002).

A recurring challenge identified across the empirical material (Case 1-4 and Paper III), is the continued reliance on document-based practices. In such approaches, information must be repeatedly reinterpreted and restructured to be usable in different project phases. This leads to inefficiencies in feedback loops and limits the systematic reuse of knowledge, as learning becomes dependent on individual experience rather than embedded in shared information structures. In some cases, the ability to reinterpret and restructure information is even perceived as a competitive advantage, reinforcing fragmentation rather than reducing it. These findings are consistent with previous research highlighting the limitations of document-based workflows and the partial integration of BIM across project phases (Pishdad & Onungwa, 2024; Rehman et al., 2025; Disney et al., 2024).

While BIM is often positioned as a key enabler of digitalisation in construction, the findings suggest that current implementations remain constrained by underlying information structures and work practices. For digitalisation to effectively address these challenges, information must be structured in a way that supports both product-oriented and process-oriented uses across the project lifecycle.

This implies a shift towards multidimensional information structures. In such structures, the same underlying data can be organised and accessed according to different purposes, including design coordination, production planning, and on-site execution. This reduces the need for repeated reinterpretation of information between project phases.

In this context, the TBS enables the alignment of product-oriented information, describing building elements and systems, with process-oriented information, defining how these elements are to be constructed, sequenced, and coordinated in production.

The analytical evaluation of the TBS (Sections 10.3–10.5) demonstrates how such a structure can be achieved by integrating spatial, temporal, and production-related dimensions within a shared framework. Through this integration, the TBS provides a mechanism for organising information according to production logic while maintaining compatibility with existing classification systems and BIM structures.

By linking model objects and related information to production phases, the TBS enables information to be filtered, visualised, and analysed based on execution requirements. This reduces the need for manual reinterpretation across project phases, as demonstrated in Section 10.7.

Against this background, the discussion is structured around three main arguments.

- The challenges observed in practice can be understood as manifestations of fragmentation across three interrelated dimensions: information structures, organisational arrangements, and production logic.

- The evaluation of the TBS artefact demonstrates how these dimensions can be partially integrated through a shared, production-oriented information structure.

- The findings point towards broader theoretical and practical implications, suggesting a shift towards a production-oriented information paradigm in construction.

By analysing the artefact in relation to these dimensions, the discussion contributes to a deeper understanding of how digital information and organisational structures must co-evolve to support more efficient and coordinated construction processes.

11.1 Reinterpreting the Problem: Fragmentation Across Information, Organisation, and Production

The empirical findings underlying this research including both the initial research problem formulation and the analysis of multiple case 1-4 together with the literature synthesis, suggest that the challenges associated with construction project delivery cannot be reduced to isolated inefficiencies or technological limitations. Instead, they reflect a more fundamental fragmentation embedded in how projects are structured, managed, and executed.

This fragmentation manifests across three interrelated dimensions: information structures, organisational arrangements, and production logic.

11.1.1 Fragmentation of Information Structures in Construction Projects

Construction project information is typically generated, structured, and managed within discipline-specific domains, reflecting the historical organisation of the industry. In this context, design information is primarily developed as product-oriented information, focusing on the representation of building elements, systems, and technical solutions.

However, when this information is transferred to downstream activities such as cost estimation, scheduling, and production planning, it must be reinterpreted and restructured into process-oriented information. This can be understood as a systematic transformation problem, in which product-oriented information is translated into process-oriented representations to support execution.

In practice, such transformation is rarely supported by a shared structuring logic, resulting in fragmentation between how information is created in design and how it is used in production. While BIM enables the aggregation of this information into shared model environments, the underlying structuring principles often remain discipline-oriented, limiting the integration between product-oriented and process-oriented information.

This challenge was consistently observed in the empirical material, particularly in projects applying takt planning (Case 4 and section 6.3), where increased demands on information flow expose the limitations of existing structures.

The analysis of work preparation processes presented in Paper III further illustrates this issue. In practice, these function as locally developed process-oriented information structures, defining activities, sequences, and resource coordination.

However, they are typically created through ad hoc reinterpretation of design information, resulting in limited traceability to the original product-oriented model.

As a result, parallel information representations emerge, where product-oriented and process-oriented information are maintained in separate and loosely connected structures. This leads to fragmented information across multiple systems and documents, reducing consistency and traceability throughout the project lifecycle.

The limitations of current information structures are further reinforced by the lack of standardised use of model elements across different applications.

Even in advanced BIM implementations, visited projects described in chapter 6, integration between 3D models, scheduling (4D), and cost management (5D) remains partial. This is not primarily a technological limitation, but a consequence of the lack of a shared structure linking product-oriented model data with process-oriented planning and control information (Pishdad & Onungwa, 2024). Similarly, the continued reliance on 2D drawings as contractual documents introduces redundancy and information loss between model-based and document-based representations (Brooks et al., 2023; Disney et al., 2024).

However, the development of Prototype 1 (Paper II, sub section 4.4.1) demonstrated a potential shift away from manual reinterpretation towards the possibility of linking information sets through a shared structuring logic. By introducing a common reference structure, information could be connected rather than recreated, suggesting that the key challenge lies not in the availability of information, but in how it is structured.

From this perspective, the problem is not primarily the absence of digital information, but rather the absence of a shared structuring logic that can connect design, planning, and production information in a consistent manner across the lifecycle.

11.1.2 Fragmentation of Organisational Structures and Project-Based Collaboration

In parallel with fragmented information structures, construction projects are characterised by highly dynamic and temporary organisational arrangements (Samuelson & Stehn, 2023; Koskela & Howell, 2002). Project teams are assembled from multiple organisations, each responsible for specific scopes of work, and are dissolved upon project completion. This project-based mode of organisation facilitates specialisation but also introduces significant coordination challenges (Samuelson & Stehn, 2023; Gebremichael et al., 2022) and is also reflected in the empirical material (Cases 1–4) and appended papers (Papers I–V).

Roles, responsibilities, and contractual relationships are typically well-defined within individual domains, yet the interfaces between actors often remain loosely coordinated. This was observed both in the case 1-4 but also well documented in the literature (Samuelson & Stehn, 2023; Koskela & Howell, 2002). As actors enter and exit the project at different stages, continuity of knowledge and information is difficult to maintain. This results in a reliance on formal documentation and meetings to coordinate activities, rather than on integrated and continuously updated information structures (Sacks et al., 2018; Succar, 2009).

The separation between design and production stages further reinforces this fragmentation. Although production actors are increasingly involved during design phases, their contributions are typically limited to evaluating specific design solutions rather than influencing how information is structured for production purposes. Empirical observations, in Case 1-4, show that even in large-scale projects, where buildings are subdivided to manage complexity, each sub-project is still designed according to traditional discipline-based coding systems, limiting the potential for integrated production planning.

Design teams develop solutions based on disciplinary logic, while production teams interpret and adapt this information to site-specific conditions. Although BIM has improved the ability to share information across actors, it has not fundamentally altered the underlying organisational structures that shape how information is produced and used. The construction industry thus remains characterised by a fragmented, project-based structure with limited integration between phases and actors (Samuelson & Stehn, 2023; Sundquist et al., 2020).

This organisational fragmentation is not only a coordination issue but also an information issue, as the structure of information reflects the structure of responsibilities. Without a shared framework that aligns information with production processes and delivery teams, the potential for integrated planning and execution remains limited.

11.1.3 Fragmentation of Production Logic and Planning Practices

A third dimension of fragmentation concerns the underlying logic of production planning and control. Traditional project management approaches in construction are largely based on a transformation view of production, where projects are decomposed into discrete activities that are planned and scheduled based on dependencies and resource constraints (Koskela & Howell, 2002; Sacks et al., 2018). This decomposition is typically operationalised through Work Breakdown Structures (WBS), which function as the primary framework for defining scope, assigning responsibilities, and structuring cost and schedule control (Globerson, 1994). However, different WBS structures can lead to fundamentally different organisational and managerial outcomes, and inconsistencies between structures across actors can create coordination challenges and inefficiencies (Globerson, 1994; Cretu, 2025). In multidisciplinary projects, the absence of a shared decomposition logic can result in duplicated work packages, hidden interfaces, and reduced transparency in planning and control (Cretu, 2025).

The findings from Paper II illustrate how efforts have been made at the organisational level to standardise scheduling practices, for example by developing company-wide templates for residential projects to enable comparison and knowledge transfer. However, these standardisation efforts remain largely at an aggregated level, while the detailed structuring of activities and naming conventions is still left to individual site managers and planners. This limits the potential for systematic learning and cross-project integration and use of data-informed AI processes.

In practice, construction production is inherently spatial and sequential, with multiple trades moving through shared locations over time. This creates interdependencies that are not fully represented in activity-based schedules, leading to coordination issues, interruptions, and variability in workflow. Approaches such as location-based planning and takt time planning have emerged to address these challenges by emphasising flow, continuity, and resource balancing.

However, implementing such approaches requires a higher level of detail and a clearer connection between building elements, locations, and activities. Research shows that detailed and hierarchically structured models, combined with WBS and resource constraints, are necessary to support production planning in BIM environments (Kolaric et al., 2022). Empirical observations, from case projects 4 and 5, further indicate that projects with prior experience in takt planning demonstrate a higher level of detail, clearer communication, and more structured information flows compared to first-time implementations.

Despite these developments, current digital tools tend to support individual aspects of planning and control rather than providing an integrated view of production. Even when BIM is used, its application in the production phase is often limited, and monitoring and control processes remain partially disconnected from the model (Sundquist et al., 2020). Only a limited number of the observed projects had begun to structure BIM models in relation to takt zones, and in these cases the application was primarily confined to interior finishing works. While takt plans across several projects displayed different groupings of takt trains, which could be interpreted as implicit representations of production phases, explicit definitions of such phases were generally lacking when discussed with project participants.

This suggests an asymmetry in how spatial and temporal aspects of production are conceptualised and operationalised. Spatial structures, such as production zones, are more readily identifiable and can be directly mapped to physical building elements within the BIM model. In contrast, temporal structures, such as production phases, are more abstract and less formally defined, making them more difficult to represent and integrate within existing information models.

As a result, while spatial decomposition has begun to find its way into model-based practices, the temporal dimension of production remains weakly articulated, limiting the ability to fully integrate planning and execution within a shared information structure.

Taken together, these observations indicate that fragmentation in construction is not confined to a single domain but emerges from the interaction between information structures, organisational arrangements, and production logic. Addressing this fragmentation requires approaches that can bridge these dimensions and provide a shared basis for coordination across the project lifecycle.

11.2 Artefact Evaluation: Integrating Information, Organisation, and Production through TBS

Building on the identified fragmentation across information structures, organisational arrangements, and production logic, this section evaluates how the proposed TBS contributes to addressing these challenges. The evaluation is not limited to assessing the artefact as a technical solution but rather focuses on its capacity to reconfigure how information is structured, shared, and used in relation to production.

11.2.1 TBS as a Shared Information Structure

A central contribution of the TBS artefact lies in its role as a shared information structure that integrates design, planning, and production perspectives. Unlike traditional approaches, where design models, schedules, and cost structures are developed independently, TBS establishes a common decomposition logic based on production phases, spatial zones, and work sequences.

From a design science perspective, this contribution is grounded in the analytical evaluation of the artefact, where TBS was conceptually assessed against existing standards and frameworks for information structuring and management. This evaluation demonstrates that TBS does not introduce a fundamentally new classification system but rather complements and operationalises existing principles found in ISO-based frameworks.

A recurring challenge identified in both the literature (Gebremichael et al., 2022; Samuelson & Stehn, 2023), and the empirical material (Cases 1–4; Papers I–V) in this study is the fragmentation of breakdown structures across disciplines, lifecycle stages, and information domains. Cost breakdowns, work breakdowns, and location-based structures are typically developed in parallel, resulting in weak interoperability and limited traceability, as highlighted by Gebremichael et al. (2022). While existing standards, such as ISO 12006-2 and ISO 81346, provide well-defined principles for classification and multi-aspect structuring, they do not explicitly address how information should be structured in relation to production processes.

Conceptually, the TBS addresses this gap by building on the integrative principles of the Unified Breakdown Structure (UBS) (Gebremichael et al., 2022), and by operationalising two complementary dimensions: a functional (temporal–organisational) dimension and a physical (spatial–operational) dimension. Production phases represent a practical implementation of a functional breakdown structure, defining coherent, time-bound scopes of work managed by dedicated delivery teams. This directly responds to empirically observed challenges in this study related to unclear responsibility allocation and fragmented information ownership.

At the same time, production zones provide a spatial structuring logic that defines where work is executed. Empirical observations highlight that spatial clarity is essential for coordination, particularly in environments characterised by trade interdependencies and workspace constraints. By combining these dimensions, the TBS establishes a spatio-temporal framework that aligns organisational responsibility, information structure, and production execution.

This structuring logic aligns with key principles in ISO 19650-2, where the definition of information containers, responsibilities, and interfaces is central to effective information management. However, rather than treating these as abstract requirements, the TBS embeds them directly into the production structure, thereby translating information management principles into an operational planning logic.

Furthermore, by linking each information object to a consistent functional identifier (production phase) and, where relevant, a spatial identifier (production zone), the TBS establishes a unified reference system across traditionally separate breakdown structures. This enables consistent structuring of cost, schedule, risk, and design information within a shared framework, improving interoperability and traceability across disciplines and lifecycle stages.

From this perspective, the key contribution of TBS is not the introduction of a new information structure, but the provision of an integrating layer that connects existing classification and structuring principles with the operational logic of construction production. This integration enables design-oriented and production-oriented information, as well as their associated organisational structures, to be aligned within a common framework.

11.2.2 Enabling Design–Production Integration

The evaluation demonstrates, sub-section 8, that TBS facilitates a more explicit integration between design information and production planning. By connecting information required for execution to production phases and production zones, the artefact creates traceable relationships between what is designed and how it is to be constructed.

This addresses a well-documented limitation in current BIM practices, where design models are often insufficiently structured to support downstream activities such as scheduling, cost control, and site logistics (Pishdad & Onungwa, 2024). In conventional workflows, this gap is bridged through manual mapping between model elements and external planning tools, introducing inefficiencies and potential inconsistencies (Sacks et al., 2018; Kolarić, 2022, Viklund Tallgren 2021). This was also explicitly observed in Case 4, where design documentation was restructured to align with the takt-based production logic.

Observations from Case 1 illustrate how even partial implementation of the TBS logic improved the ability to understand relationships between different categories of information. Project participants reported that sorting information according to the TBS structure made it easier to interpret how design, planning, and execution data were connected. This was particularly evident during the design stage, where quality risks identified by the design team were structured according to production phases. This approach was highlighted as valuable by both the building inspector and the certified inspector responsible for regulatory compliance (Swedish: *kontrollansvarig*, KA), as it provided a clearer basis for planning and organising quality control activities in production. By linking quality-related information to production phases, the TBS creates conditions for a more systematic approach to quality management. Quality-critical aspects can be defined in relation to specific phases during design and subsequently followed up during execution by the responsible actors. Rather than demonstrating a fully implemented practice, the findings indicate that such structuring provides improved preconditions for traceability and accountability. By aligning quality control with the same structure used for planning and execution, the approach has the potential to reduce the risk of overlooked or inconsistently applied quality checks, while supporting a more transparent verification process.

The project manager in Case 1 also noted that cost breakdowns no longer required restructuring to align with production flow, a task that was previously necessary to support follow-up of labour hours. Similarly, integration between model-based information and scheduling reduced the need for manual processing and improved understanding of the construction sequence. In Case 2, this enabled earlier coordination between site management and structural design, particularly in planning the execution of the structural frame.

Together, these findings demonstrate how TBS reduces the need for reinterpretation across project phases and enables a more direct use of design information in production-oriented processes. This also supports the use of 4D BIM as a planning and communication tool, where the linkage between objects and activities enhances both understanding and coordination (Rehman et al., 2025).

11.2.3 Supporting Production-Oriented Planning and Flow

Beyond information integration, the TBS contributes to a shift in planning logic from activity-based scheduling towards production-oriented planning focused on flow, sequencing, and coordination, where product- and process-oriented information are systematically integrated. By structuring information according to production phases and production zones, the artefact provides a foundation for approaches such as takt time planning and location-based scheduling.

The empirical evaluation in this study, including the SIM house experiment and its linkage to coordination challenges identified in Cases 1–4, indicates that the TBS contributes to improved coordination between trades through shared spatio-temporal references. By defining work in relation to both production phases and zones, the scope of work becomes clearer, and dependencies between trades are more explicitly represented. This supports more stable workflows and improved continuity in production.

These findings are consistent with research highlighting the importance of detailed and hierarchically structured models, integrated with WBS and scheduling logic, for enabling effective site logistics and production planning (Kolaric et al., 2022). They also align with broader productivity research emphasising flow stability and coordination as key performance drivers in construction (Bühler et al., 2025).

Empirical observations from Cases 1–4 further reinforce these findings. In particular, projects applying takt planning reported improved capabilities for procurement and logistics planning. For example, a project engineer in Case 4 highlighted that the takt-based structuring provided a clear basis for developing procurement documentation and delivery plans. Similar reflections were expressed by trade contractors in Case 4, who noted that although restructuring information required an initial effort, it resulted in increased efficiency during execution. These observations suggest that while current practices require manual restructuring of information to support production-oriented planning, TBS has the potential to embed this structure directly into the information model, thereby reducing this effort and improving consistency across projects.

11.2.4 Enhancing Organisational Coordination through Delivery Teams

In addition to its technical and informational contributions, TBS also has significant implications for organisational coordination. By structuring information around production phases and zones, the artefact provides a clear context for defining responsibilities and coordinating delivery teams.

In traditional project settings, organisational structures are often aligned with contractual scopes rather than production processes, which can obscure dependencies between actors. In contrast, TBS enables a production-oriented organisation of work, where actors can relate their responsibilities to specific phases, zones, and sequences.

Observations from projects, Case 4 applying takt planning show that the grouping of actors within takt trains creates conditions for improved communication and coordination. Teams become more self-organising around shared goals, and expectations regarding when and where work should be performed become clearer. Deviations in workflow are more easily detected, and their causes can be identified more quickly.

Interviewees also emphasised that once accustomed to such structured ways of working, they were reluctant to return to traditional approaches. The visual representation of takt sequences was described as particularly effective in supporting understanding among workers, enabling them to anticipate upcoming tasks and coordinate with preceding and following trades. Over time, this contributed to a deeper mutual understanding between disciplines and increased willingness to support each other in maintaining workflow continuity.

The TBS structure also supports regulatory and organisational requirements related to work environment management. In the Swedish context, responsibilities are divided between design (BAS-P) and production (BAS-U). By structuring the project into clearly defined production phases, TBS provides a concrete basis for planning safe execution conditions during design and ensures a more effective transfer of information to production teams. This supports clearer definition of risks, responsibilities, and required control measures prior to execution.

In this sense, TBS extends the concept of a shared breakdown structure as a “common language” across disciplines (Cretu, 2025), by embedding it within a production-oriented organisational framework.

11.2.5 Synthesis: TBS as a Socio-Technical Integrator

The evaluation of the TBS artefact (Sections 10.3–10.5), synthesised in Section 10.6, suggests that its primary contribution lies not in introducing a new technical component, but in integrating existing elements, design information, planning structures, and organisational coordination within a shared socio-technical framework.

By addressing fragmentation across the three identified dimensions, TBS can be understood as:

- an information structure that links design and production,
- a planning framework that supports flow-oriented production,
- an organisational scaffold that facilitates coordination across actors.

However, it is important to recognise that the effectiveness of TBS depends on its adoption within existing organisational and contractual contexts. As highlighted in previous research, digital transformation in construction requires not only technological solutions but also changes in organisational practices and industry structures (Samuelson & Stehn, 2023). Thus, while TBS demonstrates the potential to reduce fragmentation and support integration, its full impact depends on broader socio-technical alignment across projects and organisations. This highlights how a production-oriented structuring of information can bridge the gap between design intent and production control, particularly in relation to quality assurance.

11.3 Theoretical and Practical Implications: Towards a Production-Oriented Information Paradigm

The evaluation of the TBS artefact in section 10 provides a basis for discussing its implications beyond the specific implementation context. This section interprets the findings in relation to existing theory and practice, with particular focus on how the integration of information, organisation, and production can be conceptualised within construction project delivery.

11.3.1 From Transformation-Based Decomposition to Flow-Oriented Structuring

A key implication of this research is not a fundamental shift in production theory, but rather a clarification of the conditions required to operationalise flow-oriented approaches in practice. Traditional project management in construction is largely based on a transformation view, where projects are decomposed into discrete activities, typically structured through Work Breakdown Structures (WBS) (Globerson, 1994). While this approach supports planning and control, it often fails to capture the spatial and temporal interdependencies and flow-related dynamics that characterise construction production (Koskela & Howell, 2002).

In contrast, flow-oriented perspectives emphasise continuity, coordination, and the management of interdependencies between trades (Koskela, 2000). Despite these different approaches, the underlying objective remains the same: to establish methods and structures that maintain coherence within the project and reduce inconsistencies and incompatibilities that may prevent the project from achieving its intended purpose and vision.

The findings of this research suggest that one of the main barriers to achieving this coherence lies in how project information is structured. While flow-based planning approaches such as takt planning have demonstrated practical benefits, their implementation often requires extensive manual restructuring of information to align design, planning, and execution. Within this context, the TBS artefact does not introduce a new planning logic but provides a structuring mechanism that supports the implementation of flow-oriented approaches. By linking information to both production phases and spatial zones, TBS enables dependencies between trades to be represented more explicitly and consistently across project stages. However, the findings also indicate that the effectiveness of such structuring depends on its consistent application across both design and production. Without alignment between information structures, organisational practices, and planning methods, the potential benefits remain partially unrealised.

In this sense, TBS can be understood as an enabling structure that supports flow-oriented production, rather than as a paradigm shift in itself. This shift reflects a move from task-based decomposition towards flow-oriented and socio-technical integration, which the TBS supports through a unified information structure, linking design and production.

11.3.2 Integrating Product, Process, and Organisation Through a Shared Structure

A second key implication concerns the integration of product, process, and organisational perspectives within a shared information structure. In current construction practice, these dimensions are typically developed and managed separately: product information in design models, process information in schedules, and organisational structures through contracts and responsibilities (Sacks et al., 2018; Samuelson & Stehn, 2023). This separation contributes directly to the fragmentation identified in section 7 and limits the effectiveness of existing structuring approaches. While classification systems and breakdown structures provide important frameworks for organising information, their application across domains remains inconsistent, reducing interoperability and traceability (Serrat et al., 2023).

The findings suggest that the primary challenge is not the absence of structuring principles, but the lack of a shared structure that connects them in relation to production. The TBS artefact addresses this by establishing a common decomposition logic based on production phases and spatial zones, through which product, process, and organisational information can be aligned.

This enables different actors to relate their work not only to what is being designed, but also to when and where it will be executed, and how it connects to other activities. In this sense, TBS functions as an integrating mechanism that makes dependencies between disciplines more explicit and manageable.

This integration is particularly relevant in multidisciplinary environments, where inconsistent structuring approaches can lead to duplication, hidden interfaces, and coordination challenges (Cretu, 2025). Rather than replacing existing structures, TBS provides a framework within which they can be consistently related and applied.

11.3.3 Information as a Socio-Technical System in Construction

A third implication relates to the understanding of information as a socio-technical system. While digitalisation in construction has largely focused on technological solutions, the findings in this study reinforce that the realisation of benefits depends on the alignment between information structures, organisational practices, and project objectives.

The synthesis in section 8 indicates that fragmentation is not only a technical issue but also a consequence of how responsibilities, knowledge, and decision-making are distributed across the project. As such, improvements in information structuring must be accompanied by corresponding changes in how actors interact with that information.

Within this context, TBS can be understood as a socio-technical artefact that supports alignment between information and organisation (Samuelson & Stehn, 2023; Fisher et al., 2017). By providing a shared structure linked to production phases, it enables project participants to relate their responsibilities to a common framework, improving coordination and continuity across the lifecycle.

An important aspect identified in the findings is the relationship between project vision and operational execution. While project vision is typically defined at a high level during early stages, it often becomes fragmented as it is translated into discipline-specific requirements. The TBS structure provides a mechanism for maintaining this alignment by linking high-level objectives to concrete production phases, thereby making the purpose of each delivery more explicit in relation to the overall project goals.

This suggests that effective project delivery is not only dependent on technical solutions or planning methods, but also on the ability to maintain a coherent “red thread” between vision, design, and execution. In this regard, TBS supports a more structured translation of project intent into operational practice.

This perspective aligns with research emphasising that BIM implementation requires a holistic approach that considers organisational and process-related factors in addition to technology (Sundquist et al., 2020; Disney et al., 2024).

Furthermore, the structured definition of production phases and delivery teams creates conditions for continuous improvement. By linking outcomes to clearly defined scopes of work, deviations can be identified and analysed more systematically, and feedback can be incorporated into future planning and design decisions (Koskela, 2000; ISO 19650-1, 2018).

11.3.4 Practical Implications for Construction Project Delivery

From a practical perspective, the findings suggest that a shared, production-oriented information structure can improve consistency, traceability, and coordination across production phases, as evidenced by the empirical synthesis in Section 8 and the artefact evaluation in Sections 10.3–10.5.

By structuring information according to production phases and spatial zones, projects can reduce the need for manual reinterpretation of information and support more effective implementation of flow-oriented planning approaches. This can contribute to improved workflow stability and reduced variability in production (Bühler et al., 2025).

In addition, a shared structure provides a clearer basis for defining responsibilities and managing interfaces between actors, which can support onboarding and collaboration within delivery teams.

However, the findings also indicate that the benefits of such approaches depend on organisational alignment and consistent application. The implementation of TBS-like structures should therefore be understood as part of a broader transformation of project practices, rather than as a stand-alone technical intervention (Samuelson & Stehn, 2023).

Taken together, the implications of this research point towards the importance of a production-oriented approach to information structuring in construction. Rather than introducing new theoretical concepts, the findings highlight the need to better integrate existing principles related to classification, planning, and organisational coordination within a shared framework.

The TBS artefact contributes to this by demonstrating how such integration can be operationalised through a spatio-temporal structure linking design, planning, and production. At the same time, the findings emphasise that achieving this integration requires alignment between information structures, organisational practices, and project objectives.

12 Limitations and Future Research

While this research provides insights into how a TBS can support the integration of information, organisation, and production in construction projects, several limitations should be acknowledged. These limitations also point towards directions for future research.

12.1 Limitations of the Study

First, the evaluation of the TBS artefact is based on a limited number of empirical contexts, including analytical, experimental, and observational assessments connected to real-world case projects. While this approach strengthens the internal validity of the findings, the results remain context dependent. Construction projects vary significantly in terms of scale, complexity, contractual arrangements, and organisational settings, which may influence the applicability and effectiveness of the proposed structure.

Second, the study is situated within a specific industry and geographical context, primarily reflecting Swedish and, to some extent, Nordic construction practices. These contexts are characterised by particular classification systems, regulatory frameworks, and levels of BIM maturity that may differ from those in other regions. As the construction industry lacks universally adopted classification systems and exhibits significant variation across countries (Serrat et al., 2023), the transferability of the findings should be considered with caution.

Third, the evaluation focuses primarily on the qualitative and conceptual performance of the artefact rather than on quantitative performance outcomes. While the findings indicate improved integration, coordination, and support for production-oriented planning, the study does not provide systematic measurement of impacts on productivity, cost, or schedule performance. Given the persistent productivity challenges in construction (Bühler et al., 2025), further empirical validation is required to assess the measurable effects of TBS.

Fourth, parts of the empirical evaluation were conducted in controlled or semi-controlled environments, such as the SIM house case. While these settings allow for detailed observation and conceptual testing, they do not fully capture the complexity and variability of real-world project delivery. Factors such as contractual constraints, organisational resistance, and varying levels of digital maturity may significantly influence implementation outcomes.

Finally, the study focuses primarily on the structuring and use of information in relation to design, planning, and production. Although the TBS concept has potential relevance across the full lifecycle, including operation and maintenance, these aspects have not been fully explored within the scope of this research.

12.2 Directions for Future Research

Building on these limitations, several directions for future research can be identified.

- Further empirical studies are needed to evaluate the implementation of TBS in real-world projects. In particular, there is a need for studies that assess its impact on key performance indicators such as productivity, schedule reliability, cost control, and quality outcomes. Longitudinal studies would be especially valuable in capturing how the effects of a shared information structure develop over time.

- Future research should explore how TBS can be integrated with emerging digital technologies, such as digital twins, artificial intelligence, and automated data capture. As the value of digitalisation increasingly depends on the ability to integrate and utilise data across project stages (Bühler et al., 2025), TBS may serve as a structuring backbone for such developments.

- Further investigation is needed into how TBS can be aligned with existing standards and classification systems, including ISO-based frameworks and national implementations such as CoClass. In particular, research should examine how production-oriented structuring can be integrated with existing coding schemas to support consistent information management across the lifecycle.

- Future research should examine the organisational and institutional conditions required for successful implementation. As demonstrated in this study, the effectiveness of TBS depends not only on its technical design but also on its alignment with organisational practices, procurement strategies, and delivery models.

- Additional research is needed to explore the application of TBS across the full lifecycle of built assets, including operation and maintenance. Extending the concept beyond the project phase could enhance its relevance for asset management and long-term performance evaluation (Royano et al., 2023).

The ISO 19650 series is currently undergoing revision, with a shift from the existing separation between capital delivery and operational phases towards a more integrated lifecycle-oriented process. This development aligns with the objectives of this research, which emphasises the need for coherent information structures spanning design, construction, and operation. However, the proposed transition from the concept of "delivery teams" to "information production teams" introduces new uncertainties regarding how the revised ISO19650 define how project organisations should be structured and coordinated in practice. Further research is therefore needed to examine how such changes may influence the grouping and interaction of organisational roles, particularly in relation to the structuring principles proposed in the TBS artefact.

Finally, further work is required to refine and formalise the theoretical foundations of TBS within the Design Science Research paradigm. This includes evaluating the artefact across multiple contexts, refining its design principles, and positioning its contribution in relation to existing theories of construction management, production, and digital transformation.
In summary, while this research demonstrates the potential of TBS to address fragmentation and support integration in construction project delivery, the findings should be interpreted in light of the study's contextual and methodological limitations. At the same time, the identified research directions highlight opportunities for further empirical validation and theoretical development.

13 Contribution

This thesis contributes both theoretically and practically to the integration of design and production in construction through the development and evaluation of the TBS artefact.

13.1 Theoretical Contributions

This thesis contributes to the theoretical understanding of information management in construction by conceptualising the TBS as a socio-technical information structuring artefact that integrates product, process, and organisational dimensions within a unified framework linking design and production.

The study extends existing research on BIM, classification systems, and production planning by addressing a key gap: the lack of a coherent structuring logic that connects design-oriented information with production-oriented processes. While prior approaches consider spatial, temporal, and functional aspects, these are typically treated in isolation. This research shows how such dimensions can be integrated into a shared decomposition logic that enables consistent interpretation and coordination across disciplines and project stages.

Furthermore, the findings suggest that fragmentation in construction projects is not primarily a result of misaligned objectives, but of misaligned structures. By introducing the notion of structural alignment as a prerequisite for integrated project delivery, the thesis contributes a shift in perspective from method-centric approaches towards structure-centric approaches to project management. In this sense, TBS provides a conceptual foundation for understanding how information, organisation, and production can be aligned within a common framework to support flow-oriented and integrated project delivery.

13.2 Practical Contributions

From a practical perspective, the thesis demonstrates how TBS can be applied as an operational framework for structuring information, coordinating organisational responsibilities, and supporting production-oriented planning in construction projects.

Rather than introducing a new classification system, the study shows how existing standards and structuring principles can be operationalised through a shared framework that links production phases, activities, and production zones. This enables the establishment of a common project language, improving communication and interoperability between disciplines, and supporting the integration of design and construction processes.

The empirical findings illustrate that when TBS is consistently applied, it supports improved information flow, reduced ambiguity, and enhanced traceability across project phases. This, in turn, enables earlier identification of deviations, more reliable planning, and increased predictability in project execution.

In addition, the study highlights the importance of aligning the structuring logic with organisational practices, including the coordination of roles, responsibilities, and delivery teams. By doing so, TBS facilitates a more coherent project organisation in which design intent, production execution, and lifecycle requirements are better integrated.

Overall, the practical contribution lies in providing a structured and implementable approach that supports the transition from fragmented, document-based workflows towards integrated, model-based and production-oriented project delivery.

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