The reuseability of cast-in-situ concrete slab elements

A case study of Schiphol's C-pier

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by

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Preface

Writing this thesis marks the end of my time as a student at Delft University of Technology and the completion of an intense but incredibly rewarding chapter.

When I started my career as a junior structural engineer at Haskoning, I was eager to put my academic knowledge into practice and become part of the design world I had long admired. Early on, I was impressed by the depth of technical expertise and the collaborative spirit that drive complex projects forward. Yet I also noticed how often well established assumptions shaped design choices, and how sustainability, though increasingly discussed, still played a relatively modest role in daily engineering practice. Coming from TU Delft, where sustainability forms an integral part of the curriculum, this contrast caught my attention. It was not a matter of unwillingness; rather, it reflected how our collective knowledge, methods, and confidence in applying sustainable principles were still developing.

This realization sparked my curiosity about how structural engineers could broaden their scope, not only designing new structures, but also rethinking what already exists. I became increasingly intrigued by the potential of reuse: how materials and structures could have a second life if we approached them with a different mindset. What started as curiosity about circular design gradually evolved into a deep dive into the world of reuse, old drawings, and many engineering puzzles. That curiosity eventually guided me toward one of the most established yet underexplored materials in our field, concrete, and the question of how we might treat it not as waste, but as a valuable resource.

What followed was a journey of discovery. One that combined design, research, and collaboration in ways I hadn't anticipated. Along the way, I was fortunate to be surrounded by people who challenged my thinking, offered guidance, and made the process both meaningful and enjoyable.

I owe a huge thank-you to my supervisors at TU Delft: Dr. Florentia Karvoura, Ir. Rob Vergoossen, and Dr. Daniel Hall for their time, guidance, and honest feedback. Your mix of perspectives kept me grounded and encouraged me to connect the technical side of reuse with its wider impact. I also want to thank Ir. Hans Ramler, who chaired my committee and helped guiding the entire process of this thesis research.

This thesis would not have been the same without the collaboration with Haskoning and NACO. Working alongside practice brought a whole new dimension to this study. A special thanks goes to Ir. Michiel Visscher and Ing. John Hijma your trust, enthusiasm, and open conversations made the project both insightful and enjoyable.

Lastly, I want to thank my friends, family, colleagues and everyone who supported me along the way: for the coffee breaks, the pep talks, and for reminding me to breathe every now and then. A special thanks goes to my wonderful roommates, who patiently endured the rants, the stress, and a very grumpy version of me more often than I'd like to admit. And to my boyfriend, Jurre van der Lende, thank you for your endless patience, encouragement, and for being my constant cheer buddy even when you got so little attention in return. You all made this process much lighter, and I couldn't have done it without you.

Looking back, this thesis became more than just research. It was a chance to learn how circular thinking in engineering can actually take shape. I hope it adds something useful to that growing conversation..

Gweneira Eveline Marya van Koot
Delft, December 2025

Summary

The construction sector remains one of the largest contributors to global CO_2 emissions, with concrete alone accounting for around eight percent of the total. As the demand for sustainable and circular construction intensifies, reusing existing structural components offers a direct path to reducing embodied carbon and material waste. Yet, despite the promise of reuse, structural engineers still frequently dismiss it in the earliest stages of design, often claiming that "reuse is not possible." When questioned further, the reasons behind this rejection are rarely well-defined. This recurring pattern, premature dismissal without substantiated technical or procedural grounds, formed the starting point of this thesis.

The research stems from the conviction that reclaimed structural elements, if properly assessed and integrated, can perform safely and sustainably, and that the engineering profession must develop the tools and frameworks to make this possible. Reuse is not only a technical challenge; it represents a necessary shift in how the construction industry values existing materials. By extending the life of concrete elements rather than crushing them into aggregates, the sector can preserve the embodied carbon and craftsmanship already invested in our built environment.

Against this background, the thesis investigates how cast-in-situ concrete slab elements can be systematically verified and integrated for reuse within the current European regulatory framework. It approaches the problem along two complementary dimensions:

- a technical dimension, addressing the absence of standardized methods to assess the safety, durability, and performance of reclaimed slabs
- an organizational dimension, targeting the fragmented communication, responsibilities, and data ownership that cause reuse opportunities to be lost between demolition and design.

To address these challenges, the study applies a design-science research methodology, combining theoretical, empirical, and applied work in four interconnected stages.

1. **Theoretical background**
   The first stage comprised three interlinked literature reviews that progressively deepened the research focus. The first mapped the state of practice in piecewise concrete reuse, identifying technical, regulatory, and economic barriers to its adoption. It revealed that many challenges stem from fragmented communication and unclear responsibilities across project actors. This led to a second review on the organization of the construction value chain, analysing how information and expertise are distributed and how existing frameworks attempt to improve collaboration in circular projects. The third review focused on the persistent uncertainty surrounding the verification of reclaimed elements, analysing EN 13747, EN 206, and Eurocode 2 to explore how reused slabs could be assessed within a harmonized design context. Together, the studies exposed two fundamental gaps: the absence of a unified verification approach and a structured communication system linking all stakeholders in reuse.
2. **Learning from experience**
   Building on the literature findings, this phase examined how these challenges manifest in practice. Five European reuse projects, among them SUPERLOCAL, Prinsenhof A, and Stationsplein 107 were analysed alongside expert interviews with engineers, contractors, and clients. The cases revealed both the technical feasibility and organizational shortcomings of current practice, showing where coordination fails, testing is inconsistent, and data traceability breaks down. This empirical insight transformed theoretical understanding into practical knowledge, forming the foundation for developing the verification and communication frameworks.
3. **Framework development**
   In response to the identified gaps, two complementary frameworks were created using a design-science approach. The Verification Framework defines a structured, stepwise process for assessing reclaimed cast-in-situ slabs against Eurocode and EN-standard criteria: geometry, material

strength, durability, fire resistance, and structural performance, translating regulations into a practical workflow for project-based certification. The Communication Framework structures information, responsibilities, and deliverables along six stages of the construction value chain, introducing a dual-path alignment model that distinguishes between direct donor–target and intermediary reuse processes. Together, they integrate technical validation with project organization, turning fragmented expertise into a coherent, repeatable process.

4. **Validation**
   Both frameworks were tested through the redevelopment of Schiphol Airport's C-pier. The Verification Framework assessed the reuse potential of donor slabs, guiding early-design decisions and confirming compliance with Eurocode 2 when applied in the project context. The Communication Framework was simultaneously applied to map data flows and responsibilities between client, engineer, contractor, and reuse coordinator. Expert evaluation confirmed its practicality for real-world projects. The validation demonstrated how verification depends on structured communication and how clear coordination enables reliable data together proving the frameworks' ability to deliver a transparent, traceable, and compliant reuse process.

The results show that the reuse of cast-in-situ concrete slabs is both technically feasible and practically achievable when guided by a structured verification process. Within the Verification Framework, two key steps were introduced: the preliminary declared reuse performance (pDRP) and the verified declared reuse performance (vDRP). The pDRP was validated in the case study and showed that, by using archival data, global measurements, and where necessary conservative assumptions based on the design codes applicable at the time of construction, it is possible to make a justified early design decision about the reuse potential of reclaimed slabs. Although the vDRP could not yet be fully tested, it provides a clear and systematic approach for verifying these assumptions through targeted testing and documentation. Together, the pDRP and vDRP create a structured method that gives engineers the confidence to base reuse decisions on traceable and transparent criteria. Quantitatively, the reuse of verified slabs resulted in up to 60% reduction in embodied CO_2 compared with newly produced concrete floors, demonstrating both the environmental and structural value of reuse.

The validation of the Communication Framework showed that successful reuse depends as much on organization as on engineering. By mapping how information, responsibilities, and approvals move between actors such as the client, engineer, contractor, and reuse coordinator, the framework helped prevent data loss between donor and target projects. It created clarity about ownership of information and improved coordination across all six stages of the construction value chain. Expert feedback confirmed that the framework makes reuse projects more transparent and easier to manage, ensuring that the right information reaches the right people at the right time.

Together, the two frameworks close the gap between what is technically possible and what is practically implemented. They show that the barriers often cited in literature and experienced by engineers such as uncertainty, lack of standards, or unclear responsibilities are not the result of technical impossibility but of missing structure, communication, and confidence.

In conclusion, this thesis provides a clear and practice-tested foundation for making the reuse of cast-in-situ concrete slabs a reliable and verifiable option in modern construction. By combining technical verification with transparent communication, it transforms reuse from an uncertain experiment into a structured engineering process. The frameworks enable traceable and coordinated decision-making and demonstrate how structural engineers can play a central role in shaping a truly circular built environment.

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STEP 0

Introduction

1 Introduction

1.1. Background

The European Union has formalized its commitment to achieving carbon neutrality by 2050 through the European Climate Law, establishing itself as a leader in global climate action (European Commission, 2023). Although progress has been made in various industries, the construction sector remains a major contributor to carbon emissions. In 2022, a year after new legislation was introduced to support this transition, the construction sector was responsible for approximately 37% of global energy and process-related CO_2 emissions, reaching nearly 10 gigatonnes (United Nations Environment Programme, 2023). Thus, despite the increasing attention to sustainability, the prevailing ”take-make-dispose” model continues to dominate construction practice, leading to the premature down cycle of high-value materials, such as concrete.

Concrete, and especially structural elements like reinforced concrete slabs, play a central role in modern construction. Though they also stand out as one of the most carbon-intensive elements in buildings. The high environmental impact of reinforced concrete floors stems primarily from the energy-intensive production of cement, which alone accounts for approximately 8% of global CO_2 emissions. The extraction, processing, and transportation of raw materials further exacerbate its carbon footprint, making it a critical target for emission reduction strategies (Beatriz Rosselló, 2015). Many methods have been proposed, but despite its durability and structural potential, concrete is rarely reused in its elemental form. Instead, it is predominantly down cycled into low-grade aggregates, which reduces its embodied value (Gorgolewski, 2008).

Numerous barriers hinder the implementation of concrete element reuse, but this thesis highlights two in particular that shed light on why reuse has not yet become a widespread practice. First, although structural engineers increasingly show an interest in exploring more sustainable design alternatives, they often lack the necessary standards, guidelines, and reliable assessment methods to evaluate the feasibility of reusing structural elements. As a result, reuse proposals are frequently dismissed early in the design or demolition process. Beukers, 2016 found that concerns over structural feasibility, high costs, and uncertain data are among the main reasons for rejecting reuse. Similarly, a Canadian study (Urbaszewski & Bournas, 2015) highlights that engineers perceive insufficient technical support in the form of codes and standards, which creates uncertainty and encourages conservative choices. Recent work on the RISE methodology confirms that while assessment tools for reuse exist, their adoption is limited and fragmented, preventing reuse from becoming a default option (Björklund et al., 2023).

Second, knowledge relevant to reuse, ranging from demolition practices and structural engineering to design integration is scattered across different actors in the construction value chain, with limited mechanisms for knowledge-sharing. Herazo and Lizarralde, 2016 recognize this as a problem in general of “sustainability approaches” in the building sector: stakeholders adopt different interpretations of what sustainability entails, leading to fragmented actions and contradictory objectives. Their longitudinal case study shows that while many stakeholders begin with ambitious reform or transformation-oriented goals, these ambitions erode over the course of a project.

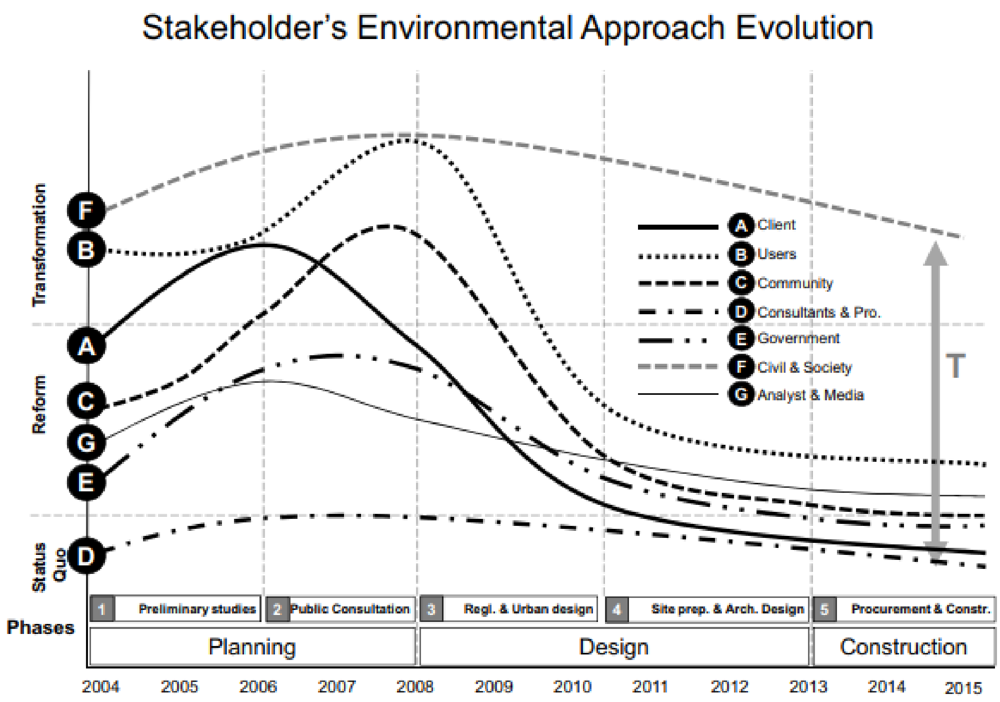


Figure 1.1: The evolution of stakeholder groups' sustainability approaches over the planning, design, and construction phases Herazo and Lizarralde, 2016

As illustrated in Figure 1.1, a critical turning point for sustainability ambitions occurs in the design stage. This "fast dip" reflects the confrontation between ambitious sustainability visions and the practical constraints of budgets, schedules, communication and technical feasibility. The trend shown in this figure is completely inline with what currently happens in projects that consider reuse. From the outset clients have high ambitious goals, but once the design phase starts and the match between the structural requirements of the donor building and the new design must be matched it is found that the alignment is poorly managed, causing mismatch and rejection of reuse potential (Küpfer et al., 2023).

1.2. Problem definition

Against this backdrop, the problem this thesis addresses is the systematic underutilization of concrete element reuse in the construction industry. Although reuse has clear environmental and economic benefits, it remains an exception rather than a norm in current project practice.

This under utilization stems from two interrelated causes. First, the absence of standardized certification systems, assessment methods, and clear responsibilities creates uncertainty for practitioners. Faced with unclear procedures, engineers and designers tend to reject reuse options at the critical design stage, reinforcing the "fast dip" in sustainability ambition identified by Herazo and Lizarralde, 2016. Second, reuse opportunities are frequently lost due to poor communication lines between demolition projects (donor sites) and new construction projects (target sites). Without reliable information flows and integrated collaboration, many potentially reusable elements are down cycled instead of being incorporated into new designs.

As a result, the construction industry fails to capitalize on a major opportunity to close material loops, reduce embodied carbon, and accelerate the transition toward a circular built environment.

1.3. Research Objective

The aim of this thesis is to investigate how the reuse of concrete slab elements can be systematically integrated into the construction industry. This requires addressing two interrelated dimensions of the problem:

- **The technical dimension,** which concerns the assessment and certification of reclaimed slabs to ensure safety and performance and with that reduce the perceived risks that come with reused elements
- **The organizational dimension,** which involves overcoming fragmented expertise and weak communication lines between donor and target projects.

By exploring both aspects, the thesis seeks to develop a framework that enables practitioners to make informed, reliable, and coordinated decisions about reuse, thereby helping to transform it from an exceptional practice into a viable and recognized strategy within the construction sector.

1.4. Research Questions

To achieve this objective, the thesis is guided by one overarching research question and two underlying sub-questions, one for the CME side of the thesis and one for the Structural Engineering side. The overarching question reflects the central ambition of this work:

How can the reuse of structural concrete elements, and specifically slabs, move from being an exception to becoming an integrated practice within the construction industry?

The two sub-questions address the identified main barriers that currently prevent this transition:

RQ1. How can fragmented areas of expertise be systematically integrated into a coherent framework to support the integration of concrete reuse in the construction industry? (CME domain)

RQ2. How can we assess whether a concrete element is suitable for reuse in a specific project context? (Structural Engineering domain)

To answer these two overarching questions, four operational research questions are formulated. These guide the structure and methods applied throughout the thesis:

SRQ1. What technical, regulatory, and practical challenges currently limit the structural reuse of concrete slab elements in buildings?

SRQ2. How can lessons from recent Dutch reuse projects inform the development of a more consistent verification and communication process?

SRQ3. How can the verification of reclaimed concrete slabs be structured to ensure safety, performance, and traceability?

SRQ4. How can communication between actors be organised to enable reuse across different projects and life-cycle stages?

The relationship between these research questions, the thesis chapters, and the applied methods is summarised in Table 1.1.

Table 1.1: Overview of research questions, corresponding chapters, methods and purposes

SRQ	Chapter(s)	Method(s)	Purpose / Expected Outcome
SRQ1	2–3	Systematic literature review; document analysis; stakeholder mapping	Identify existing barriers and conditions for reuse and define the theoretical and practical knowledge gap.
SRQ2	5	Multiple case study; semi-structured expert interviews; pattern matching	Derive empirical insights and success factors that clarify what works and what fails in practice.
SRQ3	7–10	Design-science research; Eurocode-based analytical assessment; scenario validation	Develop and test a stepwise *Verification Framework* enabling reliable certification of reclaimed slabs.
SRQ4	6, 7 & 9	Process modelling; design-science framework development; case-based validation	Design and validate a *Communication Framework* that overcomes fragmentation and aligns actor responsibilities.

1.5. Research Methodology

This thesis adopts a research design that combines theoretical study, empirical exploration, and framework development, followed by validation in a case study or practical context. The approach follows the widely recognized pattern of design-oriented research in construction management, where theory and empirical insights are iteratively integrated into structured frameworks and subsequently tested in real-world settings (Hevner et al., 2004; van Aken, 2004). In particular, the research is structured into three interconnected stages: (1) theoretical studies, (2) framework establishment, and (3) validation. This staged approach ensures that the proposed contributions are both academically grounded and practically applicable.

Stage 1: Theoretical background

The research begins with a systematic literature review that establishes the knowledge base for the thesis. Three strands are addressed. First, the concept of piecewise reuse of concrete slab elements (PRECS) is explored, outlining the technical processes involved in harvesting, assessment, and reintegration. Second, the construction value chain is examined, with a focus on stakeholders, communication barriers, and organizational challenges that influence reuse. Third, regulatory aspects are studied through an analysis of CE marking procedures and current verification methods for concrete slabs. Together, these reviews identify key barriers and contextualize the research within ongoing debates in circular construction.

Stage 2: Learning from experience

To complement the theoretical insights, empirical knowledge is drawn from case studies of successful projects in which concrete element reuse was applied. These case studies provide practical evidence on organizational setups, technical solutions, and project dynamics. In addition, semi-structured interviews with industry experts are conducted to capture perspectives on feasibility, risks, and best practices. The combined evidence base ensures that the frameworks developed later are not only conceptually rigorous but also informed by practical experience.

Stage 3: Framework development

Based on the findings from the first two stages, two interrelated frameworks are developed. The first framework focuses on the verification of cast-in-situ concrete slabs, offering structured guidance on how reclaimed elements can meet performance and regulatory requirements. The second framework addresses project organization in reuse scenarios, mapping stakeholder roles, responsibilities, and communication pathways across donor and target projects. Together, these frameworks aim to reduce fragmentation of expertise and provide practitioners with clear processes for implementing reuse.

Stage 4: Validation

The developed frameworks are then introduced into a validation case. In this step, both frameworks are applied in a real project context to assess their practical relevance and coherence. The validation focuses on testing whether the frameworks facilitate decision-making, improve clarity of roles, and support verification of reclaimed slabs under realistic project conditions. Insights from the validation are documented and analyzed, providing the basis for refining the frameworks.

Stage 5: Discussion and conclusion

Following the validation, the discussion chapter interprets the results in relation to the research objectives and the existing body of knowledge. It explains how the Verification and Communication Frameworks address the technical and organisational barriers identified earlier, reflects on their combined value, and critically evaluates their limitations and scope of applicability. The conclusion chapter then consolidates these insights by directly answering the research questions, summarising the main scientific and practical contributions, and formulating concrete recommendations for professional practice and future research aimed at advancing structural concrete reuse.

1.6. Research Scope

This master thesis was carried out within the joint degree programme Civil Engineering and Construction Management & Engineering (CME) and Structural Engineering (SE). Consequently, the research spans both disciplinary domains and is deliberately structured to integrate managerial and technical perspectives.

The overall structure and credit division

The thesis comprises 45 ECTS, divided as follows:

- 15 ECTS CME - Organization, managerial and systemic aspects (communication, collaboration, and process frameworks)
- 15 ECTS overlap (CME-SE) - methodological development where management structures and engineering verification meet (framework integration, case application)
- 15 ECTS SE - technical and analytical aspects (structural verification, design validation, Eurocode compliance).

The CME Domain - Construction Process & Organization

The CME component focuses on the systemic and managerial enables for reuse of structural concrete elements:

- Mapping of the construction value chain and identification of fragmentation barriers.
- Development of the Communication Framework, defining the flow of information, responsibilities, and decision checkpoints between donor and target projects.
- Validation of the framework through stakeholder interviews and project-based testing C-pier.

The Overlap Domain - Framework integration

The overlap section combines CME and SE through the integration of organisational and technical frameworks. Here, the Communication Framework and the Verification Framework are merged into a consistent workflow that ensures both project governance and technical reliability in reuse projects.

- Development of the Declared Reuse Performance (DRP) methodology connecting technical assessment with process control.
- Definition of how information loops (from structural testing to decision-making) ensure safe design integration.
- Application and validation through the C-Pier Schiphol case study, where the frameworks are tested against real project requirements.

This middle segment represents the essential interdisciplinary core of the thesis: ensuring that structural reuse is both technically sound and organisationally executable. It directly engages with structural design theory, Eurocode verification principles, and engineering calculations, which fall squarely under SE.

The SE domain - Strucutral verification & Design Validation

The Structural Engineering component addresses the technical dimension of reuse, focusing on safety, performance, and reliability of reclaimed slabs. It lies fully within SE as it applies Eurocode-based design theory, structural reliability, and material mechanics, beyond the managerial scope of CME.

- Development of the Verification Framework for Cast-in-Situ Slabs aligned with Eurocode 2, EN 206, and EN 1992-1-2. This framework establishes analytical procedures for ULS/SLS verification using limit-state theory, safety factors, and mechanical models, core structural design tasks.
- Definition of verification procedures for geometry, strength, durability, and fire resistance. These translate test and inspection data into design parameters through Eurocode material laws, ensuring compliance with structural and thermal performance criteria, an engineering, not organizational, activity.

- Analytical validation of reclaimed slabs from Schiphol's C-pier, including ULS/SLS checks, strengthening design, and comparison with new slabs. The calculations quantify capacity and deformation behaviour, requiring engineering judgement and application of design codes.
- Integration of Life-Cycle Assessment (LCA) within the structural analysis. Environmental impact is derived directly from structural parameters. The LCA procedure is part of the SE curiculum and therfor not part of the CME domain.

General scope assumptions and exemptions

The research focuses on the direct reuse of reinforced concrete elements, specifically the piecewise reuse of cast-in-situ floor slabs reclaimed through selective cutting. Only elements that can be recovered and verified according to current Eurocode standards are considered.

The study follows the full sequence of stages defined in the Communication Framework (Chapter 6): Initiation & Planning, Design & Engineering, Procurement & Handover, Construction & Assembly, Operation & Maintenance, and End-of-Life & Deconstruction. Of these, the analysis places particular emphasis on the stages from Initiation& Planning through End-of-Life & Deconstruction, as they encompass the technical and organizational processes most critical to enabling reuse, ranging from ambition setting, data and role definition, inspection and verification, to final deconstruction and feedback loops.

Economic valuation and cost analysis are deliberately excluded. Assessing financial feasibility or market value would require extensive modeling of depreciation, logistics, and market behavior, making the topic too broad for a single thesis. Instead, the research focuses on technical performance, structural safety, and sustainability outcomes.

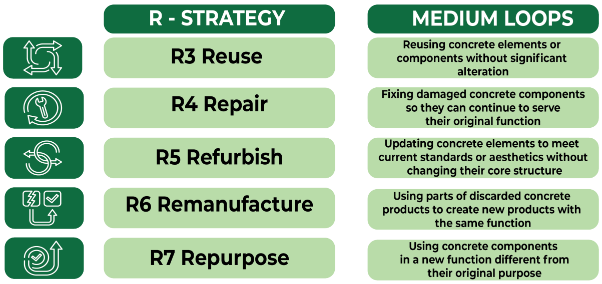
The study is based on Dutch and European practice, governed by Eurocode 2, EN 206, EN 1992-1-2, and CE-marking procedures, but the developed frameworks are designed to be transferable to other contexts with similar technical and regulatory conditions.

STEP I

Theoretical Background

2 The piecewise reuse of concrete slab elements

The reuse of concrete is becoming a more significant strategy in circular construction to reduce the environmental footprint of the built environment. When looking at the framework of the R-strategies the reuse practices as currently performed in the industry are mostly part of the medium loops (R3-R7). The industry aims to get as high on the R-strategy as possible (Malooly & Daphne, 2023). In light of this the **Piecewise Reuse of Extracted Concrete in New Structures (PRECS)** was introduced, which is a method that prioritizes reuse over recycling. As can be seen in figure 2.1 this method can therefore be placed higher on the circularity ladder creating more potential to reduce greenhouse gases (Habert et al., 2020; Küpfer et al., 2022).



R - STRATEGY	MEDIUM LOOPS
R3 Reuse	Reusing concrete elements or components without significant alteration
R4 Repair	Fixing damaged concrete components so they can continue to serve their original function
R5 Refurbish	Updating concrete elements to meet current standards or aesthetics without changing their core structure
R6 Remanufacture	Using parts of discarded concrete products to create new products with the same function
R7 Repurpose	Using concrete components in a new function different from their original purpose

Figure 2.1: The middle loop strategies adapted from Malooly and Daphne, 2023

This literature review critically examines the current body of research on the Piecewise Reuse of Extracted Concrete in new Structures (PRECS), with particular attention to studies focusing on cut-sawn concrete elements.

2.1. Introduction to the piecewise reuse of concrete elements

Piecewise reuse of extracted concrete in structures is a sustainable construction strategy that involves the selective dismantling, assessment, and reintegration of individual concrete components - such as beams, slabs, or facade panels - from decommissioned building into new structural assemblies. Unlike full building reuse or recycling into aggregate, PRECS retains the original form and function of concrete elements, preserving their embodied energy and structural value (Küpfer et al., 2023). It has demonstrated environmental benefits in multiple case studies, including reductions in CO_2 emissions of up to 90% compared to conventional construction (Roth and Eklund, 2000; Glias, 2013; Naber, 2012).

- **Component-Level Reuse**: Concrete elements are reused as whole or cut pieces, maintaining their geometric and mechanical properties with minimal reprocessing (Gorgolewski, 2008).
- **Structural Integration**: The reused components are incorporated into new load-bearing systems, such as buildings, bridges, or infrastructure, where structural performance must be verified (Devènes et al., 2022b).
- **Design Adaptation**: Projects employing PRECS often require bespoke design solutions, including customized connection details, structural assessments, and adaptation to the available stock of reclaimed components (N. Widmer, 2022; Volkov, 2019).
- **Material Origin**: Only previously used concrete is considered; newly manufactured components or objects designed for multiple uses are excluded unless repurposed differently than intended (Wong, 2016).

Although PRECS is already positioned relatively high on the R-strategies hierarchy, there remains a noticeable variation in the impact of the different levels of this reuse strategy. Ideally, the goal should be to prioritize the upcycling approach, as it offers the highest environmental and material value retention. However, due to the uncertainties and practical challenges associated with the piece wise reuse of concrete, decision-makers often opt for a lower tier within the reuse hierarchy.

- **Equivalent Reuse**: Components are reused in roles with similar structural demands.
- **Downcycling Reuse**: Components are reused in less demanding applications, often without utilizing their full structural capacity.
- **Upcycling Reuse**: Components are enhanced or combined to meet higher performance requirements than in their original use (Küpfer et al., 2023).

2.2. The development of the piecewise reuse of concrete elements

Understanding the historical trajectory of PRECS is essential to contextualize its current applications and future potential within circular construction. Küpfer et al., 2023 conducted a comprehensive review of 77 documented case studies to trace the evolution of this practice, highlighting how the reuse of concrete elements has developed over time in response to shifting technical, environmental, and socio-economic conditions. Their analysis provides valuable insight into how PRECS has progressed from isolated pragmatic applications to more sophisticated, design-integrated approaches, structured into three key chronological phases both displayed in figure 2.2 and further elaborated in table 2.1.

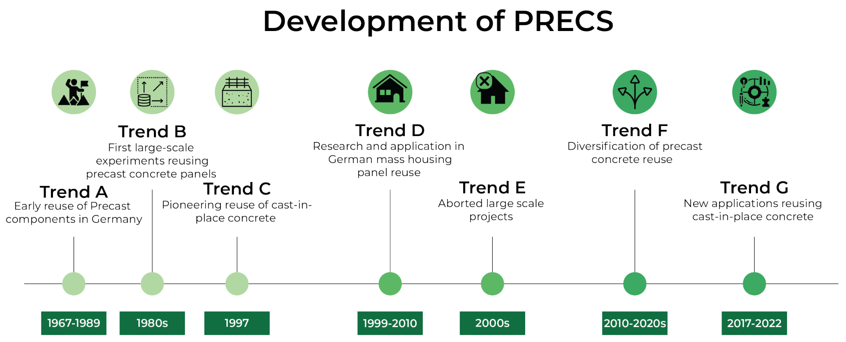


Figure 2.2: Timeline Development PRECS (own work)

Table 2.1: Summary of PRECS development trends (adapted from Küpfer et al., 2023)

Trend	Period	Focus	Key Insight
A	1967–1998	Precast reuse in East Germany	Demonstrated feasibility of local reuse with minimal alteration; mostly equivalent reuse.
B	1980s	Large-scale housing reuse in Northern Europe	Showed technical viability of modular precast reuse; introduced logistics coordination.
C	1997	First cast-in-place reuse (Udden Project, Sweden)	Proved structural reuse of monolithic elements; early evidence of environmental benefits.
D	1999–2010	German mass housing reuse	Academic support enabled innovation in resizing, connections, and aesthetics.
E	2000s	Aborted large-scale projects	Highlighted logistical, contractual, and economic barriers to scaling reuse.
F	2010s	Diversification of reuse applications	Expanded reuse to infrastructure and aesthetic applications; emphasized sustainability and local labor.
G	2017–2022	Advanced cast-in-place reuse	Introduced upcycling, composite assemblies, and digital tools for layout optimization.

Several key lessons that emerge from this diachronic analysis shown in table 2.1 are:

- **PRECS is not a new concept**- it has been practiced for over five decades, albeit sporadically and often under-documented. Early projects were driven by pragmatic reuse of available material, while later ones increasingly emphasized sustainability and innovation.
- **Technical feasibility has been repeatedly demonstrated**, particularly for precast concrete components. However, cast-in-place concrete reuse remain less explored and is often limited to down-cycling applications, highlighting a need for further research and development in this area.
- **Design flexibility and creativity are essential**. Successful projects often adapted their architectural and structural concept to the constraints of the available components, sometimes leading to novel aesthetics and spatial configurations.
- **Economic and environmental benefits are context dependent**. While some projects achieved cost savings and significant reductions in embodied carbon, others faced higher costs due to labor intensity, lack of standardization, or logistic challenges.
- **Knowledge transfer and documentation are critical**. Many valuable insights remain localized or unpublished. A more systematic effort to share technical details, performance data, and design strategies would accelerate the mainstreaming of PRECS.
- **Future potential is significant but underutilized**. With growing pressure to decarbonize the built environment, PRECS offers a viable pathway to reduce construction waste and embodied emissions. Its success will depend on integrating reuse thinking into early design stages, improving material traceability and fostering a culture of circular construction.

2.3. Current practices of the piecewise reuse of concrete slab elements

Although the reuse of structural concrete elements remains rare compared to lower ranking approaches, a growing number of pilot projects and research initiatives have demonstrated the feasibility of reclaiming and reapplying slab elements. For prefabricated elements the CROW-CUR Guideline 4:2023 provides a structured framework for the assessment and handling. It offers a more detailed approach for prefabricated girders and hollow-core slabs. Even though the focus is on prefabricated elements, parts are also relevant for in-situ applications. For in-situ elements no specific guidelines in the Netherlands have been published yet. Though recent work has expanded the scope beyond precast components. For example Dolkemade, 2021's thesis shows that in-situ slabs can also be harvested and reused when suitable cutting and handling techniques are applied.

These practices involve a sequence from harvesting elements in donor buildings to their integration in new construction. Each step introduces technical, organizational, and regulatory challenges that influence overall feasibility.

This section follows the main steps of PRECS, harvesting, assessment, processing, and integration, drawing on current literature to outline how cast-in-situ slab reuse is practiced today, where key barriers remain, and what opportunities exist for scaling reuse into mainstream construction.

2.3.1. Identification of potential reusable elements

The first and most critical step in the assessment of a building prior to demolition is the inventory of its reinforced concrete (RC) components. This process aims to gather quantitative and qualitative data on the donor structure, enabling an informed evaluation of the potential for reuse. Unlike verification procedures that focus on material testing and compliance with standards, the inventory stage concentrates on systematically documenting the stock of available components. While in practice no standardize procedure has been established for the identification stage Devènes et al., 2024 have established a method based on adapting existing structure assessment practices to the specific context of reuse and validated this through case studies.

2.3.1.1. Data Collection

The inventory begins with the collection of basic building data such as construction year, location, original function, and structural system. Existing documentation, including blueprints, reinforcement drawings, pollutant reports, and historical archives, is the preferred source of information, as it provides insights into component dimensions, rebar layouts, and material properties. When drawings are incomplete or unavailable, additional methods are employed:

- **Geometry measurements** through manual surveys, 3D scanning, or non-destructive investigations such as ground-penetrating radar to detect reinforcement layouts.
- **Material investigations** using non-destructive tools (e.g., Schmidt hammer) or selective destructive tests (e.g., core drilling for compressive strength) to confirm material characteristics.
- On-site visual inspection to document qualitative features such as surface color, accessibility, and assembly details.

2.3.1.2. Classification of Components

Once collected, data are structured into a classification system. Components are grouped into categories reflecting their structural function (e.g., slabs, beams, columns, walls, staircases, facades). Within each category, elements sharing material type, construction method, or assembly technique are further subdivided into types and subtypes according to their dimensions.

This hierarchical classification facilitates both comparison across projects and planning for reuse scenarios. It also enables designers to rapidly identify which component types make up the largest share of the building's structural volume and therefore should be prioritized in reuse strategies.

2.3.1.3. Quantification and Environmental Assessment

The inventory quantifies the number and volume of each component type, providing both absolute and relative proportions of the building's structural mass. This volumetric data can then be translated into embodied environmental impacts using life-cycle analysis databases. For example, the global warming potential of demolition and new production can be estimated, highlighting the environmental benefits of reclaiming high-volume categories such as slabs.

2.3.1.4. Limitations and Assumptions

In the absence of reinforcement drawings, approximations must be made to estimate structural capacity. These may rely on:

1. Minimal reinforcement ratios from historical standards
2. Calculations based on design load requirements from the construction period
3. Results of limited destructive and non-destructive testing

2.3.1.5. Reporting

To support reuse-oriented design, the collected data are synthesized in a structured manner. Standardized fact sheets summarize key attributes of each component type, including dimensions, quantities, reinforcement assumptions, accessibility, and indicative environmental impacts. These fact sheets, are intended as a communication tool between demolition contractors, engineers, and designers, ensuring that the available stock is transparently documented for future integration.

2.3.2. Design parameter identification and verification

Following the general inventory phase the next step in assessing the reuse potential of monolithic concrete floor slabs involves a more detailed investigation. While the inventory phase may provide a preliminary understanding of the element's characteristics, it often lacks the precision and completeness required for structural verification. Many existing buildings have limited or outdated documentation, and on-site conditions may differ from original plans due to undocumented modifications or degradation over time. Therefore, a systematic approach is needed to establish the actual properties of each slab. This stage focuses on identifying and verifying the key design parameters that determine whether a reclaimed slab can safely and effectively serve in a new structural application.

Currently there is no specific norms or standardized procedure for the verification stage. As mentioned several initiatives have been proposed to fill this gap:

- **Germany (BTU Cottbus memorandum)**: A four-phase protocol for precast panels, including preliminary review, on-site inspection, testing, and post-dismantling checks.

- **Norway (NS 3682:2022)**: A formal national standard for the reuse of hollow-core slabs, combining document review, visual inspection, material testing, and in some cases full-scale load tests.
- **Denmark (Structural Reuse project)**: A draft classification system for precast elements constructed after 1969, grouping components by characteristics and prescribing increasing testing requirements.
- **European ReCreate project:** A BIM-aided pre-deconstruction audit method, which combines digital inventories with visual inspection and selective testing.
- **CROW-CUR Guideline 4:2023 – Reuse of Structural Precast Concrete Elements**: Practical working method for assessing and reusing precast components, covering preparation, dismantling, storage, and verification of reclaimed elements. It also includes annexes specific to hollow-core slabs and prestressed bridge girders.

These initiatives illustrate a growing recognition of the need for systematic verification. However, they remain mostly limited to precast elements and are not yet fully integrated across project phases or component types. A more detailed comparison of these approaches, their scope, and limitations is provided in chapter 4 of this thesis.

2.3.3. (Selective) Deconstruction

The deconstruction phase can take place alongside the verification phase. It involves carefully dismantling structural elements to preserve their integrity for future use. Unlike demolition, which prioritizes speed, deconstruction focuses on precision and control to retain the material and structural value of components. As Dolkemade, 2021 highlights, it is not simply the reverse of construction, but a distinct process with its own technical, logistical, and safety requirements.

The choice of technique depends on the type of element. Projects such as Prinsenhof A and Stationsplein 107 show that hollow-core slabs can often be separated using hydraulic methods, while monolithic slabs require precise cutting with diamond wire or wall saws. Guiding rails and pre-cut measurements are used to achieve accuracy, especially when cutting through reinforcement.

Because slabs are often load-bearing, temporary support is essential during cutting to maintain stability and prevent cracking or collapse. A coordinated sequence of cutting, lifting, and transport ensures safe handling. Early planning and structural assessment of the existing building are therefore crucial to safeguard both safety and the quality of the reclaimed elements Dolkemade, 2021.

Worker safety is another key concern, particularly in high-rise projects where parts of the structure may already be removed. As seen in the Leiden case, additional edge protection and fall arrest systems are required to maintain safe working conditions.

After detachment, the lifting phase begins. Common lifting methods include:

- Lifting anchors, which allow controlled handling but must avoid reinforcement zones.
- Vacuum systems, which reduce damage but depend on surface condition and weight.
- Slings or clamps, which are flexible but can cause edge damage if not well balanced.

Selecting the appropriate method depends on the slab's geometry, weight, reinforcement layout, and condition, as well as site logistics such as crane reach and access. When slabs are reused in more demanding applications, stricter tolerances and more robust lifting setups are needed to preserve performance.

2.3.4. Storage

Once structural elements are harvested from existing buildings, they must be stored in a manner that preserves their physical condition and facilitates traceability. Depending on the project either long-term or short-term storage is needed. The directionality of deconstruction contrasts with the sequence of reconstruction, necessitating that elements from upper floors be stored until those from lower levels are also available. This temporal mismatch underscores the importance of a well-organized storage system (Ungureanu et al., 2025). Next to that the timeline of the donor project and the new project often do not line up. For example in Leiden the building proces of the new development starts 2 years after the demolition is done and in the Prinsenhof A case the planning of the new project had not even started before the demolition of the donor project.

A successful storage strategy involves not only physical protection of the elements but also meticulous documentation. Each element should be coded and cataloged with essential information, including its original location within the building, geometric dimensions, material properties, reinforcement details, and any modifications made during its service life. This data forms the basis of a material passport, which is instrumental in assessing the suitability of elements for reuse and in streamlining their integration into new designs (Wijte et al., 2025).

The absence of a structured storage and coding system has been identified as a key factor in the failure of past reuse initiatives. Conversely, projects that implemented comprehensive storage protocols, such as those documented in the ReCreate project, demonstrated higher success rates in reusing structural components (Team, 2025; Wijte et al., 2025).

Furthermore, the environmental and economic implications of storage must be considered. Storage facilities should be located strategically to minimize transportation distances, thereby reducing associated emissions and costs. In large-scale applications, centralized storage hubs may serve as intermediaries between deconstruction and reconstruction sites, enabling efficient logistics and quality control.

2.3.5. Design Stage - Integration in target building

In the design phase of projects involving reused concrete slabs, the approach diverges markedly from conventional practice, as it must accommodate the uncertainties and constraints of reclaimed elements. In a traditional design process, floor slabs are dimensioned and detailed on the basis of standardized material properties, predictable reinforcement layouts, and fully defined load-bearing behavior. By contrast, in reuse-oriented design, the geometry, material properties, and reinforcement of the reclaimed elements are predetermined, which necessitates an adaptive and iterative design strategy.

The design phase typically commences from the design parameters that are found in the verification stage. Since slabs originating from monolithic floors are cut into individual pieces, they can no longer be assumed as continuous members; instead, they are designed as simply supported elements, resulting in a redistribution of bending moments and a reduced effective span of approximately 70–80% of the original (Dolkemade, 2021). Structural verifications are required to determine the maximum allowable span for reuse, accounting for bending resistance, shear capacity, and both short- and long-term deflections. Where the capacity is insufficient, spans must be shortened, intermediate supports introduced or alternative strengthening methods of the slabs must be applied (N. Widmer, 2022).

Following the structural feasibility assessment, the design process proceeds with the integration of reclaimed slabs into the new structural system. This involves defining connection details to restore diaphragm action and ensure adequate transfer of vertical and horizontal loads. Solutions include steel plates, anchored connections, or supporting girders, with the choice depending on the span length and building type. The detailing must also account for tolerances introduced during cutting and handling, as well as the reversibility of joints to facilitate future reuse. Finally, logistical considerations such as transport distances, lifting limitations, and alignment with receiver-building requirements are integrated into the design to safeguard both technical feasibility and environmental benefit (Dolkemade, 2021; A. Widmer et al., 2023).

Accordingly, while conventional design emphasizes efficiency through standardization, the reuse-oriented design phase prioritizes adaptability to variable resources, robustness of connections, and the capacity to integrate existing structural elements into new configurations. This results in a design process that is not only technically distinct, but also aligned with the broader objectives of circular construction.

2.4. Barriers to the piecewise reuse of concrete elements

To structure the many challenges identified in the literature, the barriers to the integration of Piecewise Reuse of Concrete Slabs (PRECS) are grouped into several overarching themes. These capture both technical and non-technical dimensions of reuse. The technical and structural theme covers engineering issues such as geometry, performance, and durability. Economic and market barriers concern costs, business models, and the lack of established demand. Design and standards relate to insufficient codes and certification procedures, while logistics and supply chain address challenges in handling, storage, and coordination between donor and receiver projects. Regulatory and liability barriers arise from unclear legal frameworks and responsibilities, and knowledge and culture barriers stem from limited awareness and fragmented expertise. Finally, environmental–practical trade-offs highlight cases where reuse benefits are reduced by transport, energy, or processing demands.

Together, these themes provide a clear structure for analysing the barriers that currently limit the adoption of PRECS in the construction industry.

Theme	Specific Barriers	Source(s)
Technical / Structural	Uncertain geometry, reinforcement, and material condition complicate verification; cut edges lack anchorage; older designs struggle to meet current ULS/SLS criteria; possible degradation (carbonation, cracking); few validated designs for cut cast-in-place slabs.	(Küpfer et al., 2023) (Küpfer et al., 2024) (Stürwald, 2024) (Devènes et al., 2024)
Economic & Market	Demolition and new build remain cheaper and more predictable than reuse; deconstruction is labour-intensive; unclear liability and insurance; no established market for reused concrete; cutting and transport costs reduce environmental gains.	(Küpfer et al., 2024) (Küpfer et al., 2023) (Devènes et al., 2024)
Design & Standards / Codes	Current codes assume new materials; limited methods for connections, anchorage, and serviceability; no standard certification for reused components; minimal guidance on design for disassembly or adaptability.	(Küpfer et al., 2023) (Stürwald, 2024) (Devènes et al., 2024) (N. Widmer et al., 2023)
Logistics, Infrastructure & Supply Chain	Transport and storage of large slabs are costly; poor timing between donor and receiver projects; limited traceability and testing facilities; weak infrastructure for certification and storage.	(Stürwald, 2024) (Devènes et al., 2024) (Küpfer et al., 2023)
Regulatory, Liability & Institutional	Unclear responsibilities and insurance for reused elements; strict certification demands; permitting not suited to deconstruction; lack of material passports or reliable documentation.	(Küpfer et al., 2024) (Küpfer et al., 2023) (Devènes et al., 2024)
Knowledge, Awareness & Culture	Limited experience with PRECS; industry norms favour new builds; fragmented knowledge and few training pathways; perceived technical, financial, and regulatory risks remain high.	(Küpfer et al., 2023) (Küpfer et al., 2024) (Devènes et al., 2024) (Sandin et al., 2021)
Environmental vs Practical Trade-offs	Reuse benefits can be offset by transport, cutting, and repair; mismatched supply and demand; LCA outcomes depend on transport distance, lifespan, and maintenance.	(N. Widmer et al., 2023) (Küpfer et al., 2024)

Table 2.2: Barriers to the integration of PRECS (Piecewise Reuse of Concrete Slabs) in the construction industry.

2.5. Opportunities and value of the piecewise reuse of concrete elements

While the previous table highlighted the barriers that currently limit the integration of PRECS in the construction industry, it is equally important to recognize the opportunities that emerge from the same thematic areas. These opportunities point to technical innovations, regulatory adaptations, and cultural shifts that can directly address existing obstacles and create the conditions for broader adoption. By structuring the opportunities along the same themes as the barriers, it becomes clear how targeted actions, ranging from standardized design procedures to digital marketplaces and material passports, can transform constraints into pathways for progress. This parallel framing also underlines the close relationship between the challenges of reuse and the strategies required to overcome them, offering a comprehensive view of both the limitations and the potential of PRECS.

Theme	Opportunities	Source(s)
Technical / Structural	Standardized methods to assess spans and capacities of cut slabs; improved anchorage solutions (e.g., UHPFRC overlays, loops, connectors); design and testing of demountable joints to restore diaphragm action; combined destructive and non-destructive testing for reliable assessment.	(Küpfer et al., 2024); (Küpfer et al., 2023); (Stürwald, 2024); (Devènes et al., 2024)
Design & Standards / Codes	Inclusion of reuse pathways in Eurocode and national standards; guidelines and detailing libraries for PRECS; parametric and digital tools to match donor and receiver slabs; standardized grading and certification schemes for reused elements.	(Küpfer et al., 2024); (Küpfer et al., 2023); (N. Widmer et al., 2023); (Sandin et al., 2021)
Economic & Market	Digital marketplaces for second-hand elements; policy incentives and subsidies for deconstruction; pilot projects showing life-cycle savings; integration of reuse in ESG and carbon accounting frameworks.	(Küpfer et al., 2023); (Küpfer et al., 2024); (Sandin et al., 2021)
Logistics, Infrastructure & Supply Chain	Material passports and databases (e.g., Madaster, BAMB); standardized coding and storage for reclaimed slabs; digital matching of donor and receiver projects; specialized tools for cutting, handling, and transport.	(Küpfer et al., 2023); (Küpfer et al., 2024); (Devènes et al., 2024)
Regulatory, Liability & Institutional	Clear liability frameworks for reuse projects; certification and grading systems for reclaimed elements; reuse integrated into permitting processes; public procurement targets for circular construction.	(Küpfer et al., 2024); (Küpfer et al., 2023); (Sandin et al., 2021)
Knowledge, Awareness & Culture	Training for architects, engineers, and contractors; publication of best practices; cross-disciplinary collaboration platforms; awareness campaigns on reuse benefits.	(Küpfer et al., 2023); (Küpfer et al., 2024); (Sandin et al., 2021)
Environmental vs Practical Trade-offs	Use of LCA to identify high-impact reuse cases; local reuse to reduce transport emissions; integration of reused concrete and steel for carbon savings; design for multiple reuse cycles through demountable joints.	(Küpfer et al., 2024); (N. Widmer et al., 2023); (Devènes et al., 2024)

Table 2.3: Overview of opportunities supporting the integration of PRECS in the construction industry.

2.6. Knowledge gap

The review of barriers and opportunities for the PRECS highlights a wide range of challenges. Among these, two connected issues stand out as the main gaps in current research and practice:

1. **The lack of reliable methods to verify the structural performance of reclaimed slabs**
   Existing design codes and assessment methods are not suited to reclaimed elements. Verification of geometry, reinforcement, and material properties often depends on individual destructive or non-destructive tests, which are time-consuming and lack standardization. Although tools such as parametric design and material passports show potential, the absence of a unified verification framework creates uncertainty about safety and compliance, limiting engineers' confidence and keeping PRECS applications confined to small-scale pilot projects.
2. **The fragmented knowledge and coordination among stakeholders**
   Knowledge on PRECS is scattered across disciplines such as engineering, demolition, logistics, and regulation, often limited to isolated projects. There is no framework that connects technical verification with practical, organizational, and regulatory aspects. As a result, valuable expertise is lost between project phases, and decision-making remains inconsistent and incomplete.

Together, these issues form the core academic knowledge gap: there is no integrated framework that combines structural verification with construction management practices to make the reuse of concrete slabs both technically reliable and practically feasible. Bridging this gap is essential to move towards the wider adoption of PRECS.

3 Fragmentation and Collaboration in Concrete Reuse

In recent years, efforts to implement circular principles in the construction industry have highlighted the limits of traditional, linear project organization. Reuse practices disrupt established workflows by introducing additional steps, shifting responsibilities, and requiring cooperation among actors who do not normally interact. These changes create opportunities for innovation, but also expose persistent challenges of fragmented expertise and limited communication across disciplines. Understanding how these dynamics unfold in practice is essential for developing strategies that enable reuse of structural concrete elements to move beyond isolated pilot projects and towards wider adoption.

3.1. The construction value chain for concrete elements

To analyze where reuse challenges conventional practice, it is necessary to examine how construction processes are typically organized. The construction value chain describes the sequence of activities through which materials, labor, and knowledge are combined in building and infrastructure projects. For concrete, this extends from early planning and design through procurement, construction, operation, and eventually deconstruction. Each stage is associated with specific activities and decision points that determine whether the process follows a traditional linear pathway or incorporates opportunities for reuse and circularity. Mapping the value chain therefore provides a basis for identifying critical decision points and highlighting where reuse introduces new processes compared to a traditional linear project.

Table 3.1 provides an overview of these stages, highlighting the key activities undertaken and the critical choices that shape project outcomes.

Table 3.1: Traditional activities and decision points in the construction value chain of concrete slabs.

Stage	Traditional key activities	Traditional decision points
Project initiation & planning	Define project scope, objectives, budget, and feasibility; secure financing; identify requirements.	Focus on cost and feasibility; sustainability objectives optional; material choice based on best practice
Design & engineering	Develop design; specify slab systems, reinforcement, and dimensions; ensure compliance with codes.	Selection of standard slab systems; optimization for single service life.
Procurement & handover	Tendering, material ordering, and delivery coordination; transfer of completed work or components to the client or next project phase.	Focus on cost, delivery speed, and contractual completion; handover emphasizes documentation of finished work rather than material traceability.
Construction & assembly	On-site concreting or installation of precast slabs; curing; inspection; safety management.	Choice of efficient construction sequencing; no consideration for disassembly.
Operation & maintenance	Routine inspections, maintenance, and repair; ensure safety and performance over service life.	Repairs are reactive; little systematic documentation of condition
End-of-life	Rapid demolition to clear site; crushing of concrete	Decision for fast demolition over selective deconstruction; slabs treated as waste

3.1.1. Project Initiation & Planning

The initiation and planning stage lays the foundation for the project. It starts with the client defining the purpose, performance goals, budget, and schedule, supported by market studies, site selection, cost estimates, and financing. Regulatory factors such as zoning, building codes, and environmental requirements are also reviewed, setting the framework for later design decisions.

Integrating circular principles at this stage means shifting focus from short-term feasibility to long-term value creation. By including explicit reuse and sustainability goals in the project brief, clients ensure that the potential for reusing structural concrete is considered from the outset. Early feasibility studies can then assess the availability, logistics, and performance of reclaimed slabs, evaluating their structural suitability, regulatory compliance, and economic implications. Research shows that decisions made at the front end of projects have a decisive influence on circular outcomes (Winch & Leiringer, 2016).

Circular planning also calls for broader early stakeholder involvement. Alongside clients, architects, and financiers, demolition contractors, reuse brokers, testing laboratories, and regulators should participate to align expectations and define quality verification procedures (Hossain et al., 2020). Reviewing applicable regulations at this stage helps anticipate approval requirements and avoid costly design changes later.

3.1.2. Design & Engineering

The design and engineering stage translates project goals into technical specifications. Architects and structural engineers define the structural system, dimensions, and performance requirements of concrete slabs while ensuring compliance with relevant standards. Conventional designs typically assume the use of new concrete, as standardized methods and predictable costs support a linear, single-use approach with limited regard for adaptability or reuse.

Circular design shifts this focus toward reuse and future adaptability. Instead of optimizing for one service life, engineers design with reclaimed elements in mind, considering how components can be integrated from previous projects and later dismantled for future use. This requires adaptable detailing, suitable connection methods, and tolerances that accommodate both the variability of reclaimed slabs and the need for reversible assembly. Aligning design decisions with reuse logistics embeds flexibility and long-term resource efficiency into the structure itself.

Digital design tools, particularly Building Information Modelling (BIM), further support circular practice by linking material data, such as geometry, reinforcement, and provenance, directly to the design model. This improves coordination, traceability, and confidence in reused components. In doing so, design evolves from a one-off exercise to a continuous process that manages material lifecycles and enables concrete slabs to retain value across multiple applications (Jaillon & Poon, 2003).

3.1.3. Procurement & Handover

In conventional projects, procurement and handover focus on obtaining materials at the lowest cost, ensuring timely delivery, and transferring the completed structure to the client. Materials move in a linear flow from supplier to site, and any surplus is typically discarded or downcycled. Contracts and tendering procedures emphasize price, speed, and liability, leaving little room for collaboration or material traceability.

In reuse-oriented projects, this approach must be redefined. Reclaimed elements must be identified, tested, and secured early, often before budgets or designs are finalized. Procurement must therefore remain adaptable to material availability and verification outcomes, supported by flexible contract forms that enable early cooperation and shared responsibility between demolition, design, and construction partners.

The handover phase also changes fundamentally: rather than transferring a finished building, it involves transferring verified elements and their documentation from one project to another. This inter-project handover requires clear agreements on ownership, liability, and quality assurance. Because donor and target projects rarely align in time, intermediate storage becomes a shared responsibility that must be contractually organized. Storage facilities function as transitional nodes between projects, where elements are temporarily held, inspected, and managed. Their operation requires defined responsibilities for handling, protection, monitoring, and information exchange, ensuring that material integrity and traceability are maintained throughout transfer.

By integrating procurement, contracting, storage, and inter-project handover into a coordinated process, reuse projects can maintain both accountability and material quality, creating the logistical and institutional foundation for reliable structural reuse.

3.1.4. Construction & Assembly

In conventional construction, the assembly stage focuses on efficiently realizing the design through on-site concreting or installation of new precast slabs. Activities are organized to maximize productivity, minimize delays, and meet safety and quality standards. Standardized procedures optimize short-term performance but assume that materials are new and easily available. Once installed, slabs are permanently integrated into the structure, with little documentation of their properties or location, making future recovery difficult, labour-intensive, and costly.

In reuse-oriented projects, this stage must address both current integration and future disassembly. Reclaimed elements require careful handling and fitting to account for variations in geometry, reinforcement, or surface condition. Lifting, alignment, and fixing methods must protect the slabs' integrity and maintain certification. At the same time, joints and connections are designed for reversibility, allowing the elements to be removed without significant damage. Construction sequencing and temporary supports are therefore planned not only for buildability but also to enable later recovery.

To achieve this shift, site teams need training to work with reused elements and to document installation details that ensure traceability. Procurement and scheduling must allow additional preparation time for testing and adjustments. Most importantly, contractors and designers must coordinate closely so that execution aligns with circular design intent. Without these adaptations, reuse ambitions risk being lost during construction, highlighting that this stage is the critical link between circular design and its practical realization (Devènes et al., 2022a; Küpfer et al., 2023).

3.1.5. Operation & Maintenance

The operation and maintenance stage ensures that concrete slabs perform safely and reliably throughout a structure's service life. Activities typically include inspections, repairs, and rehabilitation to maintain functionality and meet safety standards. Conventional maintenance is mostly reactive, addressing deterioration as it appears and rarely considering future reuse. Consequently, decisions at this stage often reinforce a linear approach, where slabs are maintained until demolition and disposal.

A circular perspective instead treats operation as a chance to preserve the residual value of structural elements. Proactive monitoring, through non-destructive testing, structural health sensors, and digital records, can document the condition and performance of slabs for potential reuse. Maintenance strategies can also favor reversible repair methods that extend service life without hindering future disassembly. By aligning maintenance with long-term reuse goals, asset managers help create a resource-efficient lifecycle, viewing slabs not only as current structural components but also as future material assets (O. A. Akinade et al., 2017).

3.1.6. Deconstruction & End-of-Life

The end-of-life stage in conventional practice focuses on rapid demolition to clear sites for redevelopment. Concrete slabs are typically crushed and downcycled into aggregates, with little effort to preserve their structural value.

In a circular approach, this stage marks the start of a new material lifecycle. Selective deconstruction replaces demolition, using controlled methods to recover slabs while maintaining their geometry, reinforcement, and load-bearing capacity. This process requires skilled labor, specialized equipment, and careful sequencing to prevent damage. After removal, elements are tested, verified, and documented before being stored, refurbished, or directly integrated into new projects. In this way, end-of-life activities shift from being a terminal process to a gateway for reuse, keeping slabs in circulation and reducing the need for virgin concrete production (Crowther, 2005).

3.2. Stakeholder Analysis

A comprehensive understanding of the construction value chain requires not only mapping its sequential activities but also identifying the stakeholders who shape decisions at each stage. Concrete slabs move through multiple phases, each involving distinct actors with specific roles and responsibilities. These stakeholders determine how value is created, how risks are distributed, and whether projects follow a linear or circular approach.

Table 3.2 summarizes the key stakeholders across all stages of the concrete slab value chain and outlines their main responsibilities. Stakeholders or roles that change, or are newly introduced, under circular practices are highlighted in green. The following section elaborates on these adjustments, explaining how stakeholder involvement evolves when reuse and other circular strategies are integrated into construction projects.

Table 3.2: Stakeholders in the construction value chain of concrete slabs

Stage	Stakeholder	Role / Involvement
Project initiation & planning	Client / project owner	Define project objectives, budget, and scope; set sustainability targets.
	Financiers / investors	Secure financing, assess economic feasibility.
	Regulators	Ensure compliance with zoning, permits, and planning regulations.
Design & engineering	Designers	Translate project brief into designs; integrate circular design practices; specify layout and form; access structural performance
	Sustainability Consultants	LCA analysis, advisory role to meet sustainability KPI's.
	Regulators / code authorities	Approve designs for compliance with building codes.
Procurement & handover	Contractors	Manage tendering, material orders, and delivery coordination; ensure completion and transfer of work to the client.
	Suppliers	Provide and deliver new concrete materials or components; documentation focused on delivery compliance.
	Reuse brokers / storage operators	Facilitate transfer and temporary storage of reclaimed elements between projects; maintain traceability and quality records.
	Clients / procurement teams	Define procurement strategy and contract terms; oversee project handover and acceptance of completed work.
Construction & assembly	Main contractors / site managers	Supervise slab installation and on-site concreting.
	Specialized subcontractors	Execute detailed construction tasks.
	Health and safety inspectors	Monitor safety and compliance during assembly.
Operation & maintenance	Building owners / facility managers	Oversee building performance and long-term upkeep.
	Maintenance contractors	Carry out repairs, retrofitting, or strengthening;Conduct inspections and record data (material passports, BIM) to preserve reuse potential.
Deconstruction & End-of-life	Demolition contractors / deconstruction specialists	Remove slabs through selective deconstruction for reuse.
	Reuse brokers / material banks	Collect, verify, trade, and redistribute reusable slabs.
	Waste management companies	Handle non-reusable material streams.
	Regulators	Enforce reuse standards, issue permits, ensure compliance.

3.2.1. Stakeholder differences in traditional and reuse-oriented projects

In a traditional construction project, the stakeholders involved in the value chain of concrete slabs are relatively well defined. Clients, designers, contractors, and suppliers collaborate around a single project, with clear boundaries between phases such as design, procurement, construction, and operation (Küpfer et al., 2023). At the end of a building's life, demolition contractors and waste management firms are brought in, but their role is primarily to clear the site efficiently, with little interaction with the design or construction teams of new projects. This linear approach minimizes the need for cross-project coordination, as materials are considered disposable rather than resources for future use.

In contrast, projects that incorporate the reuse of concrete elements expand the stakeholder landscape significantly. In the paper by (Riuttala et al., 2019) the key actors that are needed for reuse strategy are proposed. Reuse requires linking two separate but interdependent projects: the donor building, from which slabs are harvested, and the target building, into which they are integrated. On the donor side, demolition contractors must transition towards selective deconstruction practices, often in coordination with engineers and stakeholders that provide verification services, such as those who assess the geometry, strength, and durability of reclaimed slabs. Regulatory authorities also play a more active role, since permits and quality standards must be met before reclaimed elements can re-enter the market.

On the target building side, designers and structural engineers must adapt their plans to accommodate non-standard dimensions or tolerances of reused slabs, requiring closer interaction with deconstruction teams and reuse brokers. Contractors and suppliers are joined by new intermediaries such as material banks, logistics providers specialized in handling reclaimed components, and verification bodies certifying compliance with building codes. Clients also take on an expanded role, as their early commitment to reuse is essential to justify the additional coordination, testing, and potential design adaptations required.

The critical distinction, therefore, lies in the interconnectedness of stakeholders across projects. While traditional value chains operate within the boundaries of a single building, reuse-oriented projects demand collaboration between the donor and target contexts. This shift introduces new actors, new responsibilities, and more complex communication channels, but it also creates opportunities to extend the life of concrete elements and embed circularity into the construction sector.

3.3. Fragmented expertise and communication challenges

Following the stakeholder analysis, it becomes evident that the reuse of concrete elements introduces a far more complex network of actors than conventional construction. Each stakeholder , from demolition contractors and material brokers to designers, engineers, and regulators , operates within their own domain of expertise, with distinct objectives, timelines, and contractual boundaries. While this diversity of knowledge is essential for realizing reuse, it also exposes a structural weakness in how the construction industry organizes collaboration. The interfaces between these disciplines are rarely formalized, and communication often depends on individual initiative rather than defined processes.

As a result, expertise that should complement one another instead tends to become fragmented across the project lifecycle. Information gathered during deconstruction may not reach the designers of the new building; verification data may remain isolated within testing laboratories; and regulatory interpretations may vary between authorities. This disconnection makes it difficult to coordinate donor and target projects, and even harder to maintain traceability and shared accountability throughout the reuse chain.

Fragmented expertise and communication have therefore been repeatedly identified in the literature as major barriers to implementing reuse strategies in construction projects. Because reuse requires the coordination of donor and target buildings, as well as the alignment of technical, organizational, and regulatory considerations, traditional project structures often fall short. Challenges arise from siloed responsibilities, insufficient or inaccessible information, and the absence of established frameworks to facilitate collaboration and decision-making across stakeholders. Table 3.3 summarizes the key challenges documented in research, highlighting how they affect the flow of information, the allocation of responsibilities, and ultimately the feasibility of reusing structural components.

Table 3.3: Challenges of fragmented expertise and communication in reuse-oriented construction projects

Theme	**Specific Barriers**	**Key Sources**
Siloed roles & project fragmentation	Traditional delivery splits design, demolition, logistics, and construction across separate firms and phases, making integrated reuse decisions difficult.	(O. Akinade et al., 2015; Munaro et al., 2020)
Early-stage information gaps	Lack of reliable data on geometry, condition, reinforcement, and provenance of donor assets hinders feasibility assessments.	(Rasmussen et al., 2019)
Data interoperability issues	Disparate systems (BIM, inventories, testing reports, marketplaces) do not share structured data; material passports are rarely implemented.	(O. Akinade et al., 2015; Munaro et al., 2020)
Misaligned timing	Donor deconstruction rarely aligns with target design and procurement phases, increasing the risk of late substitutions.	(Gálvez-Martos et al., 2017)
Unclear quality assurance & liability	Uncertainty about verification, warranties, and responsibility for reclaimed elements increases perceived risks.	(Charef et al., 2021; Munaro et al., 2020)
Regulatory and standards friction	Standards for new products do not align with reclaimed elements, requiring negotiation with authorities.	(Gálvez-Martos et al., 2017)
Linear procurement practices	Design–bid–build and lowest-price tendering limit early collaboration needed for reuse opportunities.	(Munaro et al., 2020)
Limited collaboration frameworks	Few reuse-specific RACI charts, BIM plans, or coordination frameworks exist; roles remain unclear.	(Gálvez-Martos et al., 2017)
High communication load	Circular processes add new interdependencies without clear budgets or channels to manage them.	(Charef et al., 2021)

The overview in Table 3.3 shows that the barriers to reuse are not only technical, but also deeply organizational and communicative. Knowledge gaps and the lack of reliable data undermine confidence in the quality of reclaimed elements, while siloed responsibilities, procurement practices, and regulatory ambiguity further complicate integration into projects. Reuse introduces new interdependencies across actors and phases, yet established mechanisms to coordinate them are missing. This fragmentation leads to duplicated efforts, lost opportunities, and a persistent reliance on conventional linear approaches. Overcoming these challenges requires more than technological solutions: it demands frameworks that support consistent information exchange, clarify responsibilities, and align the dynamics between donor and target projects.

3.4. Frameworks for integrating expertise fragmentation

A number of frameworks have already been developed to address the organizational and communication barriers that hinder material reuse in construction. Four frameworks are especially relevant in this regard: the REVERT Framework, the Digital Circular Economy (CE) Framework, the Circular Construction Evaluation Framework (CCEF), and the Circular Information Flow (CIF) Framework developed by Berglund-Brown et al. (2022). Each addresses the challenge from a different angle, through governance, digital data exchange, shared evaluation methods, or data management quality, but together they provide a clear foundation for improving coordination and reducing disciplinary silos in circular construction.

Table 3.4: Frameworks addressing communication, collaboration, and information flow in circular construction

Framework	Focus on Communication and Collaboration	Key Sources
REVERT Framework	Emphasizes stakeholder alignment and shared vision across material, building, and city scales. Defines critical success factors such as feedback loops, role clarity, and cross-sector collaboration to overcome fragmented expertise.	(Bostanci et al., 2025)
Digital Circular Economy Framework	Integrates BIM, material passports, and digital marketplaces to enable interoperable data exchange and transparency across life-cycle stages. Supports communication through connected digital platforms linking donor and receiver projects.	(Çetin et al., 2021)
Circular Construction Evaluation Framework (CCEF)	Creates a shared vocabulary and structured assessment system for circularity. Facilitates collaboration by providing common evaluation criteria and enabling dialogue among designers, engineers, and clients.	(Dams et al., 2021)
Circular Information Flow (CIF) Framework	Defines four essential qualities of effective information exchange, completeness, availability, accessibility, and integration into business strategy, establishing measurable criteria for evaluating communication performance.	(Berglund-Brown et al., 2022)

REVERT Framework

The REVERT framework tackles the problem of fragmented expertise by focusing on how stakeholders collaborate and share knowledge across different levels of the built environment, from materials and buildings to urban systems. It recognizes that circular construction depends not only on technical solutions but on coordinated decision-making between diverse actors such as designers, clients, regulators, and contractors. REVERT identifies critical success factors (CSFs) for collaboration, including transparent communication channels, well-defined roles, and feedback loops between disciplines. By aligning goals and responsibilities, REVERT helps prevent the miscommunication and role overlap that often occur when reuse is introduced into conventional project structures. Its multi-scalar perspective ensures that decisions made at one level, such as material verification or policy setting, are effectively communicated to others. In this way, REVERT provides the organizational clarity needed to bridge disciplinary gaps and foster long-term collaboration in reuse-oriented projects.

Digital Circular Economy Framework

The Digital Circular Economy (CE) Framework addresses fragmentation from a data and technology perspective. In most construction projects, information about materials, components, and design is scattered across disconnected systems, making collaboration between actors difficult. The Digital CE Framework overcomes this by promoting data interoperability through the integration of digital tools such as Building Information Modelling (BIM), material passports, and digital marketplaces. These tools link technical and commercial data across life-cycle stages, creating shared digital environments where all actors, engineers, designers, demolition contractors, and reuse brokers, can access accurate and up-to-date information. This improves transparency and traceability, reduces errors caused by missing data, and ensures that decisions are based on shared knowledge rather than isolated assumptions. For reuse projects in particular, where reliable information about material origin and performance is essential, this framework enables continuous information flow between donor and receiver projects, strengthening collaboration and coordination throughout the process.

Circular Construction Evaluation Framework (CCEF)

The Circular Construction Evaluation Framework (CCEF) focuses on improving communication and shared understanding among project participants. A frequent barrier in circular construction is that stakeholders interpret “circularity” differently, engineers may focus on structural feasibility, clients on costs, and regulators on compliance. The CCEF addresses this by creating a common language and structured method for evaluating circular performance. Through defined criteria and scoring systems, it allows project teams to discuss and assess reuse strategies on equal terms.

By providing a transparent basis for comparison, the CCEF encourages dialogue, joint evaluation, and knowledge exchange across disciplines. It reduces misunderstandings caused by inconsistent definitions and supports collaborative decision-making. As a result, it turns circularity from a loosely defined ambition into a measurable and communicable project objective, an important step toward overcoming fragmented expertise and establishing collective responsibility for circular outcomes.

CIrcular Information Flow (CIF) Framework

The Circular Information Flow (CIF) Framework proposed by Berglund-Brown et al., 2022 offers a concrete way to evaluate how effectively information supports collaboration in circular construction. It identifies four key characteristics of an effective information system:

- Completeness ensures that all necessary data about a material or element, such as geometry, condition, and recyclability, is recorded.
- Availability guarantees that this data actually exists and is collected within organizational systems.
- Accessibility focuses on making information easily retrievable and shareable among all relevant stakeholders, including those outside the firm.
- Integration embeds these data flows into everyday business operations, ensuring that collaboration and information sharing are not one-off efforts but part of a firm's long-term strategy.

Together, these four qualities define the foundations of effective communication and knowledge exchange. Without complete, available, and accessible data that is integrated into business practice, even the best-designed collaboration frameworks will fail to function. The CIF framework therefore bridges the gap between digital information management and organizational coordination, providing measurable indicators for reducing fragmentation and enabling circular knowledge flow across projects and companies.

Collectively, these frameworks show that overcoming fragmented expertise requires both organizational coordination and data transparency. The REVERT and CCEF frameworks strengthen stakeholder communication and shared understanding, while the Digital CE and CIF frameworks ensure that information is technically robust, interoperable, and accessible. Together, they highlight that successful circular construction depends on aligning people, processes, and data within a single, continuous flow of communication and collaboration across the entire value chain.

3.5. Knowledge gap

When the construction value chain is viewed through the lens of reuse, it becomes clear that activities such as deconstruction, assessment, logistics, redesign, and reintegration involve a far greater number of interdependent stakeholders than in conventional projects. Actors range from demolition contractors, testing laboratories, and logistics providers to architects, engineers, clients, and regulators. Each of these groups holds specialized expertise, yet current project delivery models provide few mechanisms to integrate their perspectives into a unified process. As a result, responsibilities remain siloed, data exchange is inconsistent, and opportunities for reuse are frequently lost.

The challenges summarized in Table 3.3 demonstrate that fragmentation occurs on both technical and organizational levels. Data gaps, poor interoperability, and unclear responsibilities limit the ability to verify reclaimed elements, while traditional procurement and regulatory structures hinder early collaboration. Communication often depends on ad-hoc coordination rather than structured processes, leading to inefficiencies and mistrust between actors. These conditions prevent reuse from becoming a reliable, repeatable practice, even where its technical feasibility has been proven.

Recent frameworks have begun to address aspects of these issues, yet none provide a comprehensive solution. The REVERT framework offers valuable guidance on stakeholder alignment and defines critical success factors for collaboration, but it remains largely conceptual and does not yet provide practical mechanisms for conflict resolution or shared accountability. The Digital Circular Economy (CE) Framework strengthens data interoperability through BIM, material passports, and digital platforms, but implementation is often hampered by uneven adoption, governance barriers, and limited cross-project integration. The Circular Construction Evaluation Framework (CCEF) helps establish a shared language and assessment structure for circularity, reducing interpretative gaps between disciplines, yet it offers limited operational guidance on coordination and communication. Finally, the Circular Information Flow (CIF) Framework proposed by Berglund-Brown et al. (2022) introduces essential qualities, completeness, availability, accessibility, and integration into business strategy, that describe how data must be managed to support collaboration. While this provides measurable indicators of effective information flow, it remains disconnected from governance and decision-making structures that could translate these principles into everyday project practice.

Together, these frameworks illuminate different facets of the problem:

- REVERT addresses stakeholder alignment and governance;
- Digital CE tackles data interoperability and transparency;
- CCEF builds shared understanding and evaluation methods;
- CIF defines the characteristics of high-quality information flow.

However, no single framework integrates these dimensions into one cohesive approach that links data quality, collaboration mechanisms, and organizational accountability. What is missing is a practically applicable framework that combines the social coordination of REVERT, the digital infrastructure of the Digital CE framework, the common evaluation language of CCEF, and the data management rigor of the CIF framework.

Bridging this gap requires developing a model that not only ensures complete, accessible, and reliable information but also embeds clear communication pathways, defined responsibilities, and feedback loops throughout the reuse process. Such an integrated framework would enable consistent decision-making between donor and target projects, support transparent verification of reclaimed elements, and ultimately transform reuse from isolated experimentation into a structured, collaborative practice within the construction industry.

4 The validation of Reclaimed Elements

From the research into the barriers of using reclaimed RC elements in the construction industry as shown in the previous chapters one of the most critical obstacles is the absence of recognized certification pathways for reclaimed structural elements. While CE marking and harmonized standards exist for newly manufactured concrete products, reclaimed elements fall outside this system. They lack the factory production control, declaration of performance, and traceability required by the Construction Product Regulation.

This absence of certification not only prevents reclaimed elements from being treated as standard construction products but also significantly increases the risk perception among project initiators, designers, and regulators. Without an accepted approval mechanism, the use of reclaimed structural components is seen as uncertain, legally complex, and potentially unsafe. As a result, many otherwise reusable elements are downcycled or discarded, undermining circular economy goals.

To address this gap, there is an urgent need to establish certification strategies that are adapted to the realities of reclaimed components. Rather than attempting to replicate CE marking for new products, the emerging approach in practice and research is to develop project-based certification methods. Such methods evaluate the properties and performance of reclaimed elements within the context of a specific project, taking into account structural capacity, durability, fire safety, serviceability, and other critical factors. They enable engineers and project stakeholders to make informed, documented, and certifiable decisions about reuse on a case-by-case basis.

This literature review therefore examines three strands of knowledge relevant to developing such a method:

1. Current certification pathways for new elements (CE marking, EN 13747, Eurocode 2)
2. The specific barriers faced by reclaimed RC elements in meeting these requirements.
3. Examples of project-based or element-specific approvals from research projects and national initiatives (ReCreate, Rotor, Bellastock, Swiss and Nordic case studies).

4.1. Current certification pathways and the barriers for reclaimed RC elements

Certification ensures that construction products meet essential requirements for safety, durability, and performance before they can be placed on the European market. For concrete elements, this process is governed by the Construction Products Regulation (CPR 305/2011), which provides the legal framework for CE marking. The CE mark demonstrates that a product has been manufactured, tested, and documented in accordance with harmonized European standards.

For new precast concrete floor and roof elements, CE marking is obtained through compliance with a set of harmonized product standards that define technical requirements, test methods, and verification procedures. The most relevant standards and their relationships are summarized in Table 4.1.

Table 4.1: Overview of standards governing CE marking of precast concrete slabs

Level	Purpose	Relevant Standard(s)	Connection / Role
EU Regulation	Legal framework for CE marking	CPR (Regulation (EU) No 305/2011)	Establishes the requirement for Declaration of Performance (DoP) and CE marking across all construction products.
Harmonized product standards (hEN)	Product-specific requirements	EN 13747 (solid/ribbed slabs), EN 1168 (hollow-core slabs)	Define essential characteristics and testing methods for each product type. Provide the direct route for CE marking.
Common rules for precast products	Generic production and testing provisions	EN 13369:2018	Provides common requirements for production control, testing procedures, and references to supporting test standards. Forms the basis for all precast product standards.
Testing and assessment standards	Determination of material and mechanical properties	EN 12390 (hardened concrete), EN 12504 (on-site tests)	Define standardized procedures for determining strength, density, modulus, and related performance parameters.
Design reference standards	Basis for structural design and declared performance	EN 1992-1-1 (Eurocode 2)	Ensures that declared mechanical resistance and durability align with European structural design principles.

These standards ensure that every CE-certified precast concrete product is produced under controlled factory conditions and verified for consistent performance. The certification process typically involves three main steps:

1. Factory Production Control (FPC) - Continuous monitoring of material quality, batching, and production procedures within the manufacturing plant.
2. Type Testing (ITT) - Laboratory testing of representative samples to verify compressive strength, durability, and other material properties.
3. Documentation and Traceability - Recording material sources, mix designs, and test results, which are compiled into the Declaration of Performance (DoP) that authorizes the CE mark.

Testing is performed according to standardized European procedures such as:

- EN 12390 - Testing of hardened concrete.
- EN 12504 - On-site testing of concrete.

The verified results are translated into declared performance values in accordance with Eurocode 2 (EN 1992-1-1). Together, these documents confirm that the product meets the required mechanical resistance, durability, and safety criteria set out under the Construction Products Regulation.

While the CE marking system guarantees quality and traceability for newly produced elements, it depends entirely on a controlled production environment with continuous documentation of materials, mix designs, and test results. Reclaimed precast elements do not meet these conditions because they:

- Lack the original Declaration of Performance (DoP) and related production records;
- Have no continuous Factory Production Control (FPC) history to verify manufacturing consistency;
- Cannot be linked to a specific production batch or certified quality record as required by EN 13369.

Once concrete elements have left their original production cycle, they are no longer under the responsibility of the manufacturer, and their quality cannot be verified through the CE route. As a result, reclaimed precast concrete elements cannot be CE-marked under current harmonized standards, even when technical testing demonstrates that they still meet performance and safety requirements.

This creates a major regulatory barrier: the current CE system provides no formal pathway for certifying reclaimed structural elements. To enable large-scale reuse, an alternative project-based verification framework is needed, one that can demonstrate equivalent reliability and safety outside the factory-controlled environment.

4.2. The design parameters under the current verification framework

The review of certification pathways in the previous section shows that reclaimed reinforced concrete slabs cannot be CE-marked under the current harmonized system. However, many of the technical requirements set out in EN 13747 can still be verified after deconstruction. This means that, although reclaimed elements fall outside the formal CE route, they can be assessed through project-specific verification procedures that demonstrate equivalent reliability.

Table 4.2 summarises the main requirements of EN 13747 for precast floor and roof elements and indicates the extent to which each criterion can be verified for reclaimed slabs. The following sections discuss these parameters in more detail, explaining the methods available for post-production verification and the limitations that remain due to missing factory documentation.

Table 4.2: Verification of EN 13747 requirements for reclaimed RC slabs

EN 13747 Requirement	Reclaimed Slab Verification	Status
Geometry & tolerances	On-site measurement, 3D scanning, or photogrammetry	✓ Verifiable
Concrete strength class	Coring, laboratory testing, and calibrated NDT methods	✓ Verifiable (often lower than required)
Durability (exposure class)	Cover depth, carbonation depth, chloride testing	◐ Partial
Structural performance (ULS/SLS)	Load testing and recalculation using verified inputs	✓ Verifiable
Fire resistance	Based on measured cover and section geometry; calculation or test	◐ Partial
FPC & traceability (DoP, CE)	Factory records unavailable after production	✗ Not possible

In a project-based verification framework, the focus shifts from what cannot be proven through missing documentation to what can be directly verified through testing and inspection. The parameters listed in EN 13747 therefore provide a practical foundation for evaluating the suitability of reclaimed elements. Each parameter, ranging from geometry and strength to durability, fire resistance, and structural performance, can be examined through targeted methods that account for the unique conditions of deconstructed slabs.

The following subsections describe these verification parameters in more detail, outlining the relevant provisions in EN 13747 and the corresponding approaches for assessing reclaimed elements within a project-specific context.

Geometry and Tolerance

EN13747 specifies that precast floor and roof elements must conform to declared nominal deminsions and to tolerance classes given in Annex A. These include maximum deviations in length, width, thickness, straightness squareness, camber and flatness, which can be found in Table 4.3 Such requirements ensure dimensional compatibility with structural design assumptions and connection details.

Table 4.3: Summary of dimensional tolerances for precast floor slabs (EN 13747:2005+A2:2010, Annex A)

Dimension	**Class 1 (stricter)**	**Class 2 (general)**
Length deviation (mm)	±10	±20
Width deviation (mm)	±10	±20
Thickness deviation (mm)	±5	±8
Camber deviation (mm)[a]	±6	±12
Squareness (mm per m)	≤ 6	≤ 10
Edge straightness (bowing)	≤ 6	≤ 10

[a] Camber tolerance depends on span and prestressing; values shown are indicative typical limits.

For reclaimed slabs, these checks are relatively straightforward: manual measurement, laser scanning, or 3D photogrammetry can be used to verify current dimensions and deviations. While damage such as spalling or chipped edges may compromise tolerances, minor repairs or trimming can restore usability. Thus, this is one of the areas where reclaimed elements can be close to fulfilling the same requirements as new CE-marked products.

Strength Class (Mechanical Resistance)

The standard requires that concrete in precast slabs achieves a characteristic compressive strength (f_{ck}) to at least strength class C25/30, unless otherwise justified by design. The classification and verification of strength follow EN206 and EN1992-1-1 provisions. Initial Type Testing (ITT) in the factory ensures compliance for new products.

For reclaimed slabs, factory test certificates are missing, but actual strength can be verified directly by coring and compressig strength testing (EN13791), supplemented by non destructive testing (NDT) such as rebound hammer or ultrasonic pulse velocity calibrated against cores. This allows a realistic assessment of existing compressive strength, though it often reveals lower classes in older strong (C12/15-C20/25). Thus, the requirements are verifiable, but many reclaimed elements fall short of the minimum demanded for CE marking.

Reinforcement Layout and Cover

EN13747 requires that reinforcement complies with the detailing provisions of Eurocode 2, including minimum reinforcement ratios, anchorage lengths, lap splices, stirrup spacing, and crack control. Cover to reinforcement must satisfy both bond requirements and the minimum durability cover ($c_{min,dur}$) defined in Eurocode 2, Table 4.4N, depending on the exposure class.

In reclaimed slabs, reinforcement can be partially verified: cover meters and ground penetrating rader (GPR) can detect par positions and cover thickness. However anchorage lengths, bar diameters and sher reinforcement arrangement may not be conform to modern detailing rules. Many elements built before the 1980s have cover depths of only 20-25 mm, below today's minimum 30-50 mm requirements for most exposures. This makes partial verification possible but highlight systematic gaps.

Duarability and Exposure requirements

Durability requirements are tied to exposure classes in Eurocode 2. For each class, the code prescribes minimum cover, maximum water/cement ration and minimum cement content. New precast elements are designed and documented accordingly under EN 206 production rules.

For reclaimed slabs, only partial verification is possible. Cover depth can be measured and compared to current requirements. Carbonation depth (phenolphthalein tet) and chloride content (lab analysis) can be checked. But the original mix composition (cement, w/c ration) cannot be reconstructed reliably. This means compliance with EN 206 exposure class requirements cannot be fully demonstrated - only inferred through in-situ testing and conservative assumptions.

Structural performance (ULS and SLS) EN 13747 requires that precast slabs achieve sufficient structural performance under both ultimate limit states (ULS)—including flexural resistance, shear, punching shear, and torsion where relevant—and serviceability limit states (SLS), which include crack width control, deflection, and vibration performance. Compliance is normally demonstrated through design calculations and initial type testing (ITT) of prototype elements.

For reclaimed slabs, this verification can, in principle, be carried out once the material properties (f_{ck}) and reinforcement characteristics are established through inspection and testing. In this context, the reinforcement layout and cover are not treated as a separate verification parameter but serve as essential input for recalculating the structural capacity. These geometric and material data directly inform the ULS and SLS checks performed according to Eurocode 2. Where uncertainties remain, load testing—as adopted for instance in Norway's NS 3682 standard for reused hollow-core slabs—can provide direct confirmation of performance. Serviceability aspects such as crack width and deflection can further be assessed through visual inspection and monitored loading. This integrated approach makes structural verification technically feasible, although it remains more resource-intensive than the standardized factory-based CE procedures.

Fire Resistance and Acoustic Performance

For fire, EN 13747 require slabs to demonstrate resistance classes such as R30, R60 and R90 depneding on intended application. Verification is typically done through calclation (Eurocode 2-1-2 Annex B) based on cover thickness and section geometry, or by fire testing. Acoustic performance (airborne and impact sound insulation) is covered by EN 13747 cross-referecen to EN ISO 717 standard, and is usually demonstrated by design thicnkess mass per unit area and laberatory tests.

Reclaimed slabs can be assessed for fire by measuring cover depth and cross-section dimensions and apply the Eurocode 2-1-2 calculation models. However, many older slabs have insufficient cover for higher fire ratings. Acoustic compliance is difficult to prove, since older slabs were not designed to meet current insulation criteria. Adaptation is often necessary e.g. adding acoustic mats, screeds aor fire protection layers.

4.3. Examples of project-based or element-specific approvals

Building on the verification parameters discussed in the previous section, several initiatives have explored how reclaimed concrete elements can be formally tested, documented, and approved within real projects. These project-based or element-specific frameworks represent early efforts to translate verification principles into practice and to demonstrate that reuse can meet structural and safety requirements outside the conventional CE-marking route. Although progress has been made, their application remains limited to pilot projects, research settings, or national standards. Common challenges include the absence of harmonized European procedures, uncertainty about structural reliability, and a lack of institutional recognition of reclaimed elements as equivalent to new products. Table 4.4 summarises the most prominent examples, ranging from the BTU Cottbus memorandum to Norway's NS 3682:2022 and the EPFL framework, highlighting both advances in technical verification and the remaining barriers to large-scale adoption.

Table 4.4: Overview of verification frameworks for reclaimed concrete elements

Framework	**Key Characteristics**	**Source**
BTU Cottbus Memorandum (Germany)	Early memorandum defining procedures for verifying reclaimed concrete elements. Focus on geometry, destructive and non-destructive strength testing, and quality assurance. Highlighted the need for standardized methods and certification pathways.	(Cottbus, 2012)
NS 3682:2022 (Norway)	National standard for reuse of construction products, including concrete. Sets documentation, quality control, and classification requirements before market re-entry.	("NS 3682:2022", 2022)
Draft Guideline for Hollow-Core Slabs (Denmark)	Draft guideline for verifying and reusing hollow-core slabs. Details geometry checks, reinforcement mapping, and structural testing. Still in draft stage but influential in Scandinavia.	(Transport & Authority, 2021)
EPFL Framework (Switzerland)	Research-based framework for assessing reliability of reclaimed elements. Combines probabilistic modelling, testing, and safety factor adjustments for design integration.	(Devènes et al., 2024; Fivet & Brütting, 2020)

4.3.1. The BTU Cottbus Memorandum (Germany)

The BTU Cottbus memorandum (Cottbus, 2012) represents one of the first systematic efforts to define how reclaimed precast concrete elements could be verified for reuse. Published in 2012, it established a step-by-step process for confirming that elements harvested from donor buildings, such as slabs, meet safety, strength, and durability requirements for integration into new structures. The framework combined geometric measurement, destructive and non-destructive strength testing, reinforcement mapping, and durability assessment (e.g., carbonation and chloride testing). This comprehensive approach demonstrated that reclaimed elements could be verified with similar rigor as new products, setting a technical benchmark for reuse verification.

A key contribution of the memorandum is its holistic treatment of verification, covering geometry, material quality, reinforcement, and long-term durability within a single methodology. It also anticipated later developments such as digital documentation, material passports, and standardized quality classification, concepts that underpin current circular construction practices. By proving that systematic testing could ensure reliability, it provided an early conceptual foundation for later frameworks such as NS 3682:2022 and the EPFL approach.

However, the memorandum's procedures were highly resource-intensive, relying on extensive laboratory testing and detailed inspections that limited practical scalability. It lacked regulatory recognition within German codes or Eurocodes, leaving its outcomes without formal approval status. Furthermore, it did not address how verified elements should be reintegrated into structural design or how to adapt safety factors for material variability. The absence of economic and logistical considerations also restricted its applicability beyond pilot projects.

In summary, the BTU Cottbus memorandum marked an important conceptual milestone by demonstrating that technical verification of reclaimed concrete is feasible. Yet its lack of regulatory alignment, design integration, and practical efficiency prevented it from becoming an operational framework for large-scale application.

4.3.2. NS 3682:2022 (Norway)

The publication of NS 3682:2022 by Standards Norway marked a significant step toward mainstreaming reuse by embedding it within a national regulatory framework ("NS 3682:2022", 2022). Unlike earlier research-based initiatives, this standard provides binding guidance on the reuse of construction products, including precast concrete elements. Its broad scope covers documentation, classification, and quality assurance requirements, reflecting the recognition that reuse depends as much on institutional structures as on technical innovation.

Central to NS 3682 is systematic documentation and traceability. Reclaimed materials must be accompanied by records of origin, previous use, and condition, ensuring transparency from deconstruction to reapplication. The standard also sets minimum requirements for demonstrating structural integrity and durability, but it leaves the choice of specific test methods to professional judgement. This principle-based approach offers flexibility while establishing a clear baseline of reliability.

The main contribution of NS 3682 lies in its regulatory legitimacy and integrative scope. As a national standard, it gives formal recognition to reuse and provides a framework that practitioners can reference with confidence. By defining general principles rather than product-specific rules, it creates a foundation for the development of sector-based verification methods and has helped lower the perceived risk associated with reuse in Norway.

However, the framework's high-level nature also limits its practical impact. The absence of standardized procedures for assessing strength, reinforcement, or durability means that engineers must rely on project-specific or research-derived methods, leading to potential inconsistencies and higher costs. Moreover, while NS 3682 legitimizes reuse nationally, its influence remains geographically restricted and does not yet contribute to European harmonization.

In summary, NS 3682 represents a crucial institutional advance that bridges the gap between research and regulation. It establishes the regulatory groundwork for reuse but highlights the continuing need for detailed, technically prescriptive frameworks that can ensure consistency and scalability across the construction industry.

4.3.3. Draft Guideline for Hollow-Core Slabs (Denmark)

In Denmark, the increasing focus on circular construction has led to the development of a draft guideline dedicated to the reuse of hollow-core floor slabs (Transport & Authority, 2021). Unlike broad frameworks such as NS 3682, this initiative concentrates on a single product type, reflecting the prevalence of hollow-core slabs in Danish construction and their potential as a scalable entry point for structural reuse. Developed collaboratively by research institutions, industry, and government, the guideline aims to translate academic knowledge into practical verification procedures for engineers and contractors.

The draft outlines clear methods for verifying geometry, mapping prestressed reinforcement, and assessing structural integrity through a combination of non-destructive and selective destructive testing. Durability checks focus on surface damage, cracking, and chemical deterioration, while a staged approval process ensures that only elements passing successive inspections are cleared for reuse. This sequential structure provides a transparent and practicable framework for technical verification.

The strength of the Danish draft lies in its clarity and product-specific focus. By tailoring verification procedures to a standardized element, it offers an accessible and implementable pathway for contractors, avoiding the generality of broader standards. Its close alignment with industry practice and collaboration with stakeholders increase its relevance and scalability within the regional market.

However, its narrow scope also limits its impact. The guideline applies only to hollow-core slabs, leaving other concrete elements outside its remit, and it remains a draft without formal regulatory status. As such, its use is largely confined to pilot projects and voluntary adoption. Furthermore, while it defines verification procedures in detail, it offers little guidance on integrating reclaimed slabs into structural design calculations or addressing economic and logistical feasibility.

Overall, the Danish draft represents a pragmatic step toward operationalizing reuse verification. It demonstrates the value of detailed, product-specific guidance in building industry confidence, but its limited scope and provisional status highlight the need for complementary frameworks that combine technical precision with regulatory legitimacy and wider applicability.

4.3.4. The EPFL Assessment and Verification Strategy (Switzerland)

A research-driven verification approach has been developed at the École Polytechnique Fédérale de Lausanne (EPFL), where scholars introduced a probabilistic framework for assessing the structural reliability of reclaimed concrete elements (Fivet & Brütting, 2020). Unlike national standards or product-specific guidelines, this framework seeks to bridge empirical testing and structural design by quantifying the uncertainties inherent in reuse. Its goal is not merely to confirm compliance with fixed thresholds but to translate measured variability into design parameters usable within Eurocode-based calculations.

The EPFL framework applies probabilistic modelling to integrate destructive and non-destructive test data into statistical distributions of material properties such as compressive strength and reinforcement layout. These are then used in reliability analyses to calculate a probability of failure, allowing reclaimed elements to be evaluated against target safety indices for new structures. This enables verification to move beyond a binary pass–fail approach and places reuse on an equivalent reliability basis with conventional design practice.

Building on this foundation, EPFL researchers later developed the *Reusability Assessment* (Devènes et al., 2024), which translates the probabilistic theory into a staged decision-making tool. It defines inspection, testing, and classification steps that determine whether elements can be reused in structural applications, downgraded, or rejected. By linking the level of verification effort to the intended reuse pathway, it offers a practical method for balancing reliability, cost, and feasibility.

The strength of the EPFL approach lies in combining scientific rigor with operational logic. It systematically addresses uncertainty while providing structured procedures that engineers can apply in practice. However, both the probabilistic model and the Reusability Assessment remain research-based: they require advanced statistical expertise, extensive testing data, and currently lack formal recognition in European standards. Economic and logistical factors are also underexplored, limiting large-scale implementation.

In summary, the EPFL initiatives provide a rigorous and forward-looking contribution to reuse verification. They demonstrate how uncertainty can be quantified and how reclaimed elements can be matched to suitable applications. Yet their adoption at scale will depend on simplifying methods, embedding them within regulatory systems, and integrating economic and practical considerations into the broader European verification landscape.

4.4. Knowledge Gap

Despite the progress achieved by recent initiatives, a unified European framework for verifying reclaimed concrete elements has yet to emerge. The BTU Cottbus memorandum demonstrated that technical verification is possible, but its procedures were too resource-intensive and lacked regulatory alignment to gain practical traction. NS 3682:2022 brought reuse into a formal regulatory context, yet its general scope and limited technical detail constrain its applicability beyond Norway. The Danish draft showed how product-specific guidance can make reuse operationally viable, but its narrow focus and provisional status restrict its broader influence. Meanwhile, the EPFL probabilistic framework and subsequent Reusability Assessment introduced methodological rigor and structured decision-making, but remain confined to research and have not been institutionalized within building codes.

Together, these examples reveal persistent fragmentation between technical reliability, regulatory legitimacy, and practical scalability. In contrast, frameworks for new materials, such as those established through European and national standards like NEN, are harmonized, codified across countries, and fully embedded in design and quality assurance systems. The resulting knowledge gap lies in creating a verification framework for reclaimed concrete that offers the same degree of trust, consistency, and formal recognition as those governing new products.

Such a framework must integrate the methodological depth of the BTU and EPFL models, the institutional authority of NS 3682, and the applied clarity of the Danish draft. By embedding verification procedures within existing European design and certification systems, it can bridge the current divide between research, regulation, and practice, transforming reuse from experimental application into a standardized, scalable component of structural design.

STEP II

Learn from Experience

5 Learn from experience

This chapter builds on the literature review by examining how the barriers and opportunities identified in theory manifest in real projects. It presents four large-scale case studies of concrete element reuse, Udden, Prinsenhof A, SUPERLOCAL, and Stationsplein 107, complemented by one prototype project, FLO:RE, which explores experimental verification methods. Together, these cases provide empirical evidence of how technical and organizational challenges observed in literature play out in practice, and how projects have sought to address them through alternative design, procurement, and verification strategies.

The analysis focuses on two dimensions. The first concerns the *technical* performance of reuse, including structural verification, design adaptation, and material assessment. The second addresses the *process* dimension, how collaboration, regulation, procurement, and logistics influence feasibility. By comparing both aspects, the chapter links the operational realities of projects to the theoretical barriers discussed earlier, showing where practice confirms, contradicts, or extends the literature.

In addition to project documentation, a series of expert interviews was conducted with engineers, demolition specialists, policymakers, and researchers. Their insights complement the case data, providing a broader perspective on industry practice and emerging standards. This combination of project-based and external perspectives allows the analysis to distinguish between project-specific solutions and structural conditions that affect reuse more generally.

The synthesis follows a multiple-case study approach based on Yin (2018) and Eisenhardt (1989). Each project was first analyzed individually (*within-case analysis*), then coded to identify recurring practices and challenges, and finally compared across cases (*cross-case analysis*) to detect patterns.

By tracing how theoretical barriers appear and are managed in real projects, the chapter connects literature and practice. The findings provide a grounded understanding of how reuse initiatives interpret, adapt, and occasionally overcome the systemic constraints identified in research, thereby offering concrete lessons for scaling structural reuse within the construction industry.

5.1. The individual case studies

5.1.1. The Udden Project - Sweden (1996)

In the early 1990's Sweden faced a change in demographics, where people started to migrate from industrial towns and smaller communities to the larger cities and suburbs associated with universities. In many towns this led to empty buildings, while in the larger cities there was a housing shortage. The same occurred in the town of Finspång and city of Linköping. The architect Grunnar Sundbaum was aware of this trend and rather than proposing a completely new-build project he suggested a novel solution.

His proposal became known as *The Udden Project*, initiated in 1996. It involved the deconstruction of two multifamily apartments in Finspång and the reuse of their structural and interior components to construct 22 student buildings in Linköping. The project is the first known attempt to integrate cast-in-place concrete into a new construction (Alén, Eklund, et al., 1999).

Because of the sudden change in housing needs the donor building was only 30 years prior to its demolition, this resulted in relatively high quality donor materials. The process began with the selective extraction of cast-in-place concrete walls and beams using diamond saws. This method enabled the recovery of large, intact elements suitable for reuse. The components were pre-selected based on their dimensions and structural condition, and were marked for specific locations in the new building. In total, 73 concrete wall elements, 41 beams, and 30 m^2 of foundation slabs were salvaged, alongside a variety of non-structural components such as doors, windows, radiators, and kitchen fixtures (Alén, Eklund, et al., 1999; Alenius, 2022).

Although the material source was off-site, the project was executed with the logistical efficiency typically associated with on-site reuse. The salvaged elements were transported approximately 64 kilometers to the new construction site in Linköping. To avoid the need for intermediate storage, which would have increased costs and risked damage, the logistics were tightly coordinated: elements were loaded directly onto trucks at the deconstruction site and lifted into place at the construction site upon arrival. This just-in-time delivery model required precise synchronization between the deconstruction and construction teams and effectively mirrored the workflow of on-site reuse, despite the geographic separation.

Once on site, the reused elements were integrated into a new structural system designed to accommodate their properties. To meet modern building codes, several adaptations were necessary. Additional concrete layers were cast onto reused beams to enhance load-bearing capacity and acoustic performance. Interior surfaces were upgraded with insulation and gypsum board to meet thermal and sound insulation standards. Some reused beams underwent load testing to verify their structural integrity, and where uncertainties remained, over-dimensioning and additional steel supports were employed to ensure compliance with safety standards. These interventions illustrate a pragmatic approach to reuse, balancing the benefits of material conservation with the demands of contemporary performance criteria (Addis, 2006; Alén, Eklund, et al., 1999).

From an environmental perspective, the project demonstrated significant benefits. A life cycle assessment conducted by Roth and Eklund, 2000 showed that the reuse of concrete elements resulted in a 50% reduction in CO_2 emissions and a 40% reduction in energy use compared to conventional construction. However, the environmental gains were sensitive to transport distances; if materials had been transported more than 140 km, nitrogen oxide emissions would have exceeded those of a conventional build. Financially, the project incurred a 10–15% cost premium, primarily due to increased labor and planning demands. These costs were partially offset by governmental grants, although these were not secured until after the project had commenced, highlighting the need for more predictable funding mechanisms for reuse initiatives.

5.1.1.1. The technical success factors and limitations

- **Design flexibility and early material assessment:** The project team adapted the building design to the available materials, rather than forcing reused elements into a fixed design. This flexibility, combined with early-stage material assessment, is essential for integrating reused structural components effectively. Later projects such as *Nya Udden* confirmed that modularity and adaptability in design strongly improve the feasibility of reuse.
- **High quality donor materials:** The donor materials were only 30 years old, which supported the just-in-time logistics strategy as the verification of these elements could be limited. It could be assumed that the materials were still in great condition and could at least hold the loads they were previously designed for. However, descendant projects showed that where donor materials were older or in poorer condition, additional testing, over-dimensioning, and strengthening interventions became unavoidable.
- **Regulatory compatibility gap:** Even though reuse was possible, reused elements rarely met all contemporary requirements without adaptation. In Udden, acoustic and insulation layers were added, while later projects found further challenges with fire safety and thermal performance. These cases highlight that future frameworks must include a clear procedure for addressing mismatches between historic materials and current regulatory standards.
- **Transport distance sensitivity:** Environmental benefits from reuse quickly diminish with longer transport distances, as seen in Udden. Later Swedish cases confirmed that a sourcing radius of approximately 100–150 km is a practical threshold for maintaining carbon advantages.
- **Storage and handling risks:** The just-in-time strategy minimized damage risk, but descendant projects that required storage observed significant losses due to cracking and poor handling. This underlines the importance of careful logistics planning and the potential role of specialized reuse intermediaries to manage storage and quality control.

5.1.1.2. The process success factors and limitations

- **Integrated project ownership and coordination:** The success of Udden was largely due to the alignment of interests between the deconstruction and construction teams, facilitated by a single project manager and a financially stable client. In contrast, descendant projects with fragmented contracts experienced misaligned incentives, careless handling, and additional costs, underlining the need for integrated procurement models or shared-risk arrangements in future reuse projects.

- **Just-in-time reuse logistics:** By coordinating transport and installation without intermediate storage, the project minimized handling damage and storage costs. This model demonstrates that off-site reuse can be operationally efficient if planned with on-site construction logics. Later projects confirmed, however, that this requires extremely precise sequencing and that delays in demolition or construction schedules can have severe cascading effects.
- **Learning and scaling effects:** As a first-of-its-kind project, Udden carried a significant innovation premium in both costs and coordination effort. Subsequent projects in Sweden reported that accumulated knowledge reduced uncertainties and improved efficiency, suggesting that reuse benefits are partly dependent on building institutional experience.
- **Policy and subsidy timing:** In Udden, governmental support was confirmed only after the project had started, exposing the client to financial risk. Descendant projects reported similar issues, showing that predictable and stable funding mechanisms are essential for mainstreaming reuse.
- **Knowledge integration and skill requirements:** Udden demanded careful craftsmanship on-site to fit reused components, which increased labor intensity. Later cases highlighted the importance of training site workers and strengthening information flows, for example through labeling systems, BIM integration, and digital inventories.

Taken together, the Udden project and its descendants offer valuable lessons for the development of verification and process frameworks for concrete reuse. They illustrate both the technical possibilities of structural reuse and the systemic barriers that must be addressed. The main takeaways include the necessity of design flexibility, early and reliable assessment of donor materials, the risks of damage and regulatory incompatibility, and the importance of integrated project ownership combined with predictable policy support. These insights form a critical empirical basis for developing more integrated frameworks that balance technical feasibility, logistical efficiency, and governance structures for the reuse of structural concrete elements.

5.1.2. The Prinsenhof A - Arnhem (2019-present)

The Prinsenhof A office building, located in the city centre of Arnhem, was originally constructed in 1984 and served as one of the administrative buildings for the Province of Gelderland. Following the inauguration of a new provincial office building, Prinsenhof A became redundant. Although the initial plan was to demolish the building using conventional methods, the province recognized its exemplary role in promoting sustainability and opted for a more environmentally responsible approach through selective deconstruction (Provincie Gelderland, 2025).

At the time of deconstruction in 2019, the building was only 35 years old. However, renovation was deemed unfeasible due to the difficulty of integrating modern sustainable technologies and the building's incompatibility with the evolving urban context. Consequently, the Province chose to engage the building in the ReCreate project, which aims to facilitate the reuse of precast concrete elements from existing structures.

Prinsenhof A featured an L-shaped floor plan comprising three main components: Wing A (nine floors), Wing B (five floors), and a central core (ten floors). The building was particularly well-suited for deconstruction due to its relatively simple and repetitive structural system. The primary structural components included load-bearing sandwich façade elements, prestressed hollow core floor slabs, and precast concrete core walls. Structural stability was provided by the central concrete core and two bracing façade walls located at the ends of the wings.

The deconstruction process was executed in three phases, beginning with Wing B, followed by the top floor of the core, and concluding with Wing A and the remaining core structure. A total of 549 hollow core slabs, 343 façade elements, and 133 core and wall elements were harvested (Vullings, Wijte, et al., 2024). A significant advantage in this case was the fact that most of the building consisted of precast elements. Prefabrication inherently facilitates deconstruction, as these elements are typically designed for modular assembly and can be dismantled with minimal intervention. In this case, only limited sawing was required to separate the components, which reduced both labor intensity and the risk of damaging the elements.

Despite the relative ease of disassembly, the demolition contractor developed a tailored strategy specifically for the removal of the prestressed hollow core floor slabs. It is essential to consider the structural characteristics of such elements during deconstruction, particularly when they are intended for reuse. Hollow core slabs are engineered to resist loads primarily in one direction, and any deviation from this loading orientation during handling or lifting could compromise their structural integrity. Therefore, the deconstruction process had to ensure that the forces applied to the elements remained within their original design capacity to preserve their reusability.

Figure 5.1: Deconstruction steps for the hollow core slab elements

- **Step 1:** The preparation stage, in which two holes were drilled into each slab along one longitudinal edge to facilitate lifting. Chains were threaded through these holes and looped back to create secure lifting points. This method ensured that the slabs were lifted in a manner consistent with their original load-bearing orientation, thereby preserving their structural integrity.
- **Step 2:** Cutting the connections. The slabs were separated from the surrounding structure using diamond saws. Two transverse cuts were made at the ends of each slab to disconnect them from the façade, and two longitudinal cuts were made between adjacent slabs. Notably, the longitudinal cuts were intentionally left approximately 2 cm short of full depth. This approach reduced wear on the saw blades and preserved the integrity of the slab edges.
- **Step 3:** Breaking the connections. To complete the separation, hydraulic jacks were employed to apply an upward force at one end of the slab. This force was sufficient to break the remaining uncut portion of the joint, allowing the slab to detach cleanly along its original seam. This method not only minimized damage but also ensured that the bottom edges of the slabs remained intact, an important consideration for reuse.
- **Step 4:** Lifting. Once fully detached, each slab was lifted using a crane. The lifting chains, already threaded through the pre-drilled holes, were connected to the crane's rigging system. Care was taken to ensure that the slabs were lifted evenly and without torsion, maintaining their structural integrity. After lifting, the slabs were lowered to the ground, where they were cleaned of residual concrete, tagged with unique identifiers and QR codes for traceability, and transported to a storage facility for future reuse.

Part of the elements have already been used to build a new sports hall in Arnhem-Zuid. The remaining elements are currently stored at a facility in Heerde and will be reused in a new building project, the Circular Centre in Heerde (Provincie Gelderland, 2025).

5.1.2.1. The technical success factors and limitations

- **Standardization of floor system harvesting:** The demolition company Lagemaat applied a standardized approach to removing the hollow core slabs, refined through earlier projects. This method combined drilling of lifting points, partial-depth sawing, and hydraulic jacking before crane lifting. By following a repeatable sequence, the process became faster, safer, and less prone to damaging the prestressed elements.
- **Element-specific handling requirements:** Prestressed hollow core slabs are engineered to carry loads in a single direction, making their handling orientation critical. The tailored lifting

strategy ensured that forces remained consistent with the original load-bearing design, preserving structural integrity and usability of the slabs.

- **Comprehensive deconstruction planning:** A carefully staged demolition sequence was designed to minimize instability and damage. By retaining the concrete core until the final phase, overall building stability was maintained, which safeguarded both workers and the integrity of the elements being harvested.
- **Availability of original documentation:** Almost all of the original design drawings and calculations were available. This gave engineers detailed insight into reinforcement layouts, connection details, and expected capacities, reducing uncertainty and streamlining both deconstruction and future reuse design.
- **Traceability and quality assurance:** Each element was labeled with unique identifiers and QR codes, enabling systematic tracking during storage and reuse. This provided transparency, supported quality assurance, and serves as a model for standardized documentation in future reuse projects.
- **Storage and handling limitations:** Unlike projects where just-in-time reuse was possible, Prinsenhof A required intermediate storage for a large number of elements. “Proper storage is crucial, hollow-core slabs, for instance, are sensitive to torsion, so they must be stored in a way that prevents deformation.” (A. van de Beek, appendix B, 2025). The storage thus introduced additional handling steps and risks of deterioration. It highlights the importance of dedicated storage facilities, protective handling methods, and monitoring protocols to maintain quality until reuse.

Prinsenhof A showed the advantages and challenges of working with precast modular elements at larger scale. The project introduced traceability systems, handling protocols, and institutional learning processes that have since become benchmarks in reuse practice. These insights, alongside those from earlier projects, feed directly into the development of more integrated frameworks that balance verification, logistics, and governance for structural concrete reuse.

5.1.2.2. The process success factors and limitations

- **Role of the main contractor:** “Involving contractors in circular projects can be challenging. Many operate within a linear construction model and are hesitant to take on the risks associated with reused materials, especially given the lack of standardized quality certifications.” (A. van de Beek, Appendix B, 2025). To address this, Lagemaat often assumed the role of main contractor, enabling them to redistribute risks more effectively and maintain flexibility in collaboration.
- **Systematic deconstruction planning:** The phased removal of the wings and central core required close coordination between engineers and demolition teams. This process confirmed the importance of developing clear deconstruction strategies that balance safety, efficiency, and reuse potential.
- **Importance of documentation:** Access to original drawings and calculations not only supported technical decisions but also streamlined the collaboration between design and site teams. Thorough documentation of harvested elements, including QR-based labeling, provided continuity throughout the reuse chain.
- **Training and collaboration:** Specialized handling of prestressed slabs and large precast elements required new skills on-site. The project highlighted the importance of training deconstruction workers in reuse-specific techniques and fostering collaboration between structural engineers and site crews.
- **Post-project evaluation and learning:** Structured evaluation of the process and outcomes provided feedback loops that improved future deconstruction practices (Vullings, Huuhka, et al., 2024). Embedding such evaluation in circular projects helps to build institutional knowledge and reduce uncertainties over time.
- **Policy and client leadership:** The Province of Gelderland actively steered the project towards selective deconstruction, demonstrating how strong public-sector leadership can accelerate circular practices and create momentum for scaling reuse approaches.

- **Scaling potential and limitations:** The large number of harvested elements showed that reuse at scale is possible with precast structures. However, it also exposed new layers of logistical complexity related to transport, storage, and long-term material management that must be addressed in future frameworks.

5.1.3. SUPERLOCAL - Kerkrade (2012-2019)

The SUPERLOCAL project (Super Circular Estate) in Kerkrade, represents one of the most ambitious European experiments in circular neighborhood development. The expermental nature of this project stems from the vision "“SuperLocal was never about proving that reuse is easy , it was about showing that it is possible.”, (Gemeente Kerkrade, Appendix G, 2025). Initiated in response to regional demographic decline and the obsolescence of post-war housing stock, the project sought to transform the demolition of three outdated high-rise apartment buildings into an opportunity for large-scale material reuse and social innovation. The housing association HEEMwonen acted as lead partner, in collaboration with the municipality of Kerkrade, several construction and demolition firms, and academic institutions such as ZUYD University. Financial support was provided through the EU’s Urban Innovative Actions (UIA) program (HEEMwonen and Municipality of Kerkrade, 2017; HEEMwonen and Partners, 2021).

The motivation for SUPERLOCAL stemmed from two intertwined challenges: population shrinkage and sustainability. Parkstad Limburg, once a mining region, has faced persistent outmigration and a surplus of outdated housing stock, leading to entire apartment blocks standing vacant. Conventional demolition would have resulted in the disposal of large amounts of building material, perpetuating linear construction practices. Instead, SUPERLOCAL established the ambition to redevelop the site according to circular principles: material loops would be closed, water systems would be decentralized, and social cohesion would be strengthened through participatory design (Municipality of Kerkrade, 2020; SHAPE Affordable Housing Platform, 2021).

Implementation proceeded in phases. One of the first symbolic actions was the selective deconstruction of one apartment block, in which entire apartment units were hoisted out to test their reuse potential. From 2017 onwards, demolition works were carried out by separating over thirty distinct material streams, ranging from concrete and steel to façade elements, with the goal of achieving reuse rates exceeding 90% in pilot dwellings. These materials were not only reintegrated into new housing but also into public spaces and infrastructure. In parallel, experimental dwellings were constructed almost entirely from reclaimed materials, including structural components, finishes, and installations (SUPERLOCAL Consortium, 2019; Verlaan et al., 2019). Social ambitions were equally prominent: former residents of the demolished flats were invited to return, and a neighborhood steering group was established to co-design public spaces, ensuring that physical circularity was matched by social continuity and inclusiveness (New European Bauhaus Prize, 2021).

The outcomes of SUPERLOCAL are multifaceted. From an environmental perspective, life-cycle assessments indicate significant reductions in embodied energy and carbon emissions. In one case, a dwelling constructed with approximately 65% reused materials demonstrated a clear reduction in both indicators compared to conventional construction (Verlaan et al., 2019). Economically, the project revealed the complexities of circular business models. Although many measures required higher upfront investment, a 70-year life-cycle analysis showed that the circular variant generated a financial advantage exceeding €160,000 in net present value when compared to a traditional approach. Moreover, residual values of reused components proved higher, and replacement costs lower, than their conventional counterparts. Nevertheless, the analysis also underscored that current real estate valuation and financing mechanisms insufficiently recognize residual value, avoided externalities, and social benefits, making subsidies essential to achieve viability (HEEMwonen and Partners, 2021).

Beyond technical and financial metrics, SUPERLOCAL has contributed to institutional learning. The project encountered barriers in regulatory compliance, procurement frameworks, and the absence of standardized data for reused materials. These challenges illustrate the broader structural issues that hinder scaling of circular construction: verification systems for reused components remain underdeveloped, legal frameworks are not adapted to reclaimed elements, and environmental databases lack reliable datasets for such applications. At the same time, SUPERLOCAL demonstrated the importance of strong governance, long-term monitoring, and resident engagement in circular area development

(HEEMwonen and Municipality of Kerkrade, 2017; SUPERLOCAL Consortium, 2019).

5.1.3.1. Technical success factors and limitations

- **Material heterogeneity:** reclaimed concrete and structural elements show significant variability in reinforcement layout, strength, and durability performance, requiring both destructive and non-destructive testing (Verlaan et al., 2019).
- **Limitations of current standards:** existing design codes provide little guidance on translating test outcomes into residual load-bearing capacity, creating uncertainty in acceptance criteria (HEEMwonen and Partners, 2021).
- **Testing methodology:** ground penetrating radar, cover meters, and core drilling proved essential in combination, underlining the need for standardized multi-method testing protocols (SUPERLOCAL Consortium, 2019).
- **Logistics influence quality:** storage and transport conditions were found to impact the integrity of reclaimed elements, highlighting the need for monitoring quality across the reuse chain (SUPERLOCAL Consortium, 2019).
- **Residual value calculation:** reliable residual value assessment depends on verifiable data on material lifespan and performance, necessitating standardized protocols for life-cycle and durability testing (HEEMwonen and Partners, 2021).

Process success factors and limitations

- **Early involvement of actors:** demolition contractors and verification experts must be integrated early in the design process, as their expertise directly shapes design feasibility (HEEMwonen and Municipality of Kerkrade, 2017).
- **Shared decision-making:** stakeholder meetings and neighborhood steering groups were effective in aligning technical decisions with broader project goals, ensuring social acceptance (New European Bauhaus Prize, 2021).
- **Terminology gaps:** the absence of standardized language for circular construction often caused confusion, showing the need for clear and shared definitions (HEEMwonen and Municipality of Kerkrade, 2017).
- **Procurement misalignment:** conventional procurement rules conflicted with the iterative and experimental nature of reuse, revealing a need for more flexible contractual frameworks (HEEMwonen and Partners, 2021).
- **Transparency and trust:** communication structures must enable open negotiation of risks, responsibilities, and verification outcomes, building confidence among stakeholders (New European Bauhaus Prize, 2021).
- **Subsidy requirement:** “Without subsidies or innovation funding, projects like this would not have been realized.” and next to that they mention a very important other aspect with the regards to the cost of the material “As long as new materials remain cheaper than reclaimed ones, large-scale reuse will be difficult to justify without subsidies.” (Gemeente Kerkrade, Appendix G, 2025)

In conclusion, SUPERLOCAL illustrates both the potential and the current limitations of circular neighborhood development. It proves that reuse of building materials at scale can generate environmental and financial value, while also revitalizing communities. However, it also highlights that systemic changes in regulation, financing, and valuation methods are required to move beyond pilot projects. As such, SUPERLOCAL functions as a niche experiment in the socio-technical transition towards circular construction, providing valuable lessons for replication in other European contexts.

5.1.4. Stationsplein 107 - Leiden (2024-present)

Stationsplein 107, locally known as the former tax office or belastingkathedraal, is situated in the Morspoort area, a site earmarked by the municipality for transformation into a dense residential neighborhood of around 500 dwellings. The redevelopment program combines social housing, private units, a social pension facility, an underground parking garage, and new public spaces, thereby positioning the demolition of the existing office building as the starting point of a wider urban renewal strategy (G. Leiden, 2025).

From the outset, the municipality emphasized the importance of carrying out the dismantling of Stationsplein 107 in a circular manner. Rather than pursuing conventional demolition, the project was framed as a harvesting operation in which materials would be recovered and prepared for reuse. A broad array of elements, ranging from windows, doors, and façade bricks to insulation, ceilings, sanitary fixtures, and electrical components, were systematically removed for later application in the new construction (Dusseldorp Infra, 2025). This selective approach reflects a growing ambition in Dutch practice to extend the lifespan of building components and reduce the demand for virgin resources.

What makes this project particularly notable is the decision to recover structural concrete floor slabs for reuse as load-bearing elements in the new buildings. These slabs were cut out of the structure, lifted, and stored, with the explicit aim of reincorporating them into the first new residential block (M1a) (G. Leiden, 2025; SloopCirculair, 2025). This constitutes a breakthrough in the Dutch context, as it moves beyond the recycling of crushed concrete and prefab elements, thereby achieving significant carbon savings while also testing the technical and logistical feasibility of such practices. The operation required careful planning, including temporary shoring of the structure to maintain stability while the slabs were removed (G. Leiden, 2025).

Alongside the ambition for material reuse, the project was also shaped by cultural heritage considerations. The building's rear façade contained a monumental glass-in-concrete artwork designed in 1965 by Jan Meine Jansen. Integrating this artwork into the new development proved both technically complex and financially demanding. Full removal and relocation was estimated at more than two million euros, due in part to asbestos in the joints and the structural integration of the piece. While some proposals suggested partial salvage, such as reusing only the glass panels, the eventual strategy became to cut the work into segments, store it safely, and reintegrate it into the new urban fabric at a later stage (Dusseldorp Infra, 2025). This process sparked debates among municipal authorities, cultural heritage organisations, and architects, revealing the tensions between cost efficiency, technical feasibility, and the preservation of cultural value in circular redevelopment projects (H. V. O. Leiden, 2025).

The phasing of the project added another layer of complexity. For a period, the building was temporarily used to house Ukrainian refugees, which required adjustments to the demolition schedule. Furthermore, the dismantling had to be coordinated with broader planning procedures for the Morspoort redevelopment, which are expected to extend over several years. The careful alignment of demolition, storage, and new construction phases exemplifies the logistical challenges inherent to circular strategies, particularly when large structural components are involved.

Despite these challenges, the project has already yielded innovative outcomes. The successful removal of the first slabs demonstrates the technical viability of reusing structural concrete elements, while the broad harvesting of materials highlights the potential scale of resource recovery when demolition is approached systematically (Dusseldorp Infra, 2025; SloopCirculair, 2025). Moreover, the intention to preserve and reincorporate the glass-in-concrete artwork illustrates how circular demolition can intersect with cultural heritage preservation, even if this raises difficult questions about costs and priorities.

The lessons drawn from Stationsplein 107 are based not only on published reports and project documentation but also on interviews with the actors directly involved, including the client, the contractor of the target buildings, demolition companies, demolition engineers, and material inventory advisors. These perspectives add depth to the case by revealing coordination challenges, uncertainties in verifying reclaimed slabs, and other matters that have not been published. Combining documentary evidence with stakeholder accounts thus provides a more comprehensive understanding of how circular ambitions were translated into practice and what barriers remain for scaling such approaches.

5.1.4.1. The technical success factors and limitations

- **Robust engineering expertise and testing capacity:** The involvement of IDDS and Witteveen+Bos provided strong analytical and practical capacity to assess the reclaimed slabs. Through a combination of non-destructive testing, selective coring and Eurocode-based recalculations, the team could verify the mechanical performance of the donor elements with acceptable confidence. As Dijk (Appendix F) noted, "*Reused concrete demands much more engineering capacity up front, you can't just assume code compliance; you have to prove it.*"

- **Appointing a harvest coordinator:** The assignment of a dedicated coordinator to oversee documentation, testing, and logistics proved crucial for maintaining traceability between donor and target projects. The harvest coordinator served as a link between demolition, engineering, and construction, ensuring consistent information flow and minimizing data loss between project stages. This role also supported the verification process by consolidating test data and photographs into a single record accessible to all partners.
- **Certification barrier and permits:** The lack of a standardized verification or certification framework continued to impede smooth permitting. As Bram Kroon (Appendix E) highlighted, "*A huge problem with reused elements is the fact that these elements cannot be certified yet. For the permit process this forms an obstacle.*" This forced the design team to rely on case-specific approvals and additional documentation, increasing lead time and administrative workload.
- **Learning-by-doing:** Despite the absence of formal procedures, the project succeeded in advancing technical understanding through experimentation. According to Kroon, "*Every reused project is a prototype, you learn the most from doing it once.*" The iterative testing and adjustment of slab layouts and connections generated valuable insights that informed later reuse projects.
- **High engineering workload:** The verification and adaptation of reclaimed elements required substantial engineering input early in the process. As Dijk emphasized, the level of pre-design analysis far exceeded conventional practice, demanding additional design iterations and coordination time. This increased workload was necessary to achieve reliability but constrained scalability under tight project timelines.

5.1.4.2. The process success factors and limitations

- **Ambition and intrinsic motivation:** The municipality of Leiden and all involved partners shared a strong intrinsic motivation to realise one of the first large-scale circular pilot projects in the region. As the client representatives expressed, "*Leiden wants to be a testing ground for circular construction, but we need practical examples that show it can work within our own projects.*" (Appendix D). This ambition legitimised experimentation and helped sustain the team's commitment despite delays and uncertainties.
- **Late involvement of key actors:** The contractor joined after the design had already been largely finalised, limiting the potential to optimise the structural and logistical approach to reuse. Kroon recalled that "*while a lot of plans were made from the outset, the contractor was involved too late, by the time the reuse strategy was finalised, the design was already locked.*" This late integration curtailed opportunities for design-for-reuse coordination.
- **Information-flow misalignment:** The project suffered from temporal gaps between the demolition and design stages. Designers required verified material data early, but as Outhuis (Appendix H) noted, "*Design and demolition processes were not synchronized: designers needed early information, while detailed data on salvaged materials only became available later.*" This misalignment resulted in iterative redesign and additional verification rounds.
- **Fragmented responsibilities and risk perception:** Liability for the reused elements remained unclear. Each actor, engineer, contractor, and client, attempted to limit exposure to potential failure, reinforcing a conservative attitude. As Dijk observed, the absence of predefined roles for reuse "*makes collaboration fragile; everyone tries to protect their own risk domain.*" Establishing clearer contractual responsibilities was identified as essential for future projects.
- **Tender and regulatory rigidity:** Although circular ambitions were embedded in the municipal vision, tender procedures still followed traditional cost-based criteria. The client acknowledged that "*Circular goals are often defined broadly, but translating them into tender criteria that contractors can actually deliver on remains difficult.*" (Appendix D). Consequently, the project relied on ad hoc flexibility rather than structural mechanisms to reward reuse performance.
- **Cultural and contractual risk aversion:** ERA Contour and Leiden Municipality highlighted that unfamiliarity and liability fears often outweigh sustainability ambitions. Without clear insurance pathways and shared-risk models, contractors default to conventional materials even when reuse is technically possible

Stationsplein 107 illustrates the growing maturity of reuse practices in the Netherlands. Three key insights stand out: (i) defining reuse functions at the start of deconstruction, (ii) appointing a harvest coordinator to connect supply and demand, and (iii) developing standardized technical protocols with embedded traceability. Together with lessons from Udden and Prinsenhof A, these findings provide direct input to the verification and process frameworks.

5.1.5. FLO:RE - Switzerland (2024)

The FLO:RE project was developed by the Structural Xploration Lab (SXL) at EPFL as an experimental prototype to demonstrate the structural reuse of reinforced concrete slab segments in combination with reclaimed steel profiles. Floors typically account for a major share of embodied carbon in buildings, and by reusing cut-out RC elements in bending rather than crushing them for downcycling, FLO:RE aims to drastically reduce environmental impact while maintaining structural performance (Küpfer et al., 2025; (SXL), 2024).

The prototype floor system, measuring 30 m^2, was constructed from sawn-out RC slabs recovered from cast-in-place donor buildings and paired with reused steel girders harvested from industrial structures. The concept relies on accommodating the imperfections and constraints of reused elements: slabs of fixed geometry, unknown reinforcement layouts, and previous loading histories. Instead of treating these as defects, the design adapted to them through hybridization and tolerance strategies.

Connections between concrete and steel were designed to be dry, bolted, and reversible. Threaded rods were prestressed through drilled holes in the slabs to connect them to the steel girders, while 2 cm gaps between slabs allowed for dimensional variation. These were subsequently filled with mortar, which could be removed during disassembly. The system was erected, tested under service loads, dismantled, reassembled, and dismantled again. Across these cycles, the elements showed no visible new damage, confirming the feasibility of reversible structural reuse (Küpfer et al., 2025; Structural Xploration Lab (SXL), 2023).

A life cycle assessment demonstrated the environmental potential of this approach. Depending on transport distances, the prototype achieved reductions of 80–94% in global warming potential compared to conventional RC floor systems. However, the assessment also showed that transport contributes disproportionately to total emissions, making reuse most effective at short sourcing distances (Küpfer et al., 2025).

5.1.5.1. The technical success factors and limitations

- **Maximizing structural reuse:** Unlike many reuse strategies that employ concrete elements only in compression, FLO:RE successfully reused RC slabs in bending, preserving both tensile reinforcement and compressive capacity.
- **Hybrid design strategy:** The combination of reused steel girders and RC segments allowed for structural flexibility and reduced demands on the reclaimed slabs, enabling broader applicability of reused elements.
- **Dry and reversible connections:** Bolted and prestressed rod connections enabled full disassembly and reassembly without damaging the components, showing that reuse can extend beyond a single cycle.
- **Tolerance accommodation:** Allowing gaps between slabs and filling them with mortar provided a practical way to deal with dimensional variability in reclaimed elements.
- **Material testing and validation:** Concrete strength, reinforcement layouts, and residual stresses of donor elements were tested prior to use, reducing uncertainty and supporting safe structural design.
- **Environmental impact:** The LCA confirmed major reductions in embodied carbon compared to new construction, but also highlighted the sensitivity of reuse benefits to transport distances.
- **Limitations in applicability:** The system's span and layout are constrained by the geometry of available slabs, while connection tolerances are tight, requiring precise execution. Furthermore, the need for drilling and mortar infill adds complexity that may not be suitable in all contexts.

5.2. Additional expert insights - Interviews

To complement the analysis of success factors and barriers identified in the case studies, a series of expert interviews were conducted with professionals both directly involved in the documented projects and others active in the wider field of circular construction and structural reuse. The interviews aimed to capture a broader professional perspective on the technical and organizational conditions that influence the feasibility of reusing concrete elements.

While many of the issues raised by the interviewees were already observed in the individual cases, the inclusion of additional experts serves to validate these findings beyond the boundaries of specific project contexts. Their reflections confirm that recurring challenges, such as fragmented communication, regulatory uncertainty, and the lack of standardized verification procedures, are not isolated incidents but systemic obstacles encountered across the industry. Likewise, their accounts provide insight into the emerging practices and institutional changes that could enable reuse at a larger scale.

This section therefore synthesizes the insights gained from these interviews to strengthen and contextualize the earlier case-based analysis, demonstrating how both project-embedded and external experts converge on similar conclusions regarding the key success factors and limitations shaping the transition toward structural concrete reuse.

5.2.1. Technical expert insights

1. **Reusability depends on quality assurance during handling and storage:** Multiple interviewees, mostly on the demolition side (e.g., Adex, Lagemaat, IDDS), emphasized that even well-harvested slabs can lose reusability due to inadequate interim storage or uncontrolled handling. Damage, torsion, or poor stacking can invalidate prior verification results. Hence, reuse frameworks must extend quality assurance beyond testing , into logistics, storage, and on-site practices
2. **Need for combined destructive and non-destructive testing protocols:** In addition to the engineering firm involved in the Stationsplein project TNO also mentioned that that a hybrid verification strategy is most reliable: using NDT for mapping and selective coring for calibration. This avoids excessive damage while ensuring representativeness of test data.
3. **Durability as the key uncertainty for reused slabs:** They also both recognized that durability is a key uncertainty, in other words the remaining lifespan of the elements. A new verification strategy to identify this is needed and with that reduce the risk that accompany the reuse of these elements.
4. **Suppliers as future certifiers:** Both Adex and IDDS indicated that material suppliers could act as intermediaries and certification hubs , testing, repairing, and re-marketing reclaimed slabs under a controlled quality label. This institutional role could close the current gap between demolition and reuse markets

5.2.2. Process/Organization expert insights

1. **Regulatory flexibility through project based certification:** TNO and Schiphols experts (Lunstroo, Vullings) that large clients can accelerate acceptance by working with authorities to pilot project-specific verification routes. These one-off approvals help establish precedents for formal standard.
2. **Early and sustained design-demolition alignment:** Across all interviews late involvement of designers was repeatedly cited as the main process bottleneck. Circularity goals must therefore be formalized before tendering, and demolition data must feed directly into concept design
3. **The reuse coordinator as missing actor:** Several experts independently called for a defined harvest/reuse coordinator responsible for cross-project alignment, communication, and documentation continuity , a role currently absent from most procurement frameworks.
4. **Policy and incentive alignment** Public clients (Schiphol, Leiden, Kerkrade) underlined that subsidies and procurement criteria remain decisive for circular projects. Stable long-term instruments , e.g., CO^2-linked budget bonuses , would help make reuse financially competitive and predictable.
5. **Knowledge standardization and open databases** In all interviews the experts highlighted the

need for a shared and open database of verfied test results and pilot project, to enable future project to benchmark reclaimed elements and more easily find solutions. This will reduce redundant testing and innovation costs.

5.3. Cross-Case Analysis of the Five Circular Reuse Projects

Building on the individual case descriptions, the cross-case analysis compares the five projects, Udden, Prinsenhof A, SUPERLOCAL, Stationsplein 107, and FLO:RE, to identify recurring mechanisms that extend beyond project-specific contexts. Following the multiple-case study logic outlined earlier (Eisenhardt, 1989; Yin, 2018), the analysis focuses on patterns that appear consistently across cases, revealing how technical and organisational factors collectively shape the feasibility of concrete reuse. In doing so, it connects the empirical findings back to the systemic barriers discussed in the literature review.

5.3.1. Coding and Theme Development

The coding process served to identify the cross-cutting mechanisms that recur across projects and expert interviews. While the methodological steps were outlined in the introduction to this chapter, this section explains how the coding outcomes were structured into analytical themes that underpin the cross-case synthesis.

To move from case-specific insights to generalised findings, a two-step coding procedure was applied. In the first step, descriptive *first-order codes* were assigned to excerpts from project reports, technical documentation, and interview transcripts. These codes captured concrete observations such as verification methods, collaboration routines, or regulatory challenges. In the second step, related first-order codes were aggregated into higher-level *axial categories* that represent broader, recurring dynamics. For example, issues concerning material testing, incomplete data, and structural reliability were grouped under “verification under uncertainty,” while challenges of coordination and information transfer were consolidated as “governance of fragmentation.”

Themes were retained for the cross-case analysis only when they appeared in at least four out of five projects for the technical dimension and in at least three for the process dimension (since FLO:RE did not include process-level data), or when repeatedly confirmed by external experts. This ensured that the synthesis focused on structural mechanisms that transcend individual contexts rather than isolated project outcomes.

The results of this process are summarised in Table 5.1, which shows the frequency of each theme across the five cases and expert interviews. These eight themes are organised into two overarching categories: *technical themes*, relating to the verification framework, and *process themes*, corresponding to the communication framework. Together, they form the analytical structure for interpreting how technical and organisational mechanisms jointly determine the feasibility of concrete element reuse.

Theme	U	SL	PA	S107	F	EI	Σ
Technical themes (verification framework)							
T1 Verification under uncertainty	✓	✓	✓	✓	✓	✓	6
T2 Durability and fire performance limitations	✓	✓		✓	✓	✓	5
T3 Adaptation and strengthening strategies	✓	✓	✓		✓	✓	5
T4 Logistical integrity and storage conditions	✓	✓	✓	✓		✓	5
Process themes (communication framework)							
P1 Governance of fragmentation		✓	✓	✓		✓	4
P2 Procurement flexibility and risk allocation	✓	✓		✓		✓	4
P3 Regulatory and certification alignment	✓	✓	✓	✓		✓	5
P4 Knowledge transfer and learning-by-doing culture	✓	✓	✓	✓		✓	5

Table 5.1: Abbreviations: U = Udden, SL = SUPERLOCAL, PA = Prinsenhof A, S107 = Stationsplein 107, F = FLO:RE, EI = Expert Interviews

Table 5.1 provides an overview of how the identified themes recur across the five projects and expert interviews. The subsequent sections elaborate on these themes in detail, beginning with the technical dimensions that relate to verification challenges, followed by the process dimensions that concern governance, communication, and collaboration structures.

Technical themes

1. **T1 Verification under uncertainty**
   This theme captures the challenge of verifying reclaimed concrete slabs when documentation, material data, or reinforcement layouts are incomplete. Across cases and interviews, engineers emphasized the need to make structural decisions under partial information and to balance safety with feasibility. Verification under uncertainty therefore concerns how practitioners establish confidence in the performance of reused elements through testing, modelling, and engineering judgement. *Examples of first-order codes:* “hybrid destructive and non-destructive testing,” “limited access to original design drawings,” “uncertainty about reinforcement anchorage,” “use of load testing for validation,” “application of conservative safety factors.”
2. **T2 Durability and fire performance limitations**
   This theme refers to the ageing-related and regulatory constraints that limit the direct reuse of existing slabs. Many older elements show carbonation or insufficient cover depth, which can affect both durability and fire resistance. These issues often require mitigation through surface treatment, added protective layers, or redesign. *Examples of first-order codes:* “insufficient REI-90 fire rating,” “application of new protective coatings,” “assessment of service-life extension.”
3. **T3 Adaptation and strengthening strategies**
   This theme addresses the range of engineering interventions developed to adapt reclaimed slabs to new structural conditions. Because reclaimed elements rarely match the design loads or geometries of the new project, additional strengthening or redesign measures are frequently required. *Examples of first-order codes:* “cast-in UHPFRC overlay,” “added reinforcement loops at supports,” “composite steel–concrete beams,” “reduction of slab span by intermediate supports,” “application of redistribution of moments in design.”
4. **T4 Logistical integrity and storage conditions**
   This theme concerns the influence of logistics, cutting, lifting, transport, and storage, on the physical quality and usability of reclaimed elements. Even when slabs are structurally sound, damage during handling or improper storage can render them unsuitable for reuse. *Examples of first-order codes:* “edge spalling during sawing,” “torsion cracks from poor stacking,” “lack of protective storage area,” “just-in-time transport to avoid intermediate storage,” “use of QR codes for traceability.”

Process themes

1. **P1 Governance of fragmentation**
   This theme captures the organisational and communication challenges caused by fragmented responsibilities across actors in reuse projects. Successful cases introduced new coordination roles or routines to bridge the gap between donor and target projects, while others suffered from misaligned timing and missing information. *Examples of first-order codes:* “appointment of reuse coordinator,” “information loss between demolition and design,” “late involvement of structural engineer,” “poor cross-project communication,” “absence of clear responsibility for verification data.”
2. **P2 Procurement flexibility and risk allocation**
   This theme refers to the contractual and procurement mechanisms that either enabled or hindered reuse. Rigid, price-driven tenders often excluded reused materials, whereas flexible or integrated models allowed iterative testing and adaptation. *Examples of first-order codes:* “integrated design–build procurement,” “contractual allowance for material uncertainty,” “shared risk model between contractor and client,” “tender criteria including reuse ambition.”
3. **P3 Regulatory and certification alignment**
   This theme describes the interface between reuse practice and formal regulatory systems. Since reclaimed slabs fall outside CE marking procedures, project teams had to negotiate custom approval routes or align with national pilot standards. *Examples of first-order codes:* “project-based

certification," "interaction with building authorities," "lack of standardized approval pathway," "temporary deviation from Eurocode requirements."

4. **P4 Knowledge transfer and learning-by-doing culture**
   This theme highlights how institutional learning, documentation, and dissemination of project results contribute to mainstreaming reuse. Many actors reported that each project functions as a prototype, and knowledge is often lost unless systematically captured. *Examples of first-order codes:* "post-project evaluation sessions," "development of reuse manuals," "training site workers in deconstruction," "collaboration with research partners," "use of BIM or databases for material passports."

Together, these themes translate the qualitative findings from the five projects and expert interviews into a coherent analytical framework. They illustrate how recurring technical challenges and process conditions jointly determine the feasibility of concrete element reuse and form the foundation for the subsequent pattern-matching and explanation-building stages.

5.3.2. Pattern matching and explanation building

The third and final analytical step aimed to move from the identification of recurring patterns to a deeper understanding of *why* they occurred and *how* they collectively explain the success or failure of concrete element reuse. This stage followed the combined logic of **pattern matching** and **explanation building** as developed by Yin (2018) and Eisenhardt (1989). Whereas Step 2 established what themes were present across the cases, Step 3 compared these empirical patterns with theoretically informed expectations—linking observable outcomes to the underlying technical and organizational mechanisms that generated them.

Pattern matching procedure

For each theme, evidence from the five case studies and the expert interviews was organised in a summary matrix that listed:

1. the observed phenomenon or practice (e.g. use of hybrid testing),
2. its contextual trigger (e.g. missing design drawings), and
3. its outcome (e.g. reduced uncertainty in verification).

These within-theme matrices were then compared across all projects to identify regular cause–effect relationships. If the same mechanism reappeared in at least three projects or was confirmed by multiple external experts, it was coded as a **recurrent mechanism**. The analysis then traced the interactions between these mechanisms to reveal reinforcing or conflicting dynamics—for instance, how procurement flexibility (P2) enabled earlier verification integration (T1), or how storage failures (T4) undermined otherwise successful durability performance (T2).

Explanation building across themes

Eight central explanatory patterns were established—four technical and four process-oriented—each linked to specific project evidence and expert validation.

T1 Verification under uncertainty.

Projects consistently faced incomplete documentation or unknown reinforcement layouts. Where early and combined destructive and non-destructive testing protocols were adopted, verification became more reliable and confidence among engineers increased. The mechanism is thus the *translation of uncertainty into measurable parameters through hybrid testing and iterative assessment*. Projects without such early verification experienced redesign delays or overly conservative assumptions.

T2 Durability and fire-performance limitations.

The limiting factor in nearly every case was the difficulty of meeting modern requirements with older concrete and guarantee the remaining life. Successful projects mitigated this through systematic screening,testing, and targeted strengthening or protective layers. Hence, the key mechanism is the *use of minimal but targeted testing to prioritise viable elements and adapt only where necessary*, maintaining both safety and environmental benefit.

T3 Adaptation and strengthening strategies.
Because reused slabs rarely matched new load paths, structural adaptation proved indispensable. The mechanism observed across Udden, Prinsenhof A, and the C-pier validation was *engineering creativity under constraint*: casting thin overlays, adding reinforcement loops, or designing composite beams to upgrade capacity without destroying reuse value. Projects that treated adaptation as an integrated design task—rather than post-hoc repair—achieved higher reuse rates.

T4 Logistical integrity and storage conditions.
Handling and storage repeatedly determined whether technically sound slabs could still be reused. Where traceability systems (e.g. QR codes) and just-in-time logistics were implemented, element quality remained intact. The mechanism here is the *extension of quality control from factory production to the logistics chain*, ensuring that verification remains valid up to installation.

P1 Governance of fragmentation.
Cross-project fragmentation emerged whenever responsibilities for verification and communication were unclear. Introducing a **Reuse Coordinator** or integrated project team mitigated these gaps. The mechanism is the *institutionalisation of coordination*—creating a single node that connects donor and target projects and safeguards information continuity.

P2 Procurement flexibility and risk allocation.
Rigid, lowest-price tenders blocked reuse, while design–build or alliance contracts allowed iterative testing and adaptation. The mechanism is the *shift from transactional to collaborative risk management*, enabling experimentation without penalising uncertainty.

P3 Regulatory and certification alignment.
Every project encountered approval ambiguities due to the absence of CE marking for reclaimed elements. Where project-based certification or cooperation with authorities was established (e.g. SUPERLOCAL), approval processes accelerated. The mechanism is the *development of context-specific compliance pathways that translate experimental practice into formally accepted verification evidence*.

P4 Knowledge transfer and learning-by-doing culture.
Projects that documented lessons, organised post-project evaluations, or partnered with research institutions advanced collective expertise far more rapidly. The mechanism is *learning embedded in project delivery*: each reuse project becomes both a construction process and a research experiment, progressively lowering barriers for the next project.

5.3.3. Integration of findings into the framework development

The insights from pattern matching directly informed the formulation of the two frameworks developed later in this thesis. From the **technical side**, mechanisms T1–T4 define the verification framework's structure:

- **T1** underpins the staged verification logic (initial assessment → hybrid testing → performance validation).
- **T2** and **T3** inform the essential characteristics explicitly linking testing, durability, and strengthening measures.
- **T4** extends the framework beyond laboratory verification to include handling and storage control stages.

From the **process side**, mechanisms P1–P4 are embedded in the communication framework:

- **P1** motivates the creation of defined roles such as the *Reuse Coordinator* and *Independent Quality Controller*, ensuring governance continuity.
- **P2** influences the integration of framework checkpoints into procurement and contracting stages, enabling flexibility in verification scope and timing. Next to that it also underlines the need for the a two pathway (Path A: direct donor–target alignment; Path B: intermediary certification). Because if the risks cannot be shared it is hard to fully commit.

- **P3**: The need for a framework that is not only structurally useful, but also highlights the process level decissions that must be made and how it can be beneficial for these decissions.
- **P4** establishes continuous feedback loops and documentation requirements, anchoring learning and knowledge transfer as explicit project deliverables.

In conclusion, the analysis of the five case studies, supported by insights from external experts, demonstrated that the reuse of concrete elements is both technically achievable and organisationally dependent. Across all projects, recurring mechanisms of verification, adaptation, coordination, and learning revealed that successful implementation emerges not from isolated innovation, but from the integration of technical rigour and collaborative project governance. These lessons form the empirical foundation for the frameworks developed in the following chapters, translating practical experience into structured guidance for future circular construction projects.

STEP III

Framework development

6 Communication Framework

6.1. Introduction and goal of the framework

The objective of this chapter is to propose a process-driven communication framework that addresses the organizational and communicative barriers identified through the literature review, case studies and interviews. These barriers, such as fragmented responsibilities, misaligned project timing, unclear data ownership, and limited knowledge exchange, were shown to be among the primary obstacles preventing the efficient reuse of concrete elements. The proposed framework therefore seeks to provide a practical coordination model through which these problems can be systematically resolved.

To achieve this, the framework directly translates the previously identified barriers into structured mechanisms for collaboration and information flow. In contrast to the fragmented communication observed in current practice, where demolition contractors, engineers, and designers often operate in isolation, the framework introduces a collaborative process of knowledge integration. It creates a structured platform through which each stakeholder contributes their own expertise, technical, logistical, financial, or regulatory, at the moment it is most valuable. In doing so, it turns communication from a passive transfer of information into an active mechanism for decision-making, reducing uncertainty and inefficiency across project boundaries.

In practical terms, the framework establishes:

- Clarity of roles and responsibilities, by defining who communicates what, when, and to whom along the value chain.
- Integration of expertise, by enabling structured collaboration between disciplines so that design, testing, logistics, and procurement decisions reinforce rather than contradict each other.
- Continuity and transparency of information, ensuring that verified data travels seamlessly from donor to target projects and remains accessible throughout the project lifecycle.
- Collaborative confidence, by creating predictable routines and shared decision checkpoints that foster trust and accountability among stakeholders.

Ultimately, the communication framework functions as both a guidance tool and a coordination mechanism, offering a repeatable process that transforms the reuse of concrete slabs from an ad-hoc initiative into a managed, multidisciplinary practice. By aligning communication with the construction value chain, it directly responds to the challenges revealed in the research, providing a structured path toward more efficient, transparent, and cooperative circular construction.

6.2. The framework logic

The framework takes the construction value chain, as established in Chapter 3, as its structural backbone, embedding communication and coordination mechanisms within its six sequential stages: project initiation and planning, design and engineering, procurement and contracting, construction and assembly, operation and maintenance, and end-of-life and deconstruction. While this value chain is inherently linear, moving from design to demolition, the framework aligns the chains of both donor and target projects to create a circular process. This alignment allows information, materials, and verification data to flow in two directions, establishing a structured interface through which reuse can be coordinated systematically.

Each stage functions as a distinct communication domain: a defined environment where specific actors, responsibilities, and information exchanges converge around shared decisions. Within these domains, the framework specifies who communicates what, when, and to whom, making communication an intentional and verifiable part of the project workflow.

To operationalize this concept, Table 6.1 maps the six stages of the construction value chain to their respective communication domains. It identifies, for each stage, the main communication focus, what needs to be aligned, and the concrete output that captures and formalizes that exchange. Together, these domains provide the procedural backbone of the framework, ensuring that every phase contributes a traceable communication deliverable that links donor and target projects.

Table 6.1: Stage-based communication domains within the process-driven framework

Stage of Value Chain	Communication Focus	Main Output
1. Initiation & Planning	Establish the reuse ambition, define stakeholder roles, and outline data and documentation requirements.	**Reuse Communication Plan** , setting out responsibilities, information needs, and the format for data exchange.
2. Design & Engineering	Translate donor information into design inputs and verification activities; align testing, analysis, and modelling procedures.	**Verification Dossier** , a consolidated record of test results, calculations, and design assumptions.
3. Procurement & Handover	Coordinate material sourcing, verification, and delivery while ensuring clear transfer of documentation and responsibilities.	**Handover Protocols & Traceability Clauses** , contractual tools ensuring continuity of information and accountability between project phases.
4. Construction & Assembly	Maintain information flow between site, design, and verification teams; document deviations and updates.	**As-Built Updates** , verified records and site reports linked to material passports.
5. Operation & Maintenance	Ensure long-term accessibility of verified data and document interventions during service life.	**Material Passport** , living documentation integrating condition data and maintenance history.
6. End-of-Life & Deconstruction	Capture lessons learned and prepare data for the next reuse cycle through selective dismantling and reassessment.	**Updated Reuse Record** , verified documentation for transfer to future projects or intermediaries.

6.2.1. Framework Logic Map

While Table 6.1 structures the framework sequentially, the following step is to explain *how* it functions as a causal system. Figure 6.1 visualises this relationship by linking the barriers identified in Chapter 12 and Chapter 5 to the mechanisms, deliverables, and outcomes that the framework introduces. In this way, the diagram makes explicit how the framework transforms systemic challenges into measurable improvements.

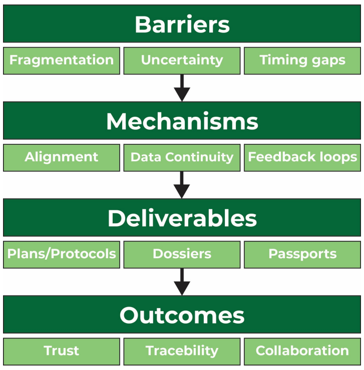


Figure 6.1: Framework Logic Map – translating barriers into mechanisms, deliverables, and outcomes

As shown in Figure 6.1, the framework operates as a process-based solution that converts recurring barriers, such as fragmented expertise, unclear responsibilities, and information loss, into structured communication mechanisms. These mechanisms generate tangible deliverables (e.g., *Reuse Communication Plan*, *Verification Dossier*, and *Traceability Protocols*) that promote trust, accountability, and data continuity between donor and target projects.

This causal logic reinforces that the framework is not merely descriptive but *performative*: it establishes a consistent sequence of inputs (barriers), transformations (mechanisms), and outputs (deliverables) that culminate in system-level outcomes, namely improved traceability, transparency, and collaborative efficiency across reuse projects.

6.2.2. Theoretical foundation of the framework

The logic outlined above is underpinned by two complementary theoretical perspectives: systems thinking and inter-organizational learning. From a systems perspective, the framework can be seen as a coordination mechanism that aligns multiple subsystems within the construction value chain, design, demolition, verification, and contracting, through shared information flows. Such systems are inherently complex and distributed: each actor operates within its own professional logic, yet project success depends on the integration of their outputs into a coherent whole.

Within this fragmented landscape, communication often breaks down at the interfaces between disciplines. To mediate these interfaces, the framework relies on what Star and Griesemer, 1989 describe as *boundary objects*, artifacts that are sufficiently flexible to be interpreted by different communities, yet robust enough to maintain a common identity across them. In the context of this research, tools such as the *Element Passport* and the *Material Offer Sheet* perform exactly this function. They allow structural engineers, contractors, and intermediaries to collaborate around shared documentation even when their technical vocabularies, responsibilities, or project objectives diverge. Through these boundary objects, the framework ensures that locally specific knowledge can be exchanged without requiring full consensus or uniform expertise, thereby sustaining system-level coherence.

Building on this, the framework also draws on insights from inter-organizational learning and process integration theory (Giezen et al., 2022). These perspectives emphasize that coordination across organizational boundaries is not a one-time alignment, but a continuous process supported by iterative feedback loops and shared data environments. Within the reuse context, such learning loops are embedded in the digital documentation flows that connect donor, intermediary, and target projects, allowing information to circulate, be updated, and inform future decisions.

By grounding the framework in these theoretical foundations, it can be understood not only as a practical coordination tool but as a socio-technical system: one that uses boundary objects to connect subsystems, and feedback mechanisms to enable organizational learning, thereby embedding continuity of knowledge and trust within the circular construction process.

6.3. Framework mechanisms

While the framework logic establishes the structural backbone of communication along the construction value chain, its effectiveness depends on a set of underlying mechanisms that determine how coordination, information exchange, and decision-making are sustained across donor and target projects. These mechanisms translate the conceptual model into operational behaviour, ensuring that communication remains consistent, accountable, and circular rather than linear.

Drawing from systems integration and inter-organizational learning theory, four complementary mechanisms underpin the framework: *responsibility alignment*, *information continuity*, *temporal synchronization*, and *feedback learning*. Together, they enable the framework to convert the fragmented and sequential nature of conventional project delivery into a process of continuous knowledge exchange.

Responsibility alignment

In conventional construction projects, responsibilities for communication are often diffuse or defined only at contractual boundaries, leading to uncertainty about who owns which information. The framework addresses this by introducing responsibility alignment as a deliberate mechanism of coordination.

Each communication domain (Table 6.1) assigns clear ownership of data production, validation, and transfer. During the *Initiation and Planning* stage, responsibilities are formalized in the *Reuse Communication Plan*, specifying who communicates what, when, and to whom. In later stages, this alignment evolves into traceable deliverables, such as the *Verification Dossier* or *Traceability Protocols*, that document accountability. This mechanism not only reduces ambiguity and overlap but also builds trust between parties, as communication duties are transparent and verifiable throughout the reuse process.

Information continuity

The second mechanism concerns the continuity and accessibility of verified information across project stages and between donor and target contexts. In conventional workflows, data often fragment as projects transition between phases or organizations. The framework prevents this through standardized deliverables that ensure information persists in usable form.

Key instruments such as the *Element Passport* and *Material Offer Sheet* function as boundary objects, bridging the communication gap between technical disciplines and project boundaries. They retain essential data on geometry, testing, and verification, while remaining interpretable by different actors. By formalizing these information carriers, the framework establishes a durable digital thread that links the origin, performance, and subsequent reuse of each element.

Temporal synchronization

A defining challenge in reuse projects is the misalignment between donor and target project timelines: elements are often available before, or long after, a suitable target project arises. Temporal synchronization addresses this by structuring the flow of information and decision-making so that reuse remains feasible even when physical timelines diverge.

In *Path A*, synchronization occurs through direct coordination between donor and target teams, where design and verification processes run in parallel. In *Path B*, the intermediary maintains temporal continuity by preserving verified data in digital form and reactivating it when a new project emerges. In both cases, the mechanism ensures that verified information remains relevant and retrievable, transforming asynchronous demolition and construction activities into a coordinated reuse cycle.

Feedback learning

Finally, the framework embeds feedback learning as a mechanism for continuous improvement across projects. Each stage of the value chain produces documentation that not only records what was done but also informs future decisions. For instance, the *Updated Reuse Record* at the end-of-life stage captures lessons learned about testing, logistics, and certification, feeding them back into subsequent *Initiation and Planning* stages.

Through these feedback loops, the framework evolves from a static coordination tool into a learning system. It enables actors to refine verification procedures, improve communication routines, and develop shared standards for future reuse scenarios. This mechanism operationalizes the inter-organizational learning principles discussed by Giezen et al. (2022), ensuring that circular construction becomes progressively more predictable and efficient over time.

Together, these four mechanisms form the operational engine of the communication framework. Responsibility alignment clarifies ownership; information continuity preserves knowledge; temporal synchronization bridges project timelines; and feedback learning drives iterative improvement. Their interaction transforms communication from an ad hoc exchange into a structured and circular process.

The following section introduces the *Dual-Path Alignment Model*, which illustrates how these mechanisms manifest in practice through two complementary coordination pathways, *Path A* (direct donor–target alignment) and *Path B* (intermediary-mediated alignment).

6.4. The dual-path alignment model

At the centre of the framework lies a dual-path alignment model that manages the connection between donor and target projects. When looking from a design-decision point of view, this represents the first crucial step. It distinguishes two possible routes through which information, materials, and verification data can circulate, depending on the level of synchronisation between the projects.

In current practice, circular ambitions are frequently formulated at the start of a project but often abandoned when it becomes clear that suitable materials cannot be supplied on time or in the required quantities. This problem stems largely from the absence of a centralised stock of reusable components, meaning that successful reuse projects today usually only occur when a donor and target project happen to be aligned from the outset. From a procurement perspective, this moment often represents the critical breaking point identified under theme **P2: Procurement flexibility and risk allocation**. When the feasibility of reuse becomes uncertain, clients and contractors are reluctant to proceed with costly testing or verification, as the financial and contractual risks are concentrated on a single party. While such direct alignment can work effectively, it is rare and limits the scalability of reuse. The dual-path model directly addresses this issue by redistributing responsibility and uncertainty: when a direct donor–target link (Path A) is not possible, an intermediary actor such as a reuse broker or material bank (Path B) can share the technical and financial risks associated with verification. In doing so, the framework creates the flexibility required for actors to explore reuse without bearing disproportionate exposure, turning risk-sharing into an enabler of circular decision-making. The following sections detail how these two configurations, Path A and Path B, function in operation, defining their respective communication channels, responsibilities, and outputs:

6.4.1. The decision between the two pathways

To operationalise the dual-path alignment model, a structured decision framework has been developed to support project teams in determining whether reuse coordination should follow Path A (Direct Donor–Target Alignment) or Path B (Intermediary Alignment).

The purpose is twofold:

- To provide a transparent and repeatable decision process that can be applied at the initiation of any reuse project
- To ensure that the chosen communication structure realistically reflects the project's logistical, legal, and technical constraints

In practice, early identification of the correct path prevents misalignment between donor and target projects, reduces redundant verification efforts, and clarifies where responsibility for material traceability resides.

The framework therefore acts as a diagnostic tool rather than a rigid classification. In early feasibility phases, projects may even begin under Path A and later transition to Path B if conditions change , for instance, when delays extend the time gap between demolition and reconstruction. The guiding principle is that the shorter and more synchronous the relationship between the donor and target project, the more viable Path A becomes; conversely, as time, ownership, or information gaps widen, the intermediary-based Path B offers a more robust governance structure.

Table 6.2: Decision framework for selecting Path A or B

Rank	Criterion	Condition for Path A (Direct Alignment)	Condition for Path B (Intermediary Alignment)
1	Temporal Alignment	Donor and target project timelines overlap or differ by ≤ 12 months.	Time gap > 12 months between demolition and construction; storage or re-certification required.
2	Ownership / Contractual Control	Aligned client interests or shared commitment to reuse enabling direct coordination.	Diverging interests or fragmented contracts requiring intermediary management.
3	Verification & Documentation	≥ 80 % of required data (geometry, reinforcement, test results) are verified and traceable.	Incomplete or outdated verification data < 80 %; additional testing and certification needed.
4	Material Availability & Volume	Donor stock covers ≥ 90 % of target project's slab quantity and type.	Donor stock < 90 % match; partial reuse or aggregation from multiple projects required.
5	Structural Compatibility	Preliminary DRP rating in green or yellow range; structural adaptation minor or not required.	Preliminary DRP rating in orange or red range; major redesign or requalification needed.
6	Risk & Liability Tolerance	Parties accept shared responsibility under joint warranty or reuse clause.	Liability separated; independent certification and insurance demanded.
7	Spatial Distance	Donor and target within ≤ 150 km transport radius.	Distance > 150 km; central logistics coordination preferred.

The hierarchy in Table 6.2 follows the logical order in which reuse decisions are made in practice. Each criterion builds on the previous one, starting with fundamental preconditions for alignment and ending with factors that optimise feasibility. The sequence reflects how technical, organisational, and contextual dependencies unfold across the construction value chain.

Temporal alignment is the primary determinant of coordination. When donor and target project timelines overlap or differ only slightly, direct coordination (Path A) is possible. If not, reclaimed elements must be stored, tested, and redistributed later, requiring an intermediary (Path B) to maintain quality and traceability. Time therefore acts as the first gateway in deciding whether reuse can occur directly.

Ownership and contractual control These organisational configurations form the second layer of the framework. When both project owners share a common stake or aligned interest in achieving reuse, such as a public authority collaborating with a social housing developer, as in the Leiden project, liability and communication can be managed directly between them, supporting Path A. In cases where interests diverge, or when donor and target projects are separated by contractual or institutional boundaries, an intermediary actor becomes essential. Under Path B, this intermediary manages certification, warranty, and information continuity, ensuring that responsibilities remain balanced and that reuse can proceed despite fragmented ownership structures.

The third criterion, **verification and documentation status**, ensures that decisions rest on reliable data. Even with strong temporal and contractual alignment, missing or outdated documentation prevents direct transfer. Intermediaries can fill this gap by performing additional testing and providing standardised data in line with the reuse verification mechanism as explained in chapter 7.

Material availability and **structural compatibility** shape the technical fit between donor and target projects. When reclaimed slabs meet most of the target's quantity and performance needs, direct reuse is efficient. Otherwise, Path B enables material pooling or redistribution through a centralised marketplace. Likewise, structural mismatches, such as span or system differences, may require adaptation or hybridisation, often supported through an intermediary setup.

Risk and liability tolerance mainly reflects organisational culture. Public clients or risk-averse teams may prefer the assurance of independent verification under Path B, while experienced practitioners might retain responsibility through Path A. As industry standards mature, this factor will likely diminish in influence.

Lastly, **spatial distance** affects the environmental and logistical efficiency of reuse rather than its feasibility. Local reuse within roughly 150 km supports direct alignment, while longer distances favour coordinated logistics through Path B.

Overall, the hierarchy shows that reuse alignment is governed first by synchronisation (time and ownership), then by verification and supply conditions, and finally by contextual preferences such as risk and distance. It transforms an often ad-hoc judgment into a transparent, stepwise process, illustrating that shifting from Path A to Path B is not a setback, but an adaptive response that enables reuse under varying project conditions.

6.4.2. Integration within the broader communication framework

The dual-path alignment model acts as the bridge between the ambition of reuse and its practical implementation. By identifying early whether a project follows Path A or Path B, the framework ensures that communication structures, such as roles, deliverables, and verification workflows, match the specific project context.

Once this alignment is established, each stage of the value chain can be organised accordingly. Path A builds on direct coordination between donor and target projects, with shared documentation and joint verification. Path B, in contrast, introduces an intermediary responsible for maintaining data continuity, traceability, and certification across projects.

In doing so, the model provides more than a classification of project types; it offers a scalable coordination logic that can be applied across different timelines, contractual setups, and technical conditions. The following sections explain how these two pathways are integrated into the stage-based communication domains of the overall framework.

6.5. Stage-based communication domains , Path A: Direct Donor–Target Alignment

Path A represents the most integrated form of coordination within the communication framework. It applies when donor and target projects can be directly connected, either because their timelines overlap, their organisational structures are compatible, or both clients share a common stake in achieving reuse. In these cases, information, materials, and verification data flow directly between project teams without the need for an intermediary actor such as a broker or material bank.

The framework translates this collaboration into six consecutive stages that mirror the construction value chain: initiation and planning, design and engineering, procurement and contracting, construction and assembly, operation and maintenance, and end-of-life and deconstruction. At each stage, communication occurs within a defined domain where specific actors, responsibilities, and deliverables converge. Communication is treated as a project deliverable, structured, documented, and traceable, rather than an informal exchange.

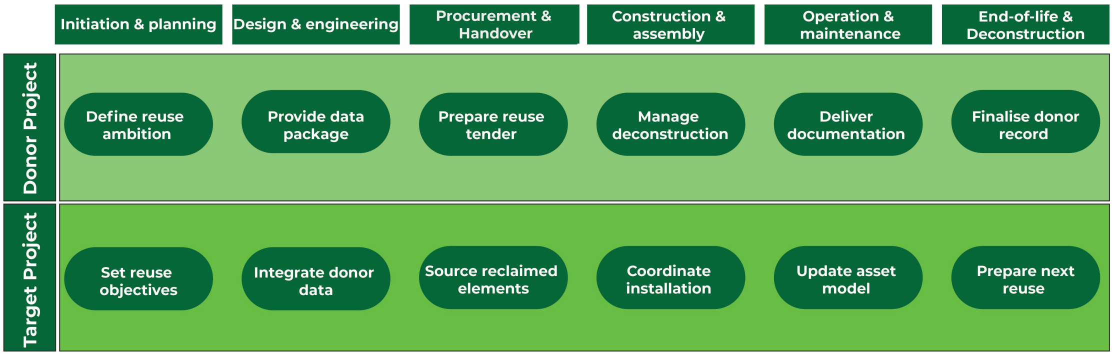


Figure 6.2: Stage-based communication overview for Path A , direct donor–target alignment.

Figure 6.2 provides an overview of these domains. It visualises how the donor and target projects interact across all six stages and how joint deliverables, such as the *Joint Reuse Plan*, *Verification*

Dossier, and *Full Material Passport*, emerge from coordinated communication efforts. The diagram highlights that both project streams progress in parallel, with continuous information exchange ensuring that data from the donor project informs the target design and that feedback from the target project refines donor documentation.

For Path A, the emphasis lies on establishing joint decision-making and shared documentation between donor and target teams. The communication framework ensures alignment on objectives, verification procedures, and data management from the earliest planning stage through to the final documentation of reused elements. As illustrated in projects such as Leiden, this form of collaboration enables reuse to succeed even across different organisations, provided that both clients maintain aligned ambitions and a balanced distribution of risk.

The following subsections describe, stage by stage, how communication under Path A develops, from the joint definition of reuse ambitions to the preparation of data for future reuse cycles. Each stage specifies its communication focus, key actors and responsibilities, expected deliverables, and value added to the reuse process. Together, these domains translate the conceptual framework of Path A into a practical workflow that can be directly applied in project environments.

Stage 1 , Initiation & Planning

Path A

◎ **Purpose** Establish the foundation for direct collaboration by agreeing reuse ambitions, responsibilities, and information needs.

Timing
Early development of both projects; planning/design schedules overlap.

Communication focus

- Reuse ambition and performance targets.
- Scope of reusable elements and available donor documentation.
- Milestone synchronisation and key dependencies.
- Data formats and initial verification requirements.

Actors & Responsibilities

Donor client / PM	Identify reusable elements; confirm documentation availability.
Target client / PM	Translate ambition into design/performance objectives within cost, schedule, and regulations.
Reuse coordinator	Facilitate dialogue; record decisions; draft the Joint Reuse Communication Plan.
IQC (optional)	Review preliminary data completeness/reliability.

Main output (checkpoint)

- *Reuse Communication Plan (RCP)* , specifies communication lines, reporting structure, and document formats; defines responsibilities for verification, documentation ownership, and approval workflow.
- *Preliminary Verification & Testing Plan* , outlines sampling strategy, testing methods, and acceptance criteria for donor slabs.
- *Circularity Performance Framework* , sets measurable KPIs for reuse contribution, embodied-carbon reduction, and waste diversion.
- *Integrated Master Schedule* , aligns demolition, testing, design, and construction activities; includes critical communication checkpoints.
- *BIM model* , using 3D scanning, the object is captured in a BIM model to explore viable reuse options.

Value added

- Clarity of roles and pathways.
- Integrated expertise from the outset.
- Transparent, continuous information flow.
- Predictable routines that build trust and accountability.

Stage outcome
Reuse ambition converted into an actionable coordination framework for the subsequent stages.

Stage 2 , Design & Engineering

Path A

◎ **Purpose** Translate the joint reuse ambition into verified technical inputs by exchanging, validating, and modelling donor data for integration in the target design.

Timing
Early design to detailed design: direct collaboration between donor and target engineering teams.

Communication focus

- Exchange and verify donor datasets (geometry, reinforcement, materials, exposure conditions).
- Document assumptions and parameters used in target design models.
- Align verification procedures, test plans, and acceptance criteria.
- Record all evidence and decisions in a shared *Verification Dossier*.

Actors & responsibilities

Donor structural engineer	Compile and validate geometric, material, and reinforcement data; confirm reuse reliability.
Target structural engineer	Integrate donor data in analysis/model; verify limit states and detailing within project requirements.
Reuse coordinator	Facilitate technical dialogue; monitor information consistency; maintain verification milestones in the plan.
Testing specialist / lab	Perform supplementary tests where data are incomplete or uncertain; report results to both teams.
IQC (independent)	Review dossier completeness, traceability, and alignment with relevant standards.

Main output (checkpoint)

- *Verification Dossier* , consolidated donor data, testing results, design assumptions, and analysis reports; links every reclaimed element to its verification record and material passport.
- *Updated BIM / Design Models* , integrate verified slabs with updated load and geometry parameters; include clash detection and design-for-assembly details.
- *Design Verification Report (DVR)* , summarises compliance with Eurocode ULS/SLS criteria, fire performance, and deflection limits; forms the technical justification for reuse approval by the authority having jurisdiction (AHJ).
- *Design Review Minutes / Decision Log* , record design meetings, assumptions, and acceptance of verification results by all parties.

Value added

- Clarity of responsibilities across donor and target engineering tasks.
- Integrated expertise: donor knowledge directly informs target modelling and design.
- Transparent continuity of information via a single, traceable dossier.
- Collaborative confidence: joint validation reduces risk and prevents rework.

Stage outcome
Reuse intent converted into verified technical knowledge, forming a common analytical basis for

procurement, contracting, and construction.

Stage 3 , Procurement & Handover

Path A

◎ **Purpose** Coordinate the controlled procurement and handover of reclaimed elements and their accompanying data between the deconstruction and construction phases. In projects where the client retains ownership of both donor and target assets, procurement primarily concerns the *harvesting and transfer of materials* rather than external contracting. This stage ensures that verified components, documentation, and logistical arrangements from the demolition phase are seamlessly transferred to the construction team for integration into the new design.

Timing

Following completion of verification and during selective deconstruction, when elements are harvested, inspected, and prepared for transport or storage.

Communication focus

- **Coordinate handover logistics** , align schedules, removal procedures, and delivery sequences between deconstruction and construction teams.
- **Transfer verification information** , ensure that all test data, inspection results, and element identifiers accompany the reclaimed components.
- **Decide on storage and handling** , define whether elements will be stored on-site or externally, and record handling and storage conditions.
- **Maintain traceability and quality control** , link each element to its verification data through digital identifiers, ensuring full data continuity through the transfer.

Actors & responsibilities

Deconstruction Contractor	Harvests and labels reclaimed elements; provides inspection records and condition assessments prior to transfer.
Construction Contractor	Receives elements and associated documentation; inspects condition and plans logistics or temporary storage.
Engineering Consultant	Confirms that transferred materials meet technical and structural requirements; updates verification documentation accordingly.
Reuse Coordinator	Oversees communication between deconstruction and construction teams; ensures that documentation and traceability protocols are followed.
Client / Project Owner	Approves material transfer, storage plans, and reuse scope; validates that circular and quality objectives are maintained.
Independent Quality Control (IQC)	Verifies the integrity of handover documentation and confirms consistency between physical elements and digital data.

Main output (checkpoint)

- *Handover Package* , consolidated set of documents from demolition including inspection reports, verification data, and photographic evidence of each reclaimed element.
- *Material Transfer Register* , formal log linking each slab's physical identifier to its verification and testing records; signed by demolition and construction representatives.
- *Storage & Logistics Plan* , decisions on storage location, handling method, and transport schedule; includes safety and traceability procedures.
- *Updated Verification Dossier* , incorporates final as-removed condition assessments and transfers responsibility for documentation to the construction team.

Value added

- Establishes a transparent and traceable transfer of materials and data between project phases.
- Prevents information loss by linking physical elements directly to their verification records.
- Promotes collaboration between demolition and construction teams through shared logistics planning.
- Reduces risks of damage, miscommunication, or delays in reuse implementation.

Stage outcome

At completion, all verified elements and associated documentation are successfully transferred from the deconstruction phase to the construction phase. The *Material Transfer Register* and *Handover Package* confirm the integrity and readiness of the reclaimed components, enabling smooth progression to **Stage 4 , Construction & Assembly**.

Stage 4 , Construction & Assembly

Generic Framework

◎ **Purpose** Manage the on-site installation and integration of reclaimed elements while maintaining quality, safety, and complete traceability. This stage focuses on direct coordination between construction teams, ensuring that verified components are correctly assembled and documented as part of the new structure.

Timing

During construction and installation; overlaps transport, on-site storage, and assembly activities.

Communication focus

- Coordinate transport, storage, and installation sequencing for reclaimed elements.
- Share real-time updates on handling, inspection outcomes, and corrective actions.
- Maintain identification codes and link all site activities to verified design data.
- Record deviations or damage and document agreed remedial measures immediately.

Actors & responsibilities

Construction Contractor / Site Manager	Oversees on-site assembly of reclaimed elements; coordinates logistics, temporary supports, and installation sequencing.
Logistics Coordinator	Organises transport and on-site storage; maintains traceability between element identifiers and installation locations.
Engineering Consultant	Provides technical supervision; verifies fit, bearing conditions, and compliance with design tolerances.
Reuse Coordinator	Facilitates communication among teams; monitors adherence to traceability and documentation protocols; updates records in the Common Data Environment (CDE).
Independent Quality Control (IQC)	Performs inspections before and after installation; certifies conformity of installed elements with verification data.

Main output (checkpoint)

- *Installation Verification Report* , confirms correct placement, orientation, and bearing conditions of all reused slabs; signed by the principal designer/engineer, IQC, and the authority having jurisdiction (AHJ).
- *Updated BIM / As-Built Model* , integrates as-installed geometries, unique identifiers, and deviations; forms the digital twin of the reused structure.
- *Construction Quality Log* , documents inspections, lifting operations, and on-site adjustments; includes photographic evidence and non-conformance records.
- *Safety & Compliance File* , compiles permits, toolbox talks, and safety inspection reports for site activities.

Value added

- Defines clear site responsibilities and communication channels between teams.
- Integrates expertise across logistics, engineering, and construction disciplines.
- Maintains unbroken traceability from verification data to as-built documentation.
- Enables real-time coordination that reduces risk and improves transparency.

Stage outcome

Reuse is implemented on site: reclaimed elements are safely and accurately integrated into the new structure through a unified communication flow and complete traceability.

Stage 5 , Operation & Maintenance

Path A

◎ **Purpose** Preserve and manage the verified reuse information beyond construction by embedding it in the building's asset management system and maintaining full traceability throughout the service life.

Timing

Post-construction and during operation; from building handover through its service life.

Communication focus

- Consolidate and transfer reuse documentation into the building's asset/BIM model.
- Record inspection results, maintenance interventions, and performance feedback.
- Link operational updates to original verification and construction data.
- Maintain a closed information loop through an *Integrated Reuse Dossier*.

Actors & responsibilities

Target owner / facility manager	Maintain operational data and condition records; safeguard reuse documentation for future transfer.
Reuse coordinator / asset manager	Ensure completeness and traceability of the reuse dossier; align with current digital and regulatory standards.
Design & engineering advisors	Provide technical input or performance review when maintenance or deviations occur.
IQC (independent)	Verify that documentation accurately reflects as-built and operational conditions.

Main output (checkpoint)

- *Integrated Reuse Dossier (IRD)* , comprehensive digital record containing as-built geometries, verification data, maintenance instructions, and inspection schedules; forms the official documentation set for future reuse.
- *Asset Information Model (AIM)* , BIM-linked dataset integrated into the client's asset management system (AMS); includes material properties, element identifiers, and maintenance metadata for each reused slab.
- *Maintenance & Inspection Plan (MIP)* , defines monitoring frequency, visual-inspection protocols, and thresholds for testing or intervention.
- *Performance Review Reports* , periodic assessments summarising the structural and durability performance of reused slabs, recorded in the AMS.

Value added

- Clear assignment of maintenance and data-management roles.
- Continued integration of design, operational, and quality-control expertise.
- Transparent information continuity through embedded digital records.
- Long-term collaborative confidence by retaining verifiable performance data.

Stage outcome
Informational integrity of the reuse process preserved beyond construction; reclaimed elements remain documented, monitorable, and ready for future adaptation or extraction at the building's next transformation cycle.

Stage 6 , End-of-Life & Deconstruction

Path A

◎ **Purpose** Prepare the building to act as a future donor by preserving verified information, traceability, and material integrity so that reclaimed elements can be reused without restarting the verification process.

Timing
Late service life and deconstruction planning; initiated while the building is still operational to ensure a seamless transition into a new reuse cycle.

Communication focus
- Evaluate residual performance and plan selective dismantling.
- Initiate dialogue with future recipient projects or reuse networks.
- Compile condition, maintenance, and alteration data into an updated *Material Passport*.
- Transfer verified datasets and documentation to enable the next donor–target alignment.

Actors & responsibilities

Target owner / facility manager	Trigger reuse planning; provide complete operational and condition data to future projects.
Reuse coordinator	Manage communication with future design and demolition teams; ensure continuity of traceability and certification.
Deconstruction contractor	Plan and execute selective dismantling in line with documented safety and handling procedures.
IQC (independent)	Verify final documentation and certify reclaimed elements prior to their next transfer.

Main output (checkpoint)

- *Updated Material Passport Set* , revised digital records for each slab including latest condition data, interventions, and dismantling instructions.
- *Residual Performance Assessment Report* , summarises remaining strength, durability, and service-life potential of each reclaimed element.
- *Selective Deconstruction Plan* , defines dismantling sequence, safety measures, logistics, and handling protocols derived from installation data.
- *Continuity of Passport Record* , integrates updated material data into the client's asset database and re-lists reusable elements for future projects or digital marketplaces.
- *Lessons-Learned Summary* , documents operational performance, maintenance outcomes, and recommendations for improving future reuse cycles.

Value added
- Defined end-of-life responsibilities linked to earlier documentation.
- Collaboration between operational, demolition, and future design teams.
- Continuous, transparent data trail from original donor to next recipient.
- Proof that reuse can be planned and verified across multiple lifecycles.

Stage outcome
End-of-life becomes the launch point for the next reuse cycle: the framework closes one circular communication loop while preserving data, accountability, and material value for the next generation of projects.

6.6. Stage-based communication domains , Path B: Intermediary Alignment

Path B applies when donor and target projects cannot be directly aligned in time, ownership, or contractual structure. In these cases, an intermediary actor, such as a reuse broker, material bank, or verification platform, facilitates coordination between the two projects. The intermediary ensures that reclaimed elements remain traceable, verified, and ready for integration once a suitable target project emerges.

This pathway reflects a more decentralised and scalable approach to circular construction, in which materials are harvested, documented, and reintroduced to the market through structured management rather than direct project-to-project exchange. The intermediary acts as the central node, bridging differences in timing, risk perception, and information quality between donor and target actors.

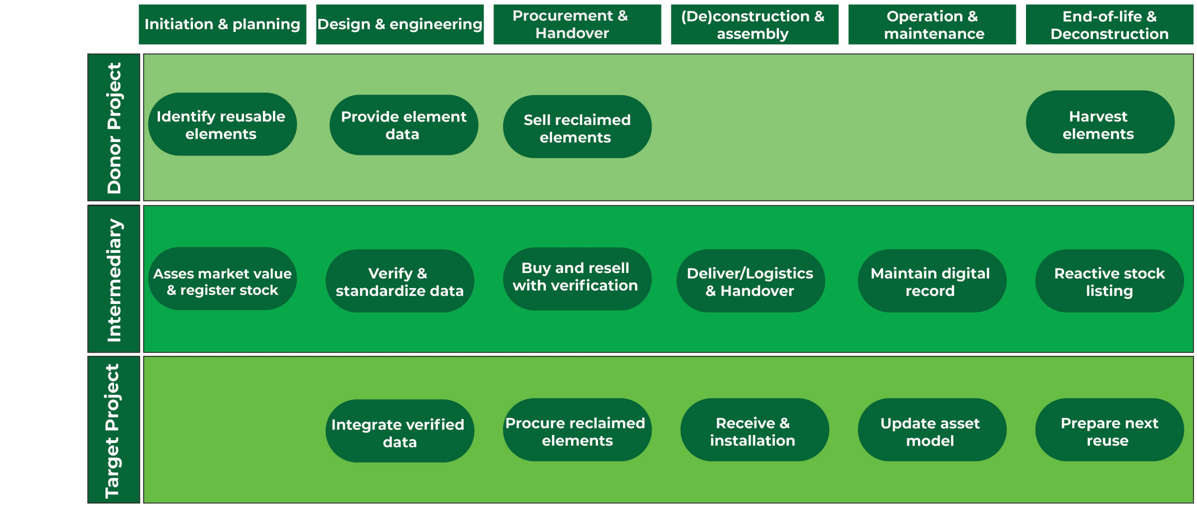


Figure 6.3: Stage-based communication overview for Path B , intermediary alignment.

Figure 6.3 illustrates how communication and responsibilities are distributed across the six stages of the value chain. In contrast to Path A, where donor and target teams coordinate directly, Path B introduces an intermediary layer that manages verification, certification, and logistics. This structure allows reclaimed elements to circulate independently of project schedules while maintaining documentation integrity through deliverables such as the *Material Database*, *Element Passport Set*, and *Verification Report*.

Within this configuration, communication domains are organised around three parallel streams, donor project, intermediary, and target project, each contributing specific information and deliverables. The intermediary assumes responsibility for data quality, market registration, and traceability, enabling donor and target teams to participate without taking on full verification or financial risk. This redistribution of responsibilities supports the mechanism identified under theme **P2: Procurement flexibility and risk allocation**, ensuring that uncertainty is managed collaboratively rather than deterring reuse efforts.

The following subsections detail how communication under Path B unfolds across the six stages, from the identification of reusable elements and creation of material databases to the procurement, installation, and re-certification of reclaimed components. Each stage describes the main communication focus, the actors involved, expected deliverables, and the added value of structured information exchange. Together, these domains demonstrate how Path B operationalises circular construction at scale by connecting independent projects through verified, traceable material flows.

Stage 1 , Initiation & Planning

Path B

◎ **Purpose** Establish the link between the donor project and an intermediary (reuse broker / material bank) to document, value, and certify reusable components for future market placement.

Timing
Early stage of donor project planning and pre-demolition; before a target project is identified.

Communication focus

- Capture reliable data on available donor stock and its condition.
- Define how materials are to be verified, stored, and made available for resale.
- Share demolition plans and documentation with the intermediary.
- Compile findings into a formal *Material Offer Sheet*.

Actors & responsibilities

Donor client / project manager	Identify reusable components; provide drawings; facilitate on-site access for assessment.
Intermediary (broker / material bank)	Record, verify, and classify donor elements; estimate market value; establish data standards for later transfer.
Reuse coordinator (optional)	Organise communication between donor and intermediary when no direct link exists.
IQC (independent)	Verify completeness and conformity of the inventory and documentation protocols.

Main output (checkpoint)

- *Reuse Communication Plan (RCP)* , roles, channels, update rhythm, document formats between donor and intermediary.
- *Preliminary Verification & Testing Plan* , sampling strategy, methods, acceptance criteria for donor stock.
- *Circularity Performance Framework* , KPIs for reuse contribution, embodied-carbon reduction, waste diversion.
- *Integrated Master Schedule* , aligns deconstruction, testing, data release, and storage windows.
- *Material Inventory Record & BIM scan* , catalogue with geometry/material data, linked to a basic BIM/IFC model.

Value added

- Clear division of early roles and data ownership.
- Integration of demolition, brokerage, and quality-control expertise.
- Transparent, standardised documentation stored centrally.
- Market confidence via traceable, pre-verified inventories.

Stage outcome
Donor project transformed into a verified source of reusable components ready for classification and market release.

Stage 2 , Design & Engineering

Path B

◎ **Purpose** Verify and standardise donor information into market-ready technical data by creating digital element passports with declared performance ratings.

Timing
After donor documentation is completed and before the element data are released to the reuse market or assigned to a target project.

Communication focus

- Coordinate verification, testing, and classification between intermediary, laboratories, and structural specialists.
- Translate test results into design-ready data in standardised BIM/IFC formats.
- Assign a preliminary *Declared Reuse Performance (DRP)* rating for each element.
- Maintain transparent documentation and traceability across all verification activities.

Actors & responsibilities

Intermediary (broker / material bank)	Coordinate testing and data validation; prepare digital element passports with DRP ratings.
Testing laboratories / specialists	Perform destructive and non-destructive tests (strength, durability, composition).
Structural engineers (consulting)	Validate outcomes; define applicable design assumptions for reuse scenarios.
Donor client / project manager	Provide additional documentation; align testing with deconstruction planning.
IQC (independent)	Review dossier completeness, traceability, and alignment with relevant standards.

Main output (checkpoint)

- *Verification Dossier (Intermediary)* , consolidated donor data, test results, and classification basis.
- *Element Passport Set* , verified properties + preliminary DRP class; linked reports and metadata.
- *Updated BIM/IFC Library* , element objects with geometry, identifiers, and design-ready parameters.
- *Design Review Minutes / Decision Log* , records of assumptions and acceptance of verification by parties.

Value added

- Clear accountability for verification and documentation.
- Integration of testing, engineering, and data-management expertise.
- Transferable technical information that reduces future design risk.
- Strengthened market confidence via standardised performance data.

Stage outcome
Donor data transformed into a verified, classified, and digitalised product library for procurement and allocation.

Stage 3 , Procurement & Handover

Path B

◎ **Purpose** Execute the commercial transfer and the *physical/data handover* of reclaimed elements and records, first from donor to intermediary, then from intermediary to target, preserving traceability and quality throughout.

Timing
After verification and classification; during ownership transfer and preparation for delivery or storage.

Communication focus

- Align schedules for removal, transport, and reception (donor → intermediary → target).
- Reference common datasets (Verification Dossier, Element Passports, DRP) in all agreements.
- Decide on storage strategy (on/off site) and handling requirements; record conditions.
- Maintain a single traceability chain across both transactions and both handovers.

Actors & responsibilities

Intermediary (broker / material bank)	Buyer from donor and seller to target; manages contracts, storage, and handover documentation.
Donor client / project manager	Execute sale and handover to intermediary; transfer ownership, liability, and documentation.
Target client / procurement officer	Purchase from intermediary; define reuse/traceability clauses in tender and contracts.
Legal advisors (all parties)	Ensure compliance and correct allocation of liability, warranty, and IP/data ownership.
IQC (independent)	Verify that physical items match records at each handover; sign off on documentation integrity.

Main output (checkpoint)

- *Sales / Purchase Agreements* (donor↔intermediary; intermediary↔target) referencing the same verified dataset.
- *Handover Package(s)* , inspection reports, verification data, photographs accompanying each shipment.
- *Material Transfer Register* , unified log mapping element IDs to documents across both handovers.
- *Storage & Logistics Plan* , storage location, handling method, and delivery sequencing with QA/traceability controls.
- *Updated Verification Dossier* , adds as-removed and as-delivered condition notes prior to installation.

Value added

- Seamless coupling of commercial transfer with technical/data handover.
- Clear accountability for quality and records at every transition.
- Reduced risk of loss, damage, or data gaps before construction.
- End-to-end auditable trail that builds market credibility.

Stage outcome

Verified elements and their records transferred to the buyer and prepared for delivery or storage with an unbroken traceability chain.

Stage 4 , Construction & Assembly

Path B

◎ **Purpose** Manage the physical transfer from intermediary custody to site and the on-site installation while preserving full traceability, quality assurance, and documentation integrity.

Timing

After procurement and handover; during delivery, inspection, and installation at the target site.

Communication focus

- Coordinate transport, delivery, and site verification between intermediary and contractor.
- Provide handling instructions, packaging, and inspection criteria.
- Check deliveries against *Element Passports*, DRP classes, and registers.
- Jointly document deviations, damage, or repairs.

Actors & responsibilities

Intermediary (broker / material bank)	Organise storage, packaging, and delivery; supervise quality checks; update records.
Transport & logistics providers	Execute transport under agreed safety, labelling, and traceability procedures.
Target contractor / site manager	Receive, inspect, and install elements per documentation and design assumptions.
Reuse coordinator / project engineer	Link installation records to verification data and design model.
IQC (independent)	Confirm compliance with traceability and quality protocols; sign off on site verification.

Main output (checkpoint)

- *Installation Verification Report* , placement/orientation/bearing confirmed; signed by principal designer/engineer, IQC, and AHJ where applicable.
- *Updated BIM / As-Built Model* , as-installed geometries, IDs, deviations.
- *Construction Quality Log* , inspections, lifting operations, NCRs with photos.
- *Safety & Compliance File* , permits, toolbox talks, and inspection reports for site activities.
- *Delivery & Verification Report* , shipment records + on-site checks consolidated post-installation.

Value added

- Clear roles for logistics, inspection, and reporting.
- Integration of intermediary, contractor, and engineering oversight.
- Unbroken traceability from market release to as-built documentation.
- Reduced risk through transparent checks and corrective actions.

Stage outcome

Verified elements installed with complete traceability and quality documentation captured in the project's records.

Stage 5 , Operation & Maintenance

Path B

◎ **Purpose** Preserve verified reuse information throughout the service life by maintaining a central registry that connects reused elements to their provenance and future reuse potential.

Timing

Post-construction and during operation; from building handover through its lifecycle.

Communication focus

- Maintain and update reuse documentation in a shared registry or material database.
- Exchange inspection results, maintenance actions, and performance updates.
- Verify and record changes affecting DRP ratings or reuse potential.
- Link operational updates to original verification and construction data.

Actors & responsibilities

Target owner / facility manager	Monitor performance; record maintenance; share updates.
Reuse coordinator / asset manager	Ensure updates are properly linked to reuse documentation.
IQC (independent)	Periodically review data integrity and alignment with records.

Main output (checkpoint)

- *Integrated Reuse Dossier (IRD)* , as-built geometries, verification data, maintenance instructions, inspection schedules.
- *Asset Information Model (AIM)* , BIM-linked dataset in the owner's AMS with properties, IDs, maintenance metadata.
- *Maintenance & Inspection Plan (MIP)* , monitoring frequency, protocols, thresholds for testing/intervention.
- *Performance Review Reports* , periodic summaries of structural/durability performance recorded in the AMS/registry.
- *Digital Material Registry* , live link back to element passports and provenance for future reuse.

Value added

- Clear separation of facility and data stewardship roles.
- Operational insights feed future verification and design.
- Transparent information continuity across reuse cycles.
- Long-term confidence via auditable, living records.

Stage outcome

Reuse data preserved and operationalised for future transfer, keeping the building a traceable resource for next-life applications.

Stage 6 , End-of-Life & Deconstruction

Path B

◎ **Purpose** Reactivate stored documentation and coordinate selective deconstruction so that verified materials and their data re-enter the reuse market, closing one lifecycle and enabling the next.

Timing

Late service life and demolition planning; initiated when the building is scheduled for transformation or replacement.

Communication focus

- Update condition data and verification records for documented elements.
- Coordinate selective deconstruction and recovery procedures.
- Refresh *Element Passports*, DRP classifications, and *Material Offer Sheets*.
- Re-list verified components on the intermediary's digital platform.

Actors & responsibilities

Target owner / facility manager	Notify intermediary; provide access to documentation and site.
Intermediary (broker / material bank)	Lead deconstruction planning; verify condition; update certifications; prepare offer sheets and listings.
Deconstruction contractor	Execute selective dismantling per protocols; document handling procedures.
IQC (independent)	Validate updated data accuracy; confirm conformity for market re-entry.

Main output (checkpoint)

- *Updated Material Passport Set* , latest condition data, interventions, dismantling instructions.
- *Residual Performance Assessment Report* , remaining strength, durability, and service-life potential.
- *Selective Deconstruction Plan* , sequence, safety, logistics, and handling protocols.
- *Continuity of Passport Record* , refreshed listings and full traceability chain linking past/presen-

t/future uses.

- *Lessons-Learned Summary* , operational performance and recommendations for next cycles.

Value added

- Defined roles for deconstruction, verification, and resale under a unified protocol.
- Integration of operational, demolition, and quality control via a central registry.
- Transparent, auditable trail across successive lifecycles.
- Higher market confidence and reduced risk at re-entry.

Stage outcome

Verified materials and documentation flow back into the reuse marketplace, restarting the circular loop with preserved data and accountability.

6.7. Implications of the communication framework

The framework introduces several implications for how circular construction projects can be organized and managed. These implications span both the *organizational* and the *technical* dimensions of reuse and directly correspond to the key barriers identified in Chapters 3 and 5. This subsection first establishes how the framework was empirically grounded in practice and then translates those insights into four overarching implications for circular project delivery.

6.7.1. Empirical grounding and translation

The development of the framework is directly informed by the empirical findings presented in Chapter 5. Table 6.3 links the barriers observed in the case studies to the mechanisms embedded within the framework, demonstrating how each conceptual component emerged from practical experience rather than theoretical abstraction.

Table 6.3: Empirical grounding of framework mechanisms

Case evidence	Barrier observed	Framework mechanism / response
Stationsplein 107 – Leiden	Fragmented coordination between demolition and design teams; structural engineers became involved only after the slabs had already been harvested.	**Temporal synchronization** , early integration of technical actors in Stage 1 and intermediary documentation to bridge timing gaps between demolition and design.
Prinsenhof A – Arnhem	Ambiguity in communication responsibilities; market actors hesitated to assume their roles due to the perceived risks and uncertainties associated with reuse.	**Responsibility alignment** , a *Reuse Communication Plan* specifying who communicates what, when, and to whom, thereby clarifying accountability across partners.
Stationsplein 107 – Leiden	Verification data and design assumptions were scattered across different project partners, limiting traceability.	**Information continuity** , standardized data carriers such as *Element Passports* and centralized digital storage managed by an intermediary to maintain consistent data access.
Udden / FLO:RE	Insights from earlier pilot projects were not transferred to subsequent ones; experiential knowledge remained localized.	**Feedback learning** , systematic end-of-life documentation (*Updated Reuse Record*) feeding lessons learned into future *Initiation & Planning* stages.

6.7.2. From evidence to implications

The empirical patterns summarized in Table 6.3 reveal that across all five case studies, communication barriers consistently constrained the reuse process. Engineers often entered projects too late, responsibilities were unclear, documentation was fragmented, and learning between projects remained localized. The framework translates these recurring barriers into structured responses through four interrelated implications. Each implication addresses one or more of the observed challenges, illustrating how the framework converts empirical lessons into systemic improvements for circular construction practice.

1. From ad-hoc to structured collaboration
The framework transforms communication from an informal, project-specific activity into a structured and traceable process. By embedding defined deliverables, such as the Reuse Communication Plan and the Verification Dossier, into each stage of the value chain, it provides a consistent procedural rhythm for collaboration. This predictability supports early alignment, reduces the dependence on individual initiative, and allows reuse projects to scale beyond isolated pilot cases. The implication directly responds to the fragmented and reactive coordination observed in Prinsenhof A and Stationsplein 107, where structured communication routines emerged only after technical challenges arose.

2. Institutionalizing data continuity
Through the use of boundary objects like the *Element Passport* and the *Material Offer Sheet*, the framework ensures that verified data are preserved and transferred across project boundaries. This continuity safeguards information quality and supports regulatory acceptance by maintaining traceable records of performance and decision-making. As a result, information management becomes a central enabler of circularity rather than a secondary administrative task. This implication builds directly on the experience of Stationsplein 107, where critical verification data were dispersed across partners and lacked a single, accountable source.

3. Integrating asynchronous project timelines
The dual-path model acknowledges that donor and target projects rarely occur simultaneously. By introducing temporal synchronization as a mechanism, the framework provides a means to manage asynchronous processes, either through direct coordination (Path A) or through the role of an intermediary (Path B). This flexibility allows reuse to occur even when demolition and reconstruction are separated by years, turning temporal misalignment into an opportunity for strategic planning. The need for this mechanism was particularly evident at Stationsplein 107, where the time lag between slab harvesting and design development created uncertainty about the suitability of the reclaimed elements.

4. Embedding learning and trust
Finally, the feedback learning mechanism transforms each project into a contributor to collective industry knowledge. Documented lessons from one reuse cycle become the starting point for the next, building organizational memory and increasing stakeholder confidence. By formalizing transparency and traceability, the framework enhances mutual trust, an essential precondition for circular collaboration among diverse actors. This implication directly reflects insights from Udden and FLO:RE, where valuable experience from early pilot projects was not systematically documented or shared with subsequent initiatives.

6.7.3. Communication intensity and actor interaction.

Building on these observations, Figure 6.4 visualises how the required effort for coordination and information exchange evolves across the six stages of the construction value chain, as well as the relative density of actor interactions within each stage. The vertical axis represents a relative communication intensity scale from 1 (minimal) to 10 (maximum). These scores were derived qualitatively to indicate the comparative level of coordination effort observed in reuse-oriented projects. A score of 1–3 represents routine, low-intensity information exchange typically managed through documentation or standard procedures; 4–6 indicates medium intensity, where multiple actors must coordinate intermittently to align technical or logistical tasks; and 7–10 reflects high-intensity phases requiring real-time, cross-disciplinary decision-making and a high degree of mutual dependency between actors. The actor interaction density, shown as shaded bars, expresses the diversity and number of stakeholders involved in each stage.

The peaks in *Initiation & Planning*, *Design & Engineering*, and *End-of-Life & Deconstruction* correspond to the most communication-intensive phases of the reuse process, precisely where circular projects have proven most vulnerable to misalignment in practice. In *Path A* (direct donor–target alignment), these stages show pronounced spikes as donor and target projects must synchronise their technical, logistical, and regulatory decisions simultaneously. In *Path B* (intermediary alignment), the curve is flatter and more evenly distributed: the intermediary buffers and redistributes information through digital documentation and standardised data carriers, lowering the overall coordination load. This results in a more stable but continuous communication profile across all stages.

These profiles underline a central implication of the framework: effective reuse depends not on constant communication, but on concentrated and well-structured interaction at predictable points in the process. By defining communication domains and deliverables for each stage, the framework transforms these high-intensity moments from potential risk zones into organised checkpoints for collaboration. In lower-intensity phases, such as *Operation & Maintenance*, information continuity is sustained through digital documentation rather than frequent exchanges, ensuring that verified data remain accessible throughout the lifecycle. Overall, the scoring highlights that circular projects require both strategically timed peaks of collaboration and steady, background information continuity to maintain reliability and traceability across the value chain.

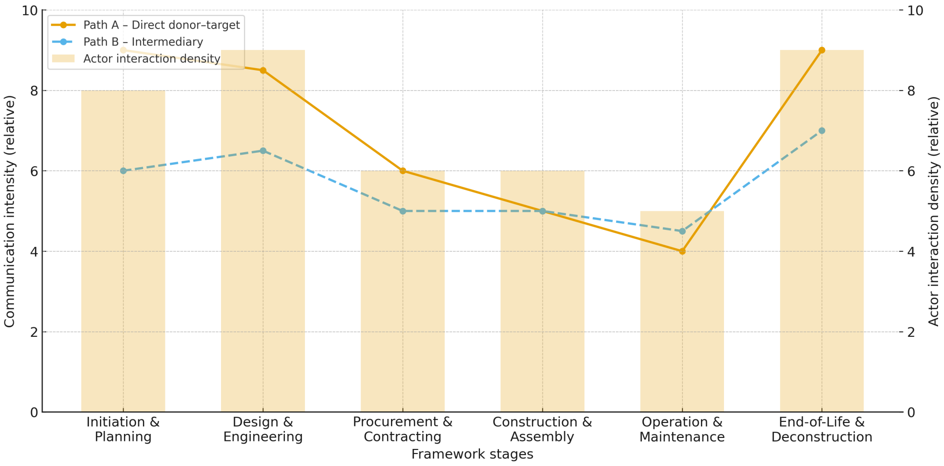


Figure 6.4: Communication intensity and actor interaction density across framework stages for Path A (direct donor–target alignment) and Path B (intermediary alignment)

6.7.4. Implications for research and policy

Beyond its practical relevance, the framework contributes to the academic and policy discourse on circular construction in several ways. First, it operationalizes the abstract concept of "communication in circular value chains" into a measurable, stage-based process. Second, it bridges two previously disconnected bodies of knowledge: the technical verification of reclaimed elements and the organizational management of reuse. Third, by clarifying roles and deliverables, it provides an empirical basis for standardization and the potential development of guidelines or future certification schemes for reuse communication.

Risk reduction through structured communication.

By addressing the systemic barriers identified in Chapter 5, the framework also functions as a risk mitigation tool. It reduces three interrelated forms of project risk:

- **Information risk** , mitigated by data traceability instruments such as the *Verification Dossier* and *Material Passport*;
- **Coordination risk** , reduced through responsibility alignment and temporal synchronization across donor–target timelines;
- **Performance risk** , managed via continuous feedback loops that ensure quality and verification data remain transparent.

These reductions translate directly into higher reliability, fewer design revisions, and a more predictable reuse process.

6.7.5. Framework success criteria

To evaluate whether the framework achieves its intended outcomes in practice, a set of qualitative and quantitative success criteria is proposed. These criteria align with the framework's four core mechanisms and the barriers it seeks to overcome. They will be used as reference points for the validation in Chapter 9.

- **Reduced information loss:** Degree to which verified data from donor projects remain accessible and usable during the target project's design and verification phases. This can be measured by comparing the completeness of documentation transferred versus that required.
- **Improved alignment efficiency:** Reduction in time and effort needed to achieve consensus among engineers, contractors, and clients regarding reuse feasibility. This reflects the success of responsibility alignment and communication structure.
- **Enhanced confidence and accountability:** Evidence of increased stakeholder trust in reuse decisions, as observed through interviews or project feedback. This indicates that communication deliverables are perceived as reliable decision instruments.
- **Effective temporal synchronization:** The framework's ability to maintain the usability of verified information over time gaps between donor and target projects. Measured through successful retrieval and reapplication of stored data.
- **Iterative learning and standardization:** Extent to which lessons from previous projects are captured, shared, and reused in subsequent cycles, demonstrating that feedback loops are functioning. This can be assessed through documentation audits or cross-project comparisons.

In summary, the framework's implications extend beyond improving communication; they reshape the organizational logic of reuse projects. By providing mechanisms for accountability, data continuity, temporal coordination, and learning, the framework creates the conditions for circular construction to become systematic rather than exceptional. The success criteria defined above serve not only as evaluation metrics but also as indicators of maturity in circular project communication. The next chapter applies these criteria to assess the framework's performance in practice, demonstrating how it can support the verification and reuse of concrete slab elements in real project environments.

7 Verification framework for cast-in-situ concrete slabs

7.1. Introduction and goal of the framework

Whereas the previous chapter addressed the organizational mechanisms required to coordinate reuse across donor and target projects, this chapter focuses on the technical dimension of reuse, specifically, on how reclaimed cast-in-situ concrete slabs can be systematically verified for structural and regulatory compliance. The goal of the verification framework is to provide engineers, inspectors, and project partners with a structured and transparent process for evaluating reclaimed slabs so that they can be safely integrated into new buildings under conditions comparable to newly manufactured elements.

The framework bridges a gap identified in both literature and practice: the absence of a standardized method that translates the performance requirements of EN 1992-1-1 and EN 1992-1-2 to the realities of reclaimed components. By defining consistent verification stages, testing methods, and documentation requirements, it enables a level of reliability equivalent to CE-marked precast products while remaining feasible for project-based certification.

In essence, the framework seeks to:

- Reduce uncertainty surrounding the mechanical performance, durability, and safety of reclaimed slabs.
- Align verification practice reused elements with existing Eurocode principles for new elements
- Provide a step-by-step structure for collecting, testing, and interpreting data on geometry, material properties, and durability.
- Create traceable documentation that supports approval by regulators and confidence among stakeholders.

Through these mechanisms, the verification framework complements the communication framework developed in Chapter 6: together, they integrate the organizational and technical dimensions of concrete reuse, ensuring that both collaboration and certification can proceed coherently from deconstruction to reintegration.

7.2. The Framework Logic

At its core, the verification framework adapts the certification logic of the CE-marking system for precast concrete products to the project-based reality of reclaimed structural elements. For new products, conformity with the Construction Products Regulation (CPR 305/2011) is demonstrated through Factory Production Control (FPC), Initial Type Testing (ITT), and continuous quality surveillance, as required by EN 13369 and the product-specific standard EN 13747:2005 +A2:2010 / NEN-EN 13747:2010. These standards define the essential characteristics, geometry, strength, durability, fire performance, and serviceability, that must be verified before a precast floor or roof element may receive a Declaration of Performance and CE-marking. Reclaimed cast-in-situ slabs fall outside this regulatory pathway because they lack the traceability and factory control that underpin the CE system. Nevertheless, the technical objectives of CE verification, demonstrating equivalent safety, serviceability, and durability, remain fully applicable.

To achieve this, the framework is guided by three core principles:

1. **Equivalence:** Reused slabs must achieve a level of structural reliability comparable to new CE-marked products, even when assessed through alternative procedures.

2. **Transparency:** Every verification decision, from inspection to documentation, must be traceable and reproducible within the project's quality system.
3. **Proportionality:** Verification efforts should correspond to the level of uncertainty and structural relevance of the element, ensuring practicality and cost-effectiveness.

Building on these principles, the framework translates the logic of the CE-marking system into a two-stage, project-based verification methodology. Continuous factory control is replaced by targeted on-site assessment and documentation, ensuring that reclaimed slabs are evaluated with the same rigour but within the constraints of reuse practice. The two complementary stages are:

1. **The Initial Element Assessment (IEA)** – analogous to Initial Type Testing in the CE system – which verifies the intrinsic properties of each reclaimed slab and establishes its *Declared Reuse Performance (DRP)*.
2. **The Reuse Production Control (RPC)** – functionally comparable to Factory Production Control – which governs the consistency of handling, storage, and documentation between assessment and final installation.

The two stages operate as interdependent layers of assurance: the IEA determines *what* each slab is capable of, while the RPC ensures *that* this verified performance is preserved as the element moves through the reuse chain. Together, they create a closed verification cycle that begins at deconstruction and concludes with the certified integration of the slab into its new structure, mirroring the logic of continuous quality control in CE-marked production.

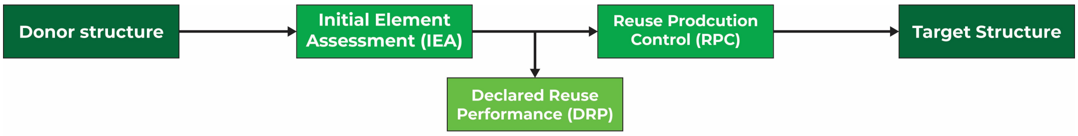


Figure 7.1: Process logic of the verification framework: from assessment to integration.

Section 7.2.1 introduces the Initial Element Assessment and the establishment of the Declared Reuse Performance, while Section 7.2.2 describes the Reuse Production Control and its role in maintaining verified performance throughout the reuse chain.

7.2.1. The Initial Element Assessment (IEA) and the Declared Reuse Performance (DRP)

The Initial Element Assessment (IEA) serves as the analytical core of the framework. It replaces the "Initial Type Testing" phase of CE-marking by verifying the actual properties of each reclaimed slab through a combination of documentation review, on-site investigation, testing, and engineering evaluation. The goal of the IEA is to establish a Declared Reuse Performance (DRP) profile, a standardized set of performance indicators that describe the verified capability of a reclaimed element.

Each DRP criterion, as shown in table 7.1 corresponds to one of the essential characteristics defined for new precast slabs in EN 13747, interpreted through the verification possibilities available for reclaimed elements.This ensures direct comparability between new and reused components while introducing flexibility where certain parameters cannot be demonstrated to the same level of certainty.

Table 7.1: Essential characteristics and Declared Reuse Performance (DRP) criteria for reclaimed floor elements.

Essential characteristic	**Measure / category**	**Declared Reuse Performance (DRP)**	**Verification method**
Geometry and tolerances	Length, width, thickness, camber, flatness	Within tolerance class (e.g., Class 2 of EN 13747)	On-site measurement, laser scanning, photogrammetry.
Concrete strength class	Characteristic compressive strength f_{ck}	Minimum C25/30 equivalent	Core tests (EN 13791), calibrated NDT (rebound hammer, UPV).
Durability	Carbonation depth, chloride ingress, surface condition	Carbonation depth $<$ reserve cover; chloride $<$ limit values	Phenolphthalein test, chloride profiles, visual inspection.
Structural performance	Bending/shear capacity, stiffness, deflection	Verified M_{Rd} and V_{Rd}; deflection within EC2 limits	EC2 recalculation with IEA inputs; selective load testing.
Fire resistance	REI classification; reinforcement cover depth	REI 60 / REI 90 depending on use class	EC2-1-2 calculation; cover survey; testing if required.
Hygiene, health and environment	Presence of hazardous substances; leaching behaviour	No asbestos/PAH; leaching values below thresholds	Targeted lab tests; visual and documentary screening.
Sustainability contribution	Reused mass; avoided embodied carbon	$\geq$30% slab area reused; LCA note (EN 15804)	Mass balance; EPD/LCA documentation; material passport.

Each DRP criterion is defined to ensure technical equivalence with the essential performance characteristics required for CE-marked elements while maintaining practical verifiability in the reuse context:

- **Directly verifiable criteria:** such as geometry, compressive strength, and reinforcement cover, can be measured with high confidence and therefore adopt the same acceptance ranges as new elements.
- **Partially verifiable criteria:** such as durability, fire resistance and structural performance, which depends on slab characteristic, which cannot directly be measured. In these cases an alternative characteristic or performance criteria must be established to achieve the DRP.
- **Context-dependent criteria:** such as sustainability and HHE, acknowledge that reuse projects must also demonstrate environmental and health compliance under current standards even if original documentation is lacking.

7.2.2. The Reuse Production Control

While the Initial Element Assessment (IEA) establishes the *Declared Reuse Performance* (DRP) for each reclaimed slab, the *Reuse Production Control* (RPC) ensures that these verified characteristics are preserved throughout the entire reuse process, from harvesting and storage to final installation. In essence, the RPC replaces the *Factory Production Control* (FPC) used in CE-marking, providing a structured and auditable quality-assurance system for elements that no longer originate from an industrial production line.

The objective of the RPC is twofold:

1. To safeguard consistency between the verified DRP values and the physical condition of the element at every handling stage.
2. To ensure traceability and accountability, so that each reclaimed slab can be re-certified for use based on verifiable documentation rather than assumptions.

The RPC is organised into three sequential stages, each corresponding to a distinct phase in the reuse chain. Together, these stages establish a closed-loop control cycle that mirrors the “plan–do–check–act” logic of industrial quality-management systems (Table 7.2).

Table 7.2: Overview of the three stages of the Reuse Production Control (RPC)

RPC Stage	Objective	Main Actors	Key Outputs
Stage 1 – Source Verification	Confirm that the reclaimed element entering the reuse process matches the DRP established in the IEA.	Demolition engineer, structural assessor	*Source Verification Report*, updated DRP, element ID record.
Stage 2 – Process Control (Handling and Storage)	Maintain the physical condition and documentary integrity of elements during transport, intermediate storage, and pre-assembly modification.	Storage operator, reuse coordinator, testing laboratory	*Process Logbook*, environmental and handling checklists.
Stage 3 – Output Control (Pre-Integration Verification)	Re-inspect each element immediately prior to installation to confirm unchanged geometry, absence of damage, and retention of DRP values.	Site supervisor, structural engineer, quality assessor	*Pre-Integration Certificate* confirming fitness for incorporation.

The RPC thus transforms the static verification achieved in the IEA into a dynamic, continuous quality-assurance process that spans the full reuse chain. By combining inspection routines, documentation standards, and clearly defined responsibilities, it establishes a level of reliability equivalent to factory-controlled production for reclaimed elements. In doing so, it provides both technical and institutional confidence that reclaimed slabs integrated through this framework comply with the same fundamental principles of safety, durability, and serviceability that underpin the CE-marking of newly manufactured precast products.

7.3. The Framework Mechanisms

The verification framework described in the previous section provides the structural foundation for assessing and certifying reclaimed slabs. To function in practice, however, this foundation must be supported by clear mechanisms that govern how verification data are generated, refined, and maintained throughout the reuse process. These mechanisms translate the framework's logic into a sequence of actions, linking inspection, testing, documentation, and control into one continuous assurance cycle.

The purpose of this section is to uncover the internal dynamics of the framework: how the Initial Element Assessment (IEA) and the Reuse Production Control (RPC) interact, how uncertainties are reduced before costly testing begins, and how results remain traceable across time and projects. By defining these mechanisms, the framework evolves from a static structure into a responsive system capable of managing variation in material quality, documentation reliability, and design-era conventions.

Three central mechanisms underpin this operation:

- **The two-step verification process**, which introduces a distinction between a *Preliminary Declared Reuse Performance* (pDRP) and a *Verified Declared Reuse Performance* (vDRP). This staged approach allows early identification of unsuitable elements in a project specification, focusing detailed testing only on promising candidates.
- **The era-based calibration approach**, which enables the estimation of unknown slab characteristics when documentation is lacking. By referencing the design codes, material standards, and construction practices of the slab's production era, this method allows missing parameters in the *Preliminary Declared Reuse Performance* (pDRP) to be inferred in line with the minimum requirements and design methodology of that time.
- **The feedback and documentation control loop**, which ensures that information produced during the IEA and the RPC remains linked, transparent, and re-verifiable whenever new conditions or deviations arise.

Together, these three mechanisms operationalise the verification framework introduced in Section 7.1. They enable a continuous and risk-managed transition from initial assessment to certified integration, ensuring that reclaimed slabs are verified with both technical accuracy and procedural clarity, conditions essential for their reliable use in modern construction.

7.3.1. The Two-Step Verification within the IEA

The verification of reclaimed slabs follows a two-step process that balances efficiency and reliability in the assessment of reuse potential. Because detailed testing and analysis can be costly and time-consuming, it is neither practical nor necessary to apply full verification to every recovered element. The framework therefore introduces a distinction between a *Preliminary Declared Reuse Performance* (pDRP) and a *Verified Declared Reuse Performance* (vDRP). This two-step verification process enables early risk screening and data-driven decision-making, ensuring that only elements with realistic potential for reuse progress to detailed testing and certification.

Step 1 , Preliminary Declared Reuse Performance (pDRP).
The pDRP represents an initial, knowledge-based estimation of a slab's expected performance, compiled before any destructive or extensive non-destructive testing is undertaken. It is derived from available documentation, visual inspection, and contextual information about the donor building, such as construction year, structural system, and standard material grades used in that period. When specific data are missing, the *era-based calibration approach* introduced in section 7.3.2 is applied to infer likely material and design parameters consistent with the norms and minimum requirements of the slab's construction era. The pDRP thus provides a reasoned approximation of geometry, reinforcement layout, concrete strength, and durability condition that serves as the basis for early feasibility decisions and test planning.

Step 2 , Verified Declared Reuse Performance (vDRP).
The vDRP is established once targeted verification has been completed through a combination of destructive and non-destructive tests, analytical recalculation, and conformity checks in line with Eurocode 2 and EN 206 procedures. At this stage, assumptions from the pDRP are either confirmed, refined, or rejected based on measured data. Only elements achieving a verified performance level consistent with their intended reuse application proceed to the Reuse Production Control (RPC). The transition from pDRP to vDRP therefore functions as a formal decision gate within the verification framework.

This staged approach reflects principles from *progressive reliability assessment* and *multi-level verification* used in the evaluation of existing structures (e.g., fib Bulletin 80, 2016; ISO 13822, 2010). These methodologies recognise that engineering decisions under uncertainty benefit from a sequential process: starting with broad, low-cost screening based on prior knowledge, and progressively incorporating higher-fidelity data as confidence increases. By adopting this logic, the two-step verification mechanism ensures that assessment effort is proportional to the potential value of the element and the level of uncertainty in the available information.

7.3.2. The Era-Based Calibration Approach

One of the most persistent limitations in verifying reclaimed concrete slabs is the frequent absence or incompleteness of original design documentation. To overcome this, the verification framework incorporates an era-based calibration approach, a method that allows missing parameters in the Preliminary Declared Reuse Performance (pDRP) to be estimated using information about the design codes, material standards, and construction practices that were prevalent at the time the slab was built. By classifying each element within a defined design and construction era, characteristic attributes, such as typical concrete strength, reinforcement type, and nominal cover, can be inferred from the regulatory and technological context of that period. This approach reduces the need for exhaustive testing while ensuring that all assumptions remain traceable and technically defensible.

The underlying logic is consistent with the principle of *knowledge-based assessment* found in ISO 13822, which recognises that the evaluation of existing structures should draw on all available sources of information, historical records, code evolution, and engineering judgement, rather than relying solely on new testing. In this framework, era-based calibration extends that philosophy by formalising how historical knowledge is translated into quantitative input for preliminary verification. Rather than prescribing new safety margins, it provides a structured way to infer likely material and detailing characteristics, ensuring that the pDRP remains evidence-based even when empirical data are limited. The following paragraphs outline how this concept is implemented through five distinct concrete-design eras, each defined by the dominant regulatory frameworks, material developments, and safety philosophies that shaped practice at the time.

The five concrete design eras

For the purposes of this framework, Dutch and European concrete design history is divided into five chronological *eras*, each characterised by distinct developments in material standards, analytical methods, and safety approaches. These divisions are not arbitrary; they represent meaningful transitions in the codification and industrialisation of concrete construction that affect the reliability of reclaimed elements.

1. **Era I – Pre-standardisation (before 1955)**
   Early reinforced-concrete structures were designed using empirical rules or company-specific guidelines. Material properties were poorly standardised, with concrete strengths typically between 10 and 20 MPa and smooth, mild-steel reinforcement bars. Detailing rules for anchorage, cover, and shear were minimal, and safety relied largely on conservative dimensions. This era represents the greatest uncertainty for reuse due to variability in both materials and workmanship.
2. **Era II – National standardisation (1955 – 1974)**
   The introduction of the first Dutch concrete code, *Gewapend Beton Voorschriften GBV 1962*, marked the beginning of systematic national regulation. Characteristic material strengths were formally defined (e.g., B25 ≈ C20/25), and design moved from allowable-stress concepts toward semi-probabilistic methods. Improvements in cement quality and curing control produced more consistent concrete, and ribbed reinforcement began to replace smooth bars, increasing bond reliability.
3. **Era III – Safety-factor reformulation (1975 – 1991)**
   The publication of *Voorschriften Betonconstructies VBC 1974* and later *VBC 1990* reflected a major conceptual shift: the adoption of the limit-state design philosophy and partial-safety-factor format. Material classes were expanded, higher-strength steels were introduced, and cover requirements were linked to exposure conditions. This era is distinguished by improved analytical consistency and greater alignment with developing European design thinking.
4. **Era IV – European harmonisation (1992 – 2004)**
   In the 1990s, Dutch codes began to align closely with emerging Eurocode principles. Reliability formats were calibrated to European statistical data, and exposure-based durability design became standard practice. The material classes from VBC 1990 were redefined in terms of characteristic strength and exposure class, creating direct compatibility with EN 206 and EN 1992.
5. **Era V – Eurocode 2 and performance-based design (2005 – present)** With the full adoption of NEN-EN 1992-1-1 and NEN-EN 1992-1-2, concrete design became fully harmonised across Europe. Reliability is now defined through partial-factor calibration at a target safety index ($\beta \approx 3.8$), and durability is addressed through performance requirements rather than prescriptive cover values. Materials are standardised through EN 206, and digital quality control and CE-marking ensure traceability of all structural elements.

The boundaries between these eras correspond to identifiable regulatory and technological transitions. The division between Eras I and II marks the shift from empirical practice to codified design, introducing the first nationwide concrete regulations. The transition to Era III reflects the adoption of the limit-state and partial-safety-factor concepts, fundamentally changing how reliability was quantified. Era IV emerges with the harmonisation of national codes with European standards, ensuring cross-border consistency, while Era V represents the culmination of this process in the fully harmonised Eurocode system. Eras II and III are sometimes considered together in practice, as both reflect the maturing of national standards, whereas Era IV and V collectively represent the European phase of code development.

7.3.3. Documentation and Feedback Control

Verification within the framework is conceived as a continuous process rather than a one-time result. To maintain alignment between the *Initial Element Assessment* (IEA) and the *Reuse Production Control*

(RPC), all information generated during inspection, testing, and handling is stored in a unified documentation and feedback system. This mechanism ensures traceability of data, transparency of decisions, and rapid updating of performance records whenever new information becomes available.

Each reclaimed slab is assigned a unique *Element ID* linked to a *Reuse Conformity File* (RCF) that compiles the preliminary and verified DRP sheets, test results, condition photos, RPC inspection notes, non-conformity reports, and the final Pre-Integration Certificate. Hosted within a digital platform or BIM environment, the RCF functions as both a project record and the technical foundation for a future material passport.

The feedback loop activates when events, such as damage, extended storage, or new test data, affect an element's verified condition. Relevant DRP parameters are then reviewed and, if needed, partially re-assessed to update the vDRP before the element re-enters the reuse chain. This closed-loop control, consistent with ISO 9001 principles of continuous quality management, preserves reliability and accountability across all verification stages.

Through this mechanism, the framework integrates the IEA and RPC into a single, self-updating assurance process, ensuring that every reclaimed slab remains verifiable and traceable from initial assessment to final integration.

7.4. The Initial Element Assessment

This section sets out the detailed methodology of the Initial Element Assessment, explaining how each essential characteristic of a reclaimed slab is evaluated to establish both the pDRP and vDRP. For every characteristic listed in Table 7.1, the relevant parameters, verification methods, and governing standards are defined. Together, these procedures provide a consistent basis for translating incomplete or uncertain information into measurable performance data. The resulting assessments form the technical foundation for the safe, transparent, and certifiable reuse of structural concrete slabs.

7.4.1. Geometry and Tolerances

Geometry & Tolerances

pDRP	vDRP
Threshold: Minimum required span and thickness under new project requirements	**Threshold: Class 2 tolerances (EN 13747) must be met**
🟢 Dimensionally compliant, directly reusable	🟢 Meets class 2 limits;directly reusable
🟡 Minor deviations, correctable through trimming or grinding	🟡 Small exceedance, correctable through trimming or grinding
🟠 Significant deviations requiring reworking or partial recasting	🟠 Major reworking needed to meet tolerances
🔴 Unsuitable spans or thickness for reuse	🔴 Geometric distortion or damage incompatible with reuse

Determination of the pDRP – Archival and Initial Measurements

The pDRP is determined based on a combination of archival documentation, on-site measurements, and visual inspection. Original drawings or digital models provide reference dimensions, while predemolition surveys verify slab length, width, and thickness using laser distance meters or total stations. Visible irregularities such as camber, spalling, or cracking are also recorded.

Measured values are then compared against the minimum required span and thickness of the new structural design. Slabs that meet these baseline requirements, or can be adjusted through minor trimming, are considered suitable for reuse and proceed to detailed verification. This rapid assessment ensures that only dimensionally viable elements are selected for further testing and harvesting.

Determination of the vDRP – Measurement and Verification

The Verified Declared Reuse Performance (vDRP) confirms compliance of extracted slabs with the Class 2 dimensional tolerances of EN 13747:2005 + A2:2010. This step establishes geometric precision and fit within the design tolerances of the receiving structure. The tolerances are based on Class 2 (general) limits for precast floor slabs, adjusted for reclaimed element variability, as shown in Table 7.3.

Table 7.3: Class 2 dimensional tolerances for precast and reclaimed reinforced-concrete floor slabs (adapted from EN 13747:2005 + A2:2010, Annex A)

Geometry measure	Class 2 tolerance	Notes / verification method
Overall length deviation	± 10 mm	Measured between end faces using total station or 3D scan
Overall width deviation	± 10 mm	Checked across slab width at multiple points
Thickness deviation	± 5 mm	Caliper, depth gauge or 3D section scan
Edge straightness (bowing)	≤ 10 mm	Deviation from straight line along full length
Squareness of corners	≤ 10 mm per m	Measured diagonally between corner points
Flatness / surface irregularity	≤ 8 mm under 2 m straightedge	Indicates local waviness or surface depression
Global camber / curvature	$\leq L/1000$ (max 10 mm)	Laser level or 3D scan profile along span
Edge damage (spalling)	≤ 5 mm deep or 5 % of edge length	Visual inspection or scan profile
Bearing length deviation	± 5 mm	Compared with design bearing length

All geometric parameters defined under Class 2 tolerances are verified after extraction using 3D laser scanning or total-station surveying as the primary method. Overall length and width are measured between slab edges at multiple points, while thickness is determined with a caliper, depth gauge, or extracted scan sections. Edge straightness is checked by comparing the edge line to a laser or stringline reference, and squareness is verified through diagonal corner measurements. Surface flatness and global camber are assessed using a laser level or 3D profile scan across the span. Edge damage is evaluated visually or through scan profiles, and bearing length is confirmed by direct measurement at the support zones. Together these checks ensure that the slab geometry conforms to the Class 2 precision required for safe structural reuse.

7.4.2. Concrete Strength Class

Concrete Strength Class

pDRP

Threshold: Minimum required class per exposure condition (EN 206 / EN 1992)

- 🟢 Verified $f_{ck,is} \geq$ required class; directly reusable
- 🟡 Slightly below target; reuse feasible with minor measures
- 🟠 Significantly below target; major intervention required
- 🔴 Strength inadequate; exclude from structural reuse

vDRP

Threshold: Minimum required class per exposure condition (EN 206 / EN 1992)

- 🟢 Verified $f_{ck,is} \geq$ required class; directly reusable
- 🟡 Slightly below target; reuse feasible with minor measures
- 🟠 Significantly below target; major intervention required
- 🔴 Strength inadequate; exclude from structural reuse

The threshold DRP

The concrete strength class is primarily required to perform the ULS and SLS verifications, as it defines the material's compressive strength used in structural calculations. However, according to Annex E of NEN-EN 1992-1-1, there is also a direct link between strength class and durability performance. Even though this annex is informative, it provides valuable guidance by indicating which minimum strength classes are suitable for different exposure classes, that is, which concretes are likely to resist corrosion and environmental degradation.

For this reason, Table E.1N from Annex E of NEN-EN 1992-1-1 is used here as a threshold reference to check whether the determined concrete strength class is adequate for the exposure class in which the reclaimed slab will be applied.

Table 7.4: Minimum concrete strength classes for reinforced concrete EN 1992-1-1 Table E.1N

Exposure class	Environmental condition	Minimum strength class
XC1	Dry or permanently dry interior environments	C20/25
XC2	Wet, rarely dry (e.g., foundations or slabs in ground contact)	C25/30
XC3	Moderate humidity; interior with occasional condensation	C25/30
XC4	Cyclic wet and dry; exposed to rain or splash water	C30/37
XD1	Moderate chloride exposure (airborne or occasional de-icing salts)	C30/37
XD2	High chloride exposure from de-icing water (e.g., splash zones)	C35/45
XD3	Extreme chloride exposure (direct contact with de-icing or seawater)	C35/45
XF1	Moderate freeze–thaw without de-icing agents (protected structures)	C30/37
XF2	Freeze–thaw with de-icing salts (e.g., car parks, roads)	C35/45
XF3	Severe freeze–thaw with water saturation	C35/45
XF4	Severe freeze–thaw with de-icing agents	C40/50

Determination of the pDRP – Archival and Initial Measurements

The pDRP for concrete strength is determined from a combination of archival sources and code-based interpretation. Original design drawings or specifications, typically expressed in historical systems such as K- or B-classes, are translated conservatively into the modern NEN-EN notation using the normative correspondence shown in Table 7.5. This translation provides an estimated equivalent C-class (e.g., B35 ≈ C28/35) that can be compared against the minimum strength requirements for the relevant exposure class in Table 7.4.

When no archival strength information is available, the minimum concrete strength class prescribed in the normative era of construction is used as an initial estimate. If no explicit minimum class was specified in that era, the most commonly used strength class is adopted instead, marked with an asterisk in Table 7.5. This assumption ensures a conservative yet realistic basis for initial assessment prior to laboratory verification.

Table 7.5: Translation of historical concrete strength systems to modern EN 206 / EN 1992 classes and indicative minimum values per era

Era	Historical class notation	Minimum or typical class used at the time	Equivalent modern class (EN 206 / EN 1992)
Era I , (before 1955)	K150–K250 (kg/cm^2)	K150[*] (≈15 MPa)	K150 ≈ C8/10 K175 ≈ C12/15 K250 ≈ C16/20 K300 ≈ C20/25
Era II , (1955–1974)	K-classes and early B-classes (GBV 1962)	K160	K150 ≈ C8/10 K250 ≈ C16/20 K300 ≈ C20/25
Era III , (1975–1991)	B15–B45 (VBC 1974–1990)	B15	B25 ≈ C20/25 B30 ≈ C25/30 B35 ≈ C28/35 B45 ≈ C35/45
Era IV , (1992–2004)	Early adoption of C-classes	C20/25	C16/20–C25/30 common; transition to full EN 206 use

[*] Indicative minimum class, actual values varied by project and local specification.

An archival concrete strength that falls slightly below the nominal strength class required for a given application does not necessarily imply that the slab is unsuitable for reuse. The 28-day characteristic strength used to define concrete classes is a conventional reference rather than an indication of the material's final performance. Extensive long-term research demonstrates that concrete continues to gain strength far beyond this age. Classical studies summarised by Neville, 2011 show that concretes stored under field conditions may reach 2–3 times their 28-day strength after several decades. More recent 10-year field data from Lee et al., 2024 confirm this behaviour, with ordinary Portland concretes increasing from roughly 30 MPa at 28 days to about 50 MPa after prolonged natural curing.

This long-term strength gain corresponds closely with the strength-development model prescribed in Eurocode 2, which predicts that concrete will reach mean strengths approximately 1.3–1.5 times the 28-day mean value depending on cement type. The Eurocode formulation reads

$$f_{cm}(t) = \beta_{cc}(t), f_{cm,28}, \qquad \beta_{cc}(t) = \exp[s(1 - \sqrt{28/t})], \tag{7.1}$$

where $s = 0.25$ for CEM I and $s = 0.38$ for CEM III. Figure 7.2 illustrates this development for two typical mixes (C16/20 and C18/22). As shown, a C16/20 concrete can be expected to reach approximately 29 MPa (CEM I) to 32 MPa (CEM III) after 500 days, significantly above its nominal 28-day classification.

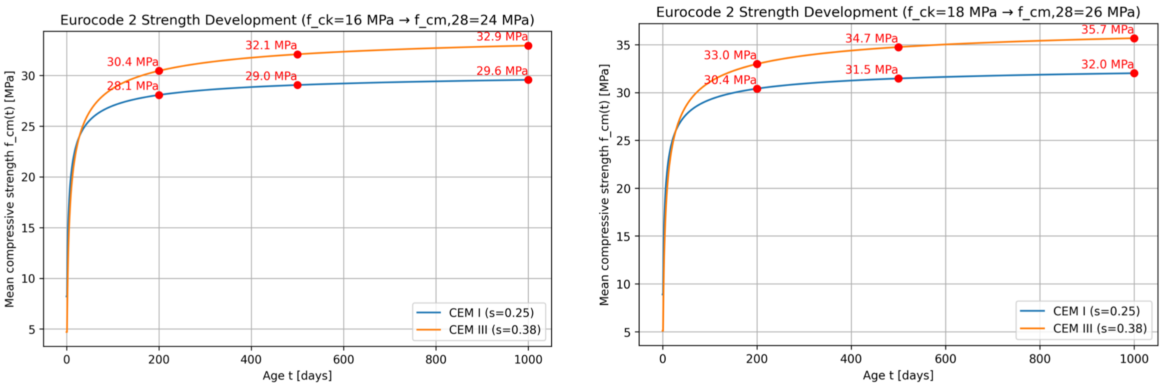


Figure 7.2: Strength development according to Eurocode 2 for two concrete classes over 1000 days.

The measured in-situ strengths obtained during assessment therefore typically reflect this decades-long hydration process and are often higher than the original design class, even when they appear slightly below the required strength at first inspection. After applying the necessary Eurocode corrections and statistical evaluations, a reliable characteristic in-situ strength can be established. This derived value may still meet, or closely approach, the performance required for reuse. Consequently, a slab that nominally “fails” a 28-day-based strength-class check can nevertheless be structurally adequate when its actual long-term strength is used within the Eurocode safety format. A minor shortfall below the nominal minimum class therefore does not automatically render an element unusable; rather, it highlights the importance of evaluating reuse potential based on measured long-term performance instead of conservative archival classifications.

Determination of the vDRP – Measurement and Verification

The vDRP is determined through direct measurement of the in-situ compressive strength in accordance with *EN 13791*. Representative core samples are extracted following *EN 12504-1* and tested under controlled laboratory conditions to establish the *characteristic in-situ compressive strength*, $f_{ck,is}$. Supplementary non-destructive methods, such as rebound hammer or ultrasonic pulse velocity testing, may be used to extend coverage, provided they are calibrated against the core test results. This verified classification translates the obtained test data into actionable design input, ensuring that the Declared Reuse Performance accurately reflects the actual mechanical capacity and durability of each slab in compliance with *EN 206* and *EN 1992*.

7.4.3. Durability

Durability

pDRP	vDRP
Threshold: Meets EN 206 minimums for target exposure (w/c, c_{nom}, cement) by documentation or era-based conservative defaults	**Threshold: Performance-based check (fib MC 2020, LoA2): remaining life for carbonation / chlorides $\geq$ required; cover $\geq$ required; XF qualitatively satisfied**
🟢 Parameters meet EN 206 for intended exposure	🟢 Remaining life $\geq$ design period; cover verified
🟡 Slight shortfall; minor measures can close gap	🟡 Slightly low; feasible with limited measures
🟠 Notable gap; major intervention or lower exposure	🟠 Below target; major mitigation or reclassification
🔴 Inadequate/unknown; exclude from structural reuse	🔴 Fails performance check; not suitable for reuse

Determination of the pDRP , Archival information and conservative assumptions

The pDRP for durability is established from archival documentation (drawings/specs with w/c, cement content, nominal cover) and, if data are incomplete, conservative era-based defaults from Table 7.6.

Table 7.6: Conservative durability defaults per design era (use when archival data are missing)

Era	Cover [mm]	w/c max	Cement min [kg/m^3]	Basis / note
Era I (before 1955)	10*	0.70*	250*	Workmanship-based practice; no codified minima. Use very conservative values and verify condition.
Era II (1955–1974)	25	0.60	280	Early national rules (GBV/NEN 3840) with basic limits; carbonation governed.
Era III (1975–1991)	30	0.55	300	VBC 1974–1990 prescriptive durability; environment-dependent cover.
Era IV (1992–2004)	35	0.55	300	Hybrid national/EN 206 approach; exposure classes introduced.

Notes: Values with * denote indicative/most common practice, not codified minima. For Eras II–IV, entries represent conservative lower bounds consistent with typical national guidance at the time.

These values are compared to the EN 206 minimums for the intended exposure class (Table 7.7).

Table 7.7: Minimum durability parameters per exposure class (EN 206 / EN 1992-1-1)

Class	Environment (typical condition)	$c_{\mathrm{min,dur}}$ [mm]	w/c max	Cement min [kg/m^3]
X0	No risk (dry indoors; permanently in fresh water)	10	0.65	260
XC1	Carbonation, dry or fully immersed	25	0.65	260
XC2	Wet, rarely dry (soil/water contact)	30	0.60	280
XC3	Moderate humidity (standard indoor)	30	0.55	280
XC4	Cyclic wet/dry (outdoor slabs, rain)	35	0.55	300
XD1	Chlorides, moderate humidity (e.g., indoor parking)	35	0.55	300
XD2	Chlorides, wet contact (soil/water)	40	0.55	320
XD3	Chlorides, cyclic de-icing	45	0.45	340
XF1	Freeze–thaw, no de-icing	35	0.55	300
XF2	Freeze–thaw with de-icing salts	40	0.55	320
XF3	Severe freeze–thaw (high saturation)	45	0.50	320
XF4	Severe freeze–thaw with de-icing	50	0.45	340

Determination of the vDRP , Measurement and performance verification

The exposure classes defined in EN 206 aim to ensure that concrete elements achieve their intended service life with minimal maintenance under specific environmental conditions. Each class prescribes mix and detailing requirements, such as maximum water–cement ratio, minimum cement content and nominal cover to provide adequate protection against deterioration. However, for reclaimed slabs only the concrete cover can still be verified directly, while parameters like water–cement ratio and cement content can no longer be determined after casting.

Because reclaimed slabs have already been in service, their actual durability performance must be assessed by evaluating their current state and forecasting their future resistance to degradation. This shifts verification from prescriptive mix requirements to measurable indicators of in-situ performance, forming the basis for the performance-based durability assessment used in the vDRP stage.

For concrete floor slabs, the primary deterioration mechanisms that reduce reinforcement protection are:

- **Carbonation-induced corrosion**, where CO_2 neutralises the concrete's alkalinity;
- **Chloride-induced corrosion**, where chlorides penetrate the cover and depassivate the reinforcement.

These mechanisms govern almost all relevant exposure conditions for reclaimed slabs, while chemical attack (XA) and freeze–thaw (XF) effects are secondary or negligible when standard protective measures, such as air entrainment and limited crack widths ($\leq$,0.3,mm), are present.

To evaluate durability, the verification adopts the fib Model Code 2020 performance-based approach, which models corrosion protection loss as a time-dependent process. By combining measured in-situ data (e.g. carbonation depth, chloride profile, and cover) with calibrated design parameters, the analysis estimates the **time to corrosion initiation** (t_{ini}) and the remaining service life(t_{remain}). This remaining-life concept offers a rational, transparent means to verify that reclaimed slabs can achieve the same durability reliability as new structures. The following sections apply this method separately to carbonation and chloride ingress using the Level of Approximation 2 (LoA2) framework of the *fib Model Code 2020*.

The carbonation model

The carbonation model used in this study estimates the time at which corrosion can begin in a carbonation-exposed environment, that is, when the carbonation front reaches the reinforcement and the concrete can no longer guarantee passive conditions. This moment does not represent structural failure, since corrosion damage develops only after a further and uncertain propagation period, but it is widely accepted as the relevant durability limit state because it marks the transition from a fully protected to a potentially corrosive condition.

For reclaimed slabs, this threshold is especially important. Reusing existing elements supports environmental goals, yet many slabs originate from older structures with concrete properties that differ from current standards. Using the initiation time as the durability criterion therefore provides a conservative and transparent safeguard: if the predicted initiation time exceeds the intended service period, the slab is judged sufficiently durable for reuse, while structural safety and serviceability are evaluated separately in the mechanical assessment.

The function used to establish the carbonation effect in the concrete in the fib Model Code 2020 is as follows:

$$x_c(t) = K_{comb} \cdot \sqrt{t} \tag{7.2}$$

where $x_c(t)$ is the carbonation depth at time t and K_{comb} is the combined carbonation coefficient incorporation reference, environmental, material and workmanship factors. The value for K_{comb} can be established in two ways:

1. Based on the calibrated factors established in the norm to achieve the required $\beta \approx 1.5$ for durability states, this is K_{design}.

Table 7.8: LoA2 design parameters for carbonation exposure classes (EN 206 XC1–XC4) calibrated to $\beta \approx 1.5$.

Exposure class	$K_{\mathrm{ref},d}$ [mm/$\sqrt{\text{year}}$]	$k_{e,d}$	$k_{c,d}$	$k_{t,d}$
XC1 – dry indoor	4.0–4.5	0.8–1.0	0.6–0.8	1.00–1.15
XC2 – wet, rarely dry	4.0–4.5	0.7–0.9	0.6–0.8	1.00–1.15
XC3 – moderate RH (sheltered)	4.0–5.0	1.0	0.6–0.8	1.00–1.15
XC4 – cyclic wet/dry	4.5–5.0	1.25–1.35	0.6–0.8	1.15–1.30

Parameter ranges based on *fib Bulletin 34* (2006).

2. Based on the measured carbonation depth in the slab $x_{c,meas}$ that has progressed over the current life time t_{past}, the resulting factor is then $K_{fit} = \frac{x_{c,meas}}{\sqrt{t_{past}}}$.

To determine a conservative value for this K_{comb} the $K_{use} = \max[K_{design}, K_{fit}]$ and this can be used to find the total time till the initiation of corrosion of the reinforcement:

$$t_{ini} = \left(\frac{c_{eff}}{K_{use}}\right)^2 \tag{7.3}$$

In this formula the $c_{eff} = c_{meas,min} - 5$mm to take into acoount the measure uncertainty. The remaining life time is then established through:

$$t_{remain} = t_{ini} - t_{past} \tag{7.4}$$

The chloride ingress model

For chloride-related durability, two situations are distinguished. In the first situation the slab originates from a chloride-exposed environment (XD/XS). In this case the measured chloride content after many years of exposure is itself a performance indicator. If the chloride concentration at or near the reinforcement depth is well below the critical range, typically less than 0.03–0.05% chloride by mass of concrete, the long-term behaviour demonstrates that ingress has been minimal. Since chloride penetration requires a continued external source, no further accumulation is expected once this exposure ceases, and ingress will remain limited even if the slab is reused in a comparable chloride environment. Under these conditions, the existing chloride measurement provides sufficient evidence that chloride-induced corrosion will not become critical in the future, and detailed diffusion modeling is not required.

In the second situation the slab has not previously been exposed to chlorides but will be reused in an XD environment. Here there is no past ingress to assess, so future behaviour must be forecast. The fib Model Code 2020 chloride ingress model is applied using design parameters for surface concentration and diffusion coefficient corresponding to the relevant exposure class together with the measured effective cover. This approach is conservative, since mature existing concrete often exhibits lower diffusion coefficients than the design values. Cracking is accounted for through the use of the minimum effective cover rather than by modifying the diffusion model itself, ensuring that the calculated time to chloride-induced depassivation provides a safe approximation.

The fib Model Code 2020 describes chloride penetration as a diffusion-controlled process governed by Fick's Second Law. The analytical solution for one-dimensional diffusion in a semi-infinite medium with a constant surface concentration is expressed as:

$$C(x,t) = C_0 + (C_s - C_0)\,\mathrm{erfc}\left(\frac{x - \Delta x}{2\sqrt{D_{app}(t)t}}\right) \tag{7.5}$$

In this formula the following variables are used:

- $C(x,t)$ is the chloride concentration at depth x and time t,
- C_s is the surface chloride concentration
- C_0 is the initial chloride content of the concrete
- Δx is a surface correction term (often taken as zero)
- $D_{app}(t)$ is the apparent, time-dependent diffusion coefficient

In this formula the apparent diffusion coefficient decreases with time due to hydration and pore refinement, following the aging model:

$$D_{app}(t) = D_{ref}\left(\frac{t}{t_{ref}}\right)^{-\alpha} \tag{7.6}$$

where D_{ref} is the reference diffusion coefficient at the reference time t_{ref} (typically 28-90 days), and α is the ageing exponent, usually between 0.2 and 0.4.

The variables in this model are based on the design values given in the fib model code:

Table 7.9: LoA2 design parameters for chloride exposure classes (EN 206 XD/XS) calibrated to $\beta \approx 1.5$.

Exposure class	$C_{0,d}$ [% cem]	$C_{s,d}$ [% cem]	$D_{\mathrm{ref},d}$ [m^2/s]	α	$C_{\mathrm{cr,d}}$ [% cem]
XD1 – low de-icing risk	0.02–0.10	0.40–0.60	(0.5–1.5)×10^{-11}	0.20–0.35	0.40
XD2 – moderate de-icing risk	0.02–0.10	0.50–0.80	(0.8–1.8)×10^{-11}	0.20–0.35	0.40
XD3 – high de-icing risk	0.02–0.10	0.60–1.00	(1.0–2.5)×10^{-11}	0.20–0.35	0.40

The parameters correspond to design conditions producing $\beta \approx 1.5$ for a 50-year design life. Verification uses $C(c_{\mathrm{eff}}, t_d) \leq C_{\mathrm{cr,d}}$ with $\Delta c \approx 15\,\mathrm{mm}$.

In order to find the time till initiation of chloride damage, the design parameters are filled into the following equation:

$$C(c_{eff}, t_{ini}) = C_{cr} \tag{7.7}$$

This equation cannot be solved analytically for t_ini and is therefore solved iteratively or numerically. Spreadsheet or root-finding methods are typically used to identify the time at which the calculated chloride concentration at the reinforcement depth equals the threshold.

The remaining initiation period can then be determined using:

$$t_{remain} = t_{ini} - t_{past} \tag{7.8}$$

Similar to the carbonation model the time to initiation is determined rather than the time till failure.

A change of environment

When a concrete slab is reused, it may move from one exposure environment to another, so the deterioration mechanism that governed its previous service life may differ from the mechanism that will govern its performance after reinstallation. Slabs originating from carbonation-driven environments (XC classes) usually show no meaningful chloride ingress because chlorides require a specific source such as de-icing salts or seawater, whereas slabs from chloride-rich environments (XD classes) may also exhibit carbonation since carbonation can occur wherever CO_2 and moisture are present.

To establish the present condition of the slab, a carbonation test is always performed to confirm whether the carbonation front has reached the reinforcement. When the slab comes from a chloride-rich environment, a chloride screening test is added to determine whether past chloride exposure has already produced critical concentrations. If it is evident that a mechanism was not active in the former environment, only minimal verification is required to confirm its absence.

Because carbonation and chloride ingress are independent processes, the deterioration model used for future assessment depends solely on the environment in which the slab will be placed after reuse. Past deterioration is accounted for only through the measured current state, and the model corresponding to the future exposure class is applied from that starting point. No interaction between the two mechanisms needs to be considered, and the mechanism that governed the previous environment does not influence the modeling of future deterioration.

Temporary storage forms a short intermediate exposure phase, typically governed by mild carbonation when slabs are kept outdoors or under shelter. This effect can be incorporated as a small additional carbonation increment, or considered negligible when storage is brief and the environmental severity is low. Chloride ingress is unlikely during storage since the slabs will not be stored in marine or de-icing salt environments.

7.4.4. Structural Performance

Structural Performance

pDRP

Threshold: Estimated bending capacity based on archival load data or minimum reinforcement provisions

- 🟢 Predicted M_{Rd} clearly exceeds design effects
- 🟡 Capacity slightly above or close to demand
- 🟠 Capacity below demand; major modification needed
- 🔴 Insufficient structural capacity; no modification possible

vDRP

Threshold: Verified ULS and SLS performance based on archival and measured reinforcement and concrete strength

- 🟢 ULS and SLS satisfied
- 🟡 Capacities slightly below or close to design effects
- 🟠 Below design capacity; major modification needed
- 🔴 Fails ULS/SLS; strengthening not possible

Determination of pDRP - Archival information and conservative assumption

In the pDRP stage, only the moment capacity is considered because bending often governs the structural performance of most floor slabs. At this stage two options to give an initial estimate for the moment capacity are used:

1. **The initial load method** by Küpfer et al., 2024 estimates moment capacity from the original design loads and safety factors, reflecting the actual reinforcement provided at the time.
2. **The minimum reinforcement method** gives a conservative lower-bound estimate based on code minima, but since most slabs contain more steel than the minimum, the load-based approach offers a more representative measure of real capacity.

Initial load method

The basis of the initial load method is the identification of the loads that these slabs were designed for. It is important to establish if the loads that were used were the characteristic load or the design load. In table 7.10 the safety concepts from the different times were used. These can be used to return the design loads to characteristic load such that they can be translated to the design load under current practice.

Table 7.10: Overview of safety concepts and typical factors applied across Dutch design eras

Era	Safety Concept	Typical Factors Applied
Era I (before 1955)	Implicit safety achieved through conservative material assumptions and large section sizes.	No explicit factors; implicit global safety margin $\gamma \approx 2.0$–2.5.
Era II (1955–1974)	Allowable stress design	Allowable stress was $0.55 - 0.60 \times f_{yk}$
Era III (1975–1991)	Semi-probabilistic design with explicit material strengths and global load factor.	Typical $\gamma = 1.8$ on total load (no distinction between G and Q).
Era IV (1992–2004)	Separate partial factors for loads and materials introduced.	$\gamma_G = 1.35$, $\gamma_Q = 1.50$, $\gamma_c = 1.50$, $\gamma_s = 1.15$.

Once the loads are determined it is important to establish the moment capacity. An important factor to take into account is the fact that the cast-in-situ slabs come from a monolithic system. In monolithic floor systems, continuity with adjacent spans and beams provides additional restraint, resulting in reduced mid-span moments and enhanced overall stiffness. When reclaimed as a simply supported element, this continuity is lost. The maximum moment capacity of a monlithic structure is thefore calculated as a slab between two rigid supports:

$$\frac{1}{24} q_d l^2 \tag{7.9}$$

Minimum reinforcement method

When no archival load calculations are available, the minimum reinforcement method provides a conservative lower-bound estimate of the slab's bending capacity.This approach assumes that the slab was at least reinforced to satisfy the minimum steel ratios required in the design code valid at the time of construction.By using these codified minima (table 7.11, the method ensures that the calculated resistance reflects the least amount of reinforcement that could have been legally placed, guaranteeing a safe estimate even when limited information is available.

Table 7.11: Typical minimum reinforcement ratios across design eras for reinforced concrete slabs

Era	Reinforcement Philosophy	Minimum Longitudinal Reinforcement Ratio ($\rho_{\min}$)	Notes / Transverse Reinforcement
Era I (before 1955)	No formal minimum; based on experience.	0.20–0.25 %* (indicative typical practice).	Transverse reinforcement irregular; based on craft practice.
Era II (1955–1974)	First formal national minima introduced under allowable-stress design.	0.25–0.30 %.	Transverse reinforcement $\approx$ 20 % of main steel.
Era III (1975–1991)	Codified minima linked to steel grade under limit-state "*Breukmethode*".	0.20–0.25 % ($f_{yk} \geq 400$ MPa → 0.20 %).	Transverse reinforcement $\geq$ 20 % of principal steel.
Era IV (1992–2004)	Same as VBC, with ductility and crack-width criteria added.	0.20–0.25 %.	Spacing and anchorage rules formalised.

Note: Values marked with * represent indicative practice only, as no codified minima existed before national standardisation.

Based on these minimum requirement the area of the reinforcement can be calculated:

$$A_{s,min,principal} = \rho_{min} bt \qquad A_{s,min,transverse} = \alpha_t A_{s,min,principal}$$

In order to then calculated the maximum moment capacity sectional equilibrium is considered between the tension and compression force, using this equilibrium the lever arm between these two forces is established. In this calculation the material strenghts are used in thier design value form:

$$f_{yd} = \frac{f_{yk}}{\gamma_s} = \frac{f_{yk}}{1.15} \qquad f_{cd} = \alpha_{cc}\frac{f_{ck}}{\gamma_c}$$

$$T = A_s f_{yd} \qquad C = \eta f_{cd} b \lambda x \qquad \Rightarrow \qquad x = \frac{A_s f_{yd}}{\eta f_{cd} b \lambda}$$

In this formula $\eta = 1.0$ and $\lambda = 0.8$ for $f_{ck} \leq 50$ MPa. For the $b = 1000$ mm is taken. The final lever arm is then:

$$z = d - \frac{\lambda}{2}x \qquad d = h - c_{nom} - \frac{\varphi}{2}$$

The h is the thickness of the slab, c_{nom} is $c_{min} + 5$ and φ the diameter of the reinforcement, in this assumption 8-10 mm would suffice. The moment capacity can be calculated using the following expression:

$$M_{Rd,min} = Tz = A_s f_{yd}\left(d - \frac{\lambda}{2}x\right) \tag{7.10}$$

Determination of vDRP - Archival information and measurements

The verified Declared Reuse Performance (vDRP) for structural performance follows a two-step approach depending on the availability of information. In both cases, the slab's bending capacity is determined using the lever-arm method explained in the minimum reinforcement strategy of the pDRP stage, from this an equivalent design load can be derived using:

$$\frac{1}{8}q_d l^2 = M_{Rd} \Rightarrow 8\frac{M_{Rd}}{l^2} \tag{7.11}$$

This relation allows the verified moment resistance to be translated into a design load for performing full ULS and SLS checks according to the Eurocode framework. The reinforcement amount that must be put in this calculation are derived using the following two steps:

1. **The archival verification:** When design drawings, reinforcement schedules, or calculation reports are available, these are reviewed to identify the reinforcement layout, bar diameters, and spacing.
2. **Measured verification:** If no reliable archival data are available, the reinforcement configuration and material properties are obtained directly from the slabs through electromagnetic scanning, selective exposure, and concrete strength testing.

7.4.5. Fire Resistance

Fire Resistance

pDRP	vDRP
Threshold: Preliminary verification using Level 1 tabulated data (EN 1992–1–2 §5.7.2) based on archival or era-based estimates of slab thickness and reinforcement distance	**Threshold: Verified compliance using measured slab thickness, reinforcement cover, and bar diameter; confirmation of non-combustible surface layers**
🟢 Meets REI limits for h_s and a	🟢 Meets fire cover + non-combustible finish
🟡 Near limit; minor fix OK	🟡 Near limit; minor adjustment OK
🟠 Below limit; major fix or downgrade	🟠 Below limit; major change needed
🔴 Far below / data missing; not reusable	🔴 Combustible finish / non-compliant

Threshold DRP

For reclaimed slabs, the verified DRP for fire resistance is determined exclusively using the Level 1 tabulated data method of EN 1992-1-2. This approach suits reclaimed floors because their geometry and exposure conditions align with the tabulated assumptions: simply supported solid slabs, exposed from one side, with regular reinforcement and homogeneous sections. The Eurocode tables already include conservative allowances for material variability, moisture, and temperature effects, making advanced analyses unnecessary for such elements. REI compliance is therefore verified by directly comparing the measured slab thickness (h_s) and reinforcement distance ($a = c + \frac{1}{2}\varphi$) with the tabulated minima. If both parameters meet these thresholds and the finishes are confirmed non-combustible, the slab is considered compliant for reuse at the required fire-resistance class.

Table 7.12: Minimum requirements for fire resistance of simply supported reinforced concrete slabs exposed from one side (adapted from EN 1992-1-2, Table 5.8)

Fire resistance class	Minimum slab thickness [mm]	Minimum reinforcement distance [mm]	Indicative application
REI 30	60	10	Internal slabs, low-risk occupancies.
REI 60	80	20	Standard residential and office floors.
REI 90	100	30	Public buildings, light industrial areas.
REI 120	120	40	Heavy occupancies, parking decks.
REI 180	150	55	Critical infrastructure, airport terminals.
REI 240	175	65	High-hazard or safety-critical facilities.

Determination of pDRP - Archival infromation and conservative assumptions

At the pDRP stage, fire resistance is assessed, based on archival or era-based information. The two required input parameters, slab thickness and reinforcement distance, are estimated from available documentation such as drawings, specifications, or historical calculation notes. If no records exist, typical nominal covers and bar diameters from the relevant code era are used to conservatively approximate a as shown in table 7.13.

Table 7.13: Era-based conservative assumptions for preliminary fire-resistance verification (pDRP) of reclaimed slabs

Design era	Nominal cover[mm]	Bar diameter[cm]	Notes
Era I (before 1955)	10–20	12–16	No codified minima; empirical detailing; large variability in workmanship.
Era II (1955–1974)	15–25	10–14	*GBV 1962* introduced minimum cover
Era III (1975–1991)	25–35	10–12	*VBC 1974/1990*; codified durability; distinct covers for interior vs. exterior exposure.
Era IV (1992–2004)	25–45	10–12	Transitional NEN 6720 + early EN 206; exposure-based cover requirements introduced.

These provisional values are compared with the Eurocode tabulated minima for the target REI class.If both parameters exceed the required limits, the slab is considered likely compliant and suitable to proceed to verification.

Determination of vDRP - Measurements

The vDRP stage confirms fire-resistance compliance through direct measurement of the slab's physical properties. The total thickness is measured at representative locations, including only non-combustible finishes, while the reinforcement distance is determined using cover-meter readings or selective exposure to verify both cover and bar diameter. The measured values are then compared with the EN 1992-1-2 Table 5.8 thresholds for the required REI rating. If both parameters meet or exceed the prescribed minima, and the finishes are confirmed to be non-combustible, the slab is verified as fire-resistant for reuse at that class.

7.4.6. Hygiene, Health and Environment

Unlike the other characteristics, hygiene, health, and environmental (HHE) aspects cannot be estimated from visual inspection or archival data. They require documented material testing and certification under standardized procedures and therefore do not form part of the DRP framework. Instead, HHE verification is a mandatory precondition for reuse: tests and documentation must be completed and approved before demolition to prevent contamination risks during both deconstruction and reconstruction.

The purpose of HHE verification is to ensure that a reclaimed element's origin, composition, and exposure history are known, and that potential risks to human health or the environment are identified and mitigated before reuse. It confirms that the element:

- contains no hazardous substances that could be released during reuse or processing;
- complies with environmental emission limits for indoor and outdoor applications; and
- can be handled, cut, and reprocessed safely by workers on site or in prefabrication facilities.

Incomplete or missing HHE documentation can delay environmental approval, increase disposal costs, or disqualify otherwise suitable elements. Early identification and testing therefore ensure safe, compliant, and efficient reuse.

HHE Verification and Required Tests

To ensure compliance with CPR and national environmental requirements, the following tests and verifications should be carried out for reclaimed concrete elements prior to deconstruction:

- **Leaching test** (NEN 7375 or EN 12457): Determines the release of heavy metals, chlorides, sulphates, and other soluble substances under standardized conditions.
- **Asbestos screening** (NEN 5896): Combines visual inspection with laboratory analysis to confirm the absence of asbestos fibres in old mortars, coatings, or repair materials.
- **PCB and PAH analysis**: Checks for persistent organic pollutants in sealants, coatings, or release agents that may have been used during the original construction.
- **Radiological assessment** (NEN 5697 / EU BSS Directive 2013/59/Euratom): Verifies that the natural radioactivity index (I_{rad}) of the concrete remains within acceptable limits for building applications.
- **VOC and formaldehyde emission tests** (EN ISO 16000 series): Required for elements with composite finishes, adhesives, or coatings intended for indoor reuse.

The results of these tests must be included in the Element Passport or reuse documentation package to confirm environmental compliance and to guarantee that the reclaimed elements can be safely handled, processed, and reused without posing health or environmental risks.

7.4.7. Sustainability contribution

The sustainability contribution is not a necessarily mandatory verification step, but it provides essential insight into the potential climate benefits of reusing reclaimed slabs. In many project, reuse decisions are influenced as much by environmental performance as by technical feasibility. Demonstrating a substantial reduction in embodied carbon compared with new production is therefor often a deciding factor for implementation.

The analysis follows the framework of EN 15804 and ISO 14040/44, using a life cycle assessment (LCA) to determine how much greenhouse gas emission can be avoided through reuse. In this analysis the embodied carbon is measure in kg CO_2 eq per m_3.

The life-cycle stages considered in the assesement

The LCA covers the production (A1–A3), construction (A4–A5), use (B1–B7), and end-of-life (C1–C4) stages. In case of most reclaimed elements no Environmental Product Declarations (EPD) are available, meaning that the data used for new slabs must be altered such that it is applicable for reclaimed slabs. In figure 7.3 the stages considered and their impact are displayed.

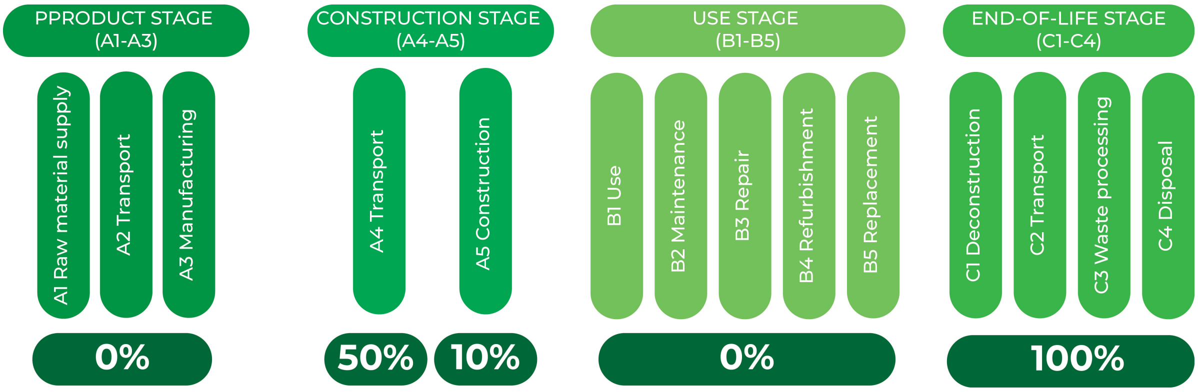


Figure 7.3: Overview of life-cycle stage considerations and applied impact shares for reclaimed concrete slabs

In accordance with EN 15804, the environmental assessment of reclaimed slabs focuses on the processes required for their second life only. The embodied impacts from the original production (Modules A1–A3) are fully attributed to the first life and therefore excluded (0 %), ensuring that the analysis reflects only the avoided emissions from new production. Modules A4 and A5 include the transport of the reclaimed slabs to the new project and their limited reconditioning and installation effort, typically accounting for 50–100 % and 5–10 % of the corresponding impacts of a new element, respectively. The use stage (Module B) and end-of-life stage (C1–C4) are considered identical to those of new slabs, as both will ultimately undergo the same demolition and recycling processes. Module D, representing potential benefits beyond the second life (such as future recycling or energy recovery), is intentionally omitted, since its inclusion would double-count benefits that belong to later life cycles. This approach isolates the true environmental advantage of reuse within the current system boundary.

Environmental Product Declaration (EPD) data

The environmental data used in this assessment are sourced from the Nationale Milieudatabase (NMD), which provides verified Environmental Product Declarations (EPDs) for Dutch construction materials. Only Category 3 datasets following the A2 assessment method are used, ensuring consistency, transparency, and comparability with standard Dutch practice.

The following tables present representative embodied carbon data for commonly used Dutch concrete strength classes (C20/25–C35/45) and cement types (CEM I, CEM IIIA, CEM IIIB, and CEM IIIC), along with corresponding reinforcement steel data. Other datasets may be substituted if they are of equivalent quality and composition. This selection ensures that differences in GWP values reflect reuse efficiency, not variations in mix design or data quality.

To apply the EPD data, the environmental impact of each life-cycle module is multiplied by the total **volume of concrete** and **mass of reinforcement steel** associated with the reclaimed elements. This can be performed either *per individual slab*—by calculating the slab volume and reinforcement ratio—or for the *entire batch of slabs* considered within the project. The global warming potential (GWP) of each module is then obtained as:

$$\text{GWP}_{\text{module}} = (\text{Volume}_{\text{concrete}} \times \text{GWP}_{\text{concrete}}) + (\text{Mass}_{\text{steel}} \times \text{GWP}_{\text{steel}})$$

Summing the contributions across all relevant modules (A4–C4 for the reuse scenario, A1–C4 for the reference new slab) provides the **total embodied carbon** of each case. Comparing these totals quantifies the **carbon reduction potential** achieved through reuse. This calculation can be applied on a **per-slab basis** for detailed verification or aggregated to the **project level** to express the overall sustainability contribution of the reuse strategy.

Table 7.14: Adjusted environmental impact values for reclaimed concrete slabs (GWP per module, kg CO_2e/m^3)

Concrete class	Cement type	A1–A3	A4 (50%)	A5 (10%)	B	C1	C2	C3	C4
C20/25	CEM I	0	8.9	2.7	–	23.9	18.0	3.53	0.15
C20/25	CEM IIIA	0	8.9	2.2	–	23.9	18.1	3.55	0.15
C20/25	CEM IIIB	0	9.0	2.0	–	23.9	18.0	3.55	0.15
C20/25	CEM IIIC	0	9.0	1.9	–	23.9	18.1	3.55	0.15
C25/30	CEM I	0	9.0	2.8	–	23.9	18.1	3.55	0.15
C25/30	CEM IIIA	0	9.0	2.3	–	23.9	18.2	3.56	0.15
C25/30	CEM IIIB	0	9.0	2.1	–	23.9	18.1	3.55	0.15
C30/37	CEM I	0	8.9	2.8	–	23.9	17.8	3.50	0.14
C30/37	CEM IIIA	0	8.9	2.3	–	23.9	17.9	3.52	0.14
C30/37	CEM IIIB	0	8.9	2.1	–	23.9	17.9	3.52	0.14
C30/37	CEM IIIC	0	8.9	1.9	–	23.9	17.9	3.52	0.14
C35/45	CEM I	0	8.7	2.9	–	23.9	17.6	3.46	0.14
C35/45	CEM IIIA	0	9.1	2.5	–	23.9	18.4	3.61	14.84
C35/45	CEM IIIB	0	9.1	2.2	–	23.9	18.4	3.61	14.84

Adjusted according to reuse scenario percentages: A1–A3 = 0%, A4 = 50%, A5 = 10%, B = 100%, C = 100%. Module D is excluded to avoid double counting benefits beyond the second life.

Table 7.15: Adjusted EPD data for reinforcement steel in reclaimed concrete slabs (kg CO_2e per tonne per module)

Material	A1–A3	A4 (50%)	A5 (10%)	B	C1	C2	C3	C4
Reinforcement steel	0	7.5	13.0	–	–	5.3	24.2	0.3

Adjusted according to reuse scenario percentages: A1–A3 = 0%, A4 = 50%, A5 = 10%, B = 100%, C = 100%. Module D excluded to maintain consistency with the system boundary shown in Figure 7.3.

7.5. The Reuse Production Protocol

The Reuse Production Control (RPC) complements the Initial Element Assessment (IEA) by safeguarding the verified quality of reclaimed slabs throughout their handling, storage, and reinstallation. While the IEA determines an element's technical suitability, the RPC ensures that this verified quality is maintained under consistent, traceable conditions, from deconstruction to integration in the new structure. Together, they form a continuous verification loop from assessment to reuse.

The RPC establishes a structured framework for maintaining verified quality after the IEA across five key activities:

1. **Selective deconstruction and handling** – safe removal and lifting without damage or loss of structural integrity.
2. **Condition verification** – inspection and testing of geometry, reinforcement, and material properties.
3. **Storage and logistics** – preservation of mechanical and environmental quality with full traceability.
4. **Reconditioning** – minor repairs or dimensional adjustments prior to reuse.
5. **Integration and assembly** – controlled installation according to design specifications.

The control framework is divided into three stages:

- **Stage 1 – Input Control:** Converts IEA results into a traceable harvesting plan, covering preparatory activities before and immediately after deconstruction.

- **Stage 2 – Process Control:** Maintains and documents slab quality during handling, transport, storage, and reconditioning.
- **Stage 3 – Output Control:** Verifies before installation that each slab still complies with its Declared Reuse Performance (DRP) and that all records confirm safe reuse.

Each stage defines specific responsibilities, documentation, and verification activities, ensuring that every reclaimed slab remains compliant and fit for structural reuse.

Stage 1 , Input Control

RPC

◎ **Purpose** Bridge the IEA and the RPC by converting verified IEA results into a safe, traceable harvesting plan, and by planning any post-harvest tests needed to complete the assessment.

Timing

Immediately before deconstruction and during the first post-harvest activities.

Verfication focus

- Confirmation of IEA outcomes and element selection (IDs, labels, datasets).
- On-site condition and stability checks of donor structure.
- Harvesting Plan: cutting patterns, lifting points, temporary supports, safety.
- Post-harvest testing plan (cores, carbonation/chlorides, reinforcement exposure).
- Traceability set-up (QR codes / element register / data linkage).

Actors & Responsibilities

Reuse coordinator	Coordinate IEA, engineer, and contractor; check completeness; approve the Harvesting Plan.
Structural engineer	Verify stability during deconstruction; review cutting/support; define post-harvest tests.
Demolition / deconstruction contractor	Execute removal per plan; record deviations/damage; ensure site safety.
IQC (independent)	Check documentation consistency; confirm traceability; sign off Pre-Harvest Verification Report.

Main output (checkpoint)

Pre-Harvest Verification Package comprising:

- **Pre-Harvest Verification Report** (IEA consolidation, remaining tests, approved Harvesting Plan),
- **Updated Element Register / Material Passport** (IDs, locations, authorisations),
- **Risk & Safety Checklist** (stability, lifting capacity, site-specific provisions).

Value added

- Ensures only technically approved elements are harvested.
- Prevents quality loss during removal through predefined methods and controls.
- Establishes end-to-end traceability from donor to storage.

Stage outcome

Verified IEA results translated into a traceable, safe harvesting plan with planned post-harvest tests and clear responsibilities.

Stage 2 , Process Control

RPC

◎ **Purpose** Maintain and document the verified quality of reclaimed elements during handling, transport, storage, and reconditioning. Ensure that the mechanical and durability properties confirmed through the IEA and Stage 1 testing remain intact and traceable throughout all operations.

Timing
During all operational phases following removal up to reinstallation or transfer to the target project.

Verification focus

- Execution of harvesting and handling following the approved Harvesting Plan.
- Post-harvest testing (cores, cover depth, carbonation, chloride).
- Visual inspections at key transfer points (site, transport, storage).
- Documentation of reconditioning or minor repairs.
- Environmental protection and correct storage conditions.
- Continuous traceability and record management of all elements.

Actors & Responsibilities

Reuse coordinator	Oversee handling and storage activities; ensure traceability between donor and target projects; maintain quality documentation.
Reuse / demolition contractor	Execute handling, transport, and storage; perform inspections; record damage or non-conformities; carry out minor reconditioning.
Structural engineer	Advise on lifting points and support; interpret post-harvest tests; assess structural implications of observed damage.
IQC (independent)	Conduct periodic inspections; verify test results and on-site conditions; approve the Reconditioning and Storage Log.

Main output (checkpoint)
Reconditioning and Storage Package containing:

- **Reconditioning and Storage Log** , record of handling steps, inspections, and tests.
- **Corrective Action Register** , documentation of damage and repairs.
- **Updated Material Passport entries** , reflecting post-harvest testing and current condition.

Value added

- Ensures verified mechanical and durability properties are preserved through all handling phases.
- Maintains transparency and traceability across operations and logistics.
- Enables early detection and correction of quality deviations.

Stage outcome
Verified quality of reclaimed slabs maintained and documented throughout handling, storage, and reconditioning, forming the traceable basis for Stage 3 output control.

Stage 3 , Output Control

RPC

◎ **Purpose** Act as the final quality gate before installation, confirming that each reclaimed slab complies with its Declared Reuse Performance (DRP) and that all documentation from the IEA and previous RPC stages supports its safe integration. Ensure that verified structural and durability properties are retained and demonstrably meet regulatory and design requirements.

Timing

Immediately before installation or handover to the target project.

Verification focus

- Review and consolidation of IEA, Stage 1, and Stage 2 documentation.
- Final visual inspection and confirmatory non-destructive or load testing.
- Verification of reconditioning works (patching, trimming, anchorage modifications).
- Approval for installation and traceable release of elements.
- Issuance of Reuse Conformity Certificates.

Actors & Responsibilities

Design engineer	Perform final structural verification; confirm compliance with design and DRP requirements.
Site supervisor	Oversee inspection and installation readiness; ensure handling and positioning follow the approved plan.
Reuse coordinator	Consolidate all documentation; confirm traceability; authorise the Reuse Conformity Certificate.
IQC (independent)	Validate inspection records, test data, and certificates; perform random on-site verification checks.

Main output (checkpoint)

Final Reuse Verification Package containing:

- **Reuse Conformity Certificate** , approval for installation of each element meeting DRP.
- **Final Quality Review** , consolidated inspection and approval records from all RPC stages.
- **Updated Material Passport entries** , with installation data and final location in the new structure.

Value added

- Ensures verified performance before integration into the new structure.
- Consolidates all quality and traceability documentation in one package.
- Provides formal approval and certification for safe, compliant reuse.

Stage outcome

Confirmed compliance of each reclaimed slab with its DRP and authorised release for installation, completing the Reuse Production Control (RPC) verification cycle.

7.6. The Framework Implication

The verification framework establishes a structured process for assessing the technical suitability of reclaimed cast-in-situ concrete slabs for reuse. Just as the communication framework addressed the organizational coordination of reuse, the verification framework operationalizes the *technical assurance* dimension of circular construction. It translates empirical lessons from case studies and standards into a transparent, test-based procedure that enables engineers to demonstrate compliance, manage uncertainty, and assign reliable Declared Reuse Performance values to reclaimed structural elements.

7.6.1. Empirical grounding and translation

The framework is directly informed by the empirical evidence drawn from the projects analyzed in Chapter 5. In each case, the absence of standardized testing and inconsistent verification practices were key obstacles to reuse. At *Stationsplein 107*, verification relied on ad-hoc testing of cores and rebar scans; in *Prinsenhof A*, reclaimed slabs were certified through project-specific tests due to the lack of European equivalence procedures; and in *FLO:RE*, Swiss probabilistic verification methods showed how safety levels could be quantified through systematic testing. Table 7.16 links these observed challenges to the framework's mechanisms, illustrating how empirical lessons informed the structured verification logic.

Table 7.16: Empirical grounding of verification framework mechanisms

Case evidence	Barrier observed	Framework mechanism / response
Stationsplein 107 – Leiden	Fragmented and inconsistent testing procedures; lack of confidence in measured strength and durability values.	**Standardized testing sequence** , introduction of fixed test quantities and verification criteria for geometry, material, and performance.
Prinsenhof A – Arnhem	No recognized equivalence to CE marking; verification repeated per project.	**Project-based certification logic** , definition of vDRP levels and proportional testing aligned with Eurocode 2 and EN 206.
FLO:RE – Switzerland	Uncertainty in probabilistic safety; limited comparability of test results.	**Verification threshold calibration** , introduction of vDRP categories linked to measured reliability levels and test reproducibility.
Udden – Sweden	Limited understanding of durability and fire resistance; empirical testing only.	**Expanded verification scope** , inclusion of durability, fire, and environmental indicators in the vDRP determination.

7.6.2. From evidence to implications

Across all projects, verification emerged as the most decisive step between ambition and implementation. While the communication framework structured *who* collaborates and *when*, the verification framework defines *what* must be proven and *how*. It bridges the empirical fragmentation observed in pilot projects by converting qualitative assessments into reproducible, quantitative thresholds. The framework therefore generates four overarching implications for circular verification and reliability.

1. From fragmented to standardized verification

The framework transforms verification from an ad-hoc, project-dependent exercise into a reproducible process. By defining five verification domains: geometry, concrete strength, durability, structural performance, and fire resistance. It ensures that reclaimed slabs are assessed in a manner that is auditable, consistent, and defensible, without implying that the slabs themselves are inherently unreliable.

Crucially, the verification domains do not seek to prove that the slab is “good enough”, as decades of safe use already demonstrate that. Instead, these tests:

- create traceable evidence that can be used in warranty, liability, and hand-over processes;
- address risk perceptions among stakeholders unfamiliar with reused structural elements;
- replace missing factory documentation that new precast elements would normally have (CE marking, FPC, declarations of performance).

Each domain contains fixed minimum testing requirements that together produce the element’s *Verification Declared Reuse Performance* (vDRP):

- **Geometry:** 3D laser scan or manual survey (minimum 3 slabs per batch); dimensional tolerance and deviation recording.
- **Concrete strength:** 6 core compression tests (EN 13791) per batch of up to 100 m^2, calibrated with 3 rebound-hammer readings per core.
- **Durability:** 3 carbonation depth tests (phenolphthalein method) and/or 3 chloride ingress tests (lab titration) per slab type.
- **Reinforcement:** 2 cover-depth scans and 2 GPR mappings per slab to verify bar spacing, diameter, and anchorage length.
- **Fire resistance:** 2 cover checks for combustible remainders.

Together, these requirements amount to approximately **20 tests per slab type or 100 m^2 of floor area**, providing a statistically robust dataset for assigning vDRP values. This quantification brings transparency, comparability, and legal defensibility to reuse verification.

2. Proportional testing and data confidence

The proportional testing logic builds directly on the pDRP–vDRP structure. Because the pDRP already shows that a slab is highly likely to be suitable, based on archival data, geometry, and minimal inspection, testing is only performed once a reuse commitment is made. Verification therefore becomes a confirmation step, not a screening step.

Testing intensity then scales with the intended reuse category: full-domain testing for equivalent reuse, reduced testing for downcycled reuse, and extended or statistical testing only for upcycled or safety-critical applications. This mirrors Eurocode reliability principles: confidence is achieved not through more testing, but through proportional, traceable evidence aligned with the intended performance class.

3. Bridging regulatory and practical verification

By aligning the vDRP categories with existing European standards (EN 206, EN 1992-1-1, EN 1992-1-2), the framework establishes a common language between engineers, regulators, and contractors. It introduces a verification dossier comparable to a Declaration of Performance but based on project-specific data, enabling authorities to review reclaimed elements using familiar documentation structures. This alignment supports the gradual institutionalization of reuse within standard certification pathways and reduces uncertainty in approval processes.

4. Enabling cumulative learning and material traceability

Each verified slab generates a digital verification record containing geometry, test results, and assigned vDRP scores. By storing these records in an *Element Passport*, the framework transforms isolated test results into reusable data assets. This ensures that future projects can access verified material data, reducing redundant testing and fostering a learning cycle between successive reuse projects. Over time, this cumulative documentation enhances both market trust and scientific understanding of long-term material performance.

Implications for research and policy

Beyond its practical function, the verification framework contributes to broader research and policy objectives. It demonstrates that reclaimed elements can be certified through transparent, test-based evidence rather than presumption of inferiority. By formalizing vDRP assessment, it provides a reference point for national authorities seeking to integrate reuse into building regulations. At the research level, it establishes a reproducible methodology for linking empirical testing with reliability modelling, enabling future calibration of partial safety factors for reused materials.

Framework success criteria

To evaluate whether the verification framework achieves its intended outcomes, several success criteria are proposed:

- **Reduction in uncertainty:** Degree to which vDRP values correlate with observed in-service performance and reduce reliance on conservative design assumptions.
- **Testing efficiency:** Ratio between number of tests performed and verified slab volume; target $\leq$ 20 tests per 100 m^2 without loss of reliability.
- **Regulatory acceptance:** Extent to which vDRP dossiers are recognized in permitting and tender processes.
- **Data continuity:** Percentage of verified elements with digital passports successfully transferred to subsequent reuse projects.
- **Cross-project comparability:** Evidence that results across projects show consistent statistical variance within ±10 % of reference strength and durability parameters.

In summary, the verification framework redefines the technical foundation of circular construction. By translating empirical uncertainty into quantifiable reliability, it creates a pathway for reclaimed slabs to re-enter the market as certified, trustworthy building components. Through standardized testing, proportional verification, and cumulative data management, it transforms verification from a barrier into a mechanism for circular confidence and structural assurance.

STEP IV

Validation

8 The Validation Case

The purpose of this chapter is to introduce and describe the validation case that will be used to test and demonstrate the applicability of the frameworks developed in this thesis. The validation case serves as a bridge between theoretical development and practical implementation, enabling an evaluation of how the proposed frameworks perform under realistic project conditions.

Specifically, the case is used to validate two complementary components of the thesis: the communication framework, which addresses the organizational and collaborative aspects of reuse projects, and the verification framework, which focuses on the technical assessment and regulatory alignment of reclaimed cast-in-situ concrete slabs. Applying both frameworks within a single case environment makes it possible to examine how they interact and reinforce one another in practice.

The selected case – the Schiphol C-pier redevelopment project – provides a representative and complex context for testing. It involves the selective deconstruction of reinforced concrete slabs from an existing structure and their intended reuse in a new airport development, aligning directly with the thesis' focus on piecewise reuse of cast-in-situ concrete floors. By exploring this case, the chapter aims to demonstrate the operational feasibility, coordination processes, and verification logic that underpin circular reuse of structural elements at scale.

The subsequent sections present (i) a general overview of the C-pier and its original construction, (ii) the structural and geometric characteristics of the harvested slabs, (iii) the design requirements for their potential reuse in the new development and the intended design, (iv) the stakeholder involvement in this project . Together, these sections establish the foundation for the following validation chapter, where the frameworks are applied to assess their usefulness and robustness in guiding reuse practice.

8.1. A general overview of the C-pier at Schiphol Airport

In 1967, Schiphol inaugurated a new terminal complex, which included a total of three piers designated for aircraft boarding. The C-pier, back then known as the Zuidpier in the design and the A-pier in use, was part of this new complex. Since then the C-pier has undergone several modification. In 1970 the building was adjusted to accommodate the larger Boeing 747. The adjustments that were done enabled the pier to handle wide-bodied aircraft, marking Schiphol's readiness for the jumbo jet era. As part of this renovation, the stick-shaped base was extended with an additional "head" and "two ears" resulting in the shape it has today. The shape is shown in figure 8.1 it also shows what is considered to be the original pier and what is considered to be the extension. The reason for this discrepancy between the two is the difference in structural elements.

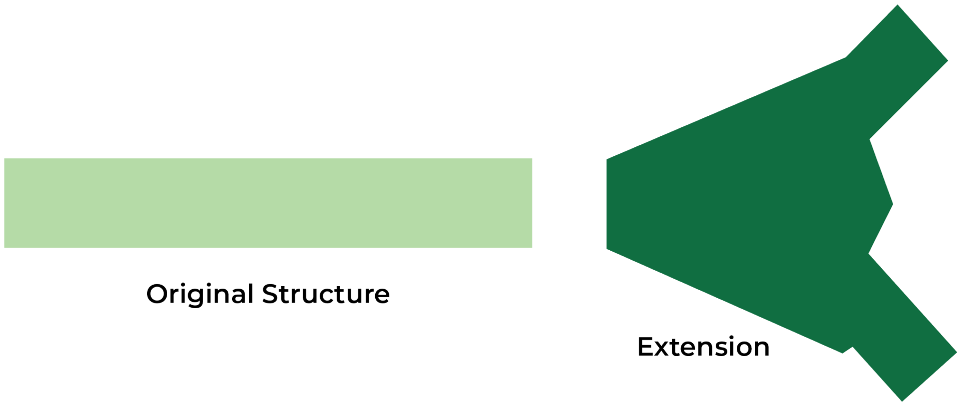


Figure 8.1: The two parts of the original C-pier

The C-pier is located in the Schengen part of the airport. The wing has 21 gates and is with around 10 million passengers and 74 thousand flights, one of the busiest wings of the airport. Most activities take place on the first floor which is an open area for passengers to wait, some shops are placed in between the gates. The lower floor is more restricted, this is were the installations are placed and some exists for passengers can be found. Though most passengers will enter the plane through the air bridges connected to the first floor.

8.1.1. The lay out of the original floor system in the C-pier

The primary focus of this thesis is the reuse potential of cast-in-situ reinforced concrete slabs. These elements constitute a significant portion of the C-pier structure, although not all floor systems within the building fall under this category. Specifically, the entire ground floor and the first floor of the original section of the C-pier are constructed using cast-in-situ slabs.

The original structural system of the pier employs a relatively straightforward construction method. Concrete frames are positioned at regular intervals of 8.25 meters and are interconnected by a series of beams. The cast-in-situ floor slabs are then placed on top of these beams. On the ground floor, the slabs have a thickness of 200 mm, while those on the first floor are 100 mm thick. A representative cross-section of one of the original structural bays is shown in figure 8.2.

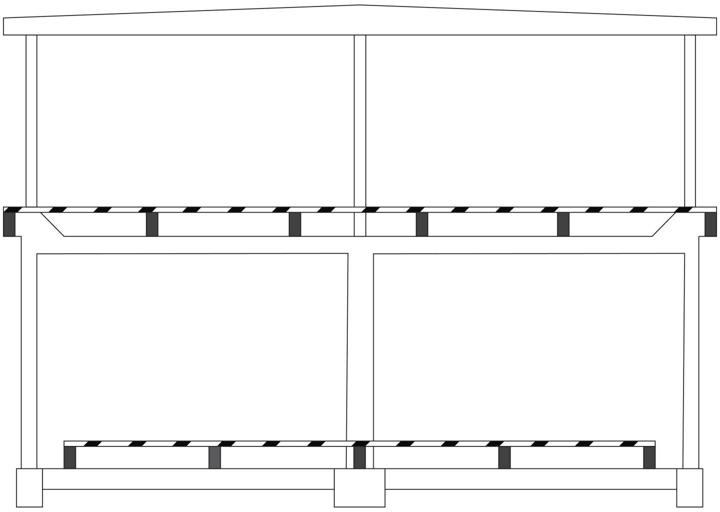


Figure 8.2: Cross-section original part C-pier

Based on the cross-section shown in figure 8.2, it can be observed that, in the typical layout, five slabs can be harvested from the first floor and four slabs from the ground floor. However, there are a few exceptions to this regular pattern, specifically where a travelator is installed on the first floor or where staircases are placed, which occurs in two instances.

In contrast to the repetitive layout of the original section of the C-pier, the extension features a more complex structural configuration, particularly in the arrangement of the floor slabs. Due to the triangular geometry of the extension, the slabs are arranged in a fan-like pattern, as illustrated in figure 8.3. This results in many slabs deviating from a standard rectangular shape, often being cut off at the edges.

For reuse purposes, it is essential that the slabs maintain a rectangular form. Therefore, slabs in the extension must be cut to the desired shape, ideally between the beams to simplify the cutting process. Similar to the original C-pier, the distance between beams is 8.25 m, which allows for harvesting slabs of comparable dimensions.

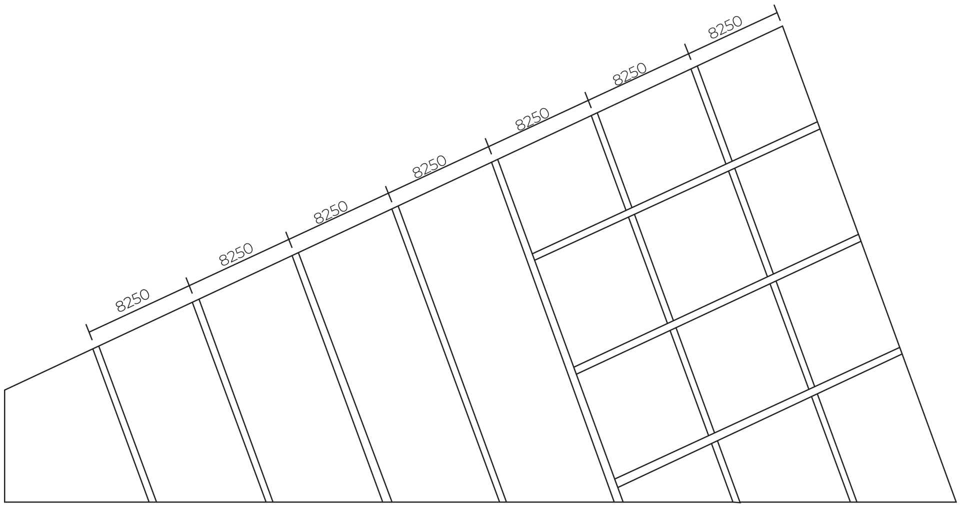


Figure 8.3: Half the floorplan of the extension of the C-pier

Like the original part of the C-pier the extension also has a ground floor and first floor. However, for the purposes of this study, only the ground floor of the extension is considered. The upper floors in this section are constructed using precast TT-slabs, which, despite their high reuse potential, especially in applications such as parking structures, fall outside the scope of this research.

8.2. Slab geometry and reinforcement

When considering the floor plans and beam configuration of both the original part and the extension of the C-pier there are three slab geometries that would be suitable for reuse. In image 8.4 the three distinct floor slabs identified for harvesting are illustrated. Each slab type -labeled A, B, c- shares the same overall dimension of 7750 mm by 3100 mm. These global dimensions are based on cutting the slabs in between the beams, to limit the wear and tare on the machinery. Also the slab width of type B and C is set to 3100, but this is not a restriction. The only reason for this is to have a uniform size, that is limited by the beams of floor type A.

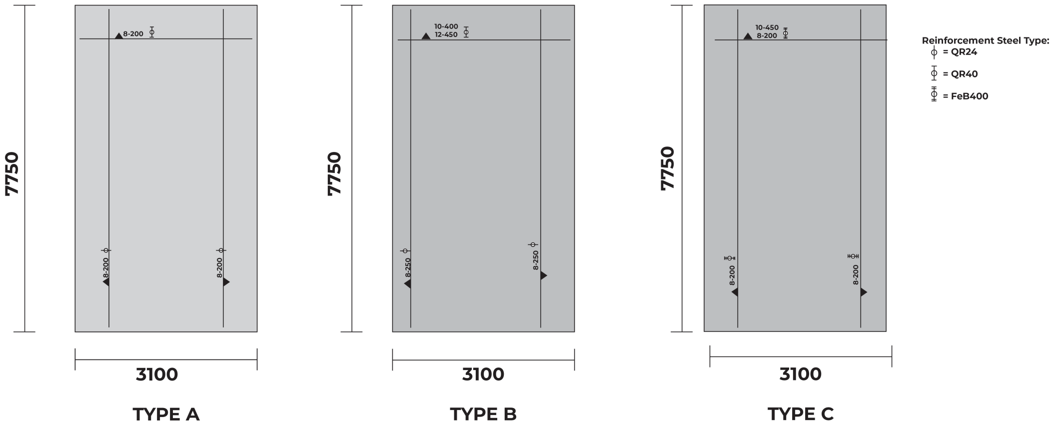


Figure 8.4: Types of available floor slabs

As can be seen in the picture the floors all have different amounts of reinforcement. Also with different steel strengths, which is shown with the flags added to the reinforcement symbol. This and the other important design parameters are summarized in table 8.1.

Table 8.1: Basic design parameters of the harvested slabs

Design parameter	Floor element A	Floor element B	Floor element C
Length l [mm]	7750	7750	7750
Width b [mm]	3100	3100	3100
Thickness t [mm]	100	200	200
Concrete strenght class f_{ck}	K300 ($f_{ck} = 19$ N/mm^2)	K300 ($f_{ck} = 19$ N/mm^2)	B22.5 ($f_{ck} = 18$ N/mm^2)
Reinforcement (principal direction) $A_{s,p}$	8–200	12–450 & 10–400	10–450 & 8–200
Steel strength (principal direction) f_{yk} [N/mm^2]	400	400	400
Reinforcement (transverse direction) $A_{t,p}$	8–200	8–250	8–200
Steel strength (transverse direction) f_{yk} [N/mm^2]	240	240	400
Concrete cover c [mm]	10	30	30
Number of slabs [–]	58	58	78

8.3. The new design of the C-pier of Schiphol

Before verifying the donor slabs from the original C-pier for reuse, it is essential to outline the conceptual basis of the new design to which they will contribute. This section therefore summarizes the preliminary design intent and boundary conditions for the reconstructed C-pier, focusing on the functional requirements, spatial layout, and key load assumptions that define the verification context.

Establishing these parameters early provides a consistent set of performance criteria, geometry, load capacity, fire resistance, and serviceability, against which the reclaimed slabs can be assessed. The presented concept reflects Schiphol Group's initial proposal for the C-pier redevelopment, defining the target span configuration, support conditions, and performance objectives of the future terminal.

8.3.1. The design requirements for the new C-pier

The following section summarizes the principal design requirements established by Schiphol Group for the reconstruction of the C-pier. These parameters define the structural reliability level, design load assumptions, material specifications, and performance criteria that govern the new pier concept. The requirements are structured in 8.2.

Table 8.2: Summary of Schiphol requirements for the reconstruction of the C-pier

Category	Requirement
Structural and Architectural	• Structural design in accordance with Eurocodes and Schiphol engineering standards. • Reliability class: Gevolgklasse CC3. • Fire performance requirement: REI 90. • Environmental exposure class: XC1. • Floor design loads: 5 kN/m^2 (upper floors) and 10 kN/m^2 (ground floor). • Preference for low-carbon materials. • Provision for expandable technical spaces within the modular layout.
Sustainability	• Circular design target with a Building Circularity Index (BCI) $\geq$ 60%. • Optimization for minimal embodied carbon.
Construction and Engineering	• Modular units designed for transport via Self-Propelled Modular Transporters (SPMTs). • Primary structure: portal frames in the transverse direction and bracing in the longitudinal direction. • Floor systems must allow safe anchoring and be fully demountable.
Safety and Health	• Reduction of on-site construction risks through off-site prefabrication. • Minimal disruption to ongoing airside operations during installation.

8.3.2. The lay-out of the new C-pier

Haskoning has developed a modular structural concept for the reconstruction of Schiphol's C-pier. The left image illustrates the proposed layout, consisting of a regular 10.8 × 9.6 m grid that allows standardized prefabrication and flexible internal configuration. The right image shows the optimized steel framework, where beam and column profiles (HEB and CHS sections) are dimensioned to achieve the lowest possible embodied carbon while maintaining the required strength and stiffness. This modular system forms the structural basis for integrating reclaimed concrete slabs, enabling efficient assembly and future adaptability within the pier's redevelopment.

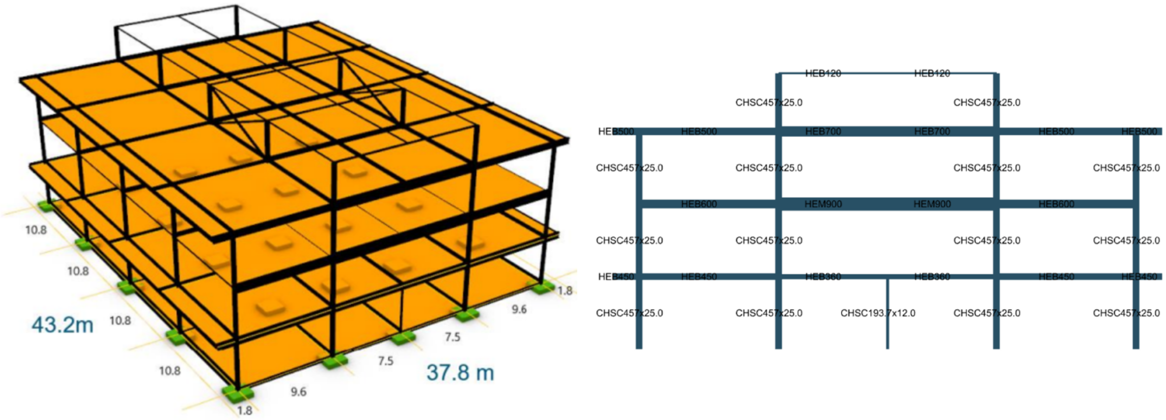


Figure 8.5: The new design for the C-pier by Haskoning

8.4. The project organization and stakeholders

The development of the C-pier follows Schiphol's integrated delivery model, first established for the Pier A expansion. In both programs, the Royal Schiphol Group (RSG) acts as asset owner and contracting authority, maintaining full control over strategy, budget, and sustainability targets while outsourcing design and construction through an integrated Design & Construct (D& C) contract. For Pier A this contract was awarded to a consortium, since it is not yet establish who this is for the C-pier a joint venture of BAM Infra Nederland and Heijmans Nederland is considerd since they are currently doing most Schiphol Project. This consortium model has been retained for the C-pier redevelopment, with Haskoning providing structural design verification, reuse assessment, and technical advisory services within the same collaborative structure. The other stakeholders are elaborated in this table:

Table 8.3: Project stakeholders and collaboration roles (based on Pier A organisational model)

Stakeholder / Organisation	Primary Role	Main Responsibilities	Collaboration Mechanisms
Royal Schiphol Group (RSG)	Client / Asset Owner	Defines functional and sustainability targets (BCI $\geq$ 60), finances works, and grants final approvals.	Chairs project board; sets circular KPIs and oversees coordination between design and construction teams.
Schiphol Technical Authority (STA)	Technical supervision	Reviews design and execution for compliance with airport safety, fire, and maintenance standards.	Participates in design reviews and quality gates.
Design & Construct Consortium (BAM–Heijmans)	Integrated contractor	Responsible for design, engineering, procurement, and construction; coordinates all site activities.	Works in co-location with RSG; maintains direct communication lines with all consultants.
Haskoning	Structural engineering advisor	Verification of reused elements, structural design consultancy, and circular design alignment.	Embedded in D&C team; leads technical interface meetings.
Suppliers / Testing Labs	Material testing and certification	Conduct compressive strength, carbonation, and reinforcement tests on reclaimed slabs.	Data verified by Haskoning and IQC before approval.

9 Validation of the communication framework

This chapter presents the validation of the Communication Framework for Reuse developed in Chapter 6. The purpose of this validation is to determine whether the framework can support effective coordination, communication, and decision-making in reuse-oriented construction projects that involve multiple actors and complex interfaces.

By conducting this validation, the chapter aims to:

- Demonstrate the framework's practical applicability to a real project context
- Assess its recognizability and coherence from a practitioner's perspective
- Evaluate its potential to improve communication structures and reduce fragmentation between project phases

The validation is therefore not intended to measure quantitative project outcomes, but rather to assess the framework's expected performance and practical usability within a realistic setting. Because the C-pier redevelopment at Schiphol is still ongoing, the assessment focuses on a reconstructed case simulation, supported by expert reflection from comparable circular construction projects. Through this approach, the validation seeks to bridge theoretical development and practical implementation, testing whether the framework provides a credible and usable structure for managing communication in reuse-driven construction practice.

9.1. The validation methodology

To assess the framework's expected performance, a two-tiered validation approach was employed that combines a reconstructive case simulation with an expert evaluation. This hybrid method enables testing of both the conceptual soundness and the practical applicability of the framework, in line with established design-science research principles (Hevner et al., 2004; van Aken, 2004).

The first step involved reconstructing the communication and coordination processes within the ongoing C-pier redevelopment project. Drawing on available design documentation, stakeholder mappings, and project records, the Communication Framework for Reuse was applied retrospectively to examine how its mechanisms, such as communication domains, decision checkpoints, and defined responsibilities, could have structured collaboration across the project's different phases. By simulating its application in this way, the reconstruction created a realistic scenario to explore how the framework might operate in a complex, multi-actor airport environment.

The second step complemented this analysis with professional reflection. Two experts with extensive experience in sustainable airport development and large-scale circular projects within the Schiphol context were invited to evaluate the reconstructed application through semi-structured interviews. They were asked to reflect on the framework's clarity, completeness, and practical usability, drawing on their own experience with comparable redevelopment projects such as the A-Pier and the New Terminal. Their insights served as a proxy for empirical validation, helping to identify the framework's perceived strengths, weaknesses, and potential areas for refinement.

Together, these two components form a constructive and explanatory validation, assessing whether the framework offers a practical and reliable structure for improving coordination and maintaining information flow in reuse-oriented construction projects.

The evaluation of the framework was guided by five criteria commonly applied in design-science research: **relevance, comprehensibility, completeness, usefulness,** and **expected impact**. These criteria reflect both scientific robustness and practical value, allowing the validation to move beyond theoretical consistency toward assessing the framework's potential for real-world application:

- **Relevance** , Tests whether the framework addresses the actual challenges faced by practitioners, such as fragmented communication, unclear responsibilities, and limited information continuity.
- **Comprehensibility** , Considers the framework's clarity, terminology, and accessibility for users from different professional backgrounds.
- **Completeness** , Evaluates whether the framework adequately covers all relevant stages, interfaces, and stakeholder relationships across the reuse process, ensuring a holistic representation of communication and decision-making.
- **Usefulness** , Examines the framework's practical utility as a coordination and decision-support tool, assessing whether it can realistically guide project teams in structuring collaboration and managing information flows.
- **Expected impact** , Measures the framework's capacity to improve project performance by enhancing coordination, promoting traceability, and supporting systemic change in circular construction practices.

By assessing the framework against these dimensions, the validation aims to determine not only whether the framework is conceptually coherent, but also whether it is understandable, comprehensive, and practically applicable within complex, multi-actor environments such as Schiphol's C-pier redevelopment.

9.2. Application of the framework to the C-pier case

9.2.1. Path Confirmation

Before applying the *Communication Framework for Reuse* to the C-pier redevelopment, it is necessary to determine which coordination pathway, Path A or Path B, best represents the project context. Based on the organizational configuration described in Section 8.4, the C-pier redevelopment fulfils most conditions for **Path A: Direct Donor–Target Alignment**. To confirm this, the project is evaluated against the seven decision parameters defined in Table 6.2 of the framework: temporal alignment, ownership structure, verification status, material availability, structural compatibility, risk tolerance, and spatial distance. Table 9.1 summarises how the C-pier case performs against each of these criteria.

Table 9.1: Path confirmation for the C-pier redevelopment (based on framework decision criteria)

Criterion	Framework Requirement	C-pier Condition	Result
Temporal alignment	$\leq$ 12 months gap between donor and target	Overlapping deconstruction and reconstruction phases	✓ Satisfied
Ownership / contractual control	Common client and contract environment	Both under RSG; single D&C consortium	✓ Satisfied
Verification & documentation	$\geq$ 80% verified data	Original drawings + new testing programme	✓ Satisfied
Material availability & volume	$\geq$ 90% match	Partial match; limited slab quantity for full redevelopment	△ Partially satisfied
Structural compatibility	Minor adaptation only	Geometry fits modular grid with notable adjustments required	△ Partially satisfied
Risk & liability tolerance	Shared within single contract	Integrated D&C model	✓ Satisfied
Spatial distance	$\leq$ 150 km	Same airside site	✓ Satisfied

As shown in Table 9.1, the C-pier redevelopment satisfies nearly all framework conditions for Path A. The project benefits from complete ownership alignment, synchronised timelines, and a single contractual environment that allows for direct coordination between donor and target activities. Although material availability and structural compatibility are only partially met, due to the limited number of reclaimable slabs and the need for design adjustments, the overall project configuration remains consistent with the logic of Path A. The following subsections elaborate briefly on each criterion.

Temporal alignment

The demolition of the existing C-pier and the construction of the new pier are planned as overlapping phases within a single redevelopment programme managed by the Royal Schiphol Group (RSG). Selective deconstruction of the donor structure and verification of the harvested slabs will take place immediately prior to the start of the new build, using the same site compound and planning horizon. This synchronisation eliminates the typical time gap between donor and target projects and thereby satisfies the first and most decisive criterion for Path A.

Ownership and contractual control

Both the donor and target assets remain under one client and ownership structure, RSG. The same organisation governs the entire lifecycle of the project, from selective dismantling to handover of the new facility. This unified ownership allows RSG to control decision-making, allocate responsibilities for verification, and manage liability within a single contractual ecosystem. Unlike Path B configurations, no intermediary or material bank is required to transfer ownership, risk, or certification between projects.

Verification and documentation

Through Haskoning's advisory role, the project already possesses detailed donor documentation, including original structural drawings, reinforcement layouts, and preliminary material data. Additional destructive and non-destructive tests will be performed during deconstruction to update this information and produce a verified *Element Passport* for each slab. The combination of existing records and planned verification ensures that the documentation threshold of at least 80%, as specified in the framework, is comfortably achieved.

Material availability and structural compatibility

The donor structure yields approximately 100 reclaimable slabs of consistent geometry (7.75 × 3.10 m) that could, in principle, align with the modular grid of the new C-pier. However, two limitations are noted: the total quantity of slabs is insufficient to complete the entire floor area, and their reuse requires substantial adaptation of the new design grid. Given the experimental nature of this study, the project remains valuable as a demonstration case; nonetheless, future applications may benefit from selecting a donor building with closer geometric and quantitative correspondence to the target design.

Risk and liability tolerance

RSG's integrated client model and the D&C consortium's engineering capacity enable risk sharing within a single contractual environment. Responsibility for structural verification remains with the engineering consultant, while execution and handling risks are managed by the contractor under supervision of Schiphol's Technical Authority. This unified approach to risk management aligns directly with the Path A logic.

Spatial distance

Because both the donor and target sites are located within Schiphol's secured perimeter, no long-distance transport or external logistics hubs are required. Reclaimed slabs can be temporarily stored and reinstalled within the same airside zone, minimising emissions and the risk of damage during handling. This local reuse further reinforces the environmental and logistical rationale for Path A.

In summary, despite minor deviations in material volume and grid compatibility, the C-pier redevelopment meets the essential conditions of Path A. The project therefore provides an appropriate and representative context for testing the *Communication Framework for Reuse* under a direct donor–target alignment scenario.

9.2.2. Mapping of the framework stages

Stage 1 , Initiation & Planning

Path A

◎ **Purpose** Establish the foundation for collaboration and information governance between all actors involved in the C-pier redevelopment. This stage translates Schiphol's high-level circular ambitions into actionable objectives, defines responsibilities for communication and verification, and aligns the planning of donor and target activities. Within the Path A configuration, it functions as the starting point for direct donor–target coordination, where both design and demolition are managed under the same client organization. Next to that if no data is available yet in this stage a suitable demolition company is already invited into the project to scan the building in order to establish a first inventory of the project.

Timing

Early development of both projects; overlapping planning and design schedules.

Communication focus

- **Define the reuse ambition** , confirm inclusion of slab reuse as a formal project objective and embed it in the project charter and performance brief.
- **Establish the Reuse Communication Plan (RCP)** , identify who communicates what, when, and through which channels; specify update frequency and document control.
- **Synchronise schedules** , align deconstruction planning, verification testing, and design milestones to avoid information gaps.
- **Determine verification scope and success metrics** , set investigation levels for donor elements (geometry, reinforcement, material strength) and link them to circular-performance indicators such as BCI ≥ 60 % and embodied-carbon targets.

Actors & responsibilities

Royal Schiphol Group (RSG)	Defines project scope, reuse ambition, and sustainability KPIs; issues circularity brief; approves verification budget and timeline.
Haskoning	Advises on structural feasibility and verification strategy for reclaimed slabs; drafts initial Reuse Communication Plan (RCP).
Design & Construct Consortium (Heijmans/BAM)	Provides input on constructability, logistics, and sequencing of selective deconstruction; validates planning assumptions.
Schiphol Technical Authority (STA)	Reviews technical requirements and ensures compliance with Schiphol Engineering Standards and Eurocodes.
Circularity & Innovation Unit (RSG)	Ensures alignment between project targets and Schiphol's circular roadmap; defines monitoring approach for circular KPIs.
Asset Management Department	Confirms requirements for documentation transfer to the asset database (BIM/ProjectWise).
Demolition/deconstruction contractor	If no fullscale BIM model is present yet with inventory information. they start the inventory process which supports the first design decisions of the project and can adjust the circularity ambitions from the outset.
Reuse Coordinator (appointed by RSG)	Facilitates stakeholder workshops, records decisions, and consolidates the Reuse Communication Plan.
Independent Quality Control (IQC)	Reviews RCP completeness and verifies traceability provisions from the outset.

Main output (checkpoint)

- *Reuse Communication Plan (RCP)* , specifies communication lines, reporting structure, and document formats; defines responsibilities for verification, documentation ownership, and approval workflow.

- *Preliminary Verification & Testing Plan* , outlines sampling strategy, testing methods, and acceptance criteria for donor slabs.
- *Circularity Performance Framework* , sets measurable KPIs for reuse contribution, embodied-carbon reduction, and waste diversion.
- *Integrated Master Schedule* , aligns demolition, testing, design, and construction activities; includes critical communication checkpoints.
- *BIM model* - Using 3D scanning the object can be put into a 3D BIM model which can be used to determine which options for reuse are available.

Value added

- Establishes clear roles and accountability, reducing the ambiguity typical of early reuse projects.
- Aligns temporal and organisational interfaces between demolition and design, preventing information loss.
- Embeds circular objectives as contractual and measurable targets rather than aspirational statements.
- Creates a traceable foundation for subsequent framework stages by defining ownership of all future data exchanges.

Stage outcome

At the end of Stage 1, the C-pier redevelopment has an agreed *Reuse Communication Plan* approved by RSG and endorsed by all design and construction partners. This document formalises the project's circular ambitions, defines verification boundaries, and establishes the digital environment for information management. The outcome ensures that reuse is embedded as a core design driver rather than an experimental add-on, enabling a seamless transition to **Stage 2 , Design & Engineering**, where donor data are translated into verified design inputs.

Stage 2 , Design & Engineering

Path A

◎ **Purpose** Operationalise the reuse ambition defined during Initiation & Planning. Donor information, geometry, reinforcement, and material data, is converted into verified design inputs for the structural and architectural development of the new C-pier. The stage focuses on integrating reclaimed elements within the modular grid of the new terminal and coordinating technical verification with design progress. Within the Path A configuration, this occurs through direct collaboration between donor and target teams under the same client, ensuring a continuous data flow between verification and design activities.

Timing

Early and detailed design phases; parallel coordination between verification, engineering, and architecture.

Communication focus

- Verification of donor data , conduct and report destructive and non-destructive testing to confirm material strength, reinforcement detailing, and durability parameters.
- Translation into design models , incorporate verified material properties and geometries into structural and architectural models for reuse integration.
- Alignment of technical assumptions , agree on design values, safety factors, and load combinations in line with Eurocode and Schiphol Engineering Standards.
- Documentation of shared results , consolidate analyses, test reports, and design assumptions in a single, traceable *Verification Dossier* accessible through the CDE.

Actors & responsibilities

Haskoning	Leads structural verification of reclaimed slabs; prepares finite-element models; validates load-bearing capacity and deflection behaviour.
Design & Construct Consortium (Heijmans/BAM)	Provides constructability feedback, lifting and installation tolerances; coordinates deconstruction and testing logistics.
MEP / Systems Engineer (Deerns or similar)	Ensures penetrations and service zones are compatible with reinforcement layouts and fire-safety requirements.
Fire Safety Engineer	Confirms REI 90 compliance through cover-depth verification and potential application of protective layers.
Architect (to be appointed)	Adapts spatial layout and floor grid to constraints of reused elements; ensures design coherence and passenger-flow requirements.
Schiphol Technical Authority (STA)	Reviews verification and design documentation for compliance with standards; approves deviations where necessary.
Reuse Coordinator	Maintains communication between verification, design, and construction teams; tracks data versioning and milestone approvals.
Independent Quality Control (IQC)	Reviews completeness of the *Verification Dossier*; confirms traceability of all input data and test reports.

Main output (checkpoint)

- *Verification Dossier* , consolidated donor data, testing results, design assumptions, and analysis reports; links every reclaimed element to its verification record and material passport.
- *Updated BIM / Design Models* , integrate verified slabs with updated load and geometry parameters; include clash detection and design-for-assembly details.
- *Design Verification Report (DVR)* , summarises compliance with Eurocode ULS/SLS criteria, fire performance, and deflection limits; forms the technical justification for reuse approval by STA.
- *Design Review Minutes / Decision Log* , record design meetings, assumptions, and acceptance of verification results by all parties.

Value added

- Establishes a direct technical link between donor-side verification and target-side design, eliminating information loss and redundant modelling.
- Enables real-time collaboration through the CDE, increasing transparency and traceability.
- Aligns multi-disciplinary assumptions (structural, MEP, fire) to avoid downstream conflicts.
- Creates a single, verifiable evidence base, the *Verification Dossier*, that underpins contractual confidence and regulatory approval.

Stage outcome

At completion, all reclaimed slabs are structurally verified and digitally integrated into the C-pier design model. The *Verification Dossier* and *Design Verification Report* together form the baseline for procurement and contractual commitments in Stage 3. The reuse ambition has therefore evolved from a conceptual target into a technically validated design decision.

Stage 3 , Procurement & Handover

Path A

◎ **Purpose** Coordinate the controlled handover of verified slabs and data between the demolition and construction phases. In the Path A configuration, the client (RSG) remains the owner of both the donor and target assets, which means that procurement primarily concerns the *harvesting and transfer of materials* rather than external contracting. This stage ensures that the outcomes of demolition, verified elements, updated documentation, and logistics planning, are seamlessly transferred to the Design & Construct (D&C) consortium for integration in the new C-pier structure. The focus lies on data continuity, storage decisions, and the physical and informational interface between the demolition and construction teams.

Timing
Immediately following verification and during the selective demolition phase, when slabs are harvested, assessed, and prepared for transport or storage.

Communication focus

- **Coordinating the handover process** , align demolition progress, slab extraction, and delivery schedules with the construction programme.
- **Transferring verification information** , ensure that all test data, inspection reports, and digital identifiers from demolition are handed over to the D&C consortium and recorded in the Common Data Environment (CDE).
- **Deciding on storage and logistics** , determine whether slabs are stored on-site or externally, establish handling procedures, and confirm traceability through the storage phase.
- **Maintaining traceability and quality assurance** , link physical slabs to their digital records and ensure condition monitoring until reinstallation.

Actors & responsibilities

Demolition / Deconstruction Contractor	Executes selective slab removal; labels and records each element; provides handover documentation including inspection reports and photos.
Design & Construct Consortium (Heijmans / BAM)	Receives reclaimed slabs and associated data; inspects condition; plans logistics and temporary storage prior to reuse.
Haskoning	Verifies that demolition data meet technical and structural requirements; confirms alignment between harvested elements and design models.
Reuse Coordinator	Manages the communication between demolition and construction teams; ensures continuity of digital data; facilitates decision-making on logistics and storage.
Royal Schiphol Group (RSG)	Oversees and approves the handover process; validates that reuse and circularity objectives are maintained during the transition.
Independent Quality Control (IQC)	Audits traceability and verifies the integrity of handover documentation; certifies that all data and identifiers match physical elements.

Main output (checkpoint)

- *Handover Package* , consolidated set of documents from demolition including inspection reports, verification data, and photographic evidence of each reclaimed element.
- *Material Transfer Register* , formal log linking each slab's physical identifier to its verification and testing records; signed by demolition and construction representatives.
- *Storage & Logistics Plan* , decisions on storage location, handling method, and transport schedule; includes safety and traceability procedures.

- *Updated Verification Dossier* , incorporates final as-removed condition assessments and transfers responsibility for documentation to the construction team.

Value added

- Establishes a transparent handover of both materials and data, preventing information loss between demolition and construction phases.
- Ensures continuous traceability through the transition from verification to assembly.
- Facilitates collaborative planning for storage, logistics, and sequencing, reducing risk of damage or misalignment.
- Maintains accountability for slab condition and data accuracy, strengthening confidence in the reuse process.

Stage outcome

At the conclusion of Stage 3, all verified slabs and their documentation have been safely transferred from the demolition contractor to the D&C consortium. The *Material Transfer Register* and *Handover Package* confirm that traceability, quality assurance, and storage arrangements are complete and approved by RSG. This marks the operational interface between the donor and target phases, ensuring that the harvested materials and their digital records are ready for integration during **Stage 4 , Construction & Assembly**.

Stage 4 , Construction & Assembly

Path A

◎ **Purpose** Oversee the on-site installation and integration of the reclaimed slabs within the new C-pier structure. Following the harvesting and handover of verified elements in Stage 3, this stage ensures that construction activities maintain full alignment with the verified design data. It focuses on quality assurance, traceability, and the creation of accurate as-built documentation, confirming that the reused elements are installed safely, correctly, and in compliance with engineering and regulatory standards.

Timing

During construction and installation of the new pier; overlaps with verification sign-off and as-built data generation.

Communication focus

- **Pre-installation verification** , confirm the condition, identification, and documentation of each reclaimed slab before placement.
- **Installation coordination** , align slab delivery, crane operations, and sequencing with the construction schedule to ensure efficient on-site assembly.
- **Real-time documentation** , record installation activities, inspection results, and any deviations within the Common Data Environment (CDE).
- **Quality and safety control** , verify compliance with Schiphol's Safety Management System (SMS) and Airside Safety Regulations (ASR) during lifting and installation operations.
- **As-built integration** , update BIM and asset data to reflect installed geometries, element identifiers, and inspection approvals.

Actors & responsibilities

Design & Construct Consortium (Heijmans / BAM)	Installs the reclaimed slabs; manages on-site logistics, lifting operations, and installation sequencing; ensures compliance with safety and quality procedures.
Haskoning	Provides structural supervision and final verification before and after installation; checks bearing conditions, reinforcement alignment, and connection detailing; updates design documentation as required.
Logistics Coordinator	Manages on-site delivery and lifting operations; maintains traceability between slab IDs and installation locations.
Safety Manager (Airside Compliance)	Oversees compliance with ASR and Schiphol SMS; coordinates access, permits, and safe working procedures.
Reuse Coordinator	Monitors communication between site, engineering, and client; ensures traceability of digital and physical data during installation; validates updates in the CDE.
Independent Quality Control (IQC)	Conducts independent inspection and sign-off after installation; certifies conformity with verification data and safety standards.
Schiphol Technical Authority (STA)	Approves installation verification reports and confirms final compliance with structural and regulatory requirements.

Main output (checkpoint)

- *Installation Verification Report* , confirms correct placement, orientation, and bearing conditions of all reused slabs; signed by Haskoning, IQC, and STA.
- *Updated BIM / As-Built Model* , integrates as-installed geometries, unique identifiers, and deviations; forms the digital twin of the reused structure.
- *Construction Quality Log* , documents inspections, lifting operations, and on-site adjustments; includes photographic evidence and non-conformance records.
- *Safety & Compliance File* , compiles ASR permits, toolbox talks, and safety inspection reports for airside construction activities.

Value added

- Ensures installation accuracy and full alignment between verified data and executed works.
- Maintains continuous traceability from donor verification to as-built documentation.
- Provides immediate visibility of quality and safety performance during installation.
- Produces a verified as-built record that enables efficient transition to operational management.

Stage outcome

At the conclusion of Stage 4, all reclaimed slabs are installed and verified in accordance with structural design and safety standards. The *Installation Verification Report*, supported by the *As-Built Model* and *Construction Quality Log*, confirms that the reuse process has been successfully executed on site. These deliverables form the verified baseline for asset documentation, enabling a seamless transition to **Stage 5 , Operation & Maintenance**, where focus shifts to long-term performance and information retention.

Stage 5 , Operation & Maintenance

Path A

◎ **Purpose** Extend the communication framework beyond construction into the operational lifespan of the new C-pier. This stage ensures that all verified information about the reclaimed slabs, their geometry, material properties, installation data, and maintenance history, remains accessible, traceable, and continuously updated throughout the building's use phase. Within the Schiphol context, this stage links project documentation to the airport's Asset Management System (AMS), forming a digital record that supports performance monitoring, maintenance planning, and future reuse opportunities.

Timing

Post-construction and throughout the service life of the new pier; from handover to end-of-life preparation.

Communication focus

- **Consolidating as-built data** , transfer all design, verification, and installation information into Schiphol's AMS and BIM environment.
- **Monitoring condition and performance** , establish inspection intervals, performance indicators, and monitoring procedures for reused elements.
- **Recording interventions** , document maintenance, retrofits, or changes that affect the residual performance of reused slabs.
- **Ensuring accessibility and continuity** , maintain open data channels between facility management, design consultants, and the Schiphol Technical Authority (STA).

Actors & responsibilities

Royal Schiphol Group – Asset Management Department	Owns and maintains as-built data; manages the asset database; ensures alignment with Schiphol's maintenance and data standards.
Facility Management Team (Operations)	Conducts routine inspections and maintenance; updates condition data and reports anomalies to the AMS.
Haskoning (as-built advisor)	Provides technical support during handover; assists in defining monitoring procedures for reused slabs.
Design & Construct Consortium (Heijmans / BAM)	Supplies complete as-built documentation and supports warranty-related inspections during the defects-liability period.
Reuse Coordinator / Digital Information Manager	Integrates construction and verification data into Schiphol's CDE and asset registers; ensures consistency of metadata.
Independent Quality Control (IQC)	Verifies completeness and consistency of the as-built documentation and asset data before final handover.
Schiphol Technical Authority (STA)	Reviews operational documentation for compliance with maintenance and safety requirements; oversees asset updates.

Main output (checkpoint)

- *Integrated Reuse Dossier (IRD)* , comprehensive digital record containing as-built geometries, verification data, maintenance instructions, and inspection schedules; forms the official documentation set for future reuse.
- *Asset Information Model (AIM)* , BIM-linked dataset integrated into Schiphol's AMS; includes material properties, element identifiers, and maintenance metadata for each reused slab.
- *Maintenance & Inspection Plan (MIP)* , defines monitoring frequency, visual-inspection protocols, and thresholds for testing or intervention.
- *Performance Review Reports* , periodic assessments summarising the structural and durability performance of reused slabs, recorded in the AMS.

Value added

- Preserves information continuity from design through operation, ensuring long-term accessibility of verification and performance data.
- Facilitates preventive maintenance and early detection of deterioration, reducing lifecycle risk for reused elements.
- Establishes a digital foundation for future reuse cycles, enabling reclaimed slabs to re-enter the construction loop at end-of-life.
- Strengthens Schiphol's institutional learning capacity by embedding circular data management within its asset-management framework.

Stage outcome

At the conclusion of Stage 5, the reused slabs are fully integrated into Schiphol's digital asset environment. All verified data, geometry, testing records, installation conditions, and maintenance plans, are accessible through the *Integrated Reuse Dossier* and linked to the *Asset Information Model*. Operational feedback is continuously captured, enabling real-time understanding of the slabs' in-service performance. This stage ensures that the benefits of reuse extend far beyond construction, preparing the groundwork for **Stage 6 , End-of-Life & Deconstruction**, where the circular cycle begins anew.

Stage 6 , End-of-Life & Deconstruction

Path A

◎ **Purpose** Reactivate the circular cycle by preparing the C-pier and its reused slabs for future selective deconstruction and secondary reuse. Rather than treating end-of-life as a terminal phase, this stage positions it as the beginning of the next reuse opportunity. It ensures that the information gathered and maintained throughout the asset's lifecycle guides safe dismantling, quality verification, and reintegration of elements into new projects. Within Schiphol's long-term *Circular Airport* strategy, this stage secures continuity of both data and material value.

Timing

Late service life and deconstruction planning; initiated while the building is still operational to ensure a seamless transition to reuse.

Communication focus

- **Evaluating residual performance** , assess condition, durability, and remaining capacity of the reused slabs through targeted inspections and testing.
- **Planning selective deconstruction** , coordinate between asset management, engineering advisors, and future project teams to define dismantling methods and sequencing.
- **Updating documentation** , revise material passports and the *Integrated Reuse Dossier* with condition data, intervention history, and removal instructions.
- **Initiating new reuse connections** , communicate with upcoming Schiphol or external projects that could receive reclaimed elements.

Actors & responsibilities

Royal Schiphol Group – Asset Management Department	Initiates end-of-life planning; provides access to asset data and maintenance history; coordinates with potential recipient projects.
Schiphol Technical Authority (STA)	Evaluates safety and structural integrity of components prior to removal; authorises dismantling works.
Haskoning (technical advisor)	Performs residual-life assessments; advises on requalification procedures and potential reuse scenarios.
Demolition / Deconstruction Contractor	Executes selective dismantling according to documented handling procedures and safety standards.
Reuse Coordinator	Facilitates communication between outgoing and incoming projects; updates documentation and ensures traceability of reclaimed elements.
Independent Quality Control (IQC)	Verifies the accuracy of updated material data; certifies reclaimed elements for the next reuse cycle.
Environmental Agency / ILT	Oversees compliance with waste and reuse regulations; validates environmental reporting.

Main output (checkpoint)

- *Updated Material Passport Set* , revised digital records for each slab including latest condition data, interventions, and dismantling instructions.
- *Residual Performance Assessment Report* , summarises remaining strength, durability, and service-life potential of each reclaimed element.
- *Selective Deconstruction Plan* , defines dismantling sequence, safety measures, logistics, and handling protocols derived from installation data.
- *Continuity of Passport Record* , integrates updated material data into Schiphol's asset database and re-lists reusable elements for future projects or digital marketplaces.
- *Lessons-Learned Summary* , documents operational performance, maintenance outcomes, and recommendations for improving future reuse cycles.

Value added

- Converts end-of-life into a data-driven starting point for the next reuse cycle, closing the framework's communication loop.
- Preserves verified traceability of reclaimed slabs, reducing redundant testing and documentation for future users.
- Embeds institutional learning by capturing long-term performance insights for continuous improvement of circular practice.
- Demonstrates compliance with European and Dutch circular-economy targets, providing a replicable model for infrastructure owners.

Stage outcome

At completion, the reused slabs of the C-pier are fully documented and prepared for potential re-extraction and redeployment in future developments. All condition and dismantling data are integrated into the *Updated Material Passport Set* and *Continuity of Passport Record*, ensuring that both structural and environmental information remain accessible long after the pier's operational life. This final stage confirms that the *Communication Framework for Reuse* achieves a closed-loop information and material flow, transforming the end of one lifecycle into the beginning of another.

9.3. Expert validation

9.3.1. The method and structure of the analysis

The expert validation follows a qualitative evaluation approach in which responses will be analysed thematically per criterion. Each criterion will be assessed based on:

1. **Expert Observations** – a concise summary of each expert's main remarks or examples.

2. **Interpretation** - how these remarks confirm, refine, or challenge the framework assumptions.
3. **Implication** - what adjustments or implementation insights emerge for improving the framework's practical applicability.

To ensure traceability, the results will be presented in a comparative matrix (Table 9.2), showing expert feedback side-by-side under each criterion.

Table 9.2: Summary of expert reflections per validation criterion

Criterion	Expert 1 – John Hijma (NACO)	Expert 2 – Alina Heemstra (NACO)
1. Relevance	Framework accurately reflects coordination and communication issues in circular airport projects. Early client leadership in defining roles essential; strongest value during initiation and design.	Confirms strong alignment with challenges in circular airport projects. Highlights the need for early ambition-setting, clear role division, and linking design decisions to donor element availability.
2. Comprehensibility	Six-phase structure clear and aligned with standard project phasing. Terms (RCP, VD, IRD) relevant but require short definitions and clarity on interrelation. Role descriptions should be more explicit.	Structure is clear and practical. Recommends adding concise definitions of key terms and specifying per phase the expected outputs, responsibilities, and handling of risks or negative verification outcomes.
3. Completeness	Covers main roles and processes; recommends inclusion of logistics/transport parties and clear allocation of new or short-term roles. Transition between design and execution identified as key handover point.	Considered comprehensive but suggests explicitly including circular demolishers, material hubs, and take-back suppliers, as they often determine feasibility and influence Path A/B decision-making.
4. Usefulness	Expected to improve collaboration and information exchange if document and data management are well defined. Advises minimizing documentation volume and clarifying information ownership and flow.	Believes it can strongly support collaboration if responsibilities and agreements are defined early. Helps embed Urban Mining consistently across phases and reduce misalignment in design and execution.
5. Expected Impact	Likely to support Schiphol's circularity targets, especially for structural reuse impacting BCI. Recommends pilot implementation and linking results to measurable KPIs (CO_2, cost).	Considers the framework capable of contributing to Schiphol's circular goals and normalising reuse, provided it is applied consistently and supported by pilots and clear client direction.
6. Final Reflection	Would have benefited earlier projects by structuring verification and reuse discussions. Success depends on client commitment, early feasibility screening, storage logistics, and focus on most influential criteria per phase.	Believes such a framework would have strengthened past Urban Mining projects. Suggests evolving it into an accessible digital tool for tracking donor elements, requirements, and responsibilities.

9.3.2. The interpretation

The remarks provided by John Hijma largely confirm the underlying assumptions of the framework, namely that circular construction within complex airport environments is hindered by fragmented communication, unclear role definition, and inconsistent documentation across project phases. His observations validate the framework's central premise that structured communication mechanisms and clearly allocated responsibilities are prerequisites for successful reuse implementation.

At the same time, Hijma's input refines the framework by stressing two aspects that require stronger emphasis: (1) the pivotal role of the client in anchoring coordination and accountability during the initiation phase, and (2) the need for simplified information management, including clear ownership of documents and data across phases. These refinements highlight that the framework should not only prescribe what communication and verification deliverables exist, but also specify who maintains, transfers, and controls them.

His feedback also challenges certain assumptions, particularly the balance between procedural thoroughness and practical feasibility. While the framework assumes that extensive documentation improves traceability, Hijma warns that excessive reporting could hinder efficiency and uptake in practice. He further challenges the implicit assumption that all roles are covered by existing contract structures, noting that logistics and temporary storage responsibilities are often overlooked and should be explicitly addressed.

The reflections from Alina Heemstra reinforce many of these points but add further nuance. She confirms the framework's relevance and clarity while emphasising the need to articulate per phase what concrete outputs, responsibilities, and risk-handling agreements are expected. Her feedback strengthens the argument that the framework must operationalise, not merely outline, communication structures. Importantly, she highlights the influential roles of circular demolishers, material hubs, and take-back suppliers, which are often decisive in determining whether Path A or Path B is feasible. This expands the framework's scope by acknowledging actors who typically operate outside traditional project boundaries but play a critical role in reuse logistics.

Heemstra also aligns with Hijma in noting that circular ambitions must be established early, as late adjustments result in design inefficiencies and mismatches with donor material availability. Additionally, she underscores the value of consistency across phases, noting that the framework could benefit from being developed into a shared digital tool to support traceability and data access for all stakeholders.

Overall, the combined reflections of both experts reinforce the validity and necessity of the framework, while calling for clearer operational guidance, the inclusion of additional actors, and proportional processes. Together, their insights highlight that role ownership must be unambiguous, information flows must remain manageable, and the practical realities of Urban Mining, particularly supply chain dependencies and data transfer, must be integrated more prominently for the framework to be realistically embedded within Schiphol's project governance.

9.3.3. Implementation refinements - Information Management System

To tackle the perceived difficulty by the experts with regards to the information complexity an operational refinement is introduced in the form of the information management system (IMS). The IMS ensures that information generated across all project stages is consistently managed, transferred, and verified within one traceable system. It builds upon the existing communication and verification processes of the framework, creating a structured link that strengthens the continuity of knowledge between the donor, design, and target projects.

Objectives and principles

The IMS is designed to safeguard traceability, transparency and continuity of all reuse-related information across the six framework stages. It therefor acts as the horizontal backbone connecting the three vertical streams of the framework: Communication, verification and information management. Its logic follows three core principles:

1. **Single source of truth:** All project data are created, checked, and stored in a single Common Data Environment (CDE), which functions as the authoritative digital record for the entire project lifecycle.
2. **Defined ownership:** Each project phase has a clearly assigned data owner who is responsible for maintaining the records, updating information, and managing version control.
3. **Cumulative development:** Information builds progressively over time rather than being reproduced. Each phase adds verified data to the existing record, ensuring continuity and reducing duplication.

Together these principles transform the framework's document-based output into a continuous digital information chain, reducing redundancy while maintaining full verifiability.

Structure of the information flow

To integrate this information flow it is structured along the framework's six stages. Each stage generated a compound deliverable instead of the multiple individual documents and ensures data consolidation within the CDE. This approach maintains the same traceability guarantee with a reduced administrative load. The six compound deliverables are summarized in table 9.3.

Table 9.3: Overview of compound deliverables, integrated documents, objectives, and formats

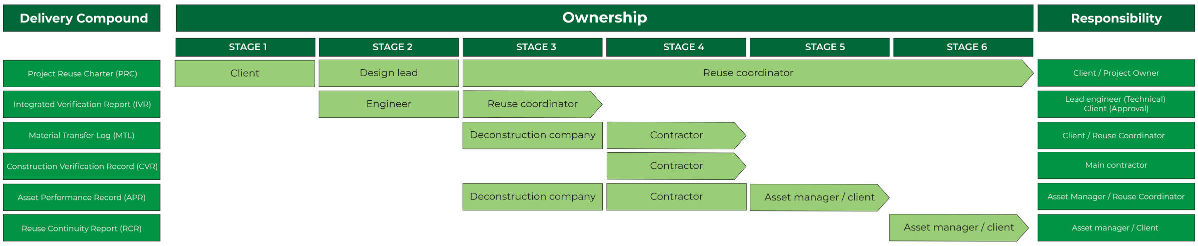
Compound Deliverable	Original Deliverables Integrated	Objective / Scope	Format & Content Type
1. Project Reuse Charter (PRC)	Reuse Communication Plan (RCP); Responsibility Matrix; Circularity Performance Framework; Integrated Master Schedule	Establishes project-wide reuse governance, roles, communication structure, and measurable circular targets.	Text-based management plan (PDF/Word) with structured annex tables (role matrix, KPI register).
2. Integrated Verification Report (IVR)	Preliminary Verification & Testing Plan; Verification Dossier; Design Verification Report; Design Review Minutes; Updated BIM / Design Models	Consolidates all technical verification and design validation data, transforming donor data into verified design input.	Digital report combining narrative, tables, and BIM-linked datasets (PDF + IFC/BIM model).
3. Material Transfer Log (MTL)	Handover Package; Material Transfer Register; Storage & Logistics Plan; Updated Verification Dossier (Post-harvest)	Provides a traceable record of all reclaimed elements from dismantling through transport, storage, and site handover.	Structured database (Excel or BIM-linked register) supported by transport certificates and inspection photos.
4. Construction Verification Record (CVR)	Installation Verification Report; Construction Quality Log; Safety & Compliance File	Documents installation accuracy, quality checks, and safety compliance during construction and assembly.	Structured QA logbook (PDF or CDE form) linked to BIM as-built geometry; includes inspection photos and NCRs.
5. Asset Performance Record (APR)	Integrated Reuse Dossier (IRD); Asset Information Model (AIM); Maintenance & Inspection Plan (MIP); Performance Review Reports	Consolidates all operational and maintenance data for long-term monitoring and future reuse readiness.	BIM-linked asset record (IFC / COBie) with maintenance schedules, inspection logs, and performance KPIs.
6. Reuse Continuity Report (RCR)	Updated Material Passport Set; Residual Performance Assessment Report; Selective Deconstruction Plan; Continuity of Passport Record; Lessons-Learned Summary	Captures end-of-life assessment, documents remaining performance, and ensures continuity for the next reuse cycle.	Final synthesis report (PDF) + data export (Excel/IFC) integrated into the circular asset management system.

Building on this overview, Figure 9.1 illustrates how the compound deliverables evolve across the six framework stages and how both ownership and responsibility are shared among project partners. Ownership refers to the party managing the deliverable within the Common Data Environment (CDE) during a specific stage, ensuring that information is updated, traceable, and accurate. Responsibility refers to the actor ultimately accountable for the correctness and approval of that information.

The client remains the central authority within the Information Management System. By approving the Project Reuse Charter at project initiation, the client sets the governance structure that defines all roles, data ownership, and decision-making lines. Throughout the process, the client, supported by the Reuse Coordinator, ensures consistent application of the framework's communication and verification procedures. While technical responsibility may shift between the engineer, contractor, or asset manager, the client retains final accountability for compliance, performance, and circularity outcomes. This structure reinforces top-down coordination and underlines that clear client leadership is vital for effective reuse implementation.

As the project progresses, ownership moves between actors such as the design lead, contractor, and asset manager, depending on who is actively involved at each stage. Responsibility is delegated to qualified experts acting on behalf of the client. For example, during design and verification, the lead engineer takes responsibility for the accuracy of the Integrated Verification Report (IVR), while the Reuse Coordinator and Asset Manager, often external specialists, ensure information quality and compliance during later stages. The Reuse Coordinator manages traceability through deconstruction and handover, whereas the Asset Manager maintains data integrity during operation and end-of-life preparation.

This division of roles keeps the client as the overall steward of the framework, while accountability for technical accuracy rests with those best qualified to ensure it. It provides a balance between flexibility and clear responsibility throughout the project lifecycle.



Delivery Compound	Ownership						Responsibility
	STAGE 1	STAGE 2	STAGE 3	STAGE 4	STAGE 5	STAGE 6	
Project Reuse Charter (PRC)	Client	Design lead	Reuse coordinator				Client / Project Owner
Integrated Verification Report (IVR)		Engineer	Reuse coordinator				Lead engineer (Technical) Client (Approval)
Material Transfer Log (MTL)			Deconstruction company	Contractor			Client / Reuse Coordinator
Construction Verification Record (CVR)				Contractor			Main contractor
Asset Performance Record (APR)			Deconstruction company	Contractor	Asset manager / client		Asset Manager / Reuse Coordinator
Reuse Continuity Report (RCR)						Asset manager / client	Asset manager / Client

Figure 9.1: The Information Management System

The Information Management System under path A and path B

The expert reflections were based on the Path A configuration, as this was the framework applied in the C-pier redevelopment at Schiphol. Consequently, the Information Management System described above mainly reflects the structure and logic of Path A. However, the IMS must also function in Path B situations, where donor and target projects are managed by different organisations. Ensuring that the same principles of information governance, verification, and traceability can be applied in both configurations is essential for its broader use.

Under Path A (Direct Donor–Target Alignment), the information flow is straightforward and linear. All data are created, verified, and approved within a single organisational structure. The client owns the Common Data Environment (CDE), while the Reuse Coordinator manages and updates all project information within this system. This arrangement enables short communication lines, quick verification, and minimal data handovers, ensuring efficient control over all reuse-related documentation.

Under Path B (Donor–Intermediate–Target Alignment), the information flow becomes more decentralised. An intermediary organisation, such as a reuse broker or material hub, temporarily manages the data exchange between the donor and target projects. In this setup, two connected environments exist: a Donor CDE, which stores verified material data from the deconstruction process, and a Target CDE, which contains the verified data used for the new design and construction. The intermediary ensures that key deliverables, such as the Material Transfer Log (MTL) and Reuse Continuity Report (RCR), remain consistent and traceable across both systems.

Although Path B introduces more interfaces, it follows the same management principles as Path A. The Reuse Coordinator acts as the link between the two environments, ensuring that data remain accurate, traceable, and aligned across all project phases. In this way, the IMS developed from the Path A framework can also be applied effectively in Path B projects, maintaining the same level of reliability and transparency even when donor and target projects are managed independently.

The Integration of the Information Management System in the framework

The Information Management System (IMS) is integrated into the existing Communication Framework for Reuse as a digital layer that connects and supports the Communication and Verification streams. While the original framework focused on organising collaboration and defining roles, the IMS ensures that the resulting information is structured, traceable, and centrally managed within the Common Data Environment (CDE).

Through this integration, each project stage now produces a single compound deliverable instead of multiple separate documents.This simplifies communication, reduces duplication, and creates a continuous flow of verified data across all stages.As a result, the framework shifts from process-based coordination to information-based collaboration, improving transparency and accountability.

In essence, the IMS enhances the existing framework by transforming it into a connected digital environment that supports consistent data exchange and long-term traceability of reuse information across both Path A and Path B projects.

The validation of the Communication Framework for Reuse confirmed its ability to structure collaboration, communication, and verification in complex reuse-oriented projects such as the C-pier redevelopment. Through expert reflection and case-based application, the framework proved both technically coherent and practically applicable, offering a clear sequence of actions and responsibilities across all stages of the reuse process. The introduction of the Information Management System (IMS) further strengthened the framework by transforming it from a process-driven model into a data-driven system, ensuring that all communication and verification activities are supported by transparent, traceable, and verifiable information flows. This refinement addressed the experts' concerns about information complexity, ownership, and accountability, clarifying the pivotal role of the client and the supporting responsibilities of the Reuse Coordinator and other specialists. Overall, the validated framework demonstrates that successful reuse depends on early coordination, clear governance, and integrated information management. Together, these elements establish a practical foundation for implementing circular construction practices in future projects within and beyond the Schiphol context.

10 Validation of the verification framework of cast-in-situ slabs

This chapter applies the developed verification framework to the case study of the C-pier at Schiphol Airport to demonstrate its functionality and evaluate its practical robustness. The aim is to determine whether the framework provides a clear, consistent, and technically reliable process for assessing the reuse potential of cast-in-situ concrete slabs.

The validation focuses on testing three interrelated aspects of the framework:

1. Whether the sequential logic, from data collection to the establishment of the Declared Reuse Performance (DRP), can be applied without ambiguity.
2. Whether the defined verification thresholds for geometry, concrete strength, durability, and structural performance are realistic and practically discriminative.
3. Whether the decision flow effectively guides the inclusion or exclusion of elements for reuse.

Within this context, validation success is defined as the framework's ability to produce consistent and traceable verification outcomes, to support transparent decision-making, and to demonstrate practical applicability under real project conditions. Given that the validation is limited to a single case, the analysis does not quantitatively verify the full set of framework success factors. Instead, it provides an initial indication of the framework's potential to reduce uncertainty, by clarifying verification logic and minimizing reliance on conservative assumptions, and to improve testing efficiency through a structured and targeted assessment sequence.

The validation is conducted through the C-pier case at Schiphol Airport, which provides a complete set of archival drawings, structural documentation, and design reports. Based on these sources, all relevant verification criteria of the framework are assessed to determine the preliminary Declared Reuse Performance (pDRP) for geometry, concrete strength, durability, structural performance, and sustainability contribution. The Hygiene, Health, and Environment (HHE) criterion and the verified DRP (vDRP) stage are excluded from this analysis, as they require real-life material testing, which was not feasible within the scope of this study.

In this chapter, the determination of each pDRP criterion is presented step by step. Based on the combined results, a decision advice is formulated that indicates whether the slabs are suitable for reuse, require significant adaptation, or should be excluded. To demonstrate the applicability and reliability of this decision process, a design for the new C-pier layout is subsequently developed regardless of the pDRP outcomes. This design serves as a proof of concept for the framework, verifying whether the decision advice meaningfully reflects the technical feasibility of reuse:

- If the majority of criteria yield red classifications, the framework correctly predicts that reuse is infeasible.
- If multiple orange classifications appear, reuse may be technically possible but environmentally or economically inefficient, an assumption verified through a comparative Life Cycle Assessment (LCA).
- If results are predominantly green or yellow, the design can proceed without major obstacles, confirming that reuse is both structurally and environmentally viable.

Through this process, the chapter validates the internal consistency and practical applicability of the verification framework, demonstrating its capacity to connect technical verification with environmental assessment and to support clear, evidence-based reuse decisions.

10.1. Determination of Preliminary Declared Reuse Performance

Geometry & Tolerances Results

Threshold pDRP: Minimum required span is 7.5 m

	pDRP value	pDRP
Type A	Minimum span principle direction 3.1m	🟠
Type B	Minimum span principle direction 3.1m	🟠
Type C	Minimum span principle direction 3.1m	🟠

As shown in Figure 8.5, Haskoning's modular steel design for the new C-pier features an irregular grid with spans of 7.5–15 m transversely and 10.8 m longitudinally. The reclaimed cast-in-situ slabs measure approximately 3.1 × 7.5 m and therefore fall short of the required transverse span. This mismatch can be resolved by adding intermediate steel beams within the modular grid to provide additional support, an acceptable geometric adaptation provided that reinforcement adequacy and load capacity are later verified. However, the sustainability impact of these new members must be weighed, as the extra steel may partially offset the carbon savings from reuse. Overall, the preliminary DRP for geometry and tolerances is rated as **orange**: reuse is feasible with major structural modification and further confirmation of environmental benefit.

Concrete Strenght Class Results

Threshold pDRP: minimum of C20/25 for XC1

	pDRP value	pDRP
Type A	K300 ≈ C18/22.5	🟡
Type B	K300 ≈ C18/22.5	🟡
Type C	B22,5 ≈ C18/22.5	🟡

The concrete strength classes of all slabs were available from the archival data set of the reclaimed elements. The remaining step was to translate the historical classes into their Eurocode 2 equivalents, either using the conversion table or a simple calculation.

Considering the provisions written down in NEN-8702 the concrete strength f_{yk} of K300 = 19 MPa and for B22,5 this is 18 MPa. This results in the following concrete classes

$$K300 \approx C18/22.5, \qquad B22{,}5 \approx C18/22.5,$$

which corresponds to a cube strength of $22.5\ \mathrm{MPa}$ and an equivalent cylinder strength of approximately

Durability Results

Threshold pDRP: XC1 Conditions: max w/c ratio: 0.65, minimum cement-content: 260 kg/m^3, minimum cover: 25 mm

	pDRP value	pDRP
Type A	w/c ratio: 0.6, min. cement content: 280, cover: 10 mm	🟠
Type B	w/c ratio: 0.6, min. cement content: 280, cover: 30 mm	🟢
Type C	w/c ratio: 0.6, min. cement content: 280, cover: 30 mm	🟢

The preliminary durability assessment verifies whether the reclaimed C-pier slabs meet the requirements for exposure class XC1 (dry indoor conditions). According to EN 206 and Eurocode 2, this class requires a maximum water–cement ratio of 0.65, a minimum cement content of 260 kg/m^3, and a concrete cover of at least 25 mm.

Historical data show that concretes from Era II in which this building was designed typically had w/c ratios of max 0.6 and cement contents of 280 kg/m^3, both compatible with current XC1 limits. Slab A, however, provides only 10 mm of cover, falling well below the modern requirements. Its durability is therefore rated orange and may even be red if the added layer compromises ULS/SLS performance. Slabs B and C, with 30 mm cover and historically adequate mix proportions, meet XC1 criteria and are rated green – acceptable for reuse under the intended indoor conditions.

Structural performance Results

Threshold pDRP: Moment capacity Type A: 21.3 and Type B and C: 25.2 kNm

	pDRP value	pDRP
Type A	Initial Load: 5.9; Minimum reinforcement: 6.5 kNm; Actual reinforcement: 7.1 kNm	🔴
Type B	Initial Load: 8.1; Minimum reinforcement: 21.3 kNm; Actual reinforcement: 24.2 kNm	🟠
Type C	Initial Load: 7.9; Minimum reinforcement: 21.1 kNm; Actual reinforcement: 23.2 kNm	🟠

This verification assesses whether the reclaimed slabs provide sufficient moment resistance under the design loads of the new C-pier. As the slabs are reused in a simply supported (hinged) configuration, flexural failure at mid-span governs the ultimate limit state (ULS).

Threshold capacity

The ULS design load is determined according to Eurocode 2 using the two formulas for CC3 calculation these are:

$$\text{ULS 1:}\quad q_{d,1} = 1.5\,G_k + 1.65 \cdot 0.4\,Q_{k,1} \tag{10.1}$$

$$\text{ULS 2:}\quad q_{d,2} = 1.3\,G_k + 1.65\,Q_{k,1} \tag{10.2}$$

where G_k is the total permanent load and $Q_{k,1}$ the leading variable load and in these formulas $\psi_0 = 0.4$ is already filled in. The ψ_0-factor used for the imposed load category ‘assembly areas’ is taken as 0.4, in accordance with the project's 'Structural Design Assumptions' document

$$M_{Ed} = \frac{1}{8} q_d l^2 \tag{10.3}$$

where $l = 3.1\ \mathrm{m}$ is the slab width.

Table 10.1 summarizes the characteristic loads used in the analysis.

Table 10.1: Characteristic loads and combination factors for the floor slabs

Load description	Load [kN/m^2]
Self-weight, G_s (slab type B and C)	2.5/5.0[a]
Permanent load, G_{pl}	4.8
Live load, q_{live}	5.0

[a] 3.0 kN/m^2 for Type A; 5.0 kN/m^2 for slab type B and C

The resulting design line loads (q_d) and mid-span moments are summarized in Table 10.9.

Table 10.2: Overview of ULS design loads and resulting bending moments for threshold

Slab type	G_k [kN/m]	$q_{d,1}$ [kN/m]	$q_{d,2}$ [kN/m]	$M_{AB,mid}$ [kNm]
A	7.3	14.3	**17.7**	21.3
B and C	9.8	18.0	**21.0**	25.2

Historical design check

Original slab design followed the *Breukmethode* (GBV 1962). The Breukmethode (GBV 1962) is a historical ultimate-limit design method in which the bending or shear capacity is first determined at the point of failure. Instead of using separate partial factors for loads and materials, the method applies a single global safety factor (γ ≈ 1.72–1.80) on the load side to obtain the allowable design load.

$$M_{Ed} = \frac{1}{24} q_d l^2 \tag{10.4}$$

The design loads in Table 10.3 are the loads multiplied by this global load-side safety factor (γ = 1.72). These resulting design loads q are then inserted into the monolithic bending formula (Eq. 10.4) to obtain the historical design moment.

Table 10.3: Design loads according to *Breukmethode* (GBV 1962)

Load type	Slab A [kN/m]	Slab B [kN/m]	Slab C [kN/m]
Self-weight G_d	4.3	8.6	8.6
Permanent $G_{pl,d}$	5.2	4.8	4.3
Variable $Q_{live.d}$	5.2	6.9	6.9
Total q_d	**14.6**	**20.3**	**19.8**

Table 10.4: Calculated design loads and effective mid-span moments

Parameter	Slab A	Slab B	Slab C
Total q_d [kN/m]	14.6	20.3	19.8
Effective moment M_{Ed} [kNm]	5.9	8.1	7.9

Minimum and actual reinforcement capacity

Per Article 32 of GBV 1962, the minimum reinforcement ratio is 0.20% of the concrete cross-section:

$$A_{s,\min} = 0.002\, l\, t \tag{10.5}$$

and the corresponding moment resistance:

$$M_{Rd} = f_{cd}\, \beta\, x_u\, b\, z \tag{10.6}$$

where $f_{cd} = 0.85\, f_{ck}/1.5$, $z = d - 0.4 x_u$, and $\beta = 0.39$.

Table 10.5: Minimum principal reinforcement and corresponding moment resistance

Slab type	$A_{s,\min}$ **[mm^2]**	M_{Rd} **[kNm]**
A	240	6.5
B	400	21.3
C	400	21.1

The actual reinforcement was verified from archival data and used to calculate the real moment capacities.

Table 10.6: Actual reinforcement and corresponding moment resistance

Slab type	A_s **[mm^2]**	M_{Rd} **[kNm]**
A	251	7.1
B	447	23.9
C	426	23.2

Slab A, with a verified capacity of $7.1\ \mathrm{kNm/m}$ against a required $22.6\ \mathrm{kNm/m}$, fails to meet the ULS threshold and is rated **red – unsuitable for reuse**. Slabs B and C show higher capacities ($\approx 23\,\mathrm{kNm/m}$) but remain below the required $25.8\ \mathrm{kNm/m}$ for the target 7.5 m span. Reuse is feasible only after geometric adjustment or structural strengthening; therefore, both are rated **orange – conditionally acceptable pending modification**.

Fire resistance results

Threshold pDRP: REI 90 critera, thickness: 100 mm and reinforcment distance: 30 mm

	pDRP value	**pDRP**
Type A	Slab thickness: 100 mm and reinforcement distance: 14 mm	🔴
Type B	Slab thickness: 200 mm and reinforcement distance: 36 mm	🟢
Type C	Slab thickness: 200 mm and reinforcement distance: 35 mm	🟢

All the information regarding the slab thickness and to determine the reinforcement distance were available based on the archival data. The only thing that is left to be done is to calculate this reinforcement distance based on the cover and reinforcement diameter.

Slab A has $c_{\text{nom}} = 10$ mm and $\phi = 8$ mm:

$$c_{\text{eff,A}} = 10 + \tfrac{1}{2} \times 8 = 14\ \text{mm},$$

which, combined with its limited 100 mm thickness, fails to meet the REI 90 criterion significantly. Slabs B and C, with $c_{\text{nom}} = 30$ mm and $\phi = 12$ mm and 10 mm respectively, give:

$$c_{\text{eff,B}} = 36 \text{ mm}, \qquad c_{\text{eff,C}} = 35 \text{ mm},$$

both exceeding the required 30 mm.

Sustainability Contribution

The sustainability contribution assessment quantifies the environmental impact of reusing the C-pier slabs. In order to establish the impact the first step is to determine the amount of concrete and reinforcement steel present in each of the slab types. In this case both the principle reinforcement and transverse reinforcement is considered. In the table below the volume for each of these slab types is summarized. Based on the EPD's provided in section 7.4.7 the total GWP of the reclaimed slabs is calculated. In this table the concrete strength class of C20/25 is used as this is the assumed concrete strength class for the slabs and the type of concrete that will be used in the new design.

Table 10.7: Per-slab material volumes and total GWP including reinforcement steel (reclaimed scenario)

Slab	$V_{\text{conc,net}}$ [m^3]	V_{steel} [m^3]	GWP CEM I	GWP CEM IIIA	GWP CEM IIIB	GWP CEM IIIC
A	2.390	0.01232	141.5	140.6	140.1	140.1
B	4.789	0.01583	280.1	278.3	277.3	277.3
C	4.788	0.01658	280.3	278.5	277.6	277.6

Calculation of the concrete per slab

The volume is determined using the following expression:

$$V_{concrete} = V_{total} - V_{steel}, \qquad V_{total} = L \cdot B \cdot t$$

Calculation of the reinforcement steel per slab

$$V_{steel} = L_{bar} \cdot A_{bar} \cdot N_{bars}, \qquad N_{bars} = \frac{W}{s} \text{rounded up to nearest integer}, \qquad A_{bar} = \frac{\pi d^2}{4}$$

If this formula is applied on for example slab A the following calculation is the result:

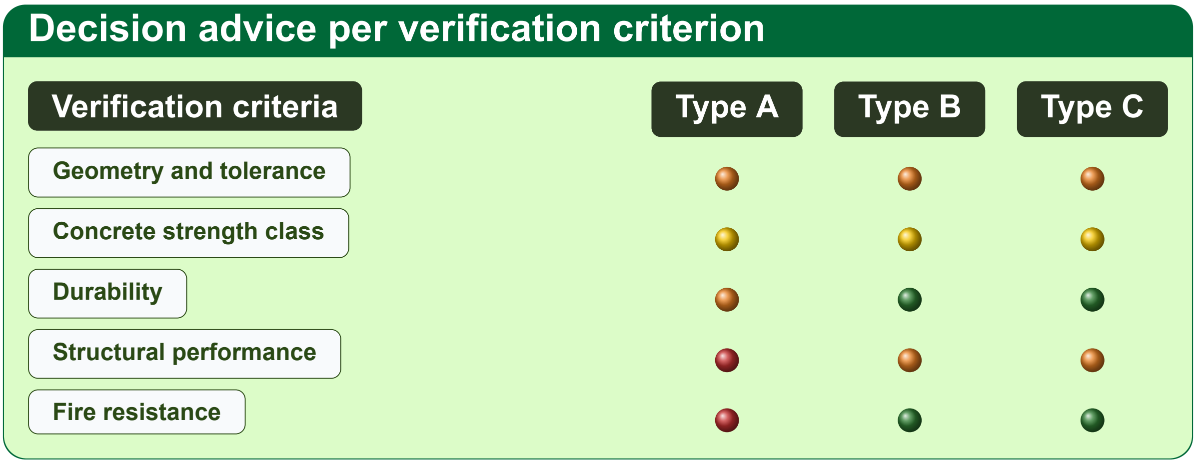
1. **Bars transverse direction (length 7.75 m, spaced across B):**

$$7.75 \cdot \frac{\pi(0.008)^2}{4} \cdot \frac{3100}{200} = 0.00623\text{mm}^3$$

2. **Bars principle direction (length 3.10, spaced across L):**

$$3.10 \cdot \frac{\pi(0.008)^2}{4} \cdot \frac{7750}{200} = 0.00609\text{mm}^3$$

10.2. Decision Advise based on pDRP Analysis



Decision advice per verification criterion

Verification criteria	Type A	Type B	Type C
Geometry and tolerance	🟠	🟠	🟠
Concrete strength class	🟡	🟡	🟡
Durability	🟠	🟢	🟢
Structural performance	🔴	🟠	🟠
Fire resistance	🔴	🟢	🟢

The decision advice indicates that Type A slabs are unsuitable for reuse, as the verification results for structural performance and fire resistance both fall below the acceptable threshold (red rating). These deficiencies imply that the element cannot meet the required load-bearing or fire safety conditions even with corrective measures, thereby excluding it from further consideration.

For Type B and Type C, the overall performance suggests that reuse is technically conceivable, but the feasibility is strongly constrained by geometric compatibility and structural performance limitations. Although both types achieve acceptable ratings for durability, concrete strength class, and fire resistance, their geometry and load-carrying capacity do not align with the dimensional and mechanical requirements of the target structure. The reduced span and reinforcement layout prevent an effective integration of the existing slab modules into the new system design. Consequently, while a design solution might theoretically be developed, it would not deliver the intended structural continuity or reduction in new material demand.

10.3. Validation through design application

To validate the feasibility of reuse under the given verification results, a design application is performed using the Type B and Type C slab elements. These slabs are rated orange, meaning that reuse is technically possible but only with notable limitations. The purpose of this validation is therefore not to produce an optimized design, but to illustrate how a reuse-based configuration can still be managed despite these shortcomings and therefor comfirm the orange outcome. Type A elements are excluded from the assessment due to their red ratings in structural performance and fire resistance, which render their reuse infeasible.

An overview of the new C-pier floor layout

To develop a new design for the floor system of the C-pier, secondary beams are introduced into the existing structural configuration. The primary objective is to ensure that the reclaimed slabs are supported only along their edges, allowing them to be idealised as simply supported elements. This approach is necessary because the slabs lack top reinforcement, which in the original construction was typically placed over the beam intersections. Since the reclaimed slabs were cut between the beams during deconstruction, most of this top reinforcement has been lost.

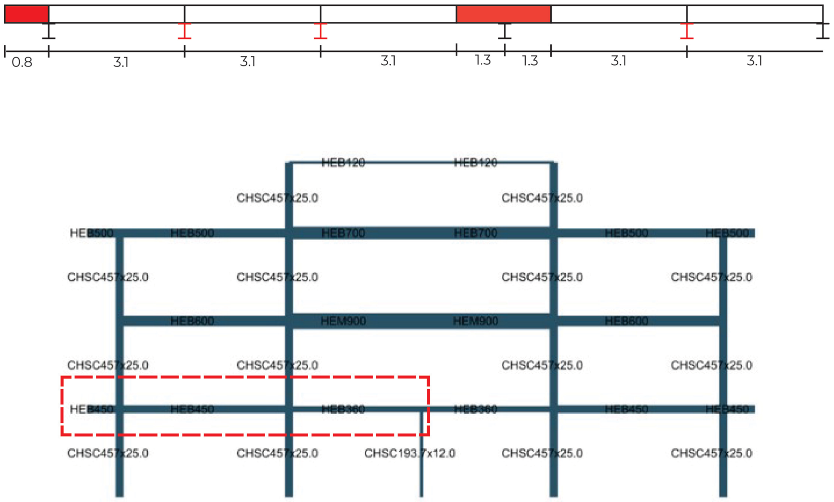


Figure 10.1: Cross-section of the floor slabs in the new design (left side till mid-column)

To accommodate this condition, the layout of the floor system has been redesigned as shown in Figure 10.1. The red members in the figure represent the newly added secondary beams required to integrate the reclaimed slabs within the structure, while the black H-profiles denote the original primary members. For proper spacing and alignment, the cantilever length has been reduced from 1.8 m in the original design to 1.0 m. The figure illustrates half of the first-floor system, showing the cantilever portion, the 9.6 m span section, and the 7.75 m span extending toward the central column.

Schematization of the floor system

In order to calculate the required reinforcement in the new slab and assess whether strengthening measures could increase the moment resistance of the reclaimed slabs, the floor system is schematized as shown in Figure 10.2. The secondary beams are assumed to be simply supported, as they are not laterally restrained by columns or other structural elements, whereas the midspan of the slab is supported by a column and can therefore be modelled as a fixed or partially restrained support.

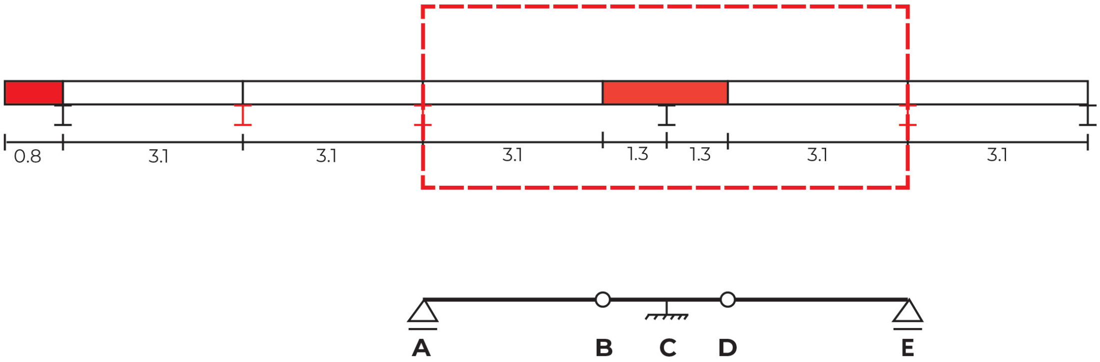


Figure 10.2: Schematization of the critical floor section

The hinged supports in this schematization represent the demountable concrete deck-to-deck connections as developed and analyzed by Brouwer, 2025 (see figure 10.3). In his research, this connection consists of high-strength friction-grip bolts (HSFGBs) positioned between adjacent concrete decks, enabling mechanical interlock and frictional shear transfer while allowing full demountability. The connection is required to provide sufficient shear capacity, stiffness, and ductility (minimum slip capacity of 6 mm per EN 1994-1-1) while maintaining composite action between the reused concrete slabs and the steel–concrete beam.

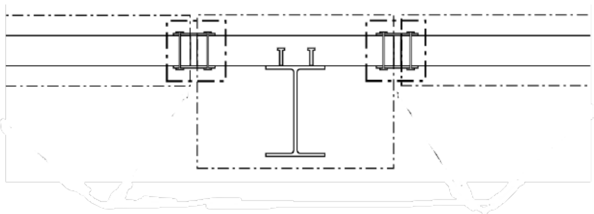


Figure 10.3: Demountable slab to slab connection (Brouwer, 2025)

Load combinations and resulting force diagrams

This section presents the applied load combinations and the corresponding shear force and bending moment distributions used to verify the structural performance of the reclaimed slab elements. To determine the ULS and SLS combinations for this design the following characteristic loads are being used.

Table 10.8: Characteristic loads and combination factors for the floor slabs

Load description	**Load [kN/m^2]**
Self-weight, G_s (slab type B and C)	5.0 / 5.9[a]
Permanent load, G_{pl}	4.8
Live load, q_{live}	5.0

[a] 5.0 kN/m^2 for Strengthening II; 5.9 kN/m^2 for Strengthening I.

Ultimate Limit State (ULS)

All calculations are carried out in accordance with **Consequence Class 3 (CC3)**, i.e. Equations (10.1)–(10.2). The resulting design line loads in the 3.1 m slab direction and the corresponding moments are summarized in Table 10.9. In addition, the governing moment in the longitudinal beam direction ($L_Y = 7.75\ \mathrm{m}$) is determined by converting the slab surface load from the governing ULS combination ($q_{d,2}$) into a line load on the primary beam using the tributary width $b_t = 3.10\ \mathrm{m}$, according to $q_{d,\text{line}} = q_{d,2}\, b_t$. For a simply supported span $L_Y = 7.75\ \mathrm{m}$, the maximum positive bending moment then becomes $M_{Y,\max} = \frac{q_{d,\text{line}}\, L_Y^2}{8}$.

Table 10.9: Overview of ULS design loads and resulting bending moments (3.1 m slab direction and 7.75 m beam direction)

Slab type	G_k **[kN/m]**	$q_{d,1}$ **[kN/m]**	$q_{d,2}$ **[kN/m]**	$M_{AB,mid}$ **[kNm]**	M_C **[kNm]**	$q_{d,\text{line}}$ **[kN/m]**†	$M_{Y,\max}$ **[kNm]**‡
B and C (Strengthening I)	10.7	19.19	**22.37**	26.88	63.99	69.35	520.64
B and C (Strengthening II)	9.8	17.85	**21.19**	25.45	60.95	65.69	493.18

† Converted line load on primary beam using tributary width $b_t = 3.10\ \mathrm{m}$: $q_{d,\text{line}} = q_{d,2}\, b_t$.

‡ Maximum moment in the longitudinal beam direction with span $L_Y = 7.75\ \mathrm{m}$: $M_{Y,\max} = \frac{q_{d,\text{line}} L_Y^2}{8}$.

The corresponding bending moment distribution across the schematized slab system is illustrated in Figure 10.4. In longitudinal direction the slab is modelled as a simply supported slab, and thus is this distribution not visualised.

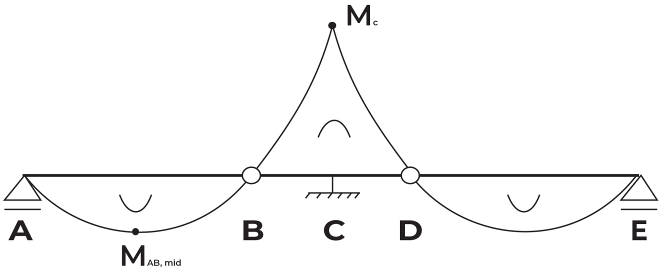


Figure 10.4: Bending moment distribution for the schematized floor system

The maximum support reactions and the shear forces for both the transverse (3.1 m slab) and longitudinal direction (7.75 m beam) derived from the ULS combinations are presented in Table 10.10.

Table 10.10: Overview of resulting shear forces at supports (transverse and longitudinal directions)

Slab type	V_B **[kN]**	V_C **[kN]**	$V_{Y,\max}$ **[kN]**[†]
B and C (Strengthening I)	34.67	63.77	268.65
B and C (Strengthening II)	32.83	60.38	254.03

[†] Maximum shear force in the longitudinal beam direction ($L_Y = 7.75\,\mathrm{m}$) determined from $V_{Y,\max} = 0.5\, q_{d,\text{line}}\, L_Y$.

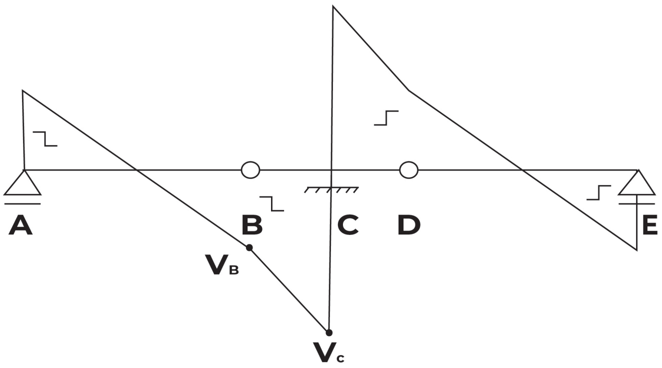


Figure 10.5: Shear force distribution for the schematized floor system

Serviceability Limit State (SLS)

Since SLS verifications were not part of the pDRP process, the quasi-permanent load combination is determined separately. For indoor floors, the quasi-permanent load is expressed as:

$$q_d = \sum G_{k,\text{perm}} + P + \sum \psi_{2,i}\, Q_{k,i}$$

where $\psi_2 = 0.3$ for imposed loads in residential-type occupancy. The corresponding SLS design loads and bending moments are shown in Table 10.11.

Table 10.11: Overview of SLS design loads and resulting bending moments

Slab type	G_k **[kN/m]**	**SLS** q_d **[kN/m]**	$M_{AB,mid}$ **[kNm]**	M_c **[kNm]**	$q_{d,\text{line}}$ **[kN/m]**[†]	$M_{Y,\max}$ **[kNm]**[‡]
B and C (Strengthening I)	10.7	12.2	14.66	34.89	37.28	283.95
B and C (Strengthening II)	9.8	11.3	13.57	32.32	35.03	263.00

The Ultimate limit state verification

The Ultimate Limit State (ULS) verification covers the primary structural components that govern the load-bearing performance of the floor system.Each element is checked for both bending and shear resistance under the applicable load combinations determined in the previous section. The verification includes the following elements:

- **Slab Type B** , the ULS check has already been done in the pDRP stage, it was found not sufficient so instead to strengthening methods are elaborated to show the new moment capacity using this approach:
  - *Method I:* application of an additional concrete overlay to increase the internal lever arm and moment capacity;
  - *Method II:* externally bonded CFRP laminates applied to the tension face to enhance flexural strength.
- **Slab Type C** , analysed using the same two strengthening approaches as Type B, with adapted reinforcement and geometry.
- **Secondary steel beams** , supporting the slab system, assessed for bending and shear under the combined tributary floor loads.
- **Concrete–steel composite beam** , located along the primary span direction and resisting the global hogging moment in the floor system; verified for composite flexural and shear capacity.

The generic verification methods

Bending resistance of RC section (Method I, overlay)

In Strengthening Method I the flexural resistance of the existing slab is enhanced by casting a new concrete overlay on top of the original element. The additional layer of 35 mm increases the total slab depth and thereby enlarges theinternal lever arm between the compressive and tensile resultants. When the overlay is properly roughened and bonded, the two concrete layers act monolithically, and the composite section behaves as a single, thicker reinforced concrete element.

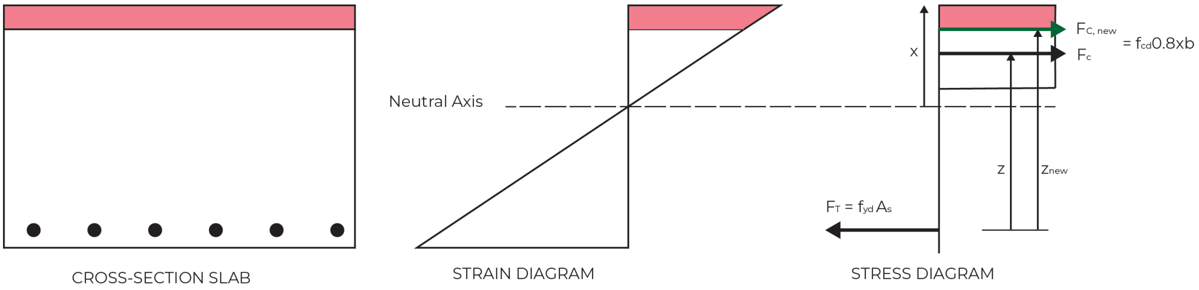


Figure 10.6: Strengthening Method I - Stress and strain diagram

As can be seen in figure 10.6 by adding the concrete overlay the anchoring point of the compressive concrete force moves upwards. This results in a larger leverarm for the internal forces and thus a higher moment resistance.

The verification follows the standard rectangular stress block model of EN 1992-1-1 for reinforced concrete in bending. The compression block is taken over the effective depth of the composite section, and the tensile reinforcement in the original slab is assumed to remain fully anchored and effective. The flexural verification proceeds in the following sequence:

1. **Determine the internal compressive and tensile force considering the rectangular estimation of EC 2:** compression in concrete $F_c = f_{cd}\,\eta\,b\,x$, in which $\eta = 0.85$ and tension in steel $F_t = f_{yd}\,A_s$
2. **Enforce equilibrium:**

$$F_t = F_c \quad \Rightarrow \quad x = \frac{A_s f_{yd}}{\eta f_{cd} b}$$

3. **Compute the lever arm:**

$$z = d - \frac{\lambda\, x}{2} = \left(h - c - \frac{\phi}{2}\right) - \frac{0.8 \cdot x}{2}$$

4. **Evaluate the design moment capacity:**

$$M_{Rd} = A_s f_{yd} z$$

5. **Check limiting conditions:**

$$x \leq x_{\max} = \frac{\xi_{\max} d}{\lambda} = \frac{0.45d}{\lambda}, \qquad z \leq 0.95\, d, \qquad \rho_l = \frac{A_s}{bd} \leq 0.02.$$

6. **Compare with design action:** verify that $M_{Ed} \leq M_{Rd}$ for the governing load combination.

Bending resistance of RC section (Method II, CFRP plates)

In Strengthening Method II, the flexural capacity of the existing slab is increased by bonding carbon-fibre-reinforced polymer (CFRP) laminates to the soffit of the concrete element. The externally bonded plate supplements the tensile reinforcement, providing an additional tensile force at a larger lever arm. Because the CFRP material behaves linearly elastic up to failure and is much stiffer than concrete, the overall strain distribution remains linear; however, the position of the neutral axis shifts upward (Figure 10.7), reducing the compressive zone depth while increasing the internal lever arm and tensile force. This results in a greater moment capacity without significantly changing the section geometry or self-weight.

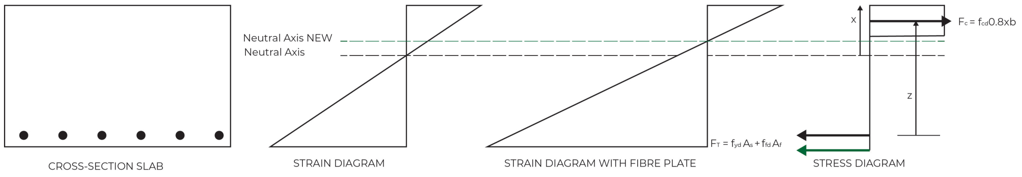


Figure 10.7: Conceptual representation of Strengthening Method II: cross-section, strain and stress distribution with externally bonded CFRP plate.

The figure illustrates the *cross-section* with the bonded CFRP plate (in green), the resulting *strain diagram*, and the corresponding *stress diagram*. The new strain distribution includes the additional tensile strain in the fibre, while the stress diagram shows two tensile resultants: one from the reinforcing steel $F_s = f_{yd}A_s$ and one from the CFRP plate $F_f = f_{fd}A_f$.

The verification is performed using a simplified rectangular stress-block model as per EN 1992-1-1, extended to include the externally bonded CFRP reinforcement. The method assumes full composite action between concrete and plate within the effective bond length and linear elastic behaviour of the CFRP until the governing strain limit is reached. The effective design strain $\varepsilon_{f,\text{eff}}$ is limited either by the material rupture strain or by the debonding limit, depending on surface preparation and adhesive properties. The flexural verification is carried out through the following steps:

1. **Establish force equilibrium:**

$$F_c = F_s + F_f \quad \Rightarrow \quad \eta\, f_{cd}\, b\, x = A_s f_{yd} + A_f f_{fd}. \quad \Rightarrow \quad x = \frac{A_s f_{yd} + A_f f_{fd}}{\eta f_{cd} b}.$$

   In this formula the strength of the CFRP layer f_{fd} is determined as $E_f \cdot \varepsilon_{fe} = 165\text{GPa} \cdot 0.004 = 660MPa$ the design facot for these place is usually 1.5 making $f_{fd} = \frac{660}{1.5} = 440$ MPa

2. **Compute lever arms:**

$$z_s = d - \frac{\lambda x}{2} = \left(h - c - \frac{\phi}{2}\right) - \frac{0.8 \cdot x}{2}, \qquad z_f = d_f - \frac{\lambda x}{2} = h - t_{adh} - \frac{t_f}{2} - \frac{0.8 \cdot x}{2}.$$

3. **Determine design moment capacity:**

$$M_{Rd} = A_s f_{yd} z_s + A_f f_{fd} z_f.$$

4. **Check limiting conditions:**

$$x \le x_{\max} = \frac{\xi_{\max} d}{\lambda}, \qquad z_s \le 0.95\, d, \qquad \rho_l = \frac{A_s}{b\, d} \le 0.02.$$

5. **Verify governing strain and bond limits:**

$$\varepsilon_{f,\text{eff}} \le \varepsilon_{f,\text{deb}} \quad \text{and} \quad L_a \ge L_{b,\text{req}},$$

   where L_a is the provided anchorage length and $L_{b,\text{req}}$ the required bond length obtained from the debonding model.

6. **Compare with design action:** check that $M_{Ed} \le M_{Rd}$ for the governing load combination.

Bending resistance of new composite beam - Transverse direction

Along this direction the slab does not act compositely with the steel beam; the section behaves exactly as in **Strengthening Method I (overlay)**: a reinforced concrete strip of unit width with total thickness h and tensile steel at depth d. Therefore the force equilibrium and stress–block assumptions are identical to Method I and are not repeated here. The only difference that can be seen in 10.8 is that in this case there is a hogging moment, thus the top of the slab is in tension and this will be where the reinforcement is placed.

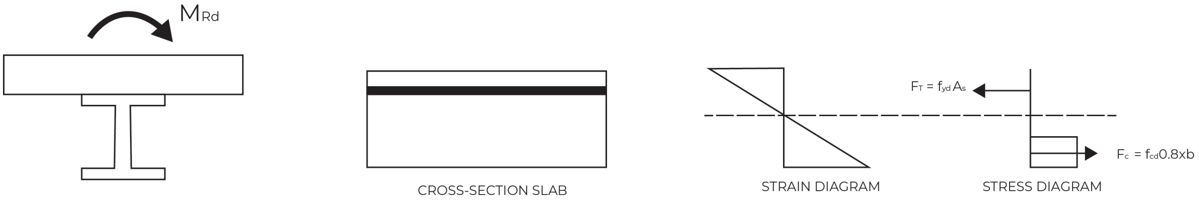


Figure 10.8: Stress-strain diagram of composite slab

The force equilibrium calculation is adjusted in such a way that the unknown A_s can be determined.

$$M_{Rd} = A_s f_{yd} \left(d - \frac{\lambda}{2} \frac{A_s f_{yd}}{\eta f_{cd} b} \right) = M_{Ed}.$$

Define

$$C = \frac{\lambda f_{yd}^2}{2\, \eta f_{cd}\, b}, \qquad K = f_{yd}\, d.$$

Then the required area is (the smaller positive root is the physical solution):

$$\boxed{A_{s,\text{req}} = \frac{K - \sqrt{K^2 - 4\, C\, M_{Ed}}}{2\, C}}$$

After sizing A_s, verify:

$$x = \frac{A_s f_{yd}}{\eta f_{cd} b} \le x_{\max} = \frac{\xi_{\max} d}{\lambda}, \qquad z = d - \frac{\lambda x}{2} \le 0.95\, d, \qquad \rho_l = \frac{A_s}{bd} \le 0.02.$$

Provide at least the minimum reinforcement per EN 1992-1-1:

$$A_{s,\min} = \max\left(0.26\, \frac{f_{ctm}}{f_{yk}}\, bd,\ 0.0013\, bd \right).$$

Once the entire check is done the actual amount of reinforcement is determined this is a practical sizing that is at least the amount determined by this calculation.

Bending resistance of new composite beam - Longitudinal

In order to determine the bending resistance of the new composite slab a plastic analysis has been done. The first step in this analysis is to determine whether this approach may be used, this depends on the following factors:

1. The cross-section is class 1, only these kinds of cross-sections can maintain a platsic hinge with redistribution.
2. Steel grade $\leq$ S355, Ensures ductility, higher steel strengths have lower strain capacity so hinges may crack concrete or tear studs prematurely.

The second factor can be checked relatively easy by the material assumption for the steel cross-section. For the class determination the following analysis must be done:

$$c = \frac{b_a - t_w - 2r}{2}, \qquad d = h_a - 2(t_f + r), \qquad \lambda_f = \frac{c}{t_f}, \quad \lambda_w = \frac{d}{t_w},$$

and verify Class 1 limits $\lambda_f \leq 9\varepsilon$, $\lambda_w \leq 72\varepsilon$ with $\varepsilon = \sqrt{235/f_y}$.

Once it is verified that the plastic analysis can be done the height of the neutral axis must be determined based on the force couple between the tensile force in the steel section and the compressive force generated in the concrete. In figure 10.9 the case in which the neutral-axis is within the steel cross-section is shown, it must be determined that this is the case.

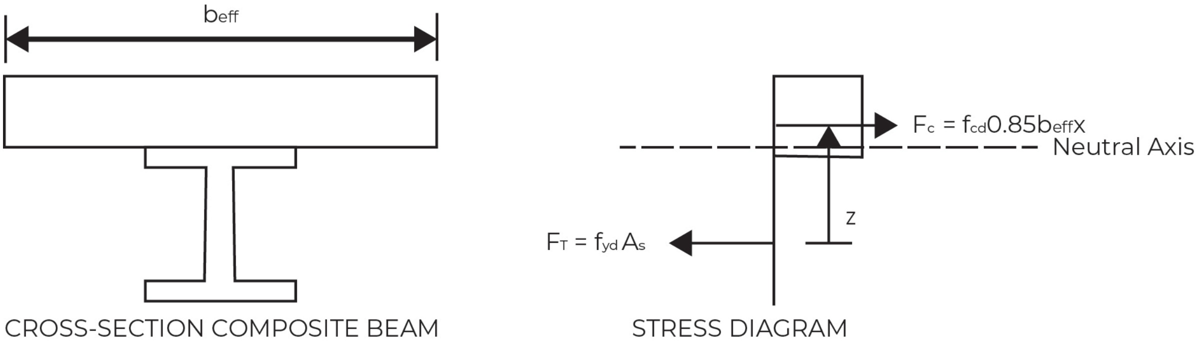


Figure 10.9: The stress-diagram of the composite beam

$$F_T = A_a\, f_{yd} \qquad F_c = 0.85\, f_{cd}\, b_{\text{eff}}\, h_c.$$

The location of the neutral-axis is then determined as follows:

- If $N_{ad} \leq N_{cd}$, the NA lies in the concrete and the compression block depth is

$$x = \frac{N_{ad}}{0.85\, f_{cd}\, b_{\text{eff}}}.$$

- If $N_{ad} > N_{cd}$, the NA lies in the steel; form the required compressed steel block in the top flange/web to equilibrate N_{ad} (not typical for floor beams with solid slabs).

Based on the location of the neutral-axis the moment resistance can be determined as:

$$z = \frac{h_{steel}}{2} + h_c - \frac{x}{2}, \qquad M_{pl,\text{sag},Rd} = N \cdot z, \quad N = \min\bigl(N_{ad},\, N_{cd}\bigr).$$

To ensure full composite action, sufficient shear connectors must be provided so that slip between the steel beam and concrete slab is prevented and the full plastic moment resistance can develop. The design shear resistance of a single headed stud is governed by the lesser of steel and concrete failure and is given by:

$$P_{Rd} = \min\left(\frac{0.8\, f_u\, A_s}{\gamma_V}, \frac{0.29\, k\, d^2 \sqrt{f_{ck}\, E_{cm}}}{\gamma_V}\right) k_t,$$

where $A_s = \pi d^2/4$ is the stud shank area, f_u the ultimate tensile strength of the stud, γ_V the partial factor for shear connection, f_{ck} and E_{cm} the concrete strength and modulus, k an empirical coefficient (≈ 1.0 for solid slabs) and k_t a reduction for studs in deck ribs ($k_t = 1.0$ for solid slabs).

Full composite interaction is obtained when the total shear capacity of the studs equals or exceeds the tensile force to be transferred, corresponding to the steel tension resultant N_{ad}. The required number of studs is therefore:

$$n_{\text{full}} = \left\lceil \frac{N_{\text{ad}}}{P_{Rd}} \right\rceil .$$

The studs are distributed symmetrically, with approximately half on each side of mid-span. The average spacing over half the span can be estimated as:

$$s_{\text{avg}} \approx \frac{L_e/2}{\lceil n_{\text{full}}/2 \rceil},$$

subject to the detailing limits for minimum spacing, edge distance and rib grouping specified in EN 1994.

If fewer studs are provided than required for full interaction, the degree of shear connection is defined as $\eta = n_{\text{installed}}/n_{\text{full}} \leq 1$. The transferable force and corresponding moment resistance are then reduced to:

$$N = \min(\eta N_{ad},\, N_{cd}), \qquad M^{(\eta)}_{pl,\text{sag},Rd} = N \cdot z.$$

Partial shear connection may be accepted provided the resulting resistance satisfies the design requirements and all ductility and spacing criteria for studs are met.

Moment resistance of the secondary beams

The bending resistance of the secondary steel beams is determined in accordance with EN 1993-1-1, §6.2.5. For Class 1 or 2 cross-sections, full plastic bending resistance may be assumed. The design plastic moment resistance is given by:

$$M_{pl,Rd} = W_{pl}\, f_{yd}, \qquad f_{yd} = \frac{f_y}{\gamma_{M0}},$$

where:

- W_{pl} is the plastic section modulus of the steel cross-section,
- f_y is the nominal yield strength of the steel,
- γ_{M0} is the partial safety factor for steel cross-section resistance (typically 1.0).

The section is adequate in bending when:

$$M_{Ed} \leq M_{pl,Rd}.$$

If the inequality is not satisfied, a larger cross-section must be selected such that $W_{pl} \geq M_{Ed}/f_{yd}$. This ensures that the steel beam can fully develop its plastic moment capacity under the applied loading.

The shear capacity check for the concrete slabs

For the concrete slabs that do not work as a composite beam, the shear resistance is determined directly in accordance with EN 1992-1-1, 6.2.2, assuming no shear reinforcement. The design shear strength is given by:

$$v_{Rd,c} = \max\Big(C_{Rd,c}\, k\, (100\, \rho_l\, f_{ck})^{1/3},\; v_{\min}\Big), \qquad v_{\min} = 0.035\, k^{3/2}\, f_{ck}^{1/2},$$

where:

- $C_{Rd,c} = 0.18/\gamma_c$ is the concrete shear coefficient,
- $k = 1 + \sqrt{200/d} \leq 2.0$ accounts for size effects,
- $\rho_l = A_s/(b_w d) \leq 0.02$ is the longitudinal reinforcement ratio,
- f_{ck} is the characteristic compressive strength of concrete.

The governing shear stress $v_{Rd,c}$ is taken as the greater of the empirical expression and the minimum limit $v_{\min}$. The corresponding design shear resistance per unit width then follows as:

$$V_{Rd,c} = v_{Rd,c}\, b_w\, d.$$

If the calculated shear stress due to design loading v_{Ed} satisfies $v_{Ed} \leq v_{Rd,c}$, the section is adequate without shear reinforcement. Otherwise, additional transverse reinforcement must be provided according to EN 1992-1-1, 6.2.3. All variables are evaluated per unit width of slab to maintain consistency with the flexural design approach.

The shear capacity check for the steel beams

In accordance with EN 1994-1-1, §6.2.2.4(2), the vertical shear in a composite beam is assumed to be resisted entirely by the steel section. Consequently, the shear verification for both the composite and the non-composite (secondary) steel beams follows the same procedure given in EN 1993-1-1, §6.2.6. The design shear resistance of the steel web is expressed as:

$$V_{pl,Rd} = \frac{A_v\, f_{yv}}{\sqrt{3}\, \gamma_{M0}},$$

where:

- A_v is the effective shear area of the web (for rolled I/H sections $A_v \approx h_w\, t_w$),
- f_{yv} is the yield strength of the web steel (normally taken equal to f_y),
- γ_{M0} is the partial safety factor for resistance of steel cross-sections (usually 1.0).

The design is satisfactory when:

$$V_{Ed} \leq V_{pl,Rd}.$$

For the present beams, the design shear force V_{Ed} from the load combinations is well below the web shear capacity $V_{pl,Rd}$ of the selected HEB sections. Therefore, both the composite and the secondary steel beams are deemed adequate in shear, and no further shear reinforcement or web stiffeners are required.

The ULS verification results per constructive element

Slab type B

The input variables for the concrete slab of type B are:

Table 10.12: Input values for slab Type B

Concrete and steel parameters	Symbol	Value	CFRP strengthening parameters	Symbol	Value
Concrete strength	f_{ck}	19 MPa	Strip width	b_f	50 mm
Slab thickness (Method I)	d_I	235 mm	Strip thickness	t_f	0.6 mm
Slab thickness (Method II)	d_{II}	200 mm	Adhesive thickness	t_{adh}	2 mm
Concrete cover	c	30 mm	CFRP modulus of elasticity	E_f	165,000 MPa
Slab width (unit width)	b_w	1000 mm	Bond length	l_b	2000 mm
Reinforcement area	A_s	447 mm^2/m	Number of CFRP strips per m width	n_f	8
Reinforcement bar diameter	ϕ	12 mm	CFRP strain	ε_f	0.004
Reinforcement yield strength	f_{yk}	400 MPa			

For this slab a total of four ULS verification tests is done: the moment capacity for both strengthening types and the shear capacity for both strengthening methods the result is the following.

Table 10.13: Summary of ULS verification results for slab Type C

Strengthening Method	M_{Ed} [kNm/m]	M_{Rd} [kNm/m]	V_{Ed} [kN]	V_{Rd} [kN]	UC OK?
Method I	26.88	28.15	63.77	84.0	✓
Method II	25.45	25.75	60.38	69.3	✓

Slab type C

The input variables for the concrete slab of type C are:

Table 10.14: Input values for slab Type C

Concrete and steel parameters	Symbol	Value	CFRP parameters	Symbol	Value
Concrete strength	f_{ck}	18 MPa	Strip width	b_f	50 mm
Slab thickness (Method I)	d_I	235 mm	Strip thickness	t_f	0.6 mm
Slab thickness (Method II)	d_{II}	200 mm	Adhesive thickness	t_{adh}	2 mm
Concrete cover	c	30 mm	CFRP modulus of elasticity	E_f	165,000 MPa
Slab width (unit width)	b_w	1000 mm	Bond length	l_b	2000 mm
Reinforcement area	A_s	426 mm^2/m	CFRP strips [#/m]	n_f	8
Reinforcement bar diameter	ϕ	10 mm	CFRP strain	ε_f	0.004
Reinforcement yield strength	f_{yk}	400 MPa			

For this slab a total of four ULS verification tests is done: the moment capacity for both strengthening types and the shear capacity for both strengthening methods the result is the following.

Table 10.15: Summary of ULS verification results for slab Type C

Strengthening Method	M_{Ed} [kNm/m]	M_{Rd} [kNm/m]	V_{Ed} [kN]	V_{Rd} [kN]	UC OK?
Method I	26.88	28.15	63.77	84.0	✓
Method II	25.45	25.75	60.38	69.3	✓

Composite beam

For the composite beam an entire new slab has to be established. In the table below the parameters for the slab that have been used are found. The filled in As in this table has been determined with the method described in the previous section. The elements that this composite beam are made up of are an HEB 220 beam on which a concrete slab is placed. The two elements are under full composite action since the number of shear connector needed to achieve this are calculated as well. The shear studs are studs with a 19 mm diameter and a tensile strength of 450 MPa.

Table 10.16: Input values for composite slab with HEB 220 steel beam

Concrete slab parameters	Symbol	Value	HEB 220 parameters	Symbol	Value
Concrete strength	f_{ck}	20 MPa	Yield strength	f_y	235 MPa
Elastic modulus	E_c	30,000 MPa	Elastic modulus	E_s	210,000 MPa
Slab thickness (method I/method II)	h_c	235-200	Section height	h	220 mm
Slab width (unit width)	b_w	1000 mm	Flange width	b_f	220 mm
Reinforcement area (method I/method II)	A_s	785/1130 mm^2/m	Cross-section area	A	9104 mm^2
Reinforcement yield strength	f_{yk}	500 MPa	Plastic section modulus	$W_{pl,y}$	827$\times$10^3 mm^3
Concrete cover	c	30 mm	Moment of inertia	I_y	80.91$\times$10^6 mm^4
Bar diameter (method I/method II)	ϕ	10/12 mm	Shear area	A_v	5300 mm^2
			Weight per metre	G	61.3 kg/m

The checks that have been done for the composite beam are firstly in the transverse slab direction. First the amount of reinforcement needed to withstand the hogging moment in C was determined and turned into an practical area $\rho 10 - 100$ which is an $A_s = 785$ mm for method I and $\rho 12 - 100$ which is $A_s = 1130$ mm for method 2. In the table below the resulting moment capacity and shear checks are shown. These checks were performed for two thickness such that they can match the thickness of the reclaimed slab.

Table 10.17: Summary of ULS verification results for composite beam transverse direction

Strengthening Method	M_{Ed} [kNm/m]	M_{Rd} [kNm/m]	V_{Ed} [kN]	V_{Rd} [kN]	UC OK?
Method I	63.99	64.15	63.77	95.40	✓
Method II	60.59	72.05	60.83	94.63	✓

Secondly in the longitudinal direction the beam is in composite action. In this direction for the two thickness a moment check was performed considering the entire beam section. Next to that the number of studs for full composite action were determined. Lastly the shear resistance was determined, which is only based on the steel section since it is expected that the shear force is taken up by the steel section.

Table 10.18: Summary of ULS verification results for composite beam longitudinal direction

Strengthening Method	M_{Ed} [kNm/m]	M_{Rd} [kNm/m]	Number of shear studs	V_{Ed} [kN]	V_{Rd} [kN]	UC OK?
Method I	520.74	593.86	27	268.77	955.17	✓
Method II	493.09	518.97	27	254.50	955.17	✓

Secondary steel beams

For the secondary steel beam an HEB 360 has been used which has the following parameters.

Table 10.19: Input parameters for HEB 360 steel beam

Parameter	Symbol	Value
Plastic section modulus	W_{pl}	2.67×10^6 mm^3
Yield strength	f_y	355 MPa
Partial safety factor	γ_{M0}	1.0 – (EC3)
Section class	cls	1
Effective shear area	A_v	10 700 mm^2
Web yield strength	f_{yw}	355 MPa
Second moment of area	I_y	5.05×10^8 mm^4

For these secondary beams the both the moment and shear checks have been done for the two load cases with the following results:

Table 10.20: Summary of ULS verification results for secondary beams

Strengthening Method	M_{Ed} [kNm/m]	M_{Rd} [kNm/m]	V_{Ed} [kN]	V_{Rd} [kN]	UC OK?
Method I	520.74	802.3	268.77	1926.62	✓
Method II	493.09	802.3	254.40	1926.62	✓

The SLS check

Crack width verification

For the serviceability limit state (SLS) it is important that the crack width of the concrete slabs remains within the limitation of the given exposure class, to make sure that the effect of water ingress and with that corrosion remains limited. The crack width is verified according to EN 1992-1-1, using the general expression.

$$w_{\text{max}} = \frac{1}{2\,\tau_{bm}}\,f_{ctm}\,\frac{\varnothing}{\rho\,E_s}\,\left(\sigma_s - \alpha\,\sigma_{sr} + \beta\varepsilon_{cs}\,E_s\right) \leq w_{max} = 0.4\ \text{mm}$$

where σ_s is the steel stress under quasi-permanent load, σ_{sr} is the steel stress at crack formation and ε_{cs} the shrinkage strain. For the exposure class XC1, allowable crack width is $w_{lim} = 0.4$ mm.

1. **The stress under service load**

   The first step in this determination is finding the steel stress under the servicibility load:

$$\sigma_s = \frac{M_{SLS}}{A_s z}$$

Since under the SLS conditions an elastic analysis is performed the stress diagram is no longer a block-shape, but follows a linear distribution (figure 10.10)

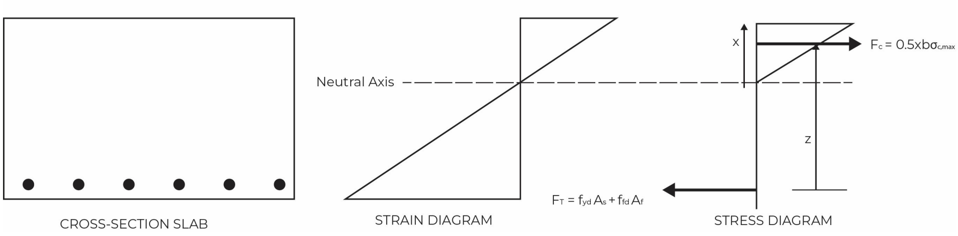


Figure 10.10: The stress-strain diagram in SLS

Based on this linear distribution the following relation can be found:

$$\frac{1}{2}bx\sigma_{c,max} = A_s\sigma_s, \qquad \frac{\sigma_s}{E_s} = \frac{d-x}{x}\frac{\sigma_{c,max}}{E_{c,eff}}, \qquad \text{since} \qquad \frac{\varepsilon_s}{\varepsilon_{c,max}} = \frac{d-x}{x}$$

By filling in these two relations into each other the following quadratic function for x can be found which is needed to determine the lever arm in the stress function:

$$\frac{1}{2}bx^2 + (A_s n)x - (A_s n) = 0, \qquad n = \frac{E_s}{E_{c,eff}}, \qquad E_{c,eff} = \frac{E_{cm}}{1+\varphi}$$

In this formula the following basic values are considered $E_s = 200$ GPa, for $E_{cm} = 22\left(\frac{f_{cm}}{10}\right)^{0.3}$ and the creep factor that is considered is based on a heated interior region with a RH between 60-70 % thus $\varphi = 2.0$ By solving the positive root of this quadratic equation the value of the neutral axis can be found:

$$x = \frac{-(A_s n) + \sqrt{(A_s n)^2 + 2b(A_s n)d}}{b}$$

The internal lever arm thus is:

$$z = d - \frac{x}{3}$$

In case of the strengthening with the CFRP plate the tensile force created by this must be considered in the force equilibrium which make the quadratic function which is used to solve x:

$$x = \frac{-(A_s n_s + A_f n_f) + \sqrt{(A_s n_s + A_f n_f)^2 + 2b\big(A_s n_s d_s + A_f n_f d_f\big)}}{b}$$

Considering the lever arm equations the total moment and with that σ_s becomes:

$$M_{\text{SLS}} = \sigma_s A_s z_s + \sigma_f A_f z_f = \sigma_s\Big(A_s z_s + r\,A_f z_f\Big) \Rightarrow \sigma_s = \frac{M_{\text{SLS}}}{A_s\big(d_s - \frac{x}{3}\big) + \frac{E_f(d_f - x)}{E_s(d_s - x)}\,A_f\big(d_f - \frac{x}{3}\big)}$$

2. **The stress at crack formation**

   The limiting steel stress for crack initiation is:

$$\sigma_{sr} = \frac{f_{ctm}(1 + \alpha_e\rho)}{\rho}$$

The expressions in this formula are:

$$\alpha_e = \frac{E_s}{E_{cm}}, \qquad \rho = \frac{A_s}{A_{c,eff}}, \qquad A_{c,eff} = h_{eff}b \qquad f_{ctm} = 0.3 \cdot f_{ck}^{\frac{2}{3}}$$

To determine $h_{eff} = \min[2.5(h-d), (h-x)/3, h/2]$

3. **Determine the cracking stage** Based on the relationship between the steel stress under SLS loading and the steel stress at crack formation the cracking stage can be determine:
   - If $\sigma_s \leq \sigma_{sr}$ the slab is still in the crack formation stage for the crackwidth formula this means the following:
     $$\alpha = 0.5, \qquad \beta = 0, \qquad \tau_{bm} = 1.6 f_{ctm}$$
     These condition apply for long term loading, which is the case for these slabs.
   - If $\sigma_s \geq \sigma_{sr}$ the slab is in the stabilized cracking stage for the crack width formula the factors then become:
     $$\alpha = 0.3, \qquad \beta = 1, \qquad \tau_{bm} = 2.0 f_{ctm}$$
     Normally this means the shrinkage strain must be accounted for, but for the reclaimed slabs it is assumed that they have previously aged and most shrinkage has already occurred. Providing that the environmental conditions of the slab remain relatively the same, so same humidity the shrinkage strain ε_{cs} is neglected and set to 0.

Based on this methodology all the factors of the crack width formula are known and the maximum crack width can be determined.

Deflection determination

Next to the crack width another factor that must be considered during the SLS check is the deflection. The maximum deflection occurs at mid span of the reclaimed slab, the secondary steel beams and the composite beam. For each of the transverse elements, so the secondary beams and the composite beam the general formula for the deflection is given as:

$$\delta_{max} = \frac{5qL^4}{384EI}$$

For the reclaimed slabs the deformation is slightly different due to the hinged support that connects the two members. So first the deflection of the hing is determined. Based on this deflection a settlement of one of the support is added after which then the deflection at midspan is determined. The mechanism that is used for this is as follows:

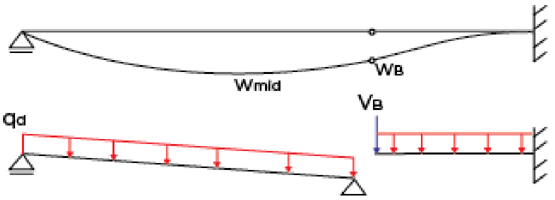


Figure 10.11: Deflection Mechanisms

In this case the maximum deflection becomes:

$$\delta_{max} = 0.5\left(\frac{1}{8}\frac{q_d L_2^4}{EI} + \frac{1}{3}\frac{V_B L_2^3}{EI}\right) + \frac{5qL_1^4}{384EI}$$

The determination of the bending stiffness EI differs for each of these components:

1. **The concrete slabs**
   Before the bending stiffness of a concrete slab can be determined it must be verified that uncracked conditions can be considered, this is the case when the M_{SLS} is smaller than M_{cr}.
   $$M_{cr} = f_{ctm}W = f_{ctm}\frac{I_g}{y}, \qquad I_g = \frac{1}{12}bh^3 \qquad y = 0.5h$$
   If this is the case, which for these reclaimed is always the case, EI become $E_c I_g$

2. **The steel secondary beams**
   For most common steel profiles like the HEB class that is used in this design the moment of inertia can be found in the design tables, for $E = 210$ GPa is used.
3. **The composite beam**
   For the composite beam a combination of the the two methods described above must be applied to find the combined bending stiffness. Since full composit action is considered both materials deform with the same curvature, and their stiffness is combined through the modular ratio:

$$n = \frac{E_s}{E_c}$$

where E_s and E_c are the Young's moduli of steel and concrete, respectively. The concrete part is transformed into an equivalent steel section using:

$$A_{c,eq} = \frac{A_c}{n}, \qquad I_{c,eq} = \frac{I_c}{n}$$

The position of the neutral axis $\bar{y}$ is found from the centroid of the transformed areas:

$$\bar{y} = \frac{\sum A_i y_i}{\sum A_i}$$

and the combined second moment of area from:

$$I_{\text{trans}} = \sum (I_i + A_i(y_i - \bar{y})^2)$$

Finally, the bending stiffness of the fully composite section becomes:

$$EI_{\text{comp}} = E_s I_{\text{trans}}$$

This EI_{comp} expresses the total flexural rigidity of the section, where the concrete primarily resists compression and the steel profile tension.

The SLS verification results per constructive element

Reclaimed Slab B

For the reclaimed slab in the SLS stage two checks are performed. The deflection at mid span and the maximum crack width.

Table 10.21: Summary of SLS verification results for slab B

Strengthening Method	w_{lim} [mm]	w_{max} [mm]	δ_{lim} [mm]	δ_{max} [mm]	**UC OK?**
Method I	0.4	0.17	12.4	0.73	✓
Method II	0.4	0.20	12.4	1.10	✓

Reclaimed Slab C

For the reclaimed slab in the SLS stage two checks are performed. The deflection at mid span and the maximum crack width.

Table 10.22: Summary of SLS verification results for slab C

Strengthening Method	w_{lim} [mm]	w_{max} [mm]	δ_{lim} [mm]	δ_{max} [mm]	**UC OK?**
Method I	0.4	0.16	12.4	0.73	✓
Method II	0.4	0.18	12.4	1.10	✓

Composite beam

For the composite in the SLS stage two checks are performed. The crack width of the concrete slab above the hogging support so in transverse direction and the deflection at mid span in the longitudinal direction. Both these checks are done for the two strengthening methods.

Table 10.23: Summary of SLS verification results for the composite slab

Strengthening Method	w_{lim} [mm]	w_{max} [mm]	δ_{lim} [mm]	δ_{max} [mm]	**UC OK?**
Method I	0.4	0.21	31	22.86	✓
Method II	0.4	0.24	31	29.46	✓

Secondary steel beams

Table 10.24: Summary of SLS verification results for the secondary steel beams

Strengthening Method	δ_{lim} [mm]	δ_{max} [mm]	**UC OK?**
Method I	31	23.37	✓
Method II	31	21.64	✓

Life Cycle Assessment (LCA) of the Reuse Scenario

The LCA quantifies the embodied carbon reduction achieved by reusing reclaimed concrete slabs instead of applying new composite steel–concrete floors. The system boundary covers modules A1–C4 in accordance with EN 15804, using a functional unit of 1 m² of structural floor area.

Baseline: composite reference floor

The original design used a 200 mm composite steel–concrete floor (C30/37 concrete on steel decking). Based on NMD Category 3 data, the embodied carbon amounts to 94.6 kg CO_2 eq / m^2, resulting in a total of 12.7 t CO_2 eq for the 140.2 m^2 floor. Next to that no composite beam was used but a HEB360 beam was used to support the slabs at mid span. Since this beam is now removed and changed into a HEB220 composite beam it is accounted for in the reduction. This beam has a total weight of 144 kg/m, so total weight of 1116 kg and thus a total CO_2 eq reduction of 2.1 t CO_2 eq.

Table 10.25: Baseline embodied carbon of the composite steel–concrete floor

Material	A1–A3	A4	A5	C1	C2	C3	C4	Total
Steel–concrete floor [kg CO_2/m^2]	76.46	6.14	5.33	2.39	3.24	0.96	0.02	94.55
HEB360 support beam [kg CO_2/kg]	1.34	0.07	0.44	0.40	0.0007	0.024	0.00006	1.87

Reuse configuration

In the reuse scenario, five reclaimed slabs (Type B or C) form a $140.2\,\mathrm{m}$ floor. Three HEB320 secondary beams are introduced for structural support. Two strengthening options are considered: (i) a 35 mm C20/25 concrete topping (Method I) and (ii) a CFRP strip system (Method II). Both are combined with a small new composite slab strip at the junction ($20.15\,\mathrm{m}$).

Component-level embodied carbon

Table 10.26: Component-level embodied carbon for reuse configuration

Component	**Description / Source**	**Quantity**	**GWP [kg CO_2-eq]**
Concrete slabs type B	CEM I	5 slabs	1400.5
Concrete slabs type C	CEM I	5 slabs	1401.5
Secondary beams (HEB320)	NMD steel profile	2.86 t	6 540
New composite beam (20.15 m²; C20/25; HEB220) , Method I	CEM I concrete + reinforcement	–	1 867
New composite beam (20.15 m²; C20/25; HEB220) , Method II	CEM I concrete + reinforcement	–	1 613
Concrete topping (Method I)	35 mm C20/25 over 120 m²	–	1 622
CFRP strengthening (Method II)	5 slabs, 8 strips per slab	–	104
		Total embodied carbon	**10 032 (I) / 8 257 (II)**

Results and comparison

The reuse alternatives achieve substantial reductions compared to the baseline of $12.7\,\mathrm{tCOeq}$ (Table 10.27). Method I achieves a 10 % reduction, while Method II achieves approximately 25 %.

Table 10.27: Comparison of total embodied carbon

Scenario	Total GWP [t CO^2 eq]	Reduction [%]
Reference (new composite floor)	14.81	–
Reuse Slab B + Strengthening I	12.49	15.6
Reuse Slab B + Strengthening II	10.71	27.6
Reuse Slab C + Strengthening I	12.49	15.6
Reuse Slab C + Strengthening II	10.71	27.6

Overall interpretation of the design validation

The design phase of this research demonstrates how the preliminary Declared Reuse Performance (pDRP) rating can indicate whether reclaimed slabs can realistically be integrated into a new structural design. In the Schiphol C-pier case, the reclaimed cast-in-situ slabs received an orange pDRP rating, indicating that reuse is technically feasible if the client chooses to prioritise it, but that notable adaptations are required to meet current design standards. These interventions, mainly the installation of secondary steel beams to address span limitations and the application of local strengthening to restore flexural capacity, allow the slabs to meet all Ultimate and Serviceability Limit State criteria in accordance with Eurocode 2.

Despite this technical success, the environmental benefit does not fully offset the additional design and construction effort involved. The resulting hybrid system requires more material, closer coordination between disciplines, and significant on-site preparation, yet achieves only a moderate reduction in embodied carbon. In this case, the total emission saving of approximately 15–27% limits the overall attractiveness of reuse from a client perspective. The orange rating therefore represents a form of *conditional feasibility*: reuse is technically possible but not inherently advantageous unless supported by strong sustainability goals, heritage values, or regulatory incentives.

To understand where these additional efforts originate, it is useful to consider the specific steps needed to integrate the reclaimed slabs into the new floor system. Unlike prefabricated elements, delivered with consistent geometry, integrated reinforcement, and ready-to-finish surfaces, the reclaimed slabs require multiple preparatory and finishing operations before they can function effectively in a new structure. The following subsections outline these essential measures and show how reuse differs from the straightforward installation of factory-produced components.

Integration requirements for reclaimed slabs

Integrating reclaimed cast-in-situ slabs into a new building system involves a series of preparatory, structural, and finishing actions that differ markedly from those for standard prefabricated installation. While new composite slabs arrive on site with tight tolerances and clean bearing surfaces, reclaimed elements vary in geometry, surface quality, and reinforcement layout due to their deconstruction. Consequently, additional work is needed to achieve structural reliability and long-term durability.

1. Preparation of slab surfaces

Before installation, the concrete surfaces of the reclaimed slabs must be cleaned and prepared to ensure proper bonding, protection, and durability. This process is critical because the performance of overlays or externally bonded reinforcement depends on the condition of the existing concrete (Fédération internationale du béton (fib), 2020). Loose material and contaminants are removed by light grinding or sandblasting to achieve a clean, slightly roughened surface. For slabs in good condition, this limited preparation is sufficient to ensure compatibility with coatings or sealers.

When a new concrete overlay is applied (Strengthening Method I), a polymer-modified bonding slurry or epoxy primer is placed immediately before casting to ensure monolithic behaviour between old and new concrete. For slabs strengthened with externally bonded CFRP laminates (Method II), the underside is cleaned, smoothed, and primed with epoxy to provide reliable adhesion and prevent premature debonding.

If strengthening is unnecessary, because reduced spans and secondary beams already provide sufficient capacity, the preparation focuses on durability. After cleaning, a silane or siloxane sealer is applied to minimise carbonation and moisture ingress, particularly along the soffit and exposed edges. Minor irregularities from deconstruction are corrected using polymer-modified mortars or levelling compounds to restore surface flatness. Together, these steps ensure that the slabs remain durable and compatible with the new structure, even without added reinforcement.

2. Treatment of cut reinforcement zones

During deconstruction, reinforcement is often cut at slab edges, leaving exposed bar ends susceptible to corrosion and loss of cover. To restore protection and local confinement, these areas are repaired before reuse. The bars are cleaned to bare metal (Sa 2½ finish) and coated with a zinc-rich primer or corrosion-inhibiting compound, after which the edge concrete is rebuilt using polymer-modified repair mortar to re-establish the required cover, typically 25–30 mm for indoor exposure conditions.

Where the original bars contributed to confinement or continuity, new tie bars or U-shaped anchors can be added using resin-bonded anchors or mechanical couplers. These do not enhance global flexural capacity but prevent edge cracking and spalling between adjacent slabs. The repaired edges are finished flush with the original surface, ready for overlays or coatings. Through these steps, the reclaimed slabs recover the durability and crack-control performance expected of new elements (Fédération internationale du béton (fib), 2020).

3. Finishing and sealing of slab surfaces

Once the repair and strengthening works are complete, final finishing and sealing ensure the long-term performance of the reused slabs. Irregularities from handling or cutting are corrected with fine levelling compounds or self-smoothing mortars to achieve the required flatness. Exposed soffits are treated with silane or siloxane coatings to protect against carbonation and moisture ingress, while flexible sealants at joints and beam interfaces accommodate small movements and prevent cracking.

If floor finishes such as screed, tiles, or resin systems are applied, the substrate is checked for moisture and surface strength to ensure proper bonding. For exposed concrete finishes, an additional sealer or curing compound can be used to improve wear resistance and provide a uniform appearance. These finishing and sealing works, though modest compared with full reconstruction, are essential to achieve the durability and surface quality expected in new construction (Fédération internationale du béton (fib), 2020).

Economic balance and stakeholder perception

Although these additional operations enable the slabs to meet current design standards, they also reduce the overall benefit of reuse. Recent research by Berglund-Brown et al. (2024) shows that stakeholders across the construction sector view circular and reuse-based approaches as significantly more costly and time-consuming than conventional construction. On average, design and construction professionals expect cost premiums of 40–50% and schedule extensions of 30–45%, primarily due to additional coordination, inspection, and on-site adaptation.

At the same time, willingness to pay for circular solutions remains limited. According to the same study, real-estate developers are willing to accept roughly a 10% increase in construction costs only when it delivers an embodied-carbon reduction of around 50%. In the C-pier case, the reuse strategy achieved only 15–27% reduction, well below this threshold. Consequently, while technically feasible and environmentally positive, the reuse approach does not align with the current economic expectations of most clients and stakeholders.

The combination of higher perceived effort, increased complexity, and modest carbon savings illustrates that, under present market conditions, the environmental benefit does not outweigh the additional investment and coordination required for reuse. Only projects with strong sustainability ambitions, policy incentives, or symbolic value would make such reuse a compelling alternative to conventional prefabricated systems.

In summary, the validation of both the design and the verification framework demonstrates that the reuse of the orange-rated C-pier slabs is technically possible, but only through significant adaptation and coordination effort. The framework proved effective in systematically identifying the key limitations of the reclaimed slabs, geometry, flexural capacity, and reinforcement detailing, while clearly defining the interventions needed to meet Eurocode performance criteria. At the same time, the validation highlights that technical feasibility alone does not guarantee practical viability. Although the applied measures enabled compliance with all structural requirements, the additional construction work and limited carbon savings reduce the overall justification for reuse. With an emission reduction of only 15–27%, the environmental benefit remains disproportionate to the required effort, making large-scale adoption unlikely without external incentives.

Nevertheless, this process confirms the value of the verification framework as a diagnostic and decision-making tool. It not only establishes whether reuse is structurally feasible but also identifies where it becomes inefficient or uneconomical under real project conditions. From a geometric standpoint, the C-pier slabs initially appeared to be good candidates for reuse: their dimensions and overall layout aligned well with the new floor grid. However, the structural configuration of the slabs proved to be the limiting factor. Because they were designed as one-way spanning elements, with primary reinforcement concentrated in the 3.1 m direction and only minimal steel provided transversely, their ability to distribute loads in the 7.75 m direction was highly restricted. This lack of two-way action made it necessary to introduce secondary steel beams to carry the loads, which in turn added material, weight, and complexity, significantly reducing the environmental and practical gains of reuse.

Had the slabs been two-way spanning, with comparable reinforcement in both directions, their flexural behaviour and stiffness would have been far better suited to the new layout. While local strengthening might still have been required to meet modern load demands, the need for secondary beams could have been avoided altogether, resulting in a simpler and more efficient design. Such a configuration would have allowed the reclaimed slabs to be reused with fewer modifications, lower material use, and a higher overall environmental return. In that case, the achievable emission reduction would likely have been high enough to justify the additional design effort, making the solution more appealing to sustainability-oriented clients such as Schiphol. Under those conditions, the slabs would not have been rated orange but would instead have qualified for a higher category, reflecting a more balanced and viable reuse scenario. The following section therefore examines a slab type with similar geometric characteristics but an inherently two-way spanning reinforcement system, representing a more practical and sustainable reuse option for the C-pier redevelopment.

10.4. Alternative case study: The Grove Schiphol Office

Even though it would have been ideal if the reclaimed slabs were two-way spanning, they are not, and therefore must be considered in their existing one-way spanning configuration. In this case, it is more logical to explore their reuse in a project context that better matches their inherent structural capacity. Office buildings offer a more favourable structural environment for reuse compared to densely used airport terminals. Typical office live loads are in the range of 2.5–3.0 kN/m^2 (EN 1991-1-1, Category B), whereas airport terminal floors are generally designed for 5.0 kN/m^2 or more. In addition, office floors usually have shorter and more repetitive spans, typically between **5 and 7 m**, which better align with the capacity of the reclaimed slabs. By placing the slabs in such a context, the design can potentially avoid the extensive strengthening and secondary beam systems that were necessary in the C-pier scenario.

An overview of the project: The Grove Schiphol

The selected reference project for this alternative case is The Grove Schiphol, a current development of an office building located within the Schiphol Trade Park near Hoofddorp. The project was initiated by the Royal Schiphol Group as part of its ambition to create a nature-inclusive, carbon-conscious, and energy-efficient business campus. The Grove is designed as a multi-tenant office complex with three storeys of workspaces arranged around a large central atrium. Its plan has a slightly O-shaped configuration as can be seen in figure 10.12, allowing daylight to enter deep into the floorplates while maintaining efficient circulation.

Figure 10.12: Architectural render of the Grove Project

Although the structural design of The Grove is not publicly available, architectural descriptions and project statements indicate that a timber structural system was chosen to minimize embodied carbon and promote biophilic design. The building's superstructure therefore likely consists of a glulam or laminated timber frame supporting cross-laminated timber (CLT) floor slabs. This approach aligns with the project's sustainability goals but also introduces several technical challenges that could, in theory, be mitigated by reusing the concrete slabs from the C-pier.

While timber floors offer excellent sustainability performance, their application in multi-storey office buildings often faces limitations related to acoustic insulation, vibration control, and fire safety. CLT slabs require additional layers such as concrete toppings or acoustic insulation mats to meet office acoustic standards, as well as surface treatments and encapsulations to achieve fire ratings of REI 60 or higher. Reusing the C-pier's reinforced concrete slabs could provide a practical alternative or hybrid solution.

Assumed structural configuration

Because no official structural design for the inner framework of The Grove is publicly available, a representative structural configuration has been developed for analysis purposes. The building is assumed to have three office levels arranged around a central atrium, supported by a regular column grid suitable for office use. A typical span of 6.0 m between supports has been adopted, reflecting common office grid dimensions (5–7 m). This span accommodates the geometry of the reclaimed C-pier slabs. Again the hybrid structure is used. Though the sizing is a bit different in this case the following floor system is considered, figure 10.13. This is one section in which the hybrid section can be repeated a number of times to get the desired full width of a floor.

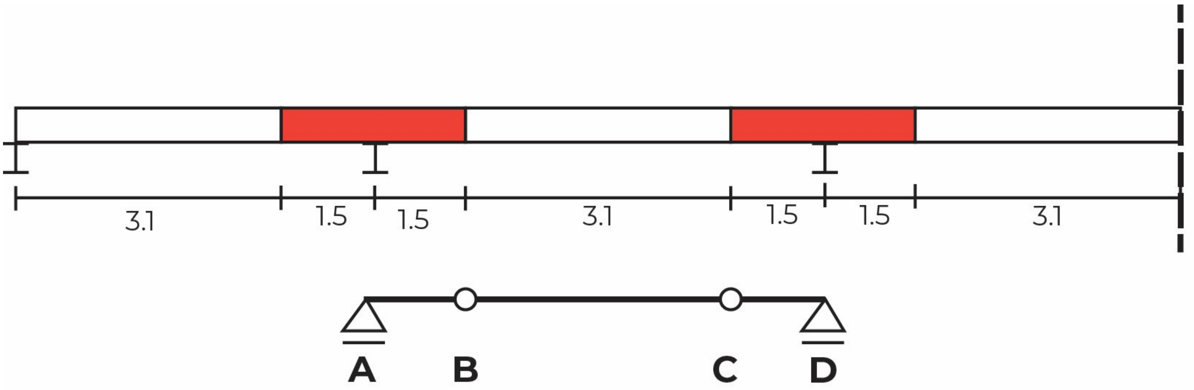


Figure 10.13: Structural overview of the Grove floor system and schematization

The load combinations and resulting force-diagrams
Load combinations and resulting force diagrams

This section presents the applied load combinations and the corresponding shear force and bending moment distributions used to verify the structural performance of the reclaimed slab elements in the second design scenario. In this case, the structural context shifts from a heavily loaded airport terminal to an office-type environment. Consequently, both the live load intensity and the required consequence class are reduced, resulting in lower design loads and moments.

Table 10.28: Characteristic loads and combination factors for the office floor slabs

Load description	Load [kN/m^2]
Self-weight, G_s (slab)	5.0
Permanent load, G_{pl}	2.0
Live load, q_{live}	2.5

Ultimate Limit State (ULS)

Because this is no longer a heavily occupied environment, the **Consequence Class** for this design is reduced from CC3 to CC2. According to EN 1990, two possible load combinations must be considered for the ULS design stage:

1. Equation 6.10a:

$$1.35\,G_k + \psi_0 \cdot 1.5\,Q_{k,1} = 1.35(5.0 + 2.0) + 0.5 \cdot 1.5(2.5) = 11.33 \text{ kN/m}^2$$

2. Equation 6.10b:

$$1.2\,G_k + 1.5\,Q_{k,1} = 1.2(5.0 + 2.0) + 1.5(2.5) = \mathbf{12.15} \text{ kN/m}^{\mathbf{2}}$$

The governing load combination corresponds to the higher value, $q_{d,2} = 12.15\ \mathrm{kN/m^2}$. The characteristic loads and ψ-factors applied are summarized below.

Table 10.29: ULS load combination according to EN 1990 (Consequence Class CC2)

Action	Symbol	Characteristic value	Combination factor ψ_0	Notes
Self-weight of slab	G_k	5.0	–	Permanent, unfavourable
Permanent load	G_{perm}	2.0	–	Permanent, unfavourable
Imposed load	Q_k	2.5	0.5	Leading variable action

The resulting design line load in the short span direction (3.1 m) and the corresponding bending moments were determined using the same approach as in the C-pier validation. The maximum positive and support moments, as well as the shear forces, are summarized in Table 10.30.

Table 10.30: Overview of ULS design results for the reclaimed slabs (CC2)

Parameter	Symbol	Maximum value
Mid-span bending moment	$M_{mid,BC}$	14.59 kNm
Support bending moment	M_C	34.75 kNm
Longitudinal bending moment	$M_{Y,max}$	282.78 kNm
Shear force at support B	V_B	18.83 kN
Shear force at support C	V_C	34.63 kN
Shear force longitudinal	$V_{Y,max}$	145.95 kN

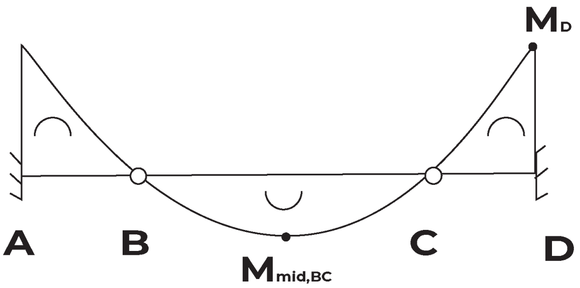


Figure 10.14: Bending moment distribution for the office building case (schematized floor system).

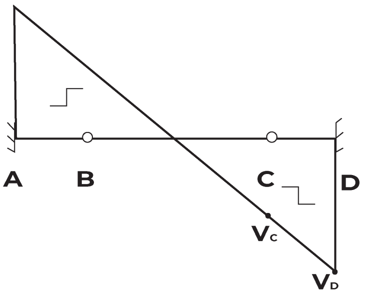


Figure 10.15: Shear force distribution for the office building case.

Serviceability Limit State (SLS)

For the SLS verifications, the quasi-permanent load combination is adopted using the same expression as in the first design. As this design falls under Category B (office-type occupancy), a combination factor of $\psi_2 = 0.3$ is applied for imposed loads:

$$q_d = G_k + G_{perm} + \psi_2 Q_k = 5.0 + 2.0 + 0.3(2.5) = \mathbf{7.75\ kN/m^2}$$

The resulting SLS moments are determined analogously to the ULS case and summarized in Table 10.31.

Table 10.31: Overview of SLS design loads and resulting bending moments (office case)

Parameter	Symbol	Maximum value
Mid-span bending moment	$M_{mid,BC}$	9.31 kNm
Support bending moment	M_C	22.17 kNm
Longitudinal bending moment	$M_{Y,max}$	180.38 kNm

The ULS check

The reclaimed slab

In the pDRP stage the moment capacity of the reclaimed slab was determined since no strengthening methods are considered in this design this is also the moment capacity of these slabs in this new design. Next to that the shear capacity of the slabs is also determined the resulting checks are:

Table 10.32: Summary of ULS verification results for reclaimed slabs - The Groove

Strengthening Method	M_{Ed} [kNm/m]	M_{Rd} [kNm/m]	V_{Ed} [kN]	V_{Rd} [kN]	UC OK?
Slab B	14.6	24.22	34.63	70.77	✓
Slab C	14.6	24.22	34.63	69.30	✓

The new composite slab

Like in the previous case for the composite slab the reinforcement must first be determined. Again to stay in line with the reclaimed slab the thickness of the slab is 200 mm and the concrete class is C20/25. Using the same approach as with the C-pier design the required reinforcement area is 514 mm^2. To meet this requirement the practical reinforcement sizing of $\phi 10 - 100$ is used which is a reinforcement area of 785 mm^2. Using this reinforcement area the moment and shear capacity in transverse direction were determined.

Table 10.33: Summary of ULS verification results for composite beam - The Groove

Strengthening Method	M_{Ed} [kNm/m]	M_{Rd} [kNm/m]	V_{Ed} [kN]	V_{Rd} [kN]	UC OK?
Composite Beam (transverse)	34.75	52.2	34.63	83.91	✓

Next to that in longitudinal direction the moment capacity of the composite beam was established as well as the shear capacity with the same assumption that the shear force is taken up by the steel beam. The steel beam has been resized to minimize the material use. For the groove case a steel beam with a HEB 180 profile and S235 was enough to meet the requirements.

Table 10.34: Summary of ULS verification results for composite beam - The Groove

Strengthening Method	M_{Ed} [kNm/m]	M_{Rd} [kNm/m]	V_{Ed} [kN]	V_{Rd} [kN]	UC OK?
Composite beam (longitudinal)	282.78	299.27	145.95	683.81	✓

The SLS check

The reclaimed slab

The two SLS checks for the reclaimed slabs are the deflection and the crack width:

Table 10.35: Summary of SLS verification results for the reclaimed slabs - The Groove

Strengthening Method	w_{lim} [mm]	w_{max} [mm]	δ_{lim} [mm]	δ_{max} [mm]	UC OK?
Slab B	0.4	0.17	12.4	0.46	✓
Slab C	0.4	0.20	12.4	0.70	✓

The composite beam

For the composite beam in transverse direction the crack width is established and in longitudinal direction the deflection.

Table 10.36: Summary of SLS verification results for composite beam - The Groove

Strengthening Method	w_{lim} [mm]	w_{max} [mm]	δ_{lim} [mm]	δ_{max} [mm]	UC OK?
Composite beam	0.4	0.11	31	29.89	✓

The LCA analysis

The Baseline design

In this case instead of determining the system in comparison to only a full concrete section the system is also measured against a timber section, since this was the preferred design choice of Schiphol for the Groove. In order to do so the thickness of a CLT slab must be determined. Which is done using the design tables of the manufacturers. From these tables it can be found that a CLT slab with the following build up is enough L200-5s to spans the similar 6m span width. Considering that both floor systems are supported by steel beams only the floor slabs are looked at in this design.

In all cases a full floor surface as depicted in figure 10.13 is analysed. This is a floor surface of 118.575 m^2. Which means that the GWP for the completely new concrete floor system is 11.2 t CO_2-eq is being used and for the CLT floor system 5.1 t CO_2-eq.

Table 10.37: Baseline embodied carbon of the composite steel–concrete floor

Material	A1–A3	A4	A5	C1	C2	C3	C4	Total
Steel–concrete floor [kg CO_2/m^2]	76.46	6.14	5.33	2.39	3.24	0.96	0.02	**94.55**
CLT-slab floor [kg CO_2/m^2]	-95.06	1.8	1.24	-	1.77	126.78	6.72	43.25

The new design

Table 10.38: Component-level embodied carbon for reuse configuration

Component	**Description / Source**	**Quantity**	**GWP [kg CO_2-eq]**
New composite beam (23.25 m^2; C20/25)	CEM I concrete + reinforcement	2 sections	3670
Concrete slabs type B	CEM I	3 slabs	840.3
Concrete slabs type C	CEM I	3 slabs	840.9
Total embodied carbon			**4511**

Results and comparison

As can be seen in the results table 10.39 of this analysis the reclaimed floor system including the two new composite sections shows a 6̃0% reduction compared to a new concrete flooring system. Next to that it still shows a 13% reduction compared to the timber alternative.

Table 10.39: Comparison of total embodied carbon

Scenario	Total GWP [t CO^2 eq]	Reduction vs concrete[%]	Reduction vs timber [%]
New concrete composite floor	11.2	–	-
Net timber floor	5.2	53.6	-
Reuse Slab B	4.5	59.8	13.4
Reuse Slab C	4.5	59.8	13.4

The validation outcomes

This alternative case confirms that placing the reclaimed one-way spanning slabs in a lower-load, office-type environment (Category B, CC2) enables straightforward compliance with ULS and SLS requirements and avoids the extensive strengthening and secondary beam interventions that were necessary in the C-pier scenario. All critical checks for the reclaimed slabs and the composite solution are satisfied with comfortable reserve, reflecting the more favourable span (≈6 m) and live-load regime (2.5–3.0 kN/m^2).

From an environmental perspective, the reuse configuration achieves a substantially larger reduction in embodied carbon than in the first case: the total GWP of the reused-slab options is roughly **60% lower** than a new concrete floor of comparable performance, and still about **13% lower** than the timber alternative considered for The Grove. Because these savings are realised without complex strengthening measures or high program risk, they are more likely to be adopted in practice than the ~ 15–30% reduction attainable in the terminal-pier application.

Placing reclaimed elements in a structural context with lower loads and shorter, repetitive spans changes reuse from a technically complex option into a practical and efficient design solution. In such applications, the slabs meet all performance requirements while offering simpler execution and significant reductions in embodied carbon.

STEP V

Discussion & Conclusion

11 Discussion

The purpose of this discussion chapter is to interpret the results of the study and reflect on what they mean in relation to the research objective. It connects the findings from the case studies and validation to the wider academic and practical context of concrete reuse. Rather than presenting new results, the discussion explains how the developed frameworks address the main barriers found in current practice and what conditions are required to make reuse a standard design and construction strategy.

11.1. Reflection on the Research goal

This thesis set out to explore how the reuse of cast-in-situ concrete slabs can progress from isolated experiments to a recognised and reliable design strategy. The research demonstrates that this transition is achievable when both the technical and organisational aspects of reuse are addressed together.

The Verification Framework provides a structured, Eurocode-aligned method for assessing reclaimed slabs. By defining clear steps for evaluating geometry, material strength, durability, and fire resistance, it replaces uncertainty with measurable evidence. This allows engineers and clients to make informed design decisions rather than relying on assumptions about risk.

The Communication Framework complements this by defining how verification data is managed and transferred between project stages. It ensures that the information collected during demolition, testing, and design remains consistent, traceable, and accessible, preventing the data loss that often hinders reuse.

Had these frameworks been applied during the planning of Schiphol's C-pier, the decision to discard reuse early in the process could have been reconsidered. The project's reluctance stemmed not from technical infeasibility but from the absence of clear responsibilities, verification procedures, and communication structures. The developed frameworks demonstrate how such barriers can be systematically managed, turning perceived risk into an organised, verifiable process.

Together, the frameworks show that reuse of cast-in-situ slabs can be implemented safely and predictably within conventional project delivery. They provide the structure and clarity needed to move from isolated pilot projects to a consistent practice, proving that technical potential can be realised when supported by coordinated project organisation.

11.2. Organizational Discussion - Communication Framework

The Communication Framework developed in this thesis directly responds to the gaps identified in Chapter 3, where four key frameworks, REVERT, the Digital Circular Economy (CE) Framework, the Circular Construction Evaluation Framework (CCEF), and the Circular Information Flow (CIF) Framework,each address part of the communication challenge in reuse-oriented construction. Collectively, these frameworks underline that overcoming fragmented expertise requires alignment between people, processes, and data. However, they remain separate in scope: none fully integrate the social, procedural, and informational dimensions of collaboration within a single, operational structure.

The REVERT Framework focuses on stakeholder alignment and shared vision across material, building, and city scales but remains conceptual about how collaboration should occur within an actual project workflow. The Communication Framework translates these high-level success factors,such as role clarity and feedback loops,into a structured sequence of communication domains that align with the project timeline. Each of the six domains defines specific responsibilities for the involved actors and identifies key outputs,such as verification dossiers, approval records, and transfer files,that support information flow between disciplines and connect directly to project milestones. In this way, the framework embeds REVERT's principles of alignment and transparency within the established rhythm of project delivery.

The Digital CE Framework promotes interoperability between BIM, material passports, and digital marketplaces but does not address how data accountability is maintained across organisations. The Communication Framework complements this by linking these digital exchanges to contractual and procedural structures. Within each stage, it specifies what data must be uploaded, who verifies it, and when these tasks occur. This converts digital interoperability from a technical concept into a managed responsibility distributed across the value chain.

The CCEF provides a shared language and criteria for evaluating circularity but offers limited operational guidance on how that shared understanding can be embedded in project routines. The Communication Framework extends this by translating these common evaluation principles into tangible deliverables. Documents such as the Reuse Communication Plan, Verification Dossier, and Traceability Protocols formalise how project teams report, review, and confirm progress on reuse objectives. These deliverables make circularity a trackable component of everyday coordination rather than an abstract goal discussed only at design reviews.

The CIF Framework defines the qualities of effective information,completeness, availability, accessibility, and integration,but not the mechanisms that guarantee them. The Communication Framework addresses this gap through its stage-based structure, which ensures that information completeness and accessibility are reviewed at fixed checkpoints. Though the completeness is more considered in the verification framework and later embedded into the communication framework.

Together, these mechanisms demonstrate how the Communication Framework consolidates the partial solutions offered by previous models into a single, project-oriented structure. It integrates the governance clarity of REVERT, the digital connectivity of the Digital CE Framework, the shared evaluation language of CCEF, and the data quality principles of CIF. By combining these dimensions within six clearly defined communication domains and two collaboration paths (direct and intermediary alignment), the framework turns broad ideas of collaboration and transparency into an operational process that can be embedded in standard project delivery and quality management systems.

11.3. Technical Discussion - Verification Framework

The Verification Framework addresses the long-standing absence of a consistent, standardised approach for assessing reclaimed concrete elements. As shown in the literature review, previous efforts such as the BTU Cottbus memorandum, NS 3682 (Norway), and EPFL's Reusability Assessment proved that reuse is technically feasible, but lacked standardisation and integration with existing design codes. Consequently, engineers and clients could not demonstrate compliance with the same level of confidence as for new materials.

This framework aligns reuse assessment with Eurocode 2 and the Construction Products Regulation, creating a two-stage process Initial Element Assessment and Reuse Production Control that mirrors the structure of factory production control. It defines clear steps for evaluating essential characteristics such as geometry, compressive strength, durability, and fire resistance. The result is a Declared Reuse Performance (DRP) that summarises verified performance values and provides a transparent, project-based certification of quality. In this way, the framework bridges the gap between research-based verification and regulatory practice.

Beyond its technical structure, the Verification Framework also introduces a project management dimension. The two declaration stages,the preliminary DRP (pDRP) and the verified DRP (vDRP),function as decision-support tools that translate technical findings into clear, project-level outcomes. The pDRP supports early decision-making by clients and project managers, indicating whether reuse is feasible and under what conditions it can be pursued. The vDRP provides engineers with the verified design parameters needed to integrate reclaimed slabs into the final design with confidence. This dual output connects technical verification directly to project planning, ensuring that reuse decisions are made on reliable data rather than assumptions about quality or risk.

Compared to earlier approaches, the framework combines the rigour of technical verification with the clarity of structured project management. It formalises roles and documentation, making verification both consistent and comprehensible to non-technical decision-makers. The process can be adapted to different project contexts, providing a flexible yet reliable blueprint for integrating reuse into standard workflows.

Overall, the Verification Framework demonstrates that the verification of reclaimed slabs can be conducted with the same methodological clarity as for new elements while remaining accessible for decision-making at the project level. It allows engineers to design with verified data, and it enables clients to make timely, evidence-based choices about reuse feasibility within normal project management procedures.

11.4. Cross-Domain Reflection

The two frameworks developed in this thesis work together to solve one of the main barriers to reuse: the loss or unavailability of verification data when it is needed for design and decision-making. In current practice, valuable information collected during demolition or testing often does not reach the right people at the right time. The Verification Framework addresses this by defining how reliable data is generated through a clear, standardised process that evaluates geometry, material strength, durability, and fire resistance. The Communication Framework ensures that this verified data is transferred, stored, and reused across the different project stages without being lost or duplicated.

Together, the frameworks create a continuous workflow in which verified information moves through the six communication domains of a reuse project. In the first two stages,Initiation and Planning and Design and Engineering,the preliminary Declared Reuse Performance (pDRP) provides clients and project managers with the basic input to decide whether reuse is feasible. As the project progresses to the later engineering stage and Construction and Assembly, the verified DRP (vDRP) is shared with designers and contractors to inform detailed design and quality control. During Operation and Maintenance and finally at End-of-Life and Deconstruction, this same verified information remains available for documentation and potential future reuse. In this way, the frameworks ensure that the data created during verification remains accessible and meaningful throughout the entire lifecycle of a project.

This integration closes an important gap between research and practice. Frameworks such as CCEF and REVERT strengthen collaboration but do not describe how verified data should flow through a project, while technical standards such as NS 3682 or the EPFL model focus on testing methods without considering how their results are communicated or reused. By combining the technical structure of verification with the communication logic of project delivery, the two frameworks establish a single, traceable process where data is both reliable and available when decisions need to be made.

11.5. Evaluation of the Validation Case

The validation of the two developed frameworks through the Schiphol C-pier case confirmed their practical relevance within real project conditions. Although reuse was not implemented during the actual project, applying the frameworks retrospectively to the C-pier process showed that the main barriers,missing data, unclear responsibilities, and poor timing,could have been addressed if their principles had been in place. The validation results demonstrate that both frameworks are compatible with existing project structures and can strengthen the management and verification of reuse within standard construction practice.

In the case of the Verification Framework, the validation focused on assessing whether the preliminary Declared Reuse Performance (pDRP) could support realistic decision-making during the design process. Since the physical slabs were no longer available for testing, the process was used to test the framework itself rather than the elements. The application confirmed that all required input parameters could be collected and translated into the pDRP format, showing that the method fits within existing documentation and design procedures. The framework classified the slabs with an orange rating, meaning that reuse at the C-pier would not be technically or environmentally favourable. While reuse was technically possible, the measures needed to meet current performance requirements would outweigh the environmental benefit. A design study and corresponding LCA analysis confirmed this conclusion, indicating a potential carbon reduction of only 15–30% and significant additional engineering effort. This outcome demonstrates that the framework works as intended: it allows reuse potential to be assessed objectively and early, preventing time and resources from being spent on elements that are unsuitable for the intended application.

At the same time, the same pDRP data indicated that the slabs would perform better under lower load and span conditions. When this information was applied in the alternative office building case, The

Grove, where live loads, consequence class, and spans were smaller, the slabs achieved a carbon reduction of more than 50%. This finding shows that the framework does more than confirm technical limitations,it also provides data that can guide the search for more appropriate reuse scenarios. The validation therefore demonstrated that the Verification Framework functions as an early-stage decision-support tool that connects sustainability assessment with practical engineering outcomes.

The Communication Framework was validated through expert review and comparison with established project experience. Stakeholders from NACO and experts involved in the Doorlaatpost 90 project,one of Schiphol's most successful circular developments,evaluated whether the framework could have resolved coordination issues observed in their earlier work. They concluded that its structured approach to information exchange would have improved communication between demolition, testing, and design teams. The six communication domains were found to align closely with the phases of the C-pier project, clearly defining what information should be transferred and when. According to the experts, this structure would have resolved many of the timing problems that typically occur between project stages, ensuring that verified data was available to the design team precisely when reuse decisions were being considered.

The experts also highlighted that the initial framework involved a large number of documents, which could make the communication process administratively demanding. This feedback led to the integration of an Information Management System (IMS) within the framework. The IMS streamlines the process by grouping related documents, defining their type and purpose, and assigning ownership and responsibility for each. This addition reduced redundancy and clarified accountability, improving the efficiency of the framework while maintaining its original intent. The validation confirmed that the Communication Framework is both practical and adaptable to existing project management systems. It provides a clear structure for information flow and traceability, while the IMS ensures that this can be managed effectively within large and complex project environments.

Together, the two frameworks create a single, connected process. The Verification Framework ensures that data on reclaimed elements is technically reliable, while the Communication Framework ensures that this verified data is transferred and used at the right stages of the project. The validation demonstrated that neither technical verification nor communication alone is sufficient: reliable data must be effectively managed to be useful, and structured communication only adds value when it is based on verified information. Applied in combination, the frameworks establish a continuous link between testing, data management, and design, enabling reuse decisions to be made earlier, with greater confidence, and supported by traceable evidence. The C-pier validation therefore confirmed that the frameworks are both valid and mutually reinforcing, together offering a practical system for integrating the reuse of structural concrete into standard project delivery.

11.6. Critical Reflection and Limitations

While the validation confirmed the coherence and practicality of both frameworks, several limitations influence how the results should be interpreted. The validation focused on testing their structure and applicability rather than their long-term performance in multiple project contexts. As such, the findings demonstrate that both frameworks work in principle, but further testing is needed to understand their behaviour across different project types, team compositions, and regulatory environments.

For the communication framework the following limitations are considered:

- **Validation based on a single case study**
  The Communication Framework was validated using only the Schiphol C-pier project. While this project provided a realistic and complex testing environment, it represents a single organisational and contractual context. As a result, the validation cannot confirm how well the framework performs in other project types,such as smaller-scale developments, public–private partnerships, or projects outside of Schiphol's governance structure. This limits the generalisability of the findings and means that the conclusions mainly apply to large, client-led infrastructure projects.
- **Limited number and diversity of expert reviewers**
  The expert validation was based on feedback from two professionals within the same organisation. Although both reviewers had relevant experience with circular projects, their shared institutional background may have influenced their assessment, leading to confirmation bias or a

limited range of perspectives. Consequently, the validation reflects a detailed but narrow view of the framework's usability, and broader industry feedback would be needed to strengthen external validity.

- **No testing in an active or time-constrained project setting**
  The validation was conducted retrospectively, not during an active project phase. This means that the framework's real-time performance,how it supports coordination under time pressure, evolving schedules, or unexpected changes,was not tested. The absence of live application prevents measurement of its practical impact on communication speed, responsiveness, or problem-solving during execution. As a result, the findings confirm the framework's conceptual soundness but not its operational efficiency.
- **Unverified performance under different project structures or team cultures**
  The C-pier validation was carried out within a traditional, client-led delivery model where the same organisation managed both the donor and receiver projects. Other delivery models, such as design–build, public–private partnerships, or projects with independent clients and contractors, may create different communication dynamics and responsibilities. Because these conditions were not tested, it remains uncertain whether the framework performs equally well in contexts with different contractual boundaries, cultural norms, or levels of collaboration.
- **Integration with digital systems (CDEs, material databases) still conceptual**
  The framework's integration with digital platforms such as Common Data Environments (CDEs) or national material databases like Madaster was only explored at a conceptual level. This means that its technical interoperability,how information is actually exchanged, stored, and retrieved between systems,has not yet been demonstrated in practice. Without empirical testing, the framework's effectiveness in supporting seamless digital data transfer across platforms remains unverified.
- **No empirical data on efficiency, decision speed, or reliability improvements**
  Because the framework has not yet been applied in a live project, no quantitative data could be collected to measure its actual benefits. Metrics such as reduced coordination errors, faster decision-making, or improved data completeness were therefore not available for validation. This limits the ability to assess the framework's performance beyond expert opinion, and future studies will need to quantify these effects to demonstrate its measurable impact on project outcomes.

While these limitations primarily concern the contextual scope and testing environment of the Communication Framework, the Verification Framework faces restrictions that are more technical in nature, relating to its analytical basis and validation boundaries:

- **Reliance on Eurocode 2 models originally developed for new concrete**
  The Verification Framework adopts Eurocode 2 as the reference for assessing the structural performance of reclaimed slabs. While this ensures consistency with current European design practice, the underlying equations were originally developed for newly produced, defect-free concrete. Their direct application to reclaimed elements assumes material homogeneity and strength behaviour that may no longer hold true after decades of service. This introduces uncertainty in the accuracy of calculated resistances, particularly for aged concrete with unknown construction quality or past loading history. As a result, the framework's structural assessments must be interpreted as conservative approximations rather than absolute performance values.
- **Limited validation of mechanical behaviour in aged or pre-cracked materials**
  No physical testing of the reclaimed slabs was conducted during the C-pier validation, meaning that the framework's assumptions about the residual mechanical properties of aged concrete were not empirically verified. The long-term effects of microcracking, creep, and reinforcement corrosion on the load-bearing capacity of reused slabs therefore remain untested within this study. This limits the confidence with which the verification results can be generalised to other aged concrete elements, particularly those retrieved from harsher environmental or loading conditions.
- **Applicability restricted to certain exposure classes (carbonation, chloride ingress)**
  The framework currently covers only exposure conditions related to carbonation and chloride ingress, as these are the most common deterioration mechanisms in reinforced concrete floors. Other exposure classes,such as freeze–thaw cycles, chemical attack, or sulphate exposure,were

excluded due to the absence of consistent testing standards and models. This restriction narrows the framework's applicability to specific environmental contexts and means that further development is required before it can be applied to a wider range of structures and durability scenarios.

- **Framework not tested through a full reuse cycle (no physical deconstruction or reinstallation)**
  The C-pier validation did not involve an actual reuse process, as the slabs were not physically reclaimed, transported, or reinstalled. Consequently, the framework could not be evaluated through all practical stages of the reuse cycle,from deconstruction to reassembly. Key variables such as damage during handling, dimensional tolerances, or alignment between reclaimed and new structural components therefore remain unverified. This limits the framework's ability to confirm its robustness in real on-site conditions.
- **Variability in reclaimed elements and site tolerances not yet evaluated**
  The validation was based on design documentation and representative slab data rather than a diverse sample of physical elements. In practice, reclaimed slabs are expected to show variation in geometry, reinforcement detailing, and residual strength. The framework's capacity to accommodate this variability and to determine acceptable tolerances for reuse was not tested. This omission restricts the framework's reliability when applied to projects involving large quantities of non-uniform reclaimed components.

In summary, this research demonstrates strong conceptual and procedural validity but remains exploratory in scope. Future work should test both frameworks across multiple projects, involving a wider range of stakeholders and active reuse implementations. Quantifying their influence on data quality, design efficiency, and project outcomes would further strengthen the empirical evidence. Through such iterative testing, the frameworks can evolve from validated prototypes into standardised instruments for mainstream circular construction.

12 Conclusion

12.1. Answer to the Research Questions

RQ1 - What technical regulatory, and practical challenges currently limit the structural reuse of concrete slab elements in buildings?

(Chapters 2-4: Literature review)
The literature review revealed that while the technical feasibility of concrete element reuse has been demonstrated, its large-scale application is hindered by fragmented regulations, inconsistent assessment methods, and organisational misalignment. Key barriers include:

- **Lack of verification and certification standards:** No harmonised Eurocode-based procedure exists to certify reclaimed elements, which leads to uncertainty about structural safety and legal liability.
- **Fragmented project responsibilities:** Knowledge relevant to reuse, ranging from demolition and testing to design integration, is dispersed among actors who seldom collaborate across projects.
- **Regulatory and logistical constraints:** CE-marking and factory production control cannot be applied to reclaimed elements, and donor-target timing mismatches often result in the loss of reusable slabs.
- **Cultural and economic barriers:** Reuse is perceived as risky and time-consuming compared to conventional new-build methods, discouraging clients and contractors from experimentation.

These findings established the dual knowledge gap addressed in this research: the absence of (1) a technical verification system for reclaimed slabs, and (2) a communication process capable of aligning the fragmented expertise required for reuse.

RQ2 – How can lessons from recent Dutch reuse projects inform the development of a more consistent verification and communication process?

(Chapter 5: Case studies and expert interviews)
Analysis of five Dutch and European reuse projects, such as SUPERLOCAL, Prinsenhof A, Stationsplein 107, and Udden, revealed that technical success and organisational coordination are inseparable. Across all cases, eight recurring mechanisms explained why some projects achieved verified, certifiable reuse while others did not. Four mechanisms were technical, relating to how uncertainty, durability, adaptation, and logistics were managed; the remaining four were organisational, concerning governance, procurement, regulation, and knowledge exchange.

From the technical perspective, the cases showed that verification under uncertainty must combine destructive and non-destructive testing to translate unknown conditions into measurable parameters (T1). Limited durability and fire performance of older concrete require targeted testing and selective strengthening rather than full replacement (T2). Structural adaptation and creative strengthening strategies, such as overlays or composite action, are essential to align reclaimed elements with new load paths (T3). Finally, maintaining traceability and proper storage is crucial to preserve the validity of verification results during logistics and reassembly (T4). Together, these insights established the staged logic of the Verification Framework: an initial assessment, hybrid testing, and performance validation extended beyond laboratory checks to include handling and storage control.

From the process perspective, recurring mechanisms highlighted that organisational alignment is as decisive as technical feasibility. Fragmentation between donor and target projects can be mitigated through formal coordination roles such as a Reuse Coordinator who safeguards information continuity (P1). Flexible procurement and shared risk allocation enable iterative testing and phased verification, supporting both direct (Path A) and intermediary (Path B) project structures (P2). Because regulatory pathways for reused concrete are still evolving, project-based certification and cooperation with authorities are required to translate experimental verification into accepted approval evidence (P3). Continuous documentation and post-project evaluation further embed learning and knowledge transfer into each project cycle (P4). These principles directly shaped the Communication Framework, defining stakeholder responsibilities, decision checkpoints, and feedback loops across the six communication domains.

In sum, lessons from recent Dutch reuse projects show that consistent verification and communication depend on the integration of two complementary dimensions: technical rigour in testing and adaptation, and institutional coordination through structured communication and learning. The derived mechanisms (T1–T4, P1–P4) form the empirical foundation of the two frameworks developed in this thesis, turning observed project practices into systematic guidance for future circular construction.

RQ3 – How can the verification of reclaimed concrete slabs be structured to ensure safety, performance, and traceability?

(Chapters 7–10: Design-science research, analytical assessment, validation)
The Verification Framework provides a structured, two-stage process that aligns the assessment of reclaimed concrete slabs with existing Eurocode 2 design logic and quality management systems. Its structure mirrors the principles of factory production control but is adapted to the project-based nature of reuse, ensuring that safety, performance, and traceability are addressed systematically rather than ad hoc.

In the first stage, the Initial Element Assessment, all available data on geometry, reinforcement, material strength, and condition are collected through a combination of archival research, visual inspection, and targeted hybrid testing. This stage translates uncertainty into measurable parameters and determines whether the slabs can theoretically meet modern design requirements. The results are documented in a preliminary Declared Reuse Performance (pDRP), which forms a transparent and traceable record of the verification basis. The pDRP provides clients and project managers with a clear, auditable overview of the slabs' potential reuse value and the additional measures that would be required to achieve compliance.

The second stage, the Reuse Production Control, verifies and validates the performance characteristics established in the first stage through systematic testing and documentation. It focuses on confirming the key performance parameters, geometry tolerances, compressive strength, durability, and fire resistance, under controlled conditions. Each verification step is recorded in inspection sheets, test reports, and summary declarations, ensuring full traceability of data sources and responsibilities. The outputs are consolidated into the verified Declared Reuse Performance (vDRP), which serves as the project's formal verification record and can be integrated into standard quality assurance documentation.

This structured two-stage process ensures safety by grounding all assessments in Eurocode-based design checks and by explicitly defining the verification methods for each essential characteristic. It ensures performance by requiring hybrid testing and performance validation before any reclaimed slab is approved for design integration. Finally, it ensures traceability through consistent documentation at every step, linking test results, design calculations, and responsibilities within an auditable verification chain.

The C-pier validation confirmed that this structure works in practice: it allowed all relevant data to be collected, verified, and transparently documented, even when reuse was ultimately not pursued. In doing so, the framework transforms the verification of reclaimed elements from an uncertain, one-off activity into a repeatable, quality-assured process that delivers verifiable safety, demonstrable performance, and continuous traceability across project stages.

RQ4 – How can communication between actors be organised to enable reuse across different projects and life-cycle stages?

(Chapters 6–10: Framework development and validation)
The Communication Framework developed in this thesis provides a structured system for organising information exchange and responsibility across the life cycle of reclaimed elements. It is based on the logic of the construction value chain and divides the reuse process into six communication domains, each corresponding to a project phase. These domains establish a consistent rhythm for information exchange, ensuring that verified data on reclaimed elements is created, transferred, and maintained

without loss of context or ownership. The framework thus transforms communication from an informal, person-dependent activity into a managed and auditable process that can operate across projects and over time.

The framework functions by defining three core dimensions of communication: timing, responsibility, and traceability. Timing is secured by aligning communication events with key project milestones, so that verification data is available when critical design and procurement decisions are made. Responsibility is established through clear role definition: the client and Reuse Coordinator safeguard overall information continuity, engineers and contractors are responsible for data accuracy within their scope, and the Independent Quality Controller validates documentation before each handover. Traceability is achieved through the use of standardised deliverables, such as the Reuse Communication Plan, Verification Dossier, and Traceability Protocol, each connected through a shared Information Management System (IMS) that records ownership, version history, and approval status.

Several design principles underpin the framework's operation. First, it follows a chain-of-custody approach, ensuring that every dataset on reclaimed elements has an identifiable owner from demolition to potential future reuse. Second, it integrates technical verification and project communication, linking the data generated through the Verification Framework to the project's management and quality-control systems. Third, it embeds flexibility through two operational pathways: Path A, for projects where donor and receiver are managed under one client, and Path B, where an intermediary organisation certifies the data for multiple users. Finally, the framework is designed to be compatible with existing digital environments, allowing it to be implemented within standard Common Data Environments (CDEs) or extended to material databases such as Madaster.

In practice, the framework ensures that communication supports reuse not by increasing documentation, but by clarifying who communicates what, when, and why. By defining responsibilities and establishing a single digital environment for documentation ownership, it creates the procedural reliability required for circular construction. The validation confirmed that this structure improves data availability, reduces uncertainty between project stages, and allows reuse decisions to be made on verified information rather than assumptions. In this way, the Communication Framework enables the long-term continuity of information and responsibility that is essential for reuse across different projects and life-cycle stages.

Main research question

How can the reuse of structural concrete elements, and specifically slabs, move from being an exception to becoming an integrated practice within the construction industry?

The research demonstrates that reuse can become an integrated practice only when technical verification and organisational communication are combined into one coherent system. The two sub-questions, addressing the technical and managerial domains, represent interdependent conditions that together enable this transition.

From the Structural Engineering perspective, the Verification Framework provides the mechanism to guarantee structural safety and durability of reclaimed slabs through Eurocode-based assessment. By producing a transparent Declared Reuse Performance (DRP), it gives clients and engineers the confidence to base design decisions on verified data rather than assumptions. This resolves the long-standing technical barrier of uncertainty that has limited reuse to experimental contexts.

From the Construction Management perspective, the Communication Framework embeds this verification process into project organisation. It defines how data, responsibilities, and approvals move through the project, ensuring that verified information remains traceable, shared, and reusable. By integrating these communication steps into existing BIM and quality-assurance systems, the framework prevents information loss and institutionalises reuse within normal project delivery.

Together, the frameworks form a dual mechanism:

- the Verification Framework establishes what can safely be reused
- the Communication Framework ensures how that information is managed and acted upon

Applied in parallel, they transform reuse from a one-off initiative into a controlled, repeatable, and auditable practice that aligns with current engineering and project-management standards. In doing so, they bridge the critical gap between proven feasibility and institutional acceptance. Thus, the reuse of structural concrete elements can move from being an exception to a mainstream practice when supported by a unified approach that guarantees both the technical reliability of reclaimed slabs and the organisational processes that make this reliability visible, trusted, and transferable across projects.

12.2. The Contribution of the Thesis

The central contribution of this thesis is the demonstration that structural reuse becomes feasible only when technical verification and organisational coordination are developed together. The dual-framework structure created in this research shows that technical reliability and process governance are interdependent. Verification of reclaimed slabs cannot be carried out effectively without structured communication between actors, and communication frameworks only function properly when supported by clear technical outputs. This integrated perspective is the overarching contribution to the growing field of circular construction.

Contributions to Structural Engineering

Scientific contribution

The scientific contributions on the Structural Engineering side address a clear gap in the literature: the lack of a Eurocode-aligned and standardisable method to verify reclaimed cast-in-situ slabs.

First, the thesis introduces a Eurocode-consistent verification methodology for reclaimed structural elements. Existing initiatives provide fragmented testing procedures, but none offer a harmonised workflow that aligns with EC2 calculations. The Verification Framework developed in this thesis fills that gap by translating the uncertain and variable conditions of reclaimed slabs into a process that produces design-ready inputs.

Second, the thesis introduces the Declared Reuse Performance (DRP), which is a new technical concept. The DRP formalises the verified capabilities of a reclaimed slab so they can be compared directly with CE-marked precast elements. Prior studies and guidelines do not define a unified output of this kind, making the DRP a new scientific element in circular structural design.

Third, the thesis contributes new methodological knowledge for dealing with uncertainty in reclaimed materials. Through the use of a preliminary and verified DRP and an era-based calibration approach, the research provides a structured method for interpreting incomplete documentation, variable reinforcement layouts, and historical concrete strength systems. This addresses a major knowledge gap identified repeatedly in the literature: how engineers can work reliably with uncertain or inconsistent material data.

Practical Contribution

The practical contributions for Structural Engineering show how the technical insights from the thesis can be applied in everyday design practice.

First, the Verification Framework has been designed to work within existing engineering processes. It aligns with Eurocode-based calculations, quality assurance procedures, and BIM-linked documentation, meaning engineers can apply it without changing their software or organisational structures.

Second, the thesis provides a clear pathway toward project-based certification of reclaimed slabs. By formalising the DRP and the verification workflow, the research offers a structure that regulators, clients, and testing laboratories can use when developing certification schemes. This contributes to the development of future standards or annexes for structural reuse.

Third, the research offers practical guidance for engineers regarding how to integrate reclaimed slabs into early design decisions, how to document assumptions transparently, and how to manage uncertain or missing information. This strengthens the professionalisation of reuse as an accepted engineering practice rather than an experimental exception.

Contribution to Construction Management and Engineering

Scientific Contributions

The scientific contributions on the CME side respond to the organisational knowledge gap identified in the literature: fragmentation, unclear responsibilities, and recurrent information loss between demolition and design phases.

First, the thesis develops a stage-based Communication Framework grounded in empirical evidence from case studies and expert interviews. Unlike earlier conceptual models, the framework specifies concrete communication requirements, responsibilities, and deliverables for each stage of the construction value chain.

Second, the thesis advances the academic understanding of communication in circular construction by operationalising communication theory. Abstract principles such as transparency, traceability, and coordination are translated into measurable project actions and structured processes.

Third, the research synthesises recurring fragmentation mechanisms across five major reuse projects. These include verification under uncertainty, mismatches in procurement structures, and gaps in responsibility between demolition and design teams. The framework is built to directly address these mechanisms, making it a scientifically grounded contribution to organisational theory in circular construction.

Practical Contributions

The practical CME contributions show how the Communication Framework can improve real-world project delivery.

First, the framework integrates seamlessly with existing project workflows and information management practices. Verification data, approvals, and design decisions can be documented and traced within the same procedures and platforms already used by project teams, improving consistency and reducing the need for new processes.

Second, the framework strengthens information traceability across the reuse chain. By linking verification outputs to material passports and reuse dossiers, the thesis provides a practical method to prevent information loss and ensure continuity from demolition through design, construction, and operation.

Third, the thesis provides clear role descriptions for clients, reuse coordinators, engineers, demolition teams, and testing laboratories. This helps practitioners understand who needs to communicate what and when, reducing coordination issues that often lead to the loss of reuse potential.

Finally, the frameworks provide immediate value for policymakers and standardisation bodies. The structured process developed here can be adopted or adapted when creating future guidelines for the verification and communication of reclaimed structural elements.

12.3. Recommendations for Practice

The findings of this thesis translate into several recommendations for practitioners who aim to integrate the reuse of structural concrete elements into mainstream project delivery. The recommendations address the three main stakeholder groups involved in the reuse process: clients and project managers, designers and engineers, and contractors and testing specialists.

Clients and Project Managers

1. **Include reuse objectives in the project brief and tender documentation** Reuse potential is often lost because it is not defined as a project requirement early on. Clients should explicitly include targets for reuse, circularity, and documentation in the tender stage, ensuring that contractors and designers allocate time and budget for assessment and verification.
2. **Appoint a reuse coordinator or circularity manager** The validation showed that reuse succeeds when a single coordinating actor connects the donor and target projects. Appointing a reuse coordinator ensures that responsibilities for verification, documentation, and communication are clearly assigned throughout the project.
3. **Adopt a risk-informed approach to decision-making** Verified reuse data should be evaluated against both safety and sustainability objectives. Clients are encouraged to make balanced de-

cisions that consider verified performance, rather than rejecting reuse solely due to unfamiliarity or perceived risk.

Designers and Engineers

1. **Integrate verification and communication steps into standard workflows** The developed frameworks are compatible with BIM and Quality Assurance systems. Designers and engineers should embed verification milestones and communication handovers into their existing project documentation (e.g., the BIM Execution Plan) to make reuse a routine rather than exceptional process.
2. **Use the Declared Reuse Performance (DRP) as a decision tool.** The DRP provides a transparent record of the verified geometry, strength, and durability of reclaimed slabs. Engineers can use this as an input for design calculations and for validating safety margins when comparing reclaimed and new elements.
3. **Plan for adaptable designs** Design strategies should anticipate the use of elements with variable geometry or capacity. Incorporating redundancy, modular spans, or hybrid systems can increase the likelihood that reclaimed slabs will fit both technical and architectural requirements.

Contractors and Testing Specialists

1. **Treat demolition as selective deconstruction** Contractors should plan and execute demolition activities with reuse in mind. Selective deconstruction, combined with detailed documentation of geometry and condition, preserves both material value and the data required for verification.
2. **Implement quality control through Reuse Production Control (RPC)** Testing specialists and contractors should coordinate during handling, storage, and transport of reclaimed elements to maintain verified performance levels. Following the RPC stages prevents damage and ensures that data collected during testing remains valid through to reuse.
3. **Use Common Data Environments for information exchange** All verification and inspection data should be uploaded to a shared CDE following the structure outlined in the Communication Framework. This ensures full traceability and allows all parties to work from a single source of verified information.

Cross-Disciplinary Recommendations

1. **Integrate reuse into contractual and procurement models** Conventional linear procurement models are poorly suited to reuse. Framework or performance-based contracts that promote early collaboration between demolition, testing, and design teams should be adopted to align project timelines and responsibilities.
2. **Develop shared digital infrastructures** The use of different Common Data Environments during the validation highlighted the need for interoperable data structures. Linking project-specific CDEs to national databases such as Madaster would enhance long-term accessibility and facilitate reuse across multiple projects.
3. **Invest in training and knowledge dissemination** Organisational maturity is a prerequisite for the effective use of both frameworks. Training programs should be introduced to familiarise engineers, project managers, and contractors with reuse verification procedures, data handling, and quality assurance methods.

12.4. Recommendations for Future Research

While this thesis has developed and validated two complementary frameworks for the reuse of cast-in-situ concrete slabs, several areas require further research to strengthen their applicability and expand their relevance across different project contexts. Future research should focus on both the technical and organisational dimensions of reuse, as well as their integration within the broader regulatory and digital environment.

Advancing Technical Verification

1. **Validation through experimental testing** The Verification Framework assumes that Eurocode-based procedures can be applied directly to reclaimed slabs, but this assumption has not yet been verified through large-scale experimental studies. Future research should include laboratory and field testing on pre-cracked and aged slabs to better understand residual capacity, bond behaviour, and serviceability performance under reuse conditions.
2. **Extension to additional exposure classes** The current framework was validated for slabs exposed to carbonation (XC) and chloride ingress (XD/XS) conditions. Further work is needed to adapt the verification procedures for other exposure classes such as freeze–thaw (XF) and chemical attack (XA), including the development of corresponding durability assessment models.
3. **Integration of probabilistic methods** Incorporating probabilistic reliability analysis would make the Declared Reuse Performance (DRP) more robust and compatible with risk-based design approaches. Research could focus on quantifying uncertainties in material properties, testing results, and degradation mechanisms, enabling a reliability-based certification method.

Expanding Organisational and Communication Frameworks

1. **Multi-project and cross-organisational validation** The Communication Framework was validated in a single case under one client using Path A (direct alignment). Future studies should test the framework across multiple projects with different contractual setups, including Path B configurations with intermediary reuse coordinators or brokers, to evaluate its scalability and adaptability.
2. **Empirical evaluation during implementation** The validation case was conducted in a preparatory phase; therefore, the framework's real-world impact on decision-making speed, data reliability, and project efficiency could not be measured. Applying the framework in live projects would allow for quantitative evaluation of its performance and user acceptance.
3. **Interoperability of digital environments** Research should explore how different Common Data Environments (CDEs), material passports, and national databases can be synchronised to maintain information continuity beyond single projects. The development of open data standards or a centralised reuse repository would greatly improve cross-project traceability.

Regulatory, Economic, and Policy Dimensions

1. **Alignment with building regulations and certification schemes** The Declared Reuse Performance (DRP) provides a transparent documentation method, but its formal recognition within national and European building regulations remains unresolved. Future research should examine how the frameworks can inform the development of new certification pathways or annexes to standards such as CROW-CUR 4 and EN 1992.
2. **Integration with economic assessment** Quantitative studies on cost-benefit ratios, life-cycle cost savings, and carbon reduction achieved through reuse are needed to support evidence-based policy decisions and client adoption. Combining the frameworks with life-cycle assessment (LCA) and life-cycle cost (LCC) analyses could demonstrate the full value of reuse.
3. **Institutional and behavioural aspects** Organisational culture and risk perception remain major obstacles to reuse. Future research should explore behavioural drivers of decision-making, training effectiveness, and incentive mechanisms that can normalise reuse practices within professional routines.

Integration and Long-Term Development

1. **Full-cycle validation of both frameworks** The C-pier case validated the frameworks in parallel but did not cover the full reuse cycle from deconstruction to reinstallation. Future work should evaluate how the two frameworks perform when applied over multiple project stages and across different types of concrete structures.
2. **Development of digital twins for reuse** Combining the frameworks with digital-twin technology could allow continuous monitoring of reclaimed elements and predictive assessment of reuse potential. Such integration would enhance traceability, performance tracking, and adaptive maintenance strategies across the built environment.

12.5. Final Statement

This thesis demonstrates that the reuse of cast-in-situ concrete slabs is not limited by technical feasibility but by the absence of structured processes that guarantee reliability and accountability. By combining the Verification Framework and the Communication Framework, this research provides both the technical method and the organisational structure needed to transform reuse from an exceptional initiative into a normalised and verifiable practice. The validation at Schiphol's C-pier confirmed that when verification and communication are aligned, reclaimed structural elements can be assessed, documented, and managed with the same rigour as new materials. In doing so, the thesis bridges the long-standing divide between engineering precision and project governance, showing that circular construction requires not only new materials, but also new systems of collaboration, verification, and trust.

Ultimately, the work presented here contributes to a shift in perspective: reuse should no longer be viewed as a compromise or experiment, but as a credible, measurable, and repeatable component of modern structural design. By embedding technical assurance within transparent communication processes, the construction industry can move towards a future in which the value of existing structures is preserved, the environmental burden of new construction is reduced, and circularity becomes an inherent quality of engineering practice.

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A Interview Ronald Lunstroo - Royal Schiphol Group

Interviewee: Ronald Lunstroo - Developer
Date: 28/07/2025
The interview was originally conducted in Dutch. The following is a translated and edited version based on the original conversation. Due to setting of the interview, this is a reconstructed summary rather than a verbatim transcript.

A.1. General company information

Can you briefly introduce your role at Schiphol in the context of circular construction?
Ronald Lunstroo is a developer at Schiphol Airport, responsible for drafting requirement specifications for designers and contractors. In this role, he works closely with stakeholders from various disciplines, including sustainability, safety, and engineering. Circular construction and the reuse of building elements are relatively new but increasingly important themes for Schiphol.

“We developed a sustainability strategy around 2018 that was broadly defined, but initially had little impact on projects because the sustainability team was still very small,” Lunstroo explains. “That’s why I took the initiative at the time to integrate sustainability into our project approach myself.”

What are Schiphol’s ambitions regarding circularity and material reuse and how have they already integrated this?
Schiphol aims to structurally integrate circularity into its construction projects. A requirement that has been provided for most new development is a circularity index, in case of the C-pier and doorlaatpost 90 this target was 90%. One of the key milesonte was the development of Doorlaatpost 90, this served as a pilot for circular construction. In this project, a freight building was demolished in a circular manner, and materials such as steel roof structures were reused one-to-one. This approach contributed to a high BCI score of 68%, showcasing the potential of circular design when applied thoughtfully.

Schiphol has also taken steps to store and process materials for reuse, such as establishing a concrete hub for airside infrastructure (e.g., taxiways and aircraft stands). While this hub currently focuses on asphalt and concrete, there are ambitions to expand it to include other materials like precast concrete slabs and thus form their own circular material hub.

A.2. Reuse in practice

What made Doorlaatpost 90 a good opportunity for a circular strategy rather than the traditional building methods?
According to Lunstroo, four main factors contributed to the decision to approach the Doorlaatpost 90 project with a circular construction strategy:

- Financial Flexibility: The project was part of a larger €100 million development, which provided the necessary budgetary room to experiment with circular methods without jeopardizing the overall financial viability.
- Independent Location: The building was situated in a standalone area on the landside of Schiphol, allowing for a clearly defined construction zone. This made it easier to implement circular practices without interfering with ongoing airport operations.
- Organizational Momentum: Around 2018–2019, there was a noticeable shift within Schiphol’s organization. A growing number of individuals began advocating for sustainability, creating a

fertile environment for piloting new approaches. Lunstroo himself played a key role in initiating and shaping the sustainability strategy for this project.

- Willingness to Experiment: All involved parties, including Schiphol, the contractor BAM, and other stakeholders were open to trying new methods. This collective mindset enabled the project team to explore circular demolition, reuse of materials, and innovative design strategies.

Which material were reused in this project and where were they harvested?
A significant portion of the steel roof structure was reused one-to-one, meaning the elements were directly reinstalled without major alterations. In addition to the steel, doors, lighting fixtures, and sanitary installations were also salvaged and reintegrated into the new building.

This process involved careful planning and collaboration. Materials were catalogued, assessed for quality, and stored externally by contractors. For example, steel components were sent to Vic Opdam for recoating and preparation, while BAM managed the storage and redistribution of other reusable elements. Although Schiphol does not yet store most materials in-house (except for asphalt and concrete in the airside concrete hub), this project demonstrated the feasibility of circular workflows when supported by the right partners and infrastructure.

How did the collaboration with parties such as designers, contractors, and demolition companies go?
Schiphol itself is a process organization meaning that our main focus is getting the right parties around the table and from there a more of a coordinating role. In this project most of the parties involved had the right mindset. Every party, BAM (the main contractor), BCN (the designers) and the demolition company, were willing to experiment.

Though in the collaboration challenges did arise, particularly around risk management and technical feasibility. Some subcontractors were hesitant to work with circular methods, due to their novelty, inexperience and uncertainty at the outcome. For example, reused lighting fixtures had to meet strict requirement for operations hours, which we had to find a consensus for. Another example are the flooring system where the sub contractor did not see it feasible to reuse certain elements due to the glue lining and the needed warrenty to provide.

What were the biggest challenges in applying reused elements?
The interview with Lunstroo highlights several key challenges Schiphol faced when implementing reused materials in the Doorlaatpost 90 project and other initiatives:

- Getting the entire supply-chain aligned: In even one party said 'I don't date to take the risk,' the whole plan falls apart. Reusing elements requires cooperation across multiple disciplines and organizations, including designers, contractors, subcontractors, and suppliers. Each party must be willing to accept certain risks and adapt their processes to accommodate reused materials.
- Lack of Standardized Processes: Circular construction was still relatively new within Schiphol, and there were no established workflows for sourcing, testing, storing, and integrating reused materials. This led to inefficiencies and required a high level of improvisation and coordination between parties.
- Operational Constraints: Schiphol is a 24/7 operational environment, which limits the flexibility of construction timelines and zones. Many projects cannot be easily isolated, making it difficult to plan and execute circular demolition and reuse without disrupting airport operations.
- Perception and Cultural Barriers: There is still a negative perception around reused materials, often seen as “second-hand” or inferior. This mindset affects decision-making and can lead to rejection of viable reused components purely based on image or unfamiliarity.
- Storage and Logistics: Schiphol does not yet have a centralized system for storing reused materials (except for asphalt and concrete in the airside hub). This means materials must be stored and managed by external partners, which can complicate logistics and reduce control over availability and quality.
- Go into too much detail: When thinking about reuse you can go too far and loosing the main aim. Sometime it needs to be accepted that reuse if not possible and find a suitable alternative.

In the future do you think a project like Doorlaatpost 90 would be done again at Schiphol?
In the future there is hope to have more project like this. The problem still remains that there must be sufficient materials. With Doorlaatpost 90 there was a special scenario in which there was a redundant building at the location where the new building must be placed. These conditions are unique, meaning that in other cases a good material stream must be found. With the current operations of Schiphol within Schiphol this is not the case yet. The sources must be found outside the project and this is often hard to find. The risks of having enough material is therefor too large. Therefor it is hard to create projects of this size with reused elements.

A.3. Future vision

What innovations and policy changes are needed to make reuse possible on a larger scale?
To enable large-scale reuse of materials in construction projects at Schiphol, several innovations and policy shifts are necessary. It is important to recognize that the current system is still in a transitional phase and aiming for the end-goal is often not the right mindset. In the role as a client it is important to make sure that you get the engineering firms and contractors to think about the possibilities of sustainable design. Often these factors are overlooked all together. s. Many parties, especially in technical disciplines, are unfamiliar with the possibilities and limitations of reused materials. Lunstroo emphasized the importance of educating stakeholders and creating a culture where reuse is seen as viable and valuable. “We had to communicate clearly to our stakeholders: this project will be different from what you’re used to.”

Other innovations that are needed to ensure circularity are:

- Embedding Circularity in Project Requirements: Circularity should be integrated into project specifications and design criteria from the outset. Schiphol has started doing this by including circularity targets (e.g., BCI scores) in tender documents and design briefs. However, more standardized and enforceable policies are needed to ensure consistent application across all projects.
- Incentivizing Reuse Through Financial bonuses: Although Schiphol does not yet formally link CO_2 savings to budget flexibility, Lunstroo expressed support for such mechanisms. Projects could be rewarded for achieving significant environmental benefits, even if they incur slightly higher costs. This would encourage long-term thinking and sustainable investment.

B Interview: Arend van de Beek - Lagemaat*

Interviewee: Arend van de Beek - Programmamanager Circulariteit at Lagemaat Date: 23/05/2025 *The interview was originally conducted in Dutch. The following is a translated and edited version based on the original conversation. Due to setting of the interview, this is a reconstructed summary rather than a verbatim transcript.*

B.1. General Company information

Could you briefly introduce Lagemaat and your role as Circular Program Manager in the demolition process?
Lagemaat is one of the leading demolition companies in the Netherlands, with a strong and growing focus on circular demolition. As Circular Program Manager, I am responsible for defining, designing, advising on, and coordinating the implementation of business models, strategic partnerships, and digital technologies that support circular entrepreneurship within Lagemaat BV.

How does Lagemaat differentiate itself in circular demolition compared to traditional demolition companies?
While many demolition companies are beginning to adopt circular practices, Lagemaat distinguishes itself by focusing on the reuse of structural elements. We are transitioning towards the R3 philosophy: Reclaim, Reuse, and Rebuild with particular emphasis on concrete and steel components. These materials have the highest impact in terms of CO_2 emissions and resource consumption, making their reuse especially valuable.

B.2. Reuse in practice

What does the process of dismantling concrete elements look like?
Before any dismantling begins, we identify potential donor buildings and assess which elements can be reused. We maintain a database of such buildings and match them with upcoming construction projects that have high potential for circular integration. Using laser scanning technology, we create detailed 3D models of the donor structures. These scans are imported into design software such as Revit, where reusable elements are incorporated into the new design.

Once the design is finalized, the demolition process begins. This is carried out with great care, tailored to the structural characteristics of the elements being harvested. A good example is the hollow-core floor slab, which is frequently reused. These slabs often have a cast-in-place compression layer. During dismantling, the slab is carefully cut around its edges while supported, and then hydraulically lifted from the structure. This method respects the slab's directional strength and minimizes damage.

After removal, elements are not always immediately reused. They may be stored for up to two or three years. Proper storage is crucial. Hollow-core slabs, for instance, are sensitive to torsion, so they must be stored in a way that prevents deformation.

How do you collaborate with designers and contractors in circular projects?
Involving contractors in circular projects can be challenging. Many operate within a linear construction model and are hesitant to take on the risks associated with reused materials, especially given the lack of standardized quality certifications. To address this, Lagemaat often assumes the role of main contractor, redistributing risk and enabling more flexible collaboration.

We typically form a joint venture for each project, either with both the design firm and a willing contractor, or solely with the design firm. We frequently collaborate with CPZ and work closely from the earliest stages. The entire design process is virtual, allowing for continuous coordination. Structural engineers are involved early to assess feasibility and risks. A detailed demolition plan is also developed, outlining the step-by-step dismantling process tailored to each element.

What criteria determine whether a project is approached with circular or traditional demolition methods?
Circular demolition is pursued when it is feasible to integrate elements from a donor building into a new project. Budget is a key factor, the goal is to keep demolition costs comparable to traditional methods. The savings come from reduced material costs in the new build, making circular practices more attractive.

Utility buildings often yield higher returns due to the size and quality of their structural elements. In residential projects, reuse is more focused on materials like bricks and glass. Demand for circular demolition is growing, particularly in government-related projects.

How is transport organized and integrated in a project?
We are currently developing our own Circular Hub for centralized storage. Though for project related harvesting, we use temporary storage facilities near project sites to limit emissions. Transport is often seen as a drawback in circular construction due to assumed higher emissions. However, traditional projects also involve multiple transport stages and longer distances. We optimize logistics by minimizing trips and maximizing truck loads, which significantly reduces transport-related emissions compared to conventional methods.

B.3. Future vision and limitations

What innovations or collaboration do you belive could enable reuse on a larger scale?
Greater adoption of modular design and standardized dimensions would significantly ease the integration of reused elements. It would simplify both dismantling and reassembly, reducing waste and increasing efficiency. Additionally, expanding the use of dry connections instead of adhesives or nails would further facilitate reuse. Encouragingly, we are already seeing progress in this area.

What do you see as the biggest challenge and the biggest opportunity for reuse in the demolition sector?
The main challenge is the lack of standardized quality assessments, which makes contractors hesitant due to perceived risks. Current regulations are designed for new materials, requiring additional specifications for reused components. A third-party quality assurance system is essential. The steel industry is already more advanced in this regard, but concrete remains more complex. The greatest opportunity lies in developing a standardized quality framework for reused materials, which would reduce risk and encourage broader adoption.

C Interview: Axel Hendriks - Adex Groep*

Interviewee: Axel Hendriks - Commercial Director at Adex Groep Date: 02/06/2025 *The interview was originally conducted in Dutch. The following is a translated and edited version based on the original conversation. Due to setting of the interview, this is a reconstructed summary rather than a verbatim transcript.*

C.1. General Company information

Could you briefly introduce Adex Groep?
Adex Groep is a leading specialist in the field of circular demolition and deconstruction. The company operates across three core divisions: Sloop & Demontage, Hubs & Bouwmaterialen, and Milieu. This structure allows Adex to approach demolition not as an endpoint, but as a crucial beginning in the construction value chain. Their mission is to maximize the reuse of materials, reduce environmental impact, and support the transition to a circular economy.

How does Adex differentiate itself in circular demolition compared to traditional demolition companies?
What truly sets Adex apart is its holistic and proactive approach to demolition. Rather than viewing demolition as the end of a building's life cycle, Adex sees it as the beginning of a new one. The company treats buildings as urban mines, rich in valuable materials that can be recovered, repurposed, and reintroduced into the construction chain. This philosophy is embedded in every project they undertake.

Adex's scale plays a crucial role in its ability to innovate. For example, the company invested in a woodworking facility that took five years to break even, something smaller firms might not have been able to sustain. This long-term vision allows Adex to experiment, learn, and lead the way in circular practices.

Moreover, Adex distinguishes itself by doing everything in-house. This includes not only the physical demolition but also the sorting, cataloging, and storage of materials. Their Urban Mine and Circulaire Hub are central to this process, enabling them to store materials even when a buyer hasn't yet been identified. This flexibility is essential in a market where supply and demand for reused materials don't always align.

C.2. Reuse in practice

What is the ratio between traditional and circular demolition projects at Adex? At Adex, we see a clear and steady shift toward circular demolition, but traditional demolition still represents a significant portion of our portfolio. However, what's important to note is that even in traditional projects, we apply circular principles wherever possible.

In practice, this means that while a project may not be labeled as "circular," we still assess the potential for material recovery, selective dismantling, and reuse. The distinction between traditional and circular is becoming increasingly blurred as more clients begin to recognize the value, both environmental and economic, of material reuse. That said, fully circular projects, where materials are dismantled with the intent of direct reuse or resale, are still in the minority, but growing steadily.

What are projects in which concrete elements are one-on-one reused that Adex was involved in?
A good example of how Adex has harvested concrete elements is a circular demolition project in Dordrecht, carried out for the development of the new Huis van Stad en regio development.

In this project, Adex was responsible for the complete dismantling of a former Rabobank office, a tax office, and a large parking garage, all located in a dense urban environment along the Spuiboulevard. The project was technically complex due to the proximity of surrounding buildings and infrastructure, but it also offered a unique opportunity to demonstrate what's possible in terms of high-value material recovery.

The concrete elements were extracted from the 16.000 m^2 parking garage. The garage consisted of TT-slab elements and originally not demountable. Adex succeeded in sawing and lifting out each element individually. The dismantling of concrete elements is a precise and carefully planned operation. Double-T slabs are typically connected with steel reinforcement. We cut these connections and use the original lifting eyes to safely hoist the elements out of the structure.

Since there was no direct buyer for this elements that slabs had been stored in Leiden for little over a year, before they were sold and reused in the build of a parking garage in Assen.

In other project we do a lot of harvesting of hollow core floor slab. We see an increasing market for these elements and compared to other structural elements they are relatively easy to harvest. In the case of hollow-core slabs, we often saw them into smaller, liftable sections. Throughout the process, we use Cirdax, a digital tool that generates material passports. Each element receives a unique ID, and we document every step, from dismantling and transport to storage and reuse. This ensures traceability and builds trust with future users of the materials.

What criteria determine whether a project is approached with circular or traditional demolition methods?
The decision between circular and traditional demolition is influenced by a combination of technical, economic, and contextual factors. At Adex, we always aim to do as much as possible in terms of reuse, but we are also realistic about the constraints.

Key criteria include:

- **Building characteristics:** If the structure is not designed for disassembly or if materials are too degraded, circular demolition may not be feasible.
- **Time constraints:** Circular demolition takes more time due to selective dismantling and documentation.
- **Client ambition:** Projects with clients who prioritize circularity tend to allow for more extensive reuse.
- **Material value:** If the materials don't have sufficient reuse potential or market value, traditional demolition may be more practical.
- **Learning potential:** Sometimes we pursue circular strategies even when they're not immediately profitable, simply because the project offers valuable insights for future work.

How is the demolition company involved in the new design, and wah shoud designers consider when aiming for reuse?
Unfortunately, demolition contractors are often brought in too late, after the design is finalized. This limits the potential for reuse. At Adex, we actively seek to be involved from the earliest design stages, so we can advise on which materials can be recovered and how they might be integrated into the new build. In successful projects, we see new partnerships emerge between demolition experts, architects, and suppliers.

Though we see more potential in working with suppliers as intermediaries. It is very hard to couple a demolition project with a new project. Often materials are harvested and then left for quite a while. By using the suppliers we can ensure the quality of the harvested materials as they can test and certify the reused materials. The suppliers also know the market, which makes it easier to find a buyer for the reused elements.

C.3. Future vision and limitations

What innovation or collaborations could enable reuse on a larger scale? We believe in the power of collaborative ecosystems. A consortium of demolition companies, designers, engineers, and suppliers with short, structured check-ins could scan upcoming projects for reuse potential. This would reduce the need for ad hoc coordination and create predictability in the reuse market. It is something we already see happening in the market for reused steel, but the concrete market is still behind in this aspect.

A key enabler is the presence of stockholding intermediaries, companies or hubs that can store and manage reclaimed materials until they're needed. This helps align supply and demand and makes reuse more scalable and commercially viable

What do you see as the biggest challenge and the biggest opportunity for reuse in the demolition sector?
The biggest challenge is that most buildings were never designed to be dismantled. This makes reuse risky and expensive. We often lack documentation, and there are hidden variables, like unknown reinforcement in concrete slabs that require destructive testing to uncover.

The biggest opportunity lies in CO_2 pricing and regulatory incentives. If the environmental cost of new materials is properly accounted for, reuse becomes much more attractive. We're also seeing manufacturers re-enter the reuse market, reclaiming their own products and creating closed-loop systems. This could be a game-changer.

D Interview: Jan Hendrik Vos and Pieter van Leeuwen - Gemeente Leiden

Interviewee: Jan Hendrik Vos - Project manager and Pieter van Leeuwen - Technisch Manager
Date: 15/07/2025
The interview was originally conducted in Dutch. The following is a translated and edited version based on the original conversation. Due to setting of the interview, this is a reconstructed summary rather than a verbatim transcript.

D.1. General company information

Could you briefly introduce yourself and the project?
The Municipality of Leiden is a historic city in the Netherlands, known for its rich cultural heritage and academic excellence. It has growing commitment towards sustainability. As part of its urban development strategy, the city has increasingly embraced circular principles in construction and demolition, aiming to reduce environmental impact and promote material reuse.

One of the initiatives within this strategy is the redevelopment of the area surrounding Stationsplein 107, located near Leiden Central Station. This site is undergoing a transformation that includes the demolition of existing buildings and the construction of four new residential blocks and an underground parking facility. The project represents a significant step in reshaping the urban fabric of Leiden, while simultaneously serving as a pilot for circular demolition practices.

In this interview I spoke with two persons working on this project:

- Jan Hendrik Vos is responsible for the urban development around Stationsplein 107 in Leiden as a project manager. He oversees the transformation of the area, including the demolition of existing buildings and the construction of four residential blocks and an underground parking garage. Jan Hendrik played a key role in initiating circular demolition within this project. His involvement spans from policy decisions to and overseeing the practical implementation.
- Pieter van Leeuwen is a technical manager at the city engineers of the Municipality of Leiden and is closely involved in the civil engineering aspects of the station area development. In the Stationsplein 107 project, he has championed the application of circular principles in demolition and redevelopment.

What was the motivation and the goals for this project?
Leiden has set ambitious goals in its sustainability and circularity policy, with one of the central aims being the high-quality reuse of materials. This approach goes beyond merely reducing waste, it actively promotes the repurposing of materials in new construction projects. Within this framework, circular demolition has emerged as a key strategy. Although the policy is still evolving and does not yet specify exact reuse targets, the Stationsplein 107 project was designed to push the boundaries of what is currently achievable. The project team aimed to maximize reuse within the practical constraints of the site and scope. As such, the initiative was not only a step toward more sustainable urban development but also a valuable learning experience that contributes directly to the refinement of municipal policy.

Practically we had a couple of ideas that we wanted to achieve. When it comes to the reuse of constructive elements we wanted to at least reuse part of the flooring systems and a portion of the columns. The later is something that was thoroughly explored, but the contractor later determined that they did not need the elements anymore.

D.2. Reuse in practice

Can you walk me through the initial steps of the project? How did you go from the municipal policy towards the circular demolition strategy, and how was it translated into the tender process and the eventual initiation of the project?
Although the municipal policy emphasized achieving ”the highest quality of reuse,” this ambition was still vaguely defined, which led to varying interpretations in practice. To better understand what was technically and practically feasible within the scope of the project, the Municipality of Leiden partnered with Witteveen+Bos. This engineering consultancy was responsible for the technical preparation and conducted a detailed inventory of reusable elements. Based on their research and material testing, they compiled a list of components suitable for reuse and developed a demolition plan.

Following this preparatory phase, the municipality engaged with the developer ERA Contour to determine which of the identified elements could be integrated into the new housing designs. In parallel, the demolition company Dusseldorp was contracted to carry out the actual demolition work.

How did the collaboration between the involved parties unfold throughout the project from the initial planning stages to execution?
The collaboration between the involved parties was generally positive, though not without its challenges. One notable limitation was that Witteveen+Bos, who had played a key role in the technical preparation and inventory of reusable elements, was not involved during the execution phase. This absence was seen as a missed opportunity, as their continued involvement could have supported a smoother transition from planning to implementation. ERA Contour took over the full design responsibilities during execution, but some of the initial reuse plans were ultimately abandoned due to evolving design choices.

Another important factor influencing the project was the nature of the parties involved. While ERA Contour showed interest in circular principles, they are ultimately a contractor, and their primary focus remains on the financial viability of the project. Convincing such parties to fully embrace circularity requires effort. This challenge is even more pronounced with social housing corporations, which operate under strict budget constraints. Initially, the methods used in this project appeared to stay within budget, but it has since become clear that the costs exceeded expectations. This financial reality is a critical consideration when initiating future circular projects.

How are the elements stored till they can be reused?
Storage of the salvaged elements presented another significant challenge during the project. In this case, the Municipality of Leiden took on the responsibility for storing the materials. Finding a suitable location proved difficult, especially when approaching market parties, who typically charge market-conform prices. These costs often exceed available budgets, particularly in this project, where the time between demolition and new construction was nearly three years.

In addition to the financial aspect, long-term storage requires proper conservation measures to ensure the materials remain usable. This includes protecting elements such as concrete and steel from environmental degradation, which adds further complexity and cost. These logistical and preservation challenges highlight the importance of planning for storage early in the process when initiating circular demolition projects.

Were the goals in this project met and would you redo a project like this in the future?
The goals of the project were partially met. While the ambition was to achieve a high level of material reuse, several challenges limited the extent to which this was realized. For example, initial plans to reuse masonry and concrete columns had to be abandoned due to technical constraints and changing design requirements. Nevertheless, a significant number of elements, such as floor tiles, window sills, doors, and glass were successfully reused, and the project provided valuable insights into the practicalities of circular demolition.

From a financial perspective, the project exceeded its initial budget, which was a key concern, especially given the lack of subsidies. The municipality acknowledges that this project served as a learning experience and that future initiatives will likely take a more streamlined approach. For example, in upcoming projects like the demolition of the old social shelter and barracks. Meaning that it the investment in this project also functions as an investment in the future.

Despite the financial and logistical challenges, both Jan Hendrik Vos and Pieter van Leeuwen expressed that they would pursue circular demolition again, albeit with adjustments based on the lessons learned. The extend to which reuse was achieved in this project seems a bit too advanced for now. Meaning that it seems more reasonable to move towards a lower grade of reuse within the financial and time constraints.

D.3. Future vision and limitations

What innovation of collaboration could enable reuse on a larger scale?

There are several things learned from this project that could enable reuse on a larger scale:

- Early involvement of designers and builders: A key lesson from the project was the importance of involving architects and developers early in the process. If the design team is aware of the available reusable materials from the start, they can incorporate them directly into the new plans. This proactive approach allows for more targeted reuse and reduces the risk of materials being discarded due to incompatibility with later design choices.
- Regional material banks and databases: One major logistical challenge was the storage of salvaged materials. To address this, the interviewees suggested the creation of regional material banks, centralized locations where reusable materials can be stored and accessed by different projects. Additionally, a digital database of buildings scheduled for demolition could help developers identify potential sources of reusable materials in advance.
- Clear Certification and Verification Standards: Reuse is often hindered by uncertainty around the quality and compliance of salvaged materials. Developing standardized certification protocols for reused elements, especially structural components like concrete and steel, would help builders trust and adopt these materials more readily.
- Financial Incentives and Subsidies: The project was completed without specific subsidies for circular demolition, which added financial pressure. Future projects could benefit from government subsidies or tax incentives that offset the additional costs of reuse, storage, and testing. These incentives could make circular practices more attractive to developers and housing corporations. Specifically since the reuse of elements is still in the early stages more costs are being made for explorations that a lot of companies do not want to carry.
- Collaborations with social enterprises, such as DNZB in this project, enabled the processing and repurposing of materials like glass and wood. Expanding such partnerships could support both circular goals and social inclusion, especially when materials require manual handling or customization.

E Interview Bram Kroon - IDDS

Interviewee: Bram Kroon - Director IDDS
Date: 11/06/2025
The interview was originally conducted in Dutch. The following is a translated and edited version based on the original conversation. Due to setting of the interview, this is a reconstructed summary rather than a verbatim transcript.

E.1. General company information

Could you briefly introduce IDDS and your role within the circular construction industry?
IDDS is a research and consultancy firm specializing in area development, with a strong focus on demolition and construction advice. Since 2015, they have been actively involved in circular demolition practices. On average, they oversee around 30 demolition projects per yea r.Their expertise lies in identifying opportunities for material reuse, integrating circular strategies into project planning, and ensuring quality and compliance through certified material inventories.

Bram, the founder and director of IDDS Bouw- en Sloopmanagement, is a leading advisor in circular construction and demolition. Since May 2021, he has been steering the company through rapid changes in the construction and real estate sectors, driven by trends like circular economy, smart buildings, BIM, and regulatory shifts. Bram focuses on translating these innovations into practical, understandable solutions, helping clients adapt to evolving market demands and seize new opportunities in sustainable building practices.

How does the advise IDDS offers differ in circular demolition compared to traditional demolition
When IDDS approaches a demolition project, they don't just see a building to be torn down, they see a potential resource hub. Unlike traditional demolition, which often focuses on speed and cost-efficiency. The strategy IDDS uses to tackle a demolition project is as follows:

- Phase 1 - Research: The journey begins with a deep dive into the building and its surroundings. IDDS conducts a comprehensive inspection to identify hazardous substances like asbestos and chromium-6. They create a Sustainable Material Inventory (SMI), which maps out all materials that can potentially be reused. This phase also includes site-specific investigations, such as soil contamination, archaeological remains, and protected species, to ensure the demolition can proceed safely and responsibly. Since in traditional demolition all the element are treated as waste this step is not even considered. For this reason the planning stage in case of circular demolition is a lot longer than that of traditional demolition.
- Phase 2 - Preparation: Once the opportunities are clear, IDDS moves into the planning phase. They draft a circular demolition specification and a Health & Safety plan, along with cost estimates for both demolition and any additional work. They also assist in selecting a suitable contractor and coordinate utility disconnections. Permits are another key focus, IDDS handles everything from demolition permits to flora and fauna exemptions. To minimize disruption, they conduct stakeholder analyses and acoustic/vibration studies, and prepare monitoring and traffic plans.
- Phase 3 - Execution: During demolition, IDDS assigns a dedicated demolition manager who oversees quality, circularity, budget, and timeline. They lead demolition meetings, review execution plans, and adjust strategies as needed. An environmental manager monitors noise and vibrations to prevent damage or nuisance, and mitigation measures are applied in real time if necessary. At the end of the project, IDDS delivers a complete demolition dossier, including documentation of all circular practices and material reuse. In contrast, traditional demolition rarely includes such oversight or accountability, and materials are typically discarded without consideration for reuse. According to IDDS the oversight is a key succes factor, without this oversight the quality of the

material cannot be assured and it is often seen that the demolition company moves away from the predetermined practices due to the fact that they are used to minimizing cost and time.

E.2. Reuse in practice

When it comes to Stationsplein 107 specific how was IDDS involved in this project?
The municipality of Leiden, as the owner of the area, outsourced the development in parcels to housing corporation Portaal. As part of the development agreement, Portaal was required to reuse part of the existing building, in collaboration with construction company EraContour. This requirement introduced a circular dimension to the project, and IDDS was brought in to plan this proces with Witteveen+Bos and then guide and manage this process together with Portaal and EraContour.

The main thing IDDS was involved with in this project were:

- Material Inventory & Assessment: IDDS conducted a Sustainable Material Inventory (SMI) to identify reusable materials and assess their quality. This included both visual inspections and destructive testing, followed by material-specific studies to ensure that reused elements could meet the standards required for new construction. As part of the SMI they also focused on checks for hazardous substances, to ensure safe reuse and compliance with environmental regulations.
- Design Integration: IDDS worked closely with EraContour to understand their design plans and determine how salvaged materials could be integrated into the new construction. This required balancing reuse potential with architectural and structural requirements.
- IDDS also held an advisory role when it came to the permits. A huge problem with reused elements is the fact that these elements cannot be certified yet. For the permit process this forms an obstacle. In this case it was easier because the municipality was involved in the project, but in a lot of cases it is a factor that results in choosing different materials.

How did the collaboration work in this project and what is important in this collaboration to make a project a success?
In case of circular demolition there is an additional layer of collaboration. Rather than considering two separate project we have a demolition and construction project that must be lined up. The foundation for this collaboration has to be built around existing roles and responsibilities. In traditional practices this means that the demolition company is done after demolition is complete. This results in the fact that their interest of activities after this milestones are not as high, while the quality they deliver is now extra important in later stages. It is therefor important to have a party that is involved in the entire process form one building to the other. IDDS stepped in to guide the process from initiation to execution, ensuring that circular goals were embedded in every phase.

What could have been done better is the early-allignement in this case. While a lot of plans were made from the outset the contractor was involved too late, which meant that certain materials that could have been reused were not reused in a later stage.

E.3. Future visions and limitations

What do you see as innovations or opportunities that could help stimulate one-on-one reuse?
Currently, there are various fragmented market places for reclaimed materials. It would be beneficial if this would be a centralized database that could be integrated into a BIM environment. This would allow designers to:

- Browse available materials real-time
- Reserve specific components for future projects
- Integrate these materials directly into their design models

This would both streamline planning and make reuse a practical part of the design proces, rather than an after thought

Next to that there is an opportunity for suppliers. Some suppliers have already adopted a dual inventory of both new an reclaimed elements. Currently there is a key concern when it comes to supply reliability. If the suppliers already have stock at hand and can do the verification of these elements this concern can be limited. Contractors can count on consistent availability of materials, whether they choose new or reused options, making circular choices more viable and less risky.

Lastly, a more systematic approach to inventory will be beneficial in doing so we can ensure that the quality of these inventories is constant. It will become easier to integrate these inventories in the rest of the planning and execution when all of them are standardized and of high enough quality.

What are the main limitations that you see when it comes to reuse?
A recurring issue is that reused components, such as old beams, can often be structurally superior to new ones, yet they fail to meet current certification standards. Without a recognized quality mark or certification, these materials cannot be officially approved for reuse, even if their performance is demonstrably better. As a result, they are excluded from the construction process, not due to technical inadequacy, but due to regulatory constraints.

This creates a paradox: materials that are perfectly suitable and sustainable are rejected simply because they lack formal documentation. The acceptance of reused materials hinges on the ability to prove their quality and compliance, which is currently a complex and often costly process.

To overcome this limitation, IDDS emphasizes the need to:

- Simplify and standardize the verification process for reused materials.
- Develop accessible certification pathways that allow older components to be tested and approved without excessive bureaucracy.
- Encourage regulatory bodies to recognize alternative forms of proof, such as material testing and historical performance data.

F Interview Maartje Dijk - Witteveen+Bos

Interviewee: Maartje Dijk - Structural Engineer - Witteveen+Bos
Date: 05/06/2025
The interview was originally conducted in Dutch. The following is a translated and edited version based on the original conversation. Due to setting of the interview, this is a reconstructed summary rather than a verbatim transcript.

F.1. General Company information

Can you tell something about the role of Witteveen+Bos in the project Stationsplein Leiden 107
Witteveen+Bos played a key advisory role in the demolition phase of the project. Their responsibilities included drafting the demolition specifications, conducting a thorough inventory of reusable elements, and identifying how these elements could be reused. They also collaborated closely with the future developer of the site and engaged with suppliers to explore possibilities for processing and adapting the salvaged elements.

Maartje Dijk was involved in this project as a Structural Engineer. An important aspect of demolition for reuse is to ensure the structural characteristics of an element throughout the harvesting process and the storage. The elements will be exposed to different loads than they were initially calculated for example during hosting the elements will need to be able to carry their self weight without supporting beams. During storage the elements are often stacked on top of each other and we must look into how the elements can be stacked without compromising the structural integrity.

F.2. Reuse in practice

What preparatory studies were conducted before the demolition began?
What preparatory studies were conducted before the demolition began? A comprehensive material inventory was carried out, documenting each material type and detailing how it should be stored and handled. This included specifications on stacking height, dimensions, and protective measures. Concrete quality was assessed through targeted testing to ensure suitability for reuse.

Visual inspections were conducted, and sample pieces were extracted for analysis. All findings were compiled into a detailed spreadsheet, listing quantities, destinations, demolition costs, and new construction costs. Additionally, a scoring system was developed for materials without a predefined destination, allowing contractors to earn higher scores by proposing reuse solutions during the tender process.

What elements were considered for reuse and how would they be repurposed?
Several elements were explored. Initially, there were plans to reuse the structural columns, but these were ultimately deemed unnecessary for the new design. Attempts to repurpose them independently were unsuccessful. The floor slabs, however, were successfully reused as ground-level flooring, even though they were overdimensioned. They were carefully cut out between the beams for reuse. Maartje Dijk provided structural input to ensure that the reused slabs met safety and performance standards in their new application.

How did collaboration between the various parties (contractor, client, advisors, etc.) unfold?
The demolition advisor was not involved during the construction phase due to procurement regulations. As a result, collaboration with the contractor was managed through the construction advisor. A cooperative client was essential to bring all parties together. The municipality of Leiden played a crucial role

by including a clause in the contract requiring the new developer to use reclaimed materials. This was vital, as there is often resistance to using reused components. The challenge was further compounded by the fact that the design process of the new development was still underway while the demolition specifications had to be finalized. Coordinating multiple overlapping projects proved to be complex.

F.3. Learning points and limitations

What were the biggest challenges during the initiation and advisory phase?
One of the main challenges was convincing potential recipients to commit to using reclaimed materials. It's often easier to purchase new materials, which means the design must be adapted to fit the dimensions and quality of the reused elements. There was also uncertainty about the long-term durability of the materials, requiring additional testing to ensure they could last another 50 years.

What were the lessons learned in this project and what would you have done differently?
Successful reuse hinges on strong collaboration and careful alignment of project timelines. This is especially important when suppliers do not maintain stock of reclaimed materials. Planning and communication are critical to ensure materials are available when needed.

One lesson learned is the importance of paying extra attention to reinforcement bars during storage. These can sometimes be misaligned and pose safety risks, especially when cut lengthwise. Temporary conservation measures should be improved to ensure safety and material integrity. It's also unfortunate that the columns couldn't be reused. In future projects, it would be beneficial to develop reuse plans earlier for materials that don't yet have a designated destination.

G Interview Victor Moura en Marco Theunissen - Gemeente Kerkrade

Interviewee: Victor Moura en Marco Theunissen - Gemeente Kerkrade
Date: 26/06/2025
The interview was originally conducted in Dutch. The following is a translated and edited version based on the original conversation. Due to setting of the interview, this is a reconstructed summary rather than a verbatim transcript.

G.1. General company information

Can you briefly introduce yourself and the organization? We work for the Municipality of Kerkrade, which was one of the core partners in the SuperLocal project. Within this collaboration, the municipality was responsible for spatial planning, permitting, and coordination between the different partners. SuperLocal was established as a circular neighborhood redevelopment in the district of Bleijerheide, in collaboration with the housing association HEEMwonen and various knowledge and market partners. The project was co-funded by the European Urban Innovative Actions (UIA) program and served as an experimental case for circular area development in the Netherlands.

What was your role within the SuperLocal project? The municipality took the lead in coordinating planning procedures and aligning the different construction and demolition processes. We ensured that activities remained compliant with local regulations and that the various stakeholders, ranging from construction firms to residents, were engaged throughout the process. In addition, we were responsible for managing the overall communication with the community and facilitating citizen participation.

G.2. Reuse in Practice

What was the reason to use a circular approach instead of traditional methods? The initiative came primarily from the housing corporation HEEMwonen, who wanted to explore more sustainable and future-oriented ways of building. Together with IBA Parkstad, they proposed to go beyond a conventional demolition and new-build process and to treat the site as a testing ground for circular construction. The contractor Dusseldorp was willing to participate and experiment with alternative techniques.

At the same time, the flats in Bleijerheide had been vacant for some time, leading to vandalism and nuisance in the area. Redevelopment therefore addressed both a social and a physical challenge. Applying circular methods allowed the partners to turn a local problem into an innovative opportunity.

What other reasons or ambitions played a role? A key motivation was to explore how we should build in the future, more modular, adaptable, and resource-efficient. The project focused not only on reusing building elements but also on testing modular construction methods that could make future reuse easier.

In the public space, a significant amount of residual material from the demolished flats was reused. Even concrete rubble and steel elements were repurposed locally. In addition, an experimental closed water system was tested: water was collected, stored, and reused within the site. Although this worked technically, it had limited added value in the Dutch context because re-injecting treated water into the ground is not permitted.

How was the collaboration organized between partners? In total, twelve partners participated in the project, each contributing specific knowledge or expertise. The collaboration's success depended heavily on the people involved, their motivation and openness to experiment. The key partners maintained regular contact, while the broader group convened periodically at both the administrative and technical levels, as required by the EU funding conditions.

How did you involve the local community? Public participation is a legal requirement in Kerkrade, but for SuperLocal it was also a moral one. We established a residents' advisory board that met every six weeks to discuss progress, share concerns, and provide input. This helped maintain trust and transparency despite the extended construction period and associated noise and dust nuisance.

G.3. Future vision and challenges

Do you take the lessons learned into new projects, and do you intend to implement this more often? Without subsidies, a project like SuperLocal would not have been feasible. Circular construction is still expensive compared to traditional methods. Therefore, we see circularity as an important learning step rather than a standard practice for now. However, modular building has proven successful, and we are investing more in this direction, about 60% of the new housing stock developed by HEEMwonen now follows modular construction principles.

What do you see as the biggest challenge and the biggest opportunity for reuse in the demolition sector? One of the biggest challenges is that drawings and reality often differ. Buildings are rarely constructed exactly as documented, which complicates selective demolition and reuse. We also found that producing recycled concrete directly on-site was unfeasible, the quality and homogeneity of the mixture could only be guaranteed in a controlled central plant.

From a financial perspective, as long as new materials remain cheaper than reclaimed ones, large-scale reuse will be difficult to justify without subsidies. Circular construction is therefore still strongly dependent on policy support.

However, there are clear opportunities as well. Modular and timber construction methods are much easier to reuse and adapt. For concrete, the key is to design buildings in such a way that elements can be removed without major damage. In the longer term, material innovations, such as adding polymers to improve recyclability may also help.

What kind of innovations or collaborations could make reuse more widespread? To make reuse scalable, the sector needs new types of partnerships that integrate demolition, design, and construction. Designers must understand how elements are dismantled, and contractors must plan with reuse in mind. Regulations also need to become more flexible, allowing room for experimentation while maintaining safety and quality.

How do you perceive the social dimension of circular projects like SuperLocal? SuperLocal did not only focus on materials but also on people. Residents had to "apply" for the new dwellings, demonstrating their motivation to live in a sustainable home. This created awareness and community engagement. It shows that circularity is not only a technical challenge but also a social one. It requires changing how people think about housing and consumption.

H Interview - Roderik Outhuis - ERA Contour

Interviewee: Roderik Outhuis - ERA Contour
Date: 04/09/2025
The interview was originally conducted in Dutch. The following is a translated and edited version based on the original conversation. Due to setting of the interview, this is a reconstructed summary rather than a verbatim transcript.

H.1. General company information

Can you briefly introduce your organization in the context of circular construction?
ERA Contour acts as both developer and builder. For each project, it is essential that the financial, contractual, and technical aspects are in order. Circularity and sustainability are relatively new themes within the organization but align closely with its ambitions as a B Corp. The main focus is on reducing CO_2 emissions throughout the entire construction process: from raw material extraction to on-site implementation. Circularity is seen as an important means to achieve this reduction.

What is your role in circular projects such as Station Square Leiden?
The interviewee represents ERA Contour in project development and works closely with the realization department. From the very beginning, he was actively involved in identifying and selecting reusable materials and coordinating collaboration with partners such as architects, the municipality, and demolition companies.

What ambitions does your organization have regarding circularity and material reuse?
ERA Contour focuses primarily on measurable CO_2 reduction. Projects are assessed against the Paris Proof indicator (target value: 350 kg CO_2/m^2 GFA), and the goal is always to achieve at least 10% less emissions. Key emission sources such as concrete structures, brick facades, and technical installations are analyzed. Circularity is considered a valuable tool to achieve this goal, although it remains a complex and challenging field.

Does your organization have specific guidelines or policies for the reuse of building materials?
Formal policy is still in development. However, there is a clear internal focus on CO_2 reduction, with reuse considered an integral part of this strategy. Each project is assessed to determine which materials can be harvested and how they can be integrated.

H.2. Reuse in Practice

What made Station Square Leiden suitable for a circular approach?
Circular ambitions were embedded in the project from the outset, strongly encouraged by the municipality. Although the team initially had little experience, their enthusiasm quickly grew. The belief that reuse directly contributes to CO_2 reduction motivated the project team to fully embrace the challenge.

Which materials were reused in this project, and where did they come from?
The existing building supplied various reusable elements, including:

- window sills,
- natural stone frames,
- green natural stone facade cladding,
- floor tiles,

- insulation material from interior walls.

One notable example is 1,000 m^2 of insulation material that could be directly applied to another ERA project, avoiding costly storage.

How did the collaboration with designers, the municipality, and demolition companies proceed?
Collaboration was characterized by enthusiasm, but also by process misalignments. Design and demolition processes were not synchronized: designers needed early information, while detailed data on salvaged materials only became available later. The municipality set ambitious goals, but technical and financial feasibility required careful balancing. Although intentions were aligned, process coordination proved to be a major challenge.

What were the main challenges in applying reused elements?

- *Process coordination:* information on salvaged materials often came too late to be integrated into the design.
- *Storage and logistics:* materials sometimes had to be stored for years, creating cost and risk issues.
- *Technical assurance:* guarantees for fire safety, acoustics, and compliance with building codes were mandatory.
- *Cost estimation:* there is little market experience in pricing and processing second-hand building materials, leading to uncertainty in budgeting.

Do you believe such circular projects can be economically viable in urban areas?
Yes, provided the sector continues to professionalize. Enthusiasm and intrinsic motivation are essential, but the market must mature in terms of experience and standardization. Reuse of materials can certainly be viable, but requires improved processes and broader acceptance from clients and investors.

How do you ensure quality assurance for reused elements?
Quality and safety are non-negotiable. Every reused element must comply with building codes and relevant certifications. ERA Contour only applies reused materials if guarantees can be provided for structural safety, fire resistance, and acoustics. This often requires additional verification and close consultation with developers and investors.

H.3. Future Vision & Challenges

Which innovations or policy changes are needed to enable reuse on a larger scale?
The interviewee highlighted several needs:

- Better process alignment between demolition, design, and new construction to ensure timely access to reliable material data.
- A stronger role for demolition companies and harvesting managers, as they know the market and can organize supply chains.
- Standardization of inventory methods, storage logistics, and pricing of reused materials to build confidence.
- Market development to create broader availability of reused materials, similar to “second-hand building markets” for large components.

Do you see opportunities for standardization or collaboration within the sector to accelerate circularity?
Yes, collaboration is crucial. Municipalities, designers, contractors, and demolition companies must align their processes more effectively. Sector-wide standardization in data exchange, product certification, and market mechanisms for reused materials would significantly accelerate scaling up.

Interview - Marcel Vullings - TNO

Interviewee: Marcel VUllings - TNO
Date: 01/07/2025
The interview was originally conducted in Dutch. The following is a translated and edited version based on the original conversation. Due to setting of the interview, this is a reconstructed summary rather than a verbatim transcript.

I.1. General company information

Could you briefly explain your role at TNO and how your work contributes to circular construction? I work at TNO as a specialist in prefabrication, sustainability, and reuse. My research focuses on developing methods and protocols that enable precast concrete elements to be reused safely and efficiently in new structures. The aim is to contribute to circular construction by reducing material, energy, and CO□ consumption and by making dismantling and reuse strategies technically and economically viable.

How does TNO collaborate with demolition contractors, designers, and builders to test or implement these connection methods? TNO works in close collaboration with partners across the entire value chain. In projects such as ReCreate, demolition companies, precast producers, and design engineers jointly test connection concepts in pilot cases. Together they develop documentation procedures, test setups, and digital tools such as BIM-based pre-demolition audits. These collaborations allow knowledge from practical experiments to be translated into standardized protocols and guidelines that industry can apply more broadly.

I.2. Reuse in practice

How do the requirements differ between reused and new elements? The formal performance requirements, strength, safety, and serviceability, are the same, but reused elements introduce additional uncertainties. Documentation from the original production is often incomplete, so supplementary inspection, testing, or recalculation is needed. The design must also account for disassembly and repeated use, which is not standard in conventional construction. Furthermore, there is no harmonized certification system for reused elements, which makes uniform quality assurance more difficult.

How is the quality and safety of reused elements ensured? Quality control relies heavily on documentation and verification:

- First, the original product data, drawings, and calculations are reviewed and compared to the actual state of the element.
- Visual inspections assess whether the element matches its expected geometry and whether any observed damage is structural.
- Structural verification is done through recalculation, often based on the original design but updated to current safety standards.
- Structural verification is done through recalculation, often based on the original design but updated to current safety standards.
- Documentation confirming that the element can safely carry the intended loads is essential; this forms the basis for re-certification.
- Finally, verification must be performed by an independent control body. Because reuse is still a

developing field, improvisation is sometimes needed, but always in consultation with the supervising authority.

Is there a need for new standards or certification systems for these elements? Yes, definitely. There is a clear need for:

- Standards that specifically address reuse and demountable connections for concrete elements.
- Certification schemes that recognize reused components as legitimate construction products.
- Harmonized guidelines that consider both technical verification and practical issues like dismantling, storage, and transport. The recently published CROW-CUR Guideline 4 (2023) for precast concrete reuse is a first step, but further development is needed for other element types and connection categories.

I.3. Future Vision & Challenges

Which innovations do you consider most promising for improving connection methods in reuse? Promising directions include:

- Dry, mechanical connectors that allow reversible assembly without damaging the concrete.
- Use of high-performance grouts or fiber-reinforced overlays to restore anchorage.
- Integration of digital inspection tools, such as 3D scanning and embedded sensors, for monitoring and documentation.
- Hybrid or modular systems that combine reused concrete with steel or timber structures to increase flexibility.

How can digital tools (such as BIM or material passports) support better use of reusable connections?

- BIM-based audits before demolition can identify which elements are suitable for reuse and how they can be connected.
- Material passports record the element's history, mechanical properties, and test data, providing traceability and confidence for engineers.
- By linking this information to design models, contractors can integrate reused components more efficiently into new projects and plan logistics.

Which policy measures or market developments could accelerate reuse ?

- Financial incentives or subsidies to compensate for the additional costs of reuse.
- Updated regulations and certification schemes that explicitly allow reused elements and demountable connections.
- Standardization of testing and documentation protocols to build trust in reused components.
- Greater transparency in cost–benefit analyses so that clients can see the environmental and economic value of circular construction choices.

J Interview - John Hijma - NACO

Interviewee: John Hijma - NACO
Date: 10/11/2025
The interview was originally conducted in Dutch. The following is a translated version based on the original correspondence. Mind that the pupose of this interview was for the verification model which is why the build up of the interview is different from the previous interviews

J.1. Relevance

1.1 Do the communication and coordination issues described in the framework align with your own experience in airport developments?

Yes, communication and coordination problems often stem from a lack of knowledge and clear agreements about roles and responsibilities, especially in circular construction and the reuse of materials.

1.2 In which project phase (planning, design, procurement, execution, operation) would this framework provide the greatest added value in your view?

The framework adds value in all phases, as circular construction is based on collaboration. However, it is crucial to establish a solid foundation during the initiation or planning phase. The definition and safeguarding of roles in this phase are decisive for success. Ideally, this should be initiated by the client.

J.2. Comprehensibility

2.1 Is the six-phase structure of the framework (Initiation → End-of-Life) clear and easy to follow from a practical perspective?

Yes, the structure is clear and aligns well with common project phases and contract forms. A detailed description of the roles per stakeholder would make the framework even stronger. The phases related to procurement and handover are particularly valuable additions.

2.2 Are the terms used, such as *Reuse Communication Plan*, *Verification Dossier*, and *Integrated Reuse Dossier*, clear and relevant within your field?

The terms are new, and if they are to be introduced as standard, a good explanation is essential. Within circular construction, many terms are already in use, so additional clarification is desirable, especially for less experienced stakeholders. It is not entirely clear whether the Reuse Communication Plan and the Verification Dossier together form the Integrated Reuse Dossier. This deserves further clarification.

J.3. Completeness

3.1 Do you feel that the framework covers all essential phases and roles in a reuse project (client, engineer, contractor, STA, asset management, regulatory authorities)?

The framework is indeed comprehensive and mentions the key roles. Additionally, transport or logistics providers could also be included, for instance as temporary storage operators. It is recommended to select contractors and other involved parties based on their experience with reuse.

Furthermore, some roles are only temporarily or partially involved in a project. It is important to contractually define under which party they fall, the client, contractor, consultancy, architect, structural engineer, government, or an independent body. A crucial point in the process is the transition from design/specification to execution, where role responsibilities could also be transferred.

3.2 Are there any important processes or actors you feel should be added or clarified?

See above.

J.4. Usability

4.1 Do you think this framework could help improve collaboration and information exchange between disciplines in projects such as the C-pier?

Yes, provided that the points mentioned under item 6 are taken into account. It is also important to define who manages the reports and dossiers between the different phases.

The framework generates a large number of documents, such as: Reuse Communication Plan (RCP), Preliminary Verification Plan, Circularity Performance Framework, Integrated Master Schedule, BIM Model, Verification Dossier, Design Verification Report, Design Review Minutes, Handover Package, Material Transfer Register, Storage & Logistics Plan, Installation Verification Report, Construction Quality Log, Safety & Compliance File, Integrated Reuse Dossier (IRD), Asset Information Model (AIM), Maintenance & Inspection Plan (MIP), Performance Review Report, Updated Material Passport Set, Residual Performance Assessment Report, Selective Deconstruction Plan, Continuity of Passport Records, and Lessons-Learned Summary.

The framework is certainly helpful, but it should also indicate how the information flow is organized and which information carriers are used. This will make data exchange easier.

4.2 Do you expect that it could help prevent misunderstandings, duplicate work, or delays in verification and documentation?

Yes, provided that reporting is done clearly and in plain language. A recommendation would be to limit the number of documents to what is truly necessary.

J.5. Expected Impact

5.1 Do you think this framework will contribute to achieving Schiphol's circularity goals (e.g., BCI ≥ 60%, improved traceability, and lower environmental impact)?

Yes, the framework will certainly support achieving circularity goals, especially in projects where structural elements such as slabs are reused. The structural domain has the greatest influence on the BCI score.

5.2 Do you think applying such a framework could help normalize reuse in future airport projects?

Yes, provided that all stakeholders are properly informed about the framework. Pilot projects could play an important role in this process.

J.6. Reflection

6.1 Are there any moments or lessons from previous projects (such as the A-pier or New Terminal) where such a framework would have been useful?

Unfortunately, I was not involved in the A-pier or Terminal-South projects, but in other large-scale Schiphol developments. However, I am convinced that the framework can make the reuse of concrete elements more accessible and discussable, and that it can help remove barriers, particularly in the verification process.

6.2 Do you have recommendations to make the framework more applicable within Schiphol's existing project procedures?

Yes. Setting up a material passport process is already a challenge at Schiphol. The success of the framework depends largely on the client. It would help if the framework were widely supported and served as a guiding document for the process. Commitment from all stakeholders is essential. Linking the framework to sustainability KPIs or demonstrable cost savings compared to new concrete slabs could also increase its applicability.

Additional recommendations:

Pay more attention to the storage location. “Within the same airside zone” is not always feasible. Landside construction is often simpler and should be included as an option in the framework. In the early phase, make a quick assessment of the key criteria and potential benefits (CAPEX, CO_2 emissions). When minimal interventions are needed, this will speed up the process. However, if each phase requires extensive effort, it may slow things down. Indicate which criteria within the framework are most important to create focus.

K Interview - Alina Heemstra - NACO

Interviewee: Alina Heemstra - NACO
Date: 01/12/2025
The interview was originally conducted in Dutch. The following is a translated version based on the original correspondence. Mind that the pupose of this interview was for the verification model which is why the build up of the interview is different from the previous interviews

K.1. Relevance

1.1 Do the communication and coordination issues described in the framework align with your own experience in airport developments?

Yes. In the circular pilot project *Doorlaatpost 90*, Urban Mining was applied using a direct donor building (Path A). Materials released during the demolition of nearby warehouses were reused in the new security post, including structural steel beams, lighting, pantry components, doors, window frames, and other elements. These materials were stored for an extended period in BAM's material hub, almost three years, partly due to COVID-19 delays. In hindsight, this long-term storage proved inefficient and costly.

What worked well, however, was that the architect could determine in advance which elements would be reused. This allowed the materials to be integrated directly into the design without requiring last-minute adjustments.

1.2 In which project phase (planning, design, procurement, execution, operation) would this framework provide the greatest added value in your view?

The framework, as structured, can be applied across all phases, which aligns with experience in circular projects. The reuse ambition must already be present in the initiation phase; it is extremely difficult, almost impossible, to introduce circular measures late in the design process without major redesign implications.

Her experience confirms the relevance of the steps emphasised in the framework:

- **Initiation & Planning** – establishing ambitions, roles, and communication structures. This phase determines the project's circular potential.
- **Design & Engineering** – translating verified data into design decisions. If ambitions are unclear, incorporating reuse later becomes challenging. Early BCI calculations and design-for-disassembly choices influence later phases.
- **Procurement & Handover** – transferring harvested elements and data. Urban Mining elements must be identified early to avoid delays if dimensions or quality do not match expectations.
- **Construction & Assembly** – installation of reused elements and updating of as-built information.
- **Operation & Maintenance** – ensuring correct use and maintenance so materials retain their reuse potential.
- **End-of-Life & Deconstruction** – preparation for future reuse; buildings designed with high BCI scores allow significantly more circular harvesting.

K.2. Comprehensibility

2.1 Is the six-phase structure of the framework (Initiation → End-of-Life) clear and easy to follow from a practical perspective?

Yes, the framework is clear and functions as a practical guide. However, each phase should define its expected products and agreements more explicitly:

- What is the expected result per phase?
- Which outcomes are required?
- How is it ensured that Urban Mining elements are actually integrated?
- Who carries responsibility in each phase?
- How are risks handled (e.g. when harvested elements prove unsuitable)?

2.2 Are the terms used, such as *Reuse Communication Plan*, *Verification Dossier*, and *Integrated Reuse Dossier* clear and relevant within your field?

Yes, the terminology is sufficiently understandable and relevant.

K.3. Completeness

3.1 Do you feel that the framework covers all essential phases and roles in a reuse project (client, engineer, contractor, STA, asset management, regulatory authorities)?

Yes, the framework is well developed. She questions whether the matrix also assists in choosing between Path A and Path B, or whether this decision lies solely with the client. She also emphasises the importance of explicitly including the role of the circular demolisher and the material hub, as these parties can strongly influence the choice between Path A and Path B.

3.2 Are there any important processes or actors you feel should be added or clarified?

Suppliers who take back materials should also be included. These actors form an increasingly important part of the Urban Mining chain. The sector is still largely in an experimental phase, and such roles should be integrated to prepare for future standardisation.

K.4. Usability

4.1 Do you think this framework could help improve collaboration and information exchange between disciplines in projects such as the C-pier?

Yes. It provides a clear guide showing how Urban Mining can be integrated throughout the project processes and can help improve interdisciplinary collaboration.

4.2 Do you expect that it could help prevent misunderstandings, duplicate work, or delays in verification and documentation?

Yes, provided that clear agreements are established between all parties. The framework can structure the process and make the role of Urban Mining within the project more transparent.

K.5. Expected Impact

5.1 Do you think this framework will contribute to achieving Schiphol's circularity goals (e.g., BCI ≥ 60%, improved traceability, and lower environmental impact)?

Yes, assuming it is applied consistently.

5.2 Do you think applying such a framework could help normalize reuse in future airport projects?

Yes. As with other innovations, successful pilot projects will help the framework become more common practice.

K.6. Reflection

6.1 Are there any moments or lessons from previous projects (such as the A-pier or New Terminal) where such a framework would have been useful?

Yes. In the *Doorlaatpost 90* project, the process was still very innovative, and parties involved had limited experience. A framework like this would have helped provide structure and clarity.

6.2 Do you have recommendations to make the framework more applicable within Schiphol's existing project procedures?

She suggests developing the framework into an online tool or platform where parties can view process steps, contribute information, and access:

- project data,
- Urban Mining requirements,
- intended elements for reuse,
- disassembly guidelines,
- and other relevant documentation.

Such a tool would increase insight, usability, and collaboration.