



The Role of Lighthouse Projects in Socio-Technical Transitions: Analysing Empa's NEST Building and its Impacts on the Decarbonisation of the Swiss Construction Sector.

GEO 511 Master's Thesis

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(Braun, 2018)

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Abstract

The ongoing climate crisis requires rapid decarbonisation of Switzerland's construction sector. Within this sector, innovative solutions and applications are crucial for enabling a wider transition. This master's thesis examines the role of lighthouse projects (LHs) in advancing socio-technical change, using Empa's NEST building as a case study. The thesis aims to provide empirical insights into transition studies by analysing how LHs contribute to transformation in carbon-intensive sectors, focusing on the four key system resources (knowledge and technology development, market formation, investment mobilisation, legitimisation). Additionally, the thesis explores the geographical influence of LHs (from local to global levels) and identifies mechanisms that support or hinder the broader dissemination of innovative solutions. Drawing on multi-system interaction (MSI) literature, it further investigates how LHs foster the development of cross-sectoral networks.

Methodologically, the research is based on fifteen semi-structured expert interviews with actors involved in the planning, construction, and operation of NEST. The findings demonstrate that NEST functions as a collaborative and interdisciplinary site that links research, industry, architecture, planning, and public authorities. It facilitates knowledge exchange, experimentation with novel materials and technologies, and the development of new partnerships. At the same time, persistent sectoral lock-ins, fragmented value chains, and regulatory constraints restrict wider adoption outside the LH environment. Geographically, NEST has impacts across multiple scales: it supports local implementation while contributing to the global circulation of ideas, technologies, and expertise.

The thesis contributes to transition studies by illustrating that LHs function as spatially rooted yet globally connected experimental spaces that link socio-technical systems. It demonstrates how intermediaries such as integrators or spin-offs facilitate the transfer of ideas, practices, and technologies across local and international networks. Furthermore, it underscores that the success of LHs relies not only on technological innovation but also on their capacity to navigate regulatory frameworks, mobilise diverse actors, and embed solutions within place-specific contexts.

Future research could further explore how interactions between subsystems – technological, institutional, economic, and spatial – influence decarbonisation pathways. Particularly, studying LH as a site of interactions could deepen understanding of how local experimental platforms contribute to broader socio-technical transitions.

Keywords: Lighthouse Projects, NEST, Transitions, Construction, Switzerland, Decarbonisation

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Glossary

CE	Circular Economy
Decarbonisation	The process of reducing carbon dioxide emissions to a minimum.
Eawag	Aquatic Research Institutes. Focuses on natural, engineering, and social sciences – part of the ETH Domain.
Empa	Materials and Technology Research. Searching for interdisciplinary solutions to significant challenges faced by industry. Part of the ETH Domain.
GHG	Greenhouse gas emission
HiLo	“High Performance - Low Emissions” Unit
LH(s)	Lighthouse project(s)
MLP	Multi-level perspective
MSI	Multi-system interactions
NEST	Modular research and innovation building of Empa and Eawag in Dübendorf (Switzerland) stands for “Next Evolution in Sustainable Building Technologies”
NZ	Net Zero. Goal of decreasing carbon emissions to a minimum
PDP(s)	Pilot and Demonstration Project(s)
Recycling	Processing of materials to maintain as much of the same (high) quality as possible and to return them into the material cycle (Swiss Recycle, 2025).
Reuse	Reuse of decommissioned product that is still in good condition and fulfils its original function by another user or for a different purpose (Swiss Recycle, 2025).
UMAR	“Urban Mining and Recycling” unit

1 Introduction

1.1 Relevance

Ongoing climate change is among the greatest threats to our environment and to our economic and social prosperity (OECD, 2025, p. 5). 2024 was not only the “warmest [year] on record” but also the first to surpass the average global temperature by 1.5 °C above pre-industrial levels (OECD, 2025, p. 5). One of the most significant contributors to climate change and other negative environmental impacts is the built environment (Wieser et al., 2019, p. 2). Globally, the construction sector accounts for 34% of greenhouse gas emissions, making it one of the largest emitters of greenhouse gas emissions (GHGs). Moreover, the sector consumes 34% of the world’s available energy (Li et al., 2025; Nweye et al., 2022; United Nations Environment Programme, 2025, p. 13).

In Switzerland, the ‘building sector’ alone is responsible for nearly a quarter of the country’s total domestic greenhouse gas emissions (22.2% in 2022) (Bundesamt für Umwelt BAFU, 2025; Richner, 2024). The overall CO₂ emissions from building and construction reached a new high in 2022, putting the entire sector off track for quick decarbonisation by 2050 (Rukikaire & Loran, 2022). However, Switzerland ratified the Paris Agreement in 2015, committing itself to limiting global warming to 1.5 °C above pre-industrial levels (Bundesamt für Meteorologie und Klimatologie MeteoSchweiz, n.d.; Federal Office for the Environment FOEN, 2024; United Nations, n.d.). Moreover, national climate policies in Switzerland include regulations for decarbonisation, such as CO₂ laws (e.g., the “CO₂ Gesetz” or “Klimaschutz-Gesetz”), funding, and action plans (Der Bundesrat, 2021, pp. 19–24). Consequently, the long-term political aim is to achieve net-zero carbon emissions by 2050 (Bundesamt für Meteorologie und Klimatologie MeteoSchweiz, n.d.). Accordingly, within the next 25 years, hard-to-decarbonise sectors with high emissions, such as construction, face a significant challenge in reducing their greenhouse gas emissions to zero.

Innovative and transformative solutions are urgently needed to fundamentally reshape the construction sector. Key strategies discussed include circular construction, reuse and recycling of materials, modular and prefabricated building methods, and the use of low-carbon or alternative materials (Adams et al., 2019; cemsuisse, 2024, p. 24). However, the sector is regarded as risk-averse and is only gradually shifting (see Harty, 2008; Mazzoni & Losacker, 2024).

1.2 Aim of Thesis and Research Questions

Given the slow pace of transition in the construction sector, achieving socio-technical transformation towards decarbonisation is considerable; however, identifying potential pathways for such a transition is difficult (Habert et al., 2020). This thesis aims to analyse an experimental space where innovation is taking place (the lighthouse, LH) and to explore how such a space might influence broader transformation (here: decarbonisation) in a hard-to-decarbonise sector like construction. For this, a socio-technical perspective is applied, drawing on approaches from transition studies. Using a Geography of Sustainability Transition (GeoST) framework, particular attention is paid to the spatially differentiated impacts of lighthouse projects on transitions, their multi-system interactions, and their role within innovation systems.

The concept of lighthouse projects analyses innovative solutions within a protected space. By developing novel and ground-breaking material or technical solutions, these projects aim to fundamentally transform their respective sectors towards more ‘sustainable’ practices. The predefined space of the lighthouse fosters ideas in a protected environment, serving as an exemplary and pioneering role for others to follow or draw inspiration from (Schelbert et al., 2023; von Wirth et al., 2019). In this sense, the concept of LHs offers a unique opportunity to demonstrate how innovative technologies and materials can be implemented within a broader industry context. Additional approaches from innovation studies enhance our understanding of the relationships among various actors involved in

exploring novel and experimental technologies and materials. Furthermore, considering sectoral connections helps to capture the spatial influence of a particular LH (Schelbert et al., 2023). Adopting a multi-system interactions (MSI) perspective further enables an analysis of the intersections between multiple actors and networks engaged in the ongoing transition.

In sum, the lighthouse concept serves as a tool for understanding how breakthrough innovations diffuse and contribute to wider decarbonisation. Despite growing interest in the role of lighthouse projects in transitions research (Hellsmark et al., 2016; Schelbert et al., 2023; Sjö & Frishammar, 2019), considerable gaps remain regarding the mechanisms by which they can enable broader systemic change. In particular, the geographical impact (de “Leuchtkraft”) as well as their capacity to connect actors across sectors have not yet been sufficiently explored. Examining the spatial dimensions of LHs, therefore, provides valuable insights into how they mobilise actors and shape sectoral transitions. Moreover, empirical research on lighthouse projects remains limited, especially within hard-to-abate sectors such as construction.

This thesis addresses these research gaps by analysing Empa¹’s NEST building and its role in decarbonising the Swiss construction sector. NEST, short for “Next Evolution in Sustainable Building Technologies”, is a modular and interactive research and demonstration platform located in Dübendorf (ZH), Switzerland. It functions as a “construction playground”, where research and industry actors collaboratively develop, test, and showcase solutions (Richner et al., 2018; Züst, 2024, pp. 3–4). The analysis focuses on three of NEST’s eleven units: UMAR², Sprint, and HiLo³, which explore circular construction practices (UMAR and Sprint) and advanced manufacturing/energy- and resource-saving construction technologies (HiLo) (Empa, n.d.-b; Sobek, n.d.).

As a lighthouse project at the intersection of research, industry, and practice, NEST serves as a testing ground for novel, innovative, and low-carbon solutions, implementing, evaluating, and showcasing them. By examining NEST’s geographical reach, its potential for commercialisation and upscaling, and its role in fostering cross-sectoral networks, this thesis explores the contributions and limitations of the lighthouse projects as catalysts for sectoral decarbonisation. Through qualitative interviews with key actors, it investigates how NEST supports network building, cross-sectoral integration, and collaboration, and how these dynamics contribute to broader transitions.

The following three research questions are intended to address the identified research gap and to provide guidance on the focus of this master’s thesis. First, the role of lighthouse projects in transforming carbon-intensive sectors is called into question, as are the four system resources (knowledge development, market formation, investment mobilisation, and legitimacy). The contributions and limitations of LHs to transitions are examined in two sub-questions.

- RQ1) What role do lighthouse projects play in the socio-technical transformation of carbon-intensive sectors?
- a. How do lighthouse projects like NEST contribute to mobilising key system resources for innovation (knowledge development, market formation, investment mobilisation, or legitimacy)? What are the limitations?

The second research question focuses on the spatial impact of LHs. It explores their impact on a geographical scale (regional/national and international). Furthermore, the question of who and where the solutions diffuse and scale to is asked.

- RQ2) What is the geographical reach of the impact of activities conducted in a lighthouse project?
- a. How far and where do the solutions in the LH scale and diffuse?

¹ Empa (German Eidgenössische Materialprüfungs- und Forschungsanstalt) is the Swiss Federal Laboratories for Materials Science and Technology (Empa, n.d.-a).

² UMAR stands for “Urban Mining And Recycling”.

³ HiLo stands for “High performance, Low emissions”.

- b. What mechanisms support or hinder the broader diffusion of solutions developed in lighthouse projects?

The third research question examines how lighthouse projects enable novel connections across sectoral boundaries. This question aims to identify the actors involved in this novel combination and to highlight the challenges associated with building a LH.

- RQ3) To what extent do lighthouse projects facilitate the formation of cross-sector networks?
- a. Who are the actors that are part of these novel combinations?
 - b. How does a lighthouse project like NEST bring together actors from construction and related sectors? What were the challenges in bridging sectoral boundaries when setting up new projects?

1.3 Structure of the Thesis

After a first introduction to this thesis, the theoretical and conceptual framing are elaborated (chapter 2). Then, the construction sector and its interconnection to climate change are addressed. Here, a first focus lies on Switzerland, followed by an introduction of alternative construction methods (chapter 3 et seq.). The next chapter starts with a brief introduction of the case study NEST and the units UMAR, Sprint, and HiLo (chapter 4). Then, the methodology is introduced, including the research design, the structure of the interview questionnaires, and the interviewees (chapter 5). The results (chapter 6) are structured along the theoretical framing and research questions. Key insights from the results are then discussed in chapter 7, including answers to the research questions and limitations of this thesis. Finally, the thesis concludes with a final review, recommendations for research and industry, and possibilities for future research (chapter 8).

2 Theoretical and Conceptual Framing

This thesis will broadly focus on the transition studies literature, with a first focus on the multi-level perspective (MLP), followed by geographies of sustainability transitions (GeoST). It will also outline the conceptual approach of this thesis, which involves lighthouse projects (LH) in transitions. Additionally, the framework of technical and global innovation systems (TIS/GIS) and the concept of multi-system interactions (MSI) will be introduced. Finally, the thesis will clarify its analytical framework.

2.1 Transition Studies

The underlying motivation for research on socio-technical transitions is to address ongoing “grand societal challenges”, such as climate change and resource depletion. Transition studies are also concerned with the conceptualisation and explanation of how fundamental changes can occur in the provision of basic societal functions, such as energy supply, water provision, construction, etc. (Köhler et al., 2019, p. 2). Such transitions are defined by the shift from one stable socio-technical regime to another. Often, this process is lengthy, spanning several decades (Geels, 2005). Additionally, transition studies look to find the underlying factors that drive the development of innovations, sectoral transformations, and regenerative urban-regional economies. Within this theoretical approach, transitions describe non-linear processes of socio-technical change (e.g., buildings or electricity) and their dynamics, drivers, and barriers are analysed. This includes examining the co-evolution of elements within socio-technical systems, such as technologies, institutions, user practices, and markets (Geels, 2010; Köhler et al., 2019, p. 2).

In the face of a major global crisis driven by ongoing climate change, “net-zero transitions across all socio-technical systems” are needed (Andersen & Geels, 2023, p. 1). The systems encompass mobility, heating, buildings, electricity, agri-food, and the production and utilisation of basic materials (e.g., steel, chemicals, and cement) (Andersen & Geels, 2023, p. 1; IEA, 2021). Furthermore, it is argued that ‘multi-purpose technologies’ are capable of solving sustainability problems across multiple sectors simultaneously, due to their capacity for transition and diffusion across diverse sectors (Finstad & Andersen, 2023, p. 1). However, the question of how to accelerate innovation across different socio-technical systems is still unanswered (see Kanger et al., 2021; Löhr & Chlebna, 2023, pp. 4, 12).

Within transition studies, the **multi-level perspective (MLP)** is a theoretical approach that analyses societal transitions, for example, transport, energy, agri-food, and construction systems (Geels, 2010, p. 507). Divided into the three interrelated analytical levels of landscape, socio-technical regimes, and niches, this perspective tries to describe socio-technical transitions as complex, multi-level re-configurations (Geels, 2004; Geels & Turnheim, 2022, p. 8). Firstly, the term **landscape** describes the macro-level context that shapes and constrains socio-technical systems. It encompasses long-term external trends, such as climate change, economic shifts, shifts in cultural values and geopolitical events, which are beyond the control of actors within the systems in question. While landscapes change slowly, they can exert pressure on existing regimes, thereby creating opportunities for innovations to emerge and drive transitions (Geels & Turnheim, 2022). Secondly, **socio-technical regimes** are complex systems composed of interdependent components, including technologies, actors (e.g., firms, users, policymakers), institutions (e.g., regulations, norms, rules), markets, and knowledge. These components are ‘coordinated’ to a certain degree and sometimes connected to “path-dependent trajectories” and lock-ins (Loorbach et al., 2020 in Jeannerat & Crevoisier, 2022; Köhler et al., 2019, p. 2; Löhr et al., 2022). However, because they do not always align perfectly, tensions and friction may emerge within a single regime (Konrad et al., 2008, p. 1191). Overall, regimes are regarded as deeply ‘taken-for-granted’ and stable configurations that provide services in a particular manner. Examples of such regimes include fossil fuel energy, industrial agrifood systems, centralised water provision, automobility, or linear material use in the construction sector (see examples of Turnheim et al., 2015; Urry, n.d.). Thirdly, **niches** are ‘protected spaces’ that shield

fundamental innovations from mainstream market selection pressure and support learning and development, transformative innovation (Köhler et al., 2019; Smith & Raven, 2012). Consequently, niches serve as ‘incubators’ for experimentation, enabling actors (e.g., innovators, startups, or niche networks) to refine and test alternative socio-technical configurations without immediate competition from the established regime (Geels & Turnheim, 2022). Fundamental innovation might then scale up from a niche to a broader industry, driving change and even bringing about regime shifts.

Path dependency is a key concept in transition studies, as established practices, investments, and infrastructure make these systems resistant to change. The transformation of socio-technical systems (regimes) requires disrupting existing path dependencies and transitioning across a range of dimensions, including technological, behavioural, policy-related, and cultural value domains (Geels & Turnheim, 2022). The existing socio-technical systems are frequently embedded in multi-dimensional and supranational network structures (Binz et al., 2025, p. 6; Fuenfschilling & Binz, 2018; Huguenin & Jeannerat, 2017, p. 624; Miörner & Binz, 2021). These networks can create **lock-in mechanisms** across regimes, which are rooted in behavioural patterns, vested interests, and institutional structures (Geels, 2010, p. 495). Such mechanisms can also be reinforced by incumbents within the network, culturally induced norms, or other systemic factors (Binz et al., 2025, p. 6; Fuenfschilling & Binz, 2018; Miörner & Binz, 2021). While lock-in mechanisms stabilise existing systems, their presence also presents a significant barrier to the implementation of radical change (Geels & Turnheim, 2022, p. 10). Additionally, scholars stress the role of agency and power within systems (Smith et al., 2005).

In summary, the MLP is one of the core analytical tools used in transition studies to describe and understand how transitions are influenced by factors across the three levels (Ryghaug & Skjølsvold, 2021). It offers a co-evolutionary perspective on change processes, showing how niches can scale up, how regimes resist or adapt, and how landscape pressures influence these dynamics. In this sense, the MLP constitutes a key element of transition studies, providing a distinctive lens for analysing socio-technical change.

However, several gaps limit the MLP in specific contexts. Scholars have noted that the MLP tends to understate issues of agency, power, and politics, providing a more structural account of transitions that insufficiently captures conflicts, interests, and strategic behaviour within regimes (Avelino & Rotmans, 2009; Meadowcroft, 2011). The perspective also conceptualises regimes as excessively stable, thus downplaying internal diversity, rapid change, or innovation emerging within regimes themselves (Genus & Coles, 2008; Smith et al., 2010). Furthermore, the MLP has been criticised for lacking spatial sensitivity, treating transitions as largely aspatial processes and overlooking geographical variation in institutional settings and socio-technical dynamics (Coenen et al., 2012a; Hansen & Coenen, 2015). Additionally, the limited focus of the MLP on user practices, everyday routines, and cultural norms, as well as its difficulty in analysing interactions between multiple socio-technological systems, has been criticised – crucial factors in sectors like construction, where material flows, regulations, and other elements might intersect (Rosenbloom, 2019). Collectively, these gaps indicate that while the MLP provides a solid foundation for understanding transitions, it requires complementary perspectives to adequately address complex, multi-system, and spatially embedded processes such as decarbonisation. The following chapters will, therefore, introduce analytical approaches to thoroughly address the research questions and better capture the multi-scalar, complex interrelations among different sectors or innovation systems.

2.2 Geographies of Sustainability Transition

Within transition studies, a line of research over the past ten years has developed a geographical lens on transitions, called **Geographies of Sustainability Transitions** (GeoST). The incorporation of elements of place, scale, and territorial embeddedness helps provide a more nuanced understanding of the drivers, barriers, and prospects for sustainability transitions (Binz et al., 2025, pp. 1–2). Hansen and Coenen (2015, p. 95) define GeoST as follows: “(...) the geography of sustainability transitions captures the distribution of different transition processes across space. Transitions form spatially, and unpacking this configuration will help us better understand the underlying processes that give rise to these patterns. This requires analysis of the particular settings (places) in which transitions are embedded and evolve, while at the same time paying attention to the geographical connections and interactions (i.e. the spatial relations) within and between that place and other places”.

As Hansen and Coenen (2015, p. 95) note, these transitions “happen in particular places, i.e. actual geographical locations with a materiality to them”. Places where sustainability transitions happen then get a scale attributed to them. This scale can range from local to global (e.g., the use of innovative materials in one building to an industry-wide transition) (Hansen & Coenen, 2015, p. 95).

One key assumption in GeoST is that the underlying dynamics among technologies, actor networks, and institutions serve as the starting point for transitions (Binz et al., 2025, p. 6). Moreover, GeoST examines how “deeply institutionalised, taken-for-granted socio-technical structures (e.g., socio-technical regimes) that give rise to path-dependent development trajectories” can be transformed (Binz et al., 2025, p. 6). Within these structures, transitions can be driven by “development, diffusion and institutionalisation of radically novel socio-technical configurations” (Binz et al., 2025, p. 6). However, external pressures or regime-internal tensions can also lead to changes within these structures, including the de-institutionalisation of incumbent regime frameworks. Consequently, complex dynamics emerge, creating multi-scalar and spatially uneven processes (Binz et al., 2025, p. 6). In their paper, Huguenin and Jeannerat inquire how a transition towards a new economy and society aligned with sustainable development values occurs, highlighting innovation as the key element (2017, p. 625). Open questions in GeoST concern the potential for transformative, mission-oriented policy interventions that incorporate a deeper understanding of GeoST (Madsen, 2022). Moreover, the question of how, through which mechanisms, and under what conditions socio-technical configurations developed in place-based experiments can scale and diffuse remains unresolved (Binz et al., 2025). Additionally, adding a spatial perspective to the sustainability transition could enhance understanding of the system’s dynamics (Luyi et al., 2024). When focusing on the niche level of socio-technical systems, an interesting approach to examining ongoing transition processes is the “light-house projects” (LH) concept.

2.3 Lighthouse Projects' Role in Transitions

Lighthouse projects (LHs) are conceptualised as environments that foster safe and supportive spaces for innovation, aimed at developing and showcasing radically novel solutions that could drive market adoption and initiate broader societal impact. Consequently, these projects are considered ‘safe’ and ‘protective’ as they enable actors to create novel socio-technical configurations beyond the dominant regime’s influence. In particular, by incentivising outcomes such as ‘user adoption’, the aim is to encourage wider, scale-up adoption of innovation, which can then be spread to other places (Schelbert et al., 2023, pp. 9–10). Nonetheless, projects within this concept are described and named in numerous ways, based on the source and context. Examples include pilot and demonstration projects (PDP), innovation projects, demonstration projects, pilot projects, flagship initiatives, landmark projects, pilot and demonstration experiments, urban living labs, prototype houses, fabrication labs, or smart grid projects (e.g., Buehler et al., 2025; Bulkeley et al., 2018; Frishammar et al., 2015; Schelbert et al., 2023; Van Winden, 2016).

Project names often indicate a project’s phase of development: ‘Pilot projects’ are implemented after preliminary research and practical implementation, and they remain closely tied to the laboratory setting. ‘Demonstration projects’ focus on obtaining feedback from real-world applications, encompassing user acceptance and emerging obstacles. Conversely, ‘lighthouse projects’ function on a larger scale with ‘technologically mature’ solutions (Schelbert et al., 2023, p. 9). **Figure 1** illustrates these different project stages (x-axis) based on ‘public sector investment volume’ and ‘market development’ (y-axis).

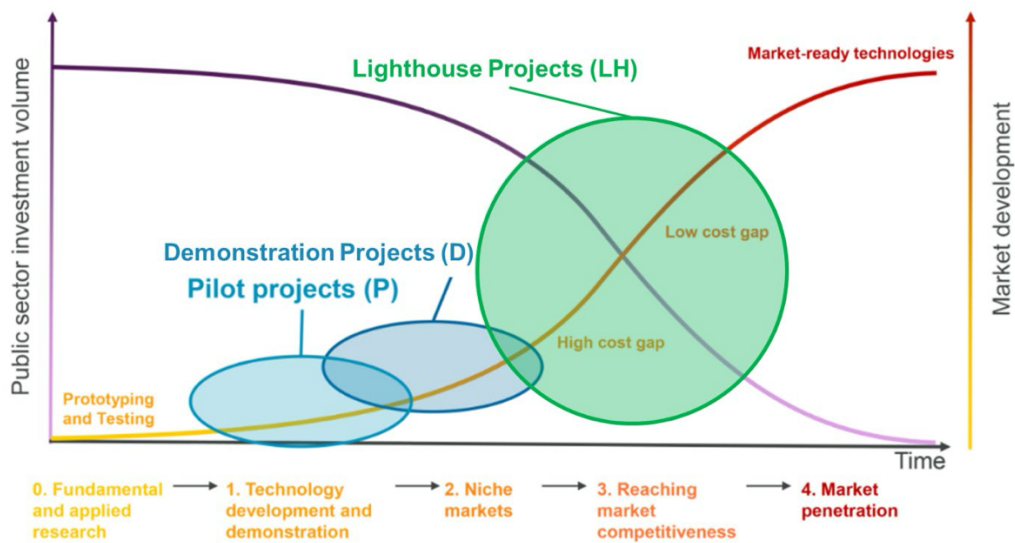


Figure 1: Typology of projects (Schelbert et al., 2023, p. 10).

Projects within the LH concept are proving to be practical tools for accelerating innovation and ultimately adapting sustainable building technologies (Buehler et al., 2025, p. 2). Innovation is not ‘just’ a linear process; the complexity of new projects needs to be considered. Instead of a stand-alone building project, the systems, infrastructure, and everything else that works around it need to be considered (Ryghaug & Skjølsvold, 2021). After Schelbert et al., LHs “happen at scale and at a stage when technologically mature solutions are available, but still lack a clear governance arrangement, mass-market and widespread legitimacy with the public and in key expert circles” (2023, p. 9). LHs can thus be seen as pivotal elements in inducing transitions, as they mediate between fundamental innovation and broader implementation in a bidirectional manner (Schelbert et al., 2023).

The role of LH in bridging the “valley of death” between research and commercialisation is widely recognised (Hellsmark et al., 2016, p. 1744; Losa & Cossent, 2024, p. 2). Project failures can result

from several factors, such as insufficient data, regulatory dependency, insufficient investment, or stakeholder acceptance (Losa & Cossent, 2024, p. 2). Additionally, a lack of understanding of how to organise or accelerate the transition from demonstration to industry-wide transition may result in a project remaining in the early stages of its development trajectory (Bossink et al., 2023). On the contrary, lighthouse projects enable the exploration of emerging technologies in real-world conditions by implementing innovative concepts, materials, and systems (Buehler et al., 2025, p. 2). To find out whether and how large-scale deployment of a transformative solution can be achieved in the future is, therefore, a very intriguing question for lighthouse projects. Looking at the scalability and replicability of a system, network, or process can provide crucial insight into the future potential of a LH (Losa & Cossent, 2024, pp. 1–2). **Figure 2** illustrates how scalability plays into the early eclipse of a novel technology.

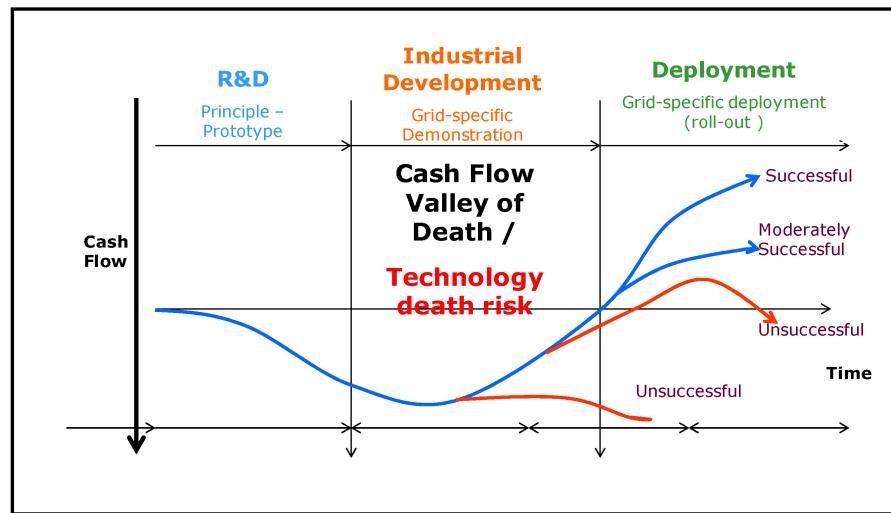


Figure 2: An innovation's valley of death (Losa & Cossent, 2024, p. 2).

As in the case with an actual lighthouse, projects that fit this concept “radiate” or diffuse their innovation to actors of a specific sector. Thus, influencing the development and future transition within their given sector, and even beyond. Therefore, an additional geographical component is present when examining LHs. For this thesis, the term “geographical impact” is used to describe the radiative power of lighthouse projects to diverse places and actor types. Using this geographical perspective, a lighthouse project’s impact on the construction sector can be illustrated on the spatial level. Accordingly, not only can the project’s effects on the actors involved and the public be studied simultaneously, but also how far this impact reaches. This way, not only can the project’s effects on the actors involved and the public be studied simultaneously, but also how far this impact reaches. As noted by GeoST scholars, the analysis of where a transition is embedded should be combined with an examination of possible geographical connections or interactions within and between places (Hansen & Coenen, 2015, p. 95). In the construction sector, this would be reflected in the consideration of how (to what extent) a LH can transform the industry and in the geographical scope of its impact. Adding a scale (from local to global) could further improve the understanding of the transformative power of a lighthouse project.

Building on this and existing transition policies, lighthouse projects can foster new values through complex processes of co-creation within society markets. This makes such projects not just technological experiments, but dynamic spaces where policy actively drives transformative change (Hedeler et al., 2019; Huguenin & Jeannerat, 2017, p. 624). Huguenin and Jeannerat (2017, p. 625) argue that a LH can enable value co-creation by legitimising a specific technology, thereby contributing to broader societal impacts. Thus, value creation is not merely a result or by-product of innovation, but involves “inquiring new values [into] society, translating them into social and technological solutions and making them valuable in markets” (Huguenin & Jeannerat, 2017, p. 625).

Therefore, LHs should not be viewed merely as shelters for innovation but as essential in creating new values that are not predetermined by innovation itself (Huguenin & Jeannerat, 2017, p. 625).

Overall, long-term backing from policymakers and the public, as well as a collaborative effort to balance scale, cost, and objectives, are vital for lighthouse projects (European Union, 2024; Schelbert et al., 2023). Other non-technical factors include coordinated flows of demonstrations (knowledge and technology development), the development of new market models and products, investments, and acceptance (legitimation) (Bossink et al., 2023, p. 1; Losa & Cossent, 2024, p. 2). Furthermore, Stubbs et al. (2024) stress the importance of external support or an “enabling environment”.

2.4 Technical and Global Innovation Systems

Adding to the concept of transition studies, with elements of multiscale and a transnational lens, are the frameworks of technical and global innovation systems (TIS/GIS). Technological innovation systems studies (TIS) focus on how a specific technology emerges and stabilises. Additionally, TIS centres on actors, technology, networks, and institutions in the early development phase of a technology (see **Figure 3**) (Ayrapetyan et al., 2025, pp. 1–2). Using TIS “functions” facilitates comprehension of the processes and interactions that underpin the development, dissemination, and utilisation of technology (Hermans et al., 2021, p. 79). However, this approach is seen as limited, as it primarily addresses a specific geographic area, particularly for complex, globalised innovations. This way, other scales and innovation systems are omitted from the analysis (Binz & Truffer, 2017).

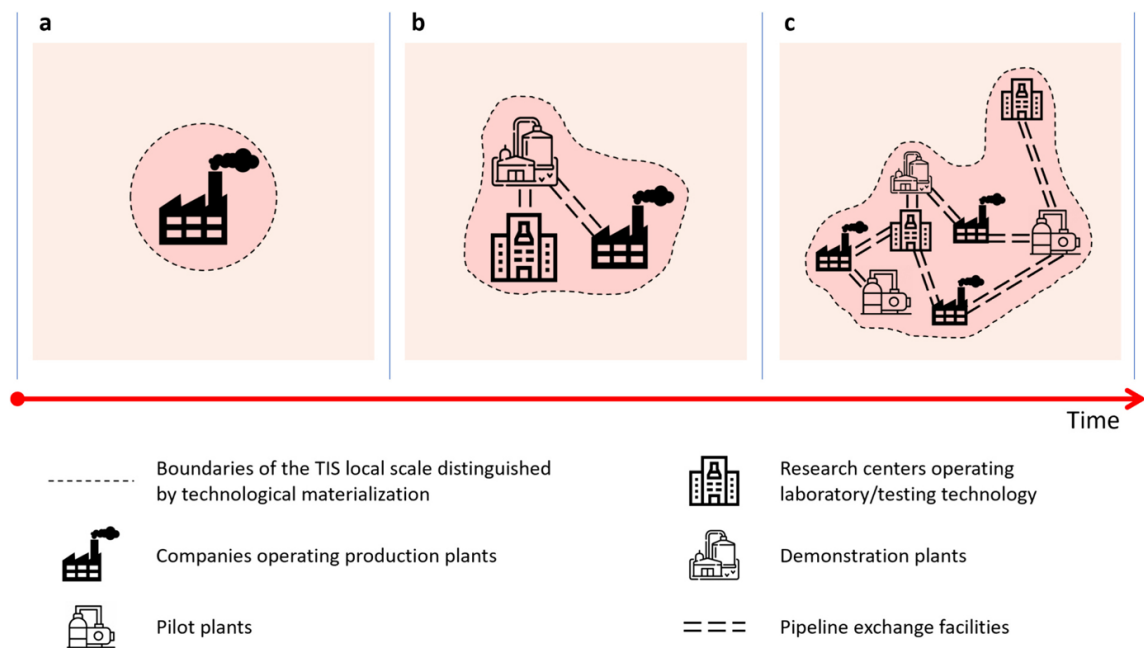


Figure 3: Temporal materialisation process of a local TIS (Ayrapetyan et al., 2025, p. 5).

The framework of global innovation systems (GIS) broadens the focus by examining multiscale interactions among local, national, and international levels of innovation processes (Binz & Truffer, 2017). Within the process of globalisation, distant places become increasingly connected, and there is a “circulation of people, knowledge, or capital” (Binz & Truffer, 2017, p. 1284; Corpataux et al., 2009). Thus, there are potentially co-evolving dynamics of innovation systems across territorial boundaries. Hence, innovation subsystems are not spatially predefined – but can either correspond or transcend national borders (Binz & Truffer, 2017, p. 1287). Furthermore, as Binz and Truffer (2017, p. 1291) illustrate across different industries, the scale of the innovation and valuation subsystem can either extend across the same or other geographical areas (from local to global). Moreover, it is argued that establishing a “global innovation system” can be facilitated by an

international perspective that encompasses the relationships between “innovation-related factors and entities” (Tian et al., 2020, p. 426).

Overall, GIS are structured around four central “system resources”: knowledge and technology development, market formation, investment mobilisation, and technology legitimisation (Binz, Truffer, et al., 2016). The first resource, **knowledge and technology development**, is focused mainly on technology innovation, research and development (R&D), and building the capabilities to operate and manage new technologies. As Su and Yan (2023, p. 2541) observe, knowledge in regional development is generated “via interactive exchanges among subjects (...) directly involved in knowledge innovation, such as enterprises, universities and research institutions”. In a GIS, knowledge is therefore shared within a knowledge subsystem, facilitating the diffusion of innovative ideas and practices (Binz & Truffer, 2017).

The other three resources are crucial to the ‘valuation process’ – where a novel technology “becomes a valued product for a specific customer segment” (Jeannerat & Kebir, 2016). The first step of this valuation is the **market formation**, as for novel innovations to prosper, initially protected market niches are needed. With greater market access, the range of suppliers available to companies and organisations increases. In addition, access to a larger market helps innovative companies to mitigate the “disadvantages of geographical distance” and improve their overall efficiency and adaptability (Liu et al., 2024, p. 9). Moreover, to ensure the provision of acceptable prices, it is vital to consider a shift in public behaviour concerning ‘use patterns’ (Dewald & Truffer, 2011, pp. 288, 298). Especially for niche-market formation, two other system resource-formation processes (mobilising financial investments and establishing technology legitimacy) are key. Both of them are connected to “proactive social construction processes” (Binz, Harris-Lovett, et al., 2016; Binz & Truffer, 2017, p. 1289). Additionally, Tian et al. (2020, p. 427) emphasise the importance of “culture” as a key variable and driver of the innovation process, influencing not only ‘innovation activities’, innovation output, and diffusion, but also the perception and acceptance of new products, as well as the internationalisation of resource and development (R&D). Therefore, the system resource ‘market formation’ is essential not only for reaching potential customers and markets but also for commercialising innovation, thereby increasing a company’s sales and growth (Binz & Truffer, 2017).

The resource **investment mobilisation** includes financial resources supporting research and development (R&D) activities, scaling operations, and bringing innovations to market. This investment can come from private investors, venture capital, or public funding (Binz & Truffer, 2017). According to Moon (2022, p. 9), public investments such as R&D grants are vital to an underinvested innovation sector. However, receiving (public) R&D grants to foster innovation can also lead to a decline in external financing. Therefore, investing in “innovating capacity” or facilitating market access is crucial for novel technologies to participate in a market (Moon, 2022, p. 9). However, as the Ellen MacArthur Foundation states, “far more capital and activity will be needed to scale the circular economy and fully seize its opportunity” (2020, p. 15). Thus, greater financial investment to accelerate the transition is crucial – especially for innovations to succeed in the long term (Ellen MacArthur Foundation, 2020, p. 15).

Legitimation is the third key system resource essential for the acceptance and valuation of an innovation by various stakeholders (e.g., consumers, government, industry actors, and media) and for aligning novel technologies and solutions with relevant societal institutions (regulative, normative, and cognitive) in a specific context (Ayrapetyan et al., 2025; Bergek et al., 2008; Binz, Harris-Lovett, et al., 2016). Additionally, technology legitimacy is seen as both an input and an outcome of a system-building process and is often conflated with an overall indicator for system development (Bergek et al., 2008). Gaining trust and establishing efficient use of the technology, including demonstrating the innovation, are also part of this resource (Rohe & Mattes, 2022, p. 61). In essence, ‘legitimation’ has a pivotal influence on the process of transition and is inherently interconnected with the other three resources, exemplified by its capacity to (positively) influence investment and resource mobilisation (Wesche & Skjølsvold, 2025, pp. 1–2).

All four resources emerge in specific subsystems, which are connected to multi-scalar actor networks and institutional contexts. In their paper, Binz and Truffer (2017, p. 1284) consider resources emerging within “multi-locational subsystems.” Within GIS, individual processes are seen as influenced by actors, global connections (networks), and institutions. Moreover, territorial subsystems are conceptualised as interdependent on an international scale. However, it depends on each innovation system, how relevant and ‘porous’ a territorial boundary remains (Binz & Truffer, 2017, p. 1285). For this study, using the four system resources provides a valuable heuristic tool for evaluating the impact of lighthouse projects in decarbonisation.

The behaviour of actors and their involvement in (in)formal networks and institutions is then condensed into the structural component of an innovation system. In addition to the four system resources, this includes fostering new cross-sectoral connections. Particularly in a sector such as construction, understanding these interdependencies and intersectoral relationships is vital for the sustainability transition. Additionally, knowledge exchange and spillover effects, facilitated by scientific communities and networks, are crucial for system interactions (Binz & Truffer, 2017, p. 1294). Therefore, integrating the GIS approach within a multi-sectoral or dynamic framework could offer valuable insights by highlighting emerging “positive externalities” within an innovation system. Subsequently, a LH can act as a foundation for analysing connections between local and global levels involving various subsystems or networks. Considering a LH as one of these innovation systems – linked across sectors, legitimacy, landscape factors, etc. – could help develop a deeper understanding of the ongoing dynamics. To achieve this, the thesis will evaluate LH’s geographical impact in each unit, in terms of local/national and global impacts on decarbonisation.

2.5 Multi-System Interactions

Recent research in transition studies emphasises interactions across socio-technical systems, as many real-world transitions (in innovation) are increasingly characterised by change processes involving multiple systems (Andersen & Geels, 2023, p. 1; Andersen & Markard, 2024, p. 2; Käsbohrer et al., 2024, p. 2; Köhler et al., 2019, pp. 21–22; Rosenbloom, 2019; Schultz, 2022, p. 821). Here, multi-system interactions (MSI) describe the concrete processes of interaction between different socio-technical systems (e.g., transport, construction, waste) (Andersen & Markard, 2020; Bakhuis et al., 2024; Finstad & Andersen, 2023, p. 1; Kaiser & Prange-Gstöhl, 2013, pp. 1316–1321; Kanger et al., 2021; Konrad et al., 2008).

In understanding interactions among systems, the concept of **couplings** is a valuable tool. Broadly, couplings are classified into structural (organisational, technological, and institutional) and functional couplings (Andersen & Geels, 2023; Konrad et al., 2008).

Structural couplings describe the interactions of two or more elements within a system, across three structural dimensions of organisations (actors), technologies, or institutions (Andersen & Geels, 2023; Konrad et al., 2008; Löhr et al., 2022, p. 263; Tsouri et al., 2021). Importantly, ‘structural similarities’ between two systems do not inherently imply a coupling (Konrad et al., 2008, p. 1193). **Organisational couplings** explain how diverse actors – such as companies, government agencies, NGOs, research institutes, projects, spin-offs, or innovation platforms – with their perceptions, strategies, and actions, create new structural couplings between systems. This makes them key drivers of transition. **Technological couplings** establish the structural linkages between systems through shared infrastructures, devices, or interfaces. **Institutional couplings** combine “institutional structures and governance arrangements” (i.e., a set of rules) (Andersen & Geels, 2023, p. 6; Konrad et al., 2008, pp. 1193–1194). The “configuration of structural couplings” facilitates or gives rise to functional couplings and changes within innovation systems (Andersen & Geels, 2023, pp. 2–3). These **functional couplings** are connections between various material elements (“input-output relations”) and include the transfer of materials, data, or resources (e.g., economic resources) (Käsbohrer et al., 2024, p. 2; Konrad et al., 2008, p. 1193). Therefore, using the same resources simultaneously can eventually create functional interdependencies.

For couplings, the **site of interaction** is crucial for the development and stabilisation of (multi-system) interactions (Rosenbloom, 2020). A site of interaction is a location (physical, organisational, or institutional) where different systems, actors, or practices meet, enabling connections to form or be negotiated. Additionally, actors may interact, share data, and set objectives. Furthermore, the relationship between technological innovation and existing system entanglements, as well as the shifting system boundaries concerning institutions and the role of actor networks, is central (Käsbohrer et al., 2024, pp. 2–3). In summary, sites of interaction are spaces for experimentation and coordination where structural couplings (organisational, technological, institutional) are ‘materialised’, and functional couplings are facilitated, allowing MSIs to be negotiated in practice (see **Figure 4**).

The interactions of complex multi-socio-technical systems have not yet been widely studied. According to Andersen and Markard (2024), a more integrated and nuanced approach to exploring these multi-system transitions is needed. Contrary to research on MSI, the primary research focus of transition studies still lies on single systems. Instead of examining multi-system processes such as climate change impacts, transition studies focus on the socio-technical configuration of a specific societal function (Kanger et al., 2021, p. 2; Rosenbloom, 2019). Looking into how different systems interact can, to a certain degree, explain the trajectory and, finally, the success of a transition. Additionally, dynamics within a socio-technical landscape may open ‘windows of opportunity’ for novel technologies to enter (Konrad et al., 2008, p. 1190).

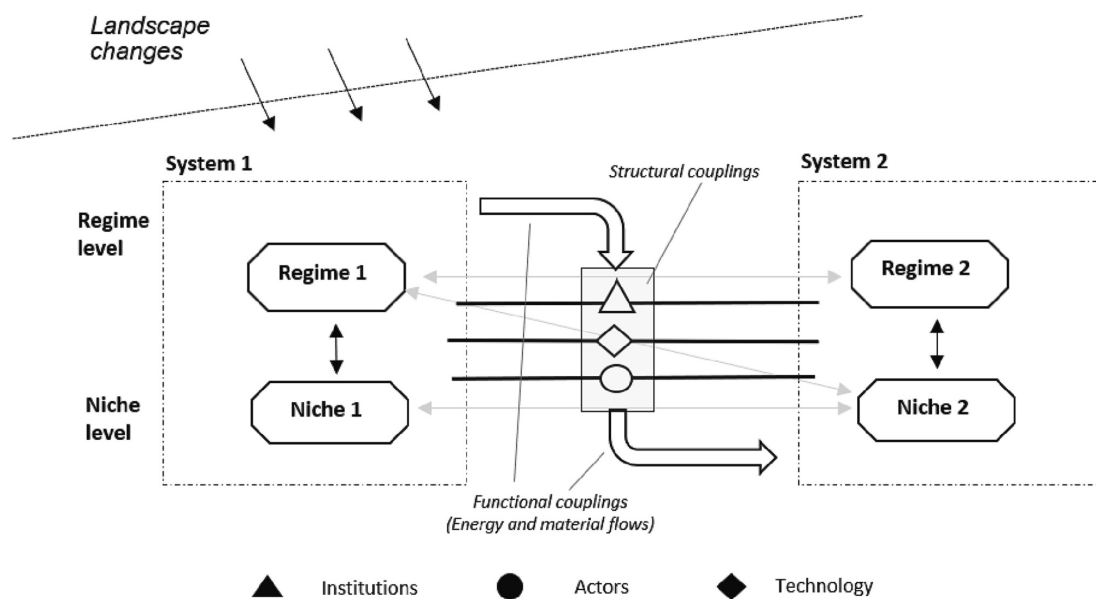


Figure 4: MSI interactions during transitions (Andersen & Geels, 2023, p. 3).

Here, couplings are a valuable tool, offering insights into relations/overlaps within and between elements in a socio-technical system. A better understanding of the many interactions is essential when analysing a complex, multi-system subject like decarbonisation. Overall, couplings – structural or functional – can lead to new and surprising interactions between sectors (Ryghaug & Skjølsvold, 2021, p. 17). This “space” between systems, where interactions take place, is named “site of interaction” (Löhr & Chlebna, 2023, p. 2). The emerging structural and functional couplings between sectors can help better understand and eventually explain (emerging) multi-sectoral dynamics or multi-system interactions (Löhr & Chlebna, 2023). Konrad et al. (2008, p. 1193) propose “drawing regime boundaries depending on the density and strength of couplings between the elements of socio-technical configurations”. A comprehensive investigation into individual couplings requires a focus on the specific elements of the system, including actors, technology, and institutions. This thesis

places particular emphasis on organisational couplings, as the actors within the LH make a significant contribution to understanding innovation subsystems such as LHs.

Subsequently, a lighthouse project could be conceptualised as a complex site of interaction, filling the space between two or more (sub-)systems with increasingly overlapping and shared sustainability goals (e.g., low-carbon materials, recycling, robotics) (Elzen et al., 2012, p. 16). Moreover, LHs bring together actors and technologies from diverse sectors, creating opportunities for novel couplings and cross-sectoral learning (multi-system interactions). However, how these individual subsystems interact, form new connections, or depend on each other remains underexplored (Bakhuis et al., 2024; Kanger et al., 2021, p. 2; Rosenbloom, 2019). Analysing LHs through an MSI lens, as applied in this thesis, could therefore reveal how innovative solutions interact with an established industry and whether these interactions contribute to broader sectoral transformation, for example, decarbonisation.

2.6 Research Gap and Analytical Framework

This chapter identifies key research gaps in the role of lighthouse projects in socio-technical transitions and outlines the analytical framework guiding this study.

Despite growing interest in the role of lighthouse projects (LHs) in socio-technical transitions, there remain considerable research gaps regarding the mechanisms by which they can enable broader systemic change. In particular, the geographic reach of their impact and diffusion (in German “Leuchtkraft”) as well as their capacity to connect actors across sectors have not been sufficiently explored yet. Examining the spatial dimensions of LHs can provide valuable insights into how they mobilise actors, stimulate learning processes, and shape sectoral transitions. Moreover, empirical research on LHs remains limited, especially in hard-to-decarbonise sectors.

As Huguenin and Jeannerat (2017) argue, LHs are often protected by institutions or specific regulatory frameworks that create a safe space where actors are encouraged to “think outside the box” and develop innovative solutions beyond established norms. This thesis examines a secure yet experimental environment within Empa’s NEST building, which offers an institutionalised “safe space” for collaboration between research and industry to develop and test innovative technologies and materials within the often very risk-averse construction sector.

Previous studies show LHs stimulate innovation in materials, technologies, and networks, but less is known about their role in scaling up these innovations and driving sector-wide transitions. Meanwhile, several studies examine how LHs bridge research and industry and legitimise new solutions (Hellsmark et al., 2016; Huguenin & Jeannerat, 2017; Schelbert et al., 2023, p. 10). Yet, more in-depth empirical work is required to understand how these projects contribute to system transformation in specific contexts. This thesis, therefore, addresses the first research gap by exploring the role of NEST in driving decarbonisation in the Swiss construction sector. It analyses how innovative solutions developed within this LH get replicated in practice and influence wider sectoral structures, using the GIS’s four key system resources (knowledge and technology development, market formation, financial investment, technology legitimisation) as an analytical lens to assess the LH’s impact.

A second research gap concerns the geographical impact and the multi-scalar nature of transitions. It remains unclear why innovations and transition processes succeed in some locations but not in others, and how spatial relations across scales influence these processes. The Geography of Sustainability Transitions framework provides valuable insights into the special embeddedness of innovation (Hansen & Coenen, 2015). Applying this perspective enables a better understanding of how innovative solutions diffuse spatially across different scales (from regional/national to international).

A third research gap relates to the dynamics of multi-system interactions induced by LHs. The construction sector exemplifies a complex socio-technical field that spans multiple subsystems that are

increasingly overlapping through shared sustainability goals (e.g., energy, recycling, robotics) (Elzen et al., 2012, p. 16). Empa's NEST unites actors and technologies from diverse domains, creating opportunities for novel couplings and cross-sectoral learning. However, how these individual subsystems interact, form new connections, or depend on each other remains underexplored (Bakhuis et al., 2024; Kanger et al., 2021, p. 2; Rosenbloom, 2019). Analysing NEST through an MSI lens reveals how experimental niches within the building's units interact with an established industry, and whether these interactions contribute to broader sectoral transformations.

To address these three research gaps, NEST is seen in this thesis as a lighthouse project comprising several interconnected subsystems (units). This framing enables an investigation of how novel materials and technologies developed within these protected niches connect with existing regimes, and how these connections shape sectoral transition pathways. While predicting the long-term impact of such an experimental project remains challenging, understanding its underlying mechanisms and dynamics can shed light on how LHs contribute to broader decarbonisation efforts – and on the potential limitations of such attempts. In the main, this thesis integrates insights from transition studies, GeoST, and innovation systems to better understand the spatial and relational dynamics of LHs in transitions. By applying MSI and GIS frameworks, it examines the role of lighthouse projects, such as NEST, in the transition of hard-to-decarbonise sectors, such as construction.

3 The Construction Sector

3.1 The Construction Sector and Climate Change: Most Pressing Challenges

Increased anthropogenic greenhouse gas emissions are one of the fundamental reasons why our climate is changing⁴ (Federal Office for the Environment FOEN, 2024). One sector that plays a crucial role in combating climate change is the construction industry. Globally, the construction sector accounts for approximately 27% of CO₂ emissions and consumes 30% of available energy⁵ (see Figure 5) (Li et al., 2025, p. 2; Rukikaire & Loran, 2022; United Nations Environment Programme, 2022, pp. 37–45).

Many of the materials used in building today, such as cement (the key component of concrete) and steel, contribute significantly to greenhouse gas emissions (Churkina et al., 2020 in Fischer & Losacker, 2024, p. 15). Concrete, in particular, is often depicted as a major contributor to today's high emissions and energy consumption in the construction sector. While the data support this view, it is primarily the vast quantity of concrete used that drives its environmental impact. Additionally, the key components of cement, such as clinker, are themselves highly detrimental to the environment (Lehne & Preston, 2018). Given that by 2050 the global population is expected to grow by around 2.1 billion people, creating demand for an additional 190 billion m² of floor area, these challenges are likely to intensify further. As Schelbert et al. (2023) note, meeting climate transition targets requires not only transforming conventional building methods but also developing cross-sectoral solutions. Achieving such change, therefore, demands collaboration between researchers, practitioners, and clients (Ranaudo, 2025).

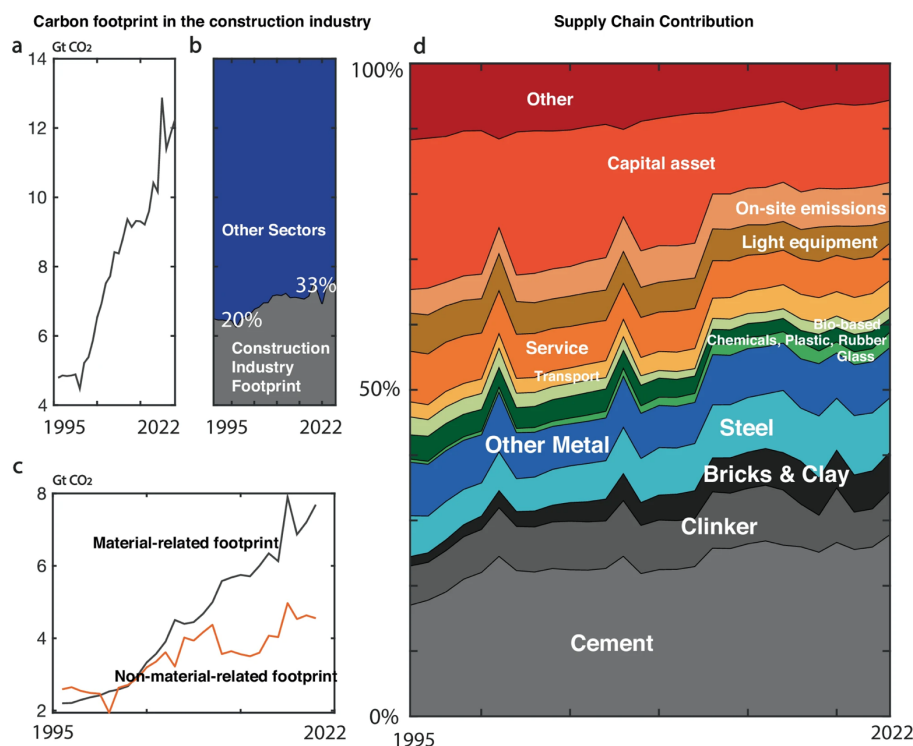


Figure 5: Carbon footprint (Li et al., 2025).

⁴ Examples include: Sea level rises, increase of heat waves and droughts, storms worsen, species disappearing, changes of migration patterns, and disrupted production and supply (Federal Office for the Environment FOEN, 2024).

⁵ When mentioning the consumption of energy and emissions within the construction sector, the terms "embodied" and "operational" are important. After Circular Ecology (2025), "embodied carbon" the whole energy consumed – including end of life, raw material extraction, transportation (to gate or site), manufacture, and fabrication/construction of a material or product – is translated into the carbon footprint. This carbon footprint is equal to the sum of carbon [CO₂] to produce a material – e.g., a building (Circular Ecology, 2025). Then, the operational energy or emission happening during the operation of a product, like a building, is added to get the sum of embodied and operational emissions.

Importantly, the high energy consumption and emissions are only the tip of the iceberg. Resource extraction and excess building materials amplify the sector's negative impact, making construction the largest consumer of raw materials and a major producer of waste worldwide (Fahy et al., 2024, p. 714; Ranaudo, 2025). In the EU alone, the construction sector accounted for half of all extracted materials and generated over a third of the region's waste. According to the ETH Zurich (2018), the rapid depletion of raw materials will "leave the world without enough sand and steel to build in concrete" by 2050. Here, the "carbon footprint" aims to explain the construction industry's environmental impact relative to other sectors (see **Figure 5**) (Li et al., 2025).

As Li et al. (2025) forecast in their recent paper, the industry's footprint is likely to increase further, contrary to international targets, such as the Paris Agreement. In 1995, half of global CO₂ emissions were attributable to major emitters, including Europe, the USA, and East Asian countries such as South Korea and Japan. Today, the largest share comes from countries such as China and India. Although regions such as Europe still produce absolute emissions levels similar to 30 years ago, their relative shares have declined – underlining the need to account for local contexts when developing effective mitigation measures (Li et al., 2025, p. 3). This highlights how emission trends differ regionally and throughout seasons (Delmastro & Chen, 2023). Overall, there is a strong 'regionalism' in the construction sector. Partly, this is linked to evolving structures within a country's construction industry. Moreso, 'high-income countries' are associated with having "stricter environmental regulations, better access to advanced technologies, and more economic incentives to use sustainable construction materials" (Li et al., 2025, p. 3).

This thesis focuses on Switzerland's construction sector. Because of Switzerland's geographical location, the effects of climate change are more pronounced than the global average (Brupbacher & Vögeli, 2025). According to Switzerland's Federal Office for the Environment (2024), emissions from the building sector have decreased by 46% since 1990. Therefore, a partial decarbonisation has already happened. However, the construction sector remains one of the largest emitters of GHG, accounting for 9.06 Mio tonnes of CO₂ equivalents in 2023, around a fourth of all domestic emissions⁶ (BAFU 2025; Richner, 2024).

3.2 Alternatives

Rapid decarbonisation in the construction industry requires multiple parallel strategies and transitions across sectors. Overall, solutions on how to decarbonise the industry are diverse and include the introduction of circular economy principles, shifts in production methods and technology, advanced manufacturing with 3D printing, low-carbon materials, or biobased solutions (Adams et al., 2019; Gagg, 2014; Ghoneim et al., 2022; Habert et al., 2020; Roijen Van et al., 2025). To achieve long-term change, it is also essential that innovative approaches and materials are scalable. To this end, interaction between previously unconnected sectors and the involvement of various stakeholders are crucial for the decarbonisation of the entire construction sector (United Nations Environment Programme, 2023).

In the selected case study, the focus is on two different thematic areas (see chapter 4). The units UMAR and Sprint, as well as HiLo, each embody one of the core strategies for transforming construction practices. The following two sections, therefore, provide brief overviews of **urban mining and recycling** and of **resource-efficient and advanced construction technologies**, respectively.

The first focus is on **urban mining and recycling**. The conventional economy is often described as a "take-make-waste" economy – being highly extractive and wasteful (Zandee et al., 2022). Across diverse sectors such as agri-food, textiles, and construction, the negative impacts of such an economic

⁶ In 2022, the share of the 'building sector' of Switzerland's GHG was 22.2 % (BAFU 2025). This statistic combines households as well as services. However, the numbers do not include the 'infrastructure' needed for the buildings. On the other side, it does include the 'operation of buildings' alongside the primary construction (operational and embodied energy). Therefore, the actual number could even be slightly bigger.

system on the environment and the economy are massive (Ellen MacArthur Foundation, 2013). In contrast, moving towards a circular economy (CE) presents a (multi-trillion-dollar) opportunity, with potential in both technological and financial fields (Ellen MacArthur Foundation, 2013). Moreover, CE describes an economy in which products, components, and materials are maintained at their highest utility and value – at all times (Fahy et al., 2024, p. 714). Instead of viewing building waste as a problem, it is redefined as a resource in itself – valuable and reusable (Fahy et al., 2024, pp. 714–715; Guerra et al., 2021).

Additionally, the circular economy extends beyond recycling. CE is designed as a “regenerative system” that eliminates waste, decreases the need for primary raw materials, and allows products and materials to circulate through various methods such as reuse, repair, or recycling by designing materials, products, business models, and processes (Bill, 2023; Swiss Recycle, 2025). In Switzerland, the “10Rs” strategy emphasises the core principles for implementing CE: “Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover” (Swiss Recycle, 2025). To advance this idea further, the global warming potential formula describes an optimised construction lifecycle: reduce, improve, prolong, reuse, and recycle (Ranaudo, 2025).

The second focus is on **resource-efficient and advanced construction technologies**. Under the umbrella term ‘advanced manufacturing’, a range of technological approaches related to building materials, such as concrete, is subsumed. Within this context, resource-efficient or “climate-friendly” concrete – in which carbon is stored or even sequestered – is considered to offer significant potential for emission reduction in the construction sector. Examples of such technological approaches include carbon capture and storage (CCS), the use of supplementary cementitious materials (SCMs), light-weight concrete structures, or computational design advances (e.g., LC3⁷, BIM⁸) (LC3, 2024; neustark, 2024; Van Mele et al., n.d.). According to Peter Richner, former lead of the NEST project and now host of the NEST Podcast, the industry also seeks to improve its public image; however, approaches such as carbon-storing concrete remain approximately 50% more expensive than conventional alternatives, limiting their competitiveness (SRF Podcast, 2025).

⁷ LC3 is a SCM and stands for “Limestone Calcinated Clay Cement” technology. The aim is to achieve a reduction of the clinker content in cement production by up to 50% (Sika Schweiz AG, 2022, p. 5).

⁸ Building information modelling. Associated with increasing productivity in the construction sector (Schweizerischer Baumeisterverband, 2025).

4 Empa's NEST

Within Switzerland's transition towards decarbonising the construction sector, one lighthouse project stands out: NEST. This acronym stands for "Next Evolution in Sustainable Building Technologies". It is a modular research and innovation building of the research institutes Empa⁹ and Eawag¹⁰ in Dübendorf (Switzerland) (Empa, 2025c, 2025b; Grimm, 2024; Lydon et al., 2015). Demonstrating innovation in the built environment and integrating solutions at a "household level", up to fifteen building units fit the facility (Konrad et al., 2008, p. 1194). Under the motto "building the future together", these units are modular and temporal, integrating into a "Plug-and-Play" process (Empa, 2016; Lindner SE, 2024). Each unit revolves around a specific topic or technology pathway, including 'decarbonization/expansion of electricity production', 'electrification of systems', 'energy efficiency improvements', 'carbon capture and storage' (CCS), and 'behaviour change' (Andersen & Geels, 2023, p. 1). After the 'Karlsruher Institut für Technologie' KIT (2021), NEST is "demonstrating what a paradigm shift in the construction industry, reacting to the limitation of the world's natural resources, might look like".

Overall, the individual units function as living laboratories for testing and displaying ground-breaking innovative construction methods, sustainable materials, and technologies. Thus, they are "innovation accelerators" for materials and technologies, moving them from the laboratory to the market (Richner, n.d.; Richner et al., 2018). Furthermore, the units not only show scalability but also attract imitators and inspire wider adoption, illustrating the transformative potential of LHs. Moreover, construction in NEST is carried out in accordance with common building standards; thus, end-users and customers receive a product ready for use. However, Enrico Marchesi from NEST emphasises the importance of error values in fostering innovation (Züst, 2024). The units, therefore, act as a "place of validation" of new materials and incubators in the construction sector (Richner, 2024). Individuals and companies can collaborate with NEST in three different forms: technological, material/service-related, or financial collaboration (Empa, 2025d). In total, NEST as a platform unites over 150 actors from research, the economy, and the public sector (Empa, n.d.-c, p. 25).

This thesis will discuss three of Empa's NEST units, which are centred around two key innovations in the construction sector: 'urban mining and recycling' (UMAR and Sprint units) and 'resource-efficient and advanced construction technologies' (HiLo). As Andersen and Geels write, "creating novel interactions and alignments across multiple emitting systems" is key and a core contribution of NEST (2023, p. 1). Consequently, the innovative solutions developed in Empa's NEST units provide an illustrative example of potential interactions among the various sectors within a given space. Here, the NEST building in Switzerland stands as a unique example of a lighthouse project within the country's sustainability transition landscape.

⁹ „Eidgenössische Materialprüfungs- und Forschungsanstalt" (German). „Swiss Federal Laboratories for Materials Science and Technology" (English) (Empa, 2025a).

¹⁰ "Swiss Federal Institute of Aquatic Science and Technology" of the ETH domain (Eawag, 2025).

4.1 Urban Mining and Recycling

In the two units, **UMAR**¹¹ and **Sprint**, the focus is on urban mining and recycling. These units demonstrate circular economy principles by introducing fully reusable, recyclable, or compostable materials. Examples include untreated wood and repurposed materials, with a focus on waste-free deconstruction. Engaging various sectors and technologies, the units highlight how buildings can function as material repositories and drive sustainable practices in construction (Empa, 2025f; Sobek, n.d.).

The first unit, **UMAR**, was designed by Werner Sobek, Dirk E. Hebel, and Felix Heisel. Interestingly, it also serves as a student flat of 125 m², with two students occupying 18 m² rooms surrounding a large “eat-in kitchen” (Kaltenbach, 2018). Overall, the UMAR unit places “life cycle thinking at the forefront of the design” and describes the transition from linear material consumption towards circular material cycles. After the KIT, the UMAR unit proved that “the responsible use of natural resources, the recycling of materials and modern architecture can go hand in hand” (KIT, 2021). The unit itself was paraphrased as an “ideal and real” testing environment for innovative solutions (Empa, 2020). Here, resources are not disposed of – but seen as merely “borrowed” and therefore put back into circulation at the end of use. Not only are building materials re- and upcycled, but also reused and repurposed. Thus, the units are seen as a laboratory for new materials and a “temporary material storage”. Overall, the emphasis lies on maximal modularisation and prefabrication (Sobek et al., 2018). Examples include the ceiling with its stainless-steel panelling for the water pipes.



Figure 6: UMAR unit, showing innovative wall materials (e.g., Tetra Pak) (Braun, 2018).

Energy efficiency was also a priority; therefore, a self-learning heating and cooling control system was developed. By integrating artificial intelligence (AI) into an intelligent control system, the unit became more energy-efficient and more comfortable. Compared to conventional buildings, integrating “predictive cooling” reduced cooling energy use by a quarter and “comfort constraint violations” by over 70% (Bünning et al., 2020). Although such systems had been used in large-scale building projects (e.g., factories, airports, and office buildings), their use in private apartments/buildings was novel (Empa, 2020). In UMAR, the respective room temperature is regulated with an experimental

¹¹ UMAR stands for “Urban Mining And Recycling”.

valve system, ensuring temperatures between 23 and 25 degrees Celsius. For this to work, the intelligent control system used data from the previous 10 months from the Federal Office for Meteorology and Climatology. This way, energy consumption could be reduced significantly. By testing the technology within UMAR, these “controllers based on machine learning” systems could later, in a larger field trial, be built into a few apartments within an apartment block (Der Bundesrat, 2022). Moreover, this heating system can also be used when retrofitting an existing building (Empa, 2022).

The second unit, **Sprint**, follows the “design for disassembly” principle (see **Figure 7**) (Zeller, 2022). This principle focuses on the demolition of construction material and its subsequent reuse in new projects. Therefore, Sprint is strongly linked to the overall circular construction concept that both units follow. Moreover, the unit demonstrates collaboration among actors from research, the economy, and the public sector. Again, different actors came together to design and build an innovative space. In Sprint, while following reuse principles, an office space was created that complies with market requirements (“fast and flexible construction”) (Empa, 2025e; HUSNER AG Holzbau, 2021).



Figure 7: NEST's Sprint unit (Zeller, 2022).

4.2 Resource-efficient and Advanced Construction Technologies

In the **HiLo**¹² unit, attractive architectural design is combined with **advanced, resource-efficient construction technologies**. The aim is to construct efficient concrete structures using innovative planning and design methods, while applying self-learning and adaptive building technologies (Block et al., 2017). Buildings have an estimated energy saving potential of 50 to 90% – presently, this potential is still ‘underutilised’ (Pandiani, n.d.). Overall, improving the “building envelope performance, energy systems efficiency and onsite power generation” stands in the centre when thinking about how to minimise energy use (Block et al., 2017, p. 332). Thus, improving building stocks – including their envelope – is essential when looking to reduce operational energy consumption (ETH Zurich in Svetozarevic et al., 2019, p. 671). This building envelope controls energy transfer (daylight), as well as heat and air transfer between the external and internal environment (Svetozarevic et al., 2019, p. 671). For this, a total of four key innovations were introduced in HiLo: “a lightweight, unreinforced funicular floor system; a flexibly formed, concrete shell sandwich roof; a soft actuated, adaptive solar facade and an automated, occupant-centred control system” (Block et al., 2017, p. 332).

Firstly, motivated by the rapid depletion of raw materials like sand, a **lightweight, unreinforced funicular floor system** has been developed (ETH Zurich, 2025; Longobardi, 2024; Van Mele et al., n.d.). Interestingly, the “Rippmann Floor System (RFS)” is expected to deliver reductions of up to

¹² HiLo stands for “**H**igh performance, **L**ow emissions”.

70% in mass, 90% in steel usage, and 80% in equivalent carbon emissions compared to conventional concrete floors, all at a lower cost (Longobardi, 2024).

Secondly, the “**flexibly formed, concrete shell roof**” is an eye-catching feature of HiLo (see **Figure 8**) (Braun, 2018; Van Mele et al., n.d.). The doubly curved roof spans 7.85m by 17.20m and was realised using a lightweight, reusable cable-net and fabric formwork system. The innovative use of cable-net was highly efficient, requiring less human and financial investment than a conventional project. Also, the two individual reinforced concrete layers are thin, only 5cm (inner layer) and 3cm (outer layer) each. In between this “sandwich” roof is a layer of 10cm insulation. With this roof, a way to rethink the building envelope was created (Block et al., 2017).

Thirdly, “**dynamic photovoltaic building envelopes**” have been used for “adaptive energy and comfort management” (Svetozarevic et al., 2019, p. 671). Compared to other improved building envelopes, this approach goes beyond reducing energy demands through changes in insulation or shading. Instead, using lightweight modules enables the active adapting of solar radiation for “local energy generation, passive heating, shading and daylight penetration” (Svetozarevic et al., 2019, p. 671). Solar radiation influences both “thermal comfort” and “daylight quality” - here, dynamic envelopes provide a solution, as light permeability can be adjusted. With changes in weather and similar conditions, the dynamic envelope adapts. However, the “cost and reliability” of these envelopes remains a challenge (Svetozarevic et al., 2019, p. 671). In Hilo, a total of 30 modules have been installed on the unit’s façade (Svetozarevic et al., 2019, p. 677). Moreover, such a climate-adaptive building envelope was built by connecting soft-robotic solar trackers to “optimally distribute(d) [solar radiation] in space to minimise the overall energy need of the built environment” (Solskin, 2025; Svetozarevic et al., 2019, p. 672). These smart solar trackers follow the position of the sun – generating an annual energy surplus of almost 40% (146kWh) (Pandiani, n.d.; Solskin, 2025; Svetozarevic et al., 2019, p. 677).

Lastly, **other innovative technologies** in HiLo include optimising building control systems using machine learning. Here, recent strategies include model-predictive approaches and artificial intelligence. Additionally, to avoid inefficient energy conversion in solar panels, devices in HiLo use direct current rather than alternating current (Empa, n.d.-b).



Figure 8: HiLo's roof (Braun, 2018).

5 Methodology

5.1 Positionality

As a master's student at the University of Zurich, I approach this research as a young, white, female scholar with an outsider's perspective on the construction sector. My academic background in geography and environmental studies – focusing on solutions for sustainable futures – shapes my viewpoint for this thesis. This position enables me to engage critically with the industry while maintaining a level of detachment that fosters objective inquiry. However, I recognise that personal bias remains significant throughout the research process, including during interviews (see Kuckartz & Rädiker, 2022, p. 26).

Also, even though I educated myself on terminology and topics related to the construction sector as best as I could, misunderstandings or misinterpretations are possible, and a careful review of the information and qualitative results is required (Khan et al., 2023). To prevent misunderstandings, assess the study's usefulness, and enable the transferability of my results to a broader context, comparing the statements of the different interviewees through triangulation will be beneficial (Kuckartz & Rädiker, 2022, pp. 251–254).

5.2 Research Design

To gain deeper insights into the selected case study, this paper uses qualitative research methods. According to Kuckartz and Rädiker (2022, p. 39), qualitative content analysis allows for systematic, methodologically controlled scientific analysis of interviews, not only describing but also testing known theories and discovering new connections (Mayring, 2022).

For this thesis, semi-structured expert interviews were chosen to gain a deeper understanding of lighthouse projects in transition, with a focus on the NEST case study. By directly engaging with NEST actors, the concept of lighthouses in the Swiss construction sector was explored, along with the unit's specific geographical impact. Moreover, the interview structure focuses on the research questions, which are essential for an overall understanding and later transferability of results.

Additionally, interviews allow a focus on the interviewees, their solutions, and their roles within the units. Moreover, interviews give everyone the 'same' weight – even if one perspective or person is more prominent in the media, for example. Interviews also make sense in relation to the research questions posed, particularly in a more technical field where specific topics of conversation are less prevalent or less directly discussed. Thus, interviews are an effective way to give these topics space and apply them to the lighthouse concept. New or unknown impressions and connections, important for answering the research questions, were revealed.

5.3 Data Collection

The following three sub-chapters provide a more detailed description of the data collection and analysis, including desk research, the interview questionnaire, and expert interviews.

5.3.1 Desk Research

To understand how Switzerland's construction sector has developed in the last few years, comprehensive desk research was conducted. In doing so, extensive information was collected before expanding the scope of the thesis to the construction sector, with a focus on the three units UMAR, Sprint, and HiLo. Here, gaining information regarding these units and technologies was especially important. Moreover, during the interview phase, actors provided more details on additional units such as 'STEP2', 'DFAB HOUSE', 'Solare Fitness & Wellness', and NEST's structure and impact in general.

5.3.2 Interview Questionnaire

To prepare for the interviews, an initial interview questionnaire was drafted. For this, a review of theoretical concepts relevant to the research questions was essential for designing the semi-structured interviews (Helffferich, 2011; Kuckartz & Rädiker, 2022; Mühlenen, 2016, pp. 67–68; Wintzer, 2014, 2021). After several revisions, the questionnaire was evaluated with individuals from my immediate circle (who knew about NEST and had limited knowledge of the construction sector). During this process, the overall length was shortened, and some questions were deleted or combined to create a clearer structure and make it easier for the interviewees to navigate. Finally, four questionnaires were developed. As the interviewees spoke either Swiss German, Standard German or English, the questionnaire was available in both languages. Because of the units' two different thematic focuses, four (slightly) different questionnaires were created: two for UMAR/Sprint and two for HiLo (each in English and German). Later in the interview process, the questionnaires were adjusted to better align with the diverse set of interviewees (e.g., field of work, function, or responsibilities).

After a first personal introduction and definition of LHs, the questions were structured after the four key system resources and multi-system interactions, followed by final questions. In most cases, interviewees were asked whether they could suggest anyone else for an interview (snowballing sampling). Overall, the proposed time needed to answer all questions was approximately one hour. To achieve this time limit while still having some extra time to spare for additional comments, 'focus questions' were highlighted, while 'back-up questions' were coloured light grey (see questionnaires attached in chapter 10.1). With more experience after the first interviews, almost all of the 'back-up questions' were eventually dropped.

5.3.3 Expert Interviews

At the beginning, the objective was to conduct five semi-structured expert interviews for each thematic focus (UMAR/Sprint and HiLo). These experts could include NEST actors from the sector, such as researchers, industry representatives, architects, or public authorities. Here, the desk study and online research laid the groundwork for an initial list of potential interviewees. With valuable feedback and support from Empa's NEST team, the list was subsequently refined to include the most suitable actors for this study. In the next step, an email including a project brief was sent to the relevant individuals.

Finally, a total of fifteen interviews were conducted, which can be divided into the following groups: UMAR and Sprint units (4), HiLo (8), and NEST¹³ (3). The reasons for the unequal distribution between UMAR/Sprint and HiLo varied and included: stays abroad by different individuals, organisational structures within companies that challenged easy communication, and personal or time-related factors. Consequently, the perspectives of spin-offs or research were absent in the UMAR/Sprint units. Here, some individuals could have contributed interesting insights that should be considered in future work. Nevertheless, as the statements from different interviewees corroborate each other, the results are valuable despite the uneven number of interviewees. Furthermore, including the perspective of an SME¹⁴ from another unit added a valuable perspective to the other fourteen interviews, despite being from another unit (STEP2, HiLo's "follow-up").

Overall, all the actors (or their companies/departments) were directly involved in planning the units (or NEST in general). Some experts also possess strong knowledge of a specific sector within the construction industry or have a broader overview of the topics. In line with Kuckartz and Rädiker (2022, p. 176), the interviewees can be categorised into six groups: NEST managers, architects, spin-offs, researchers, industry actors/NEST partners (including start-ups), and public authorities (see **Table 1**).

¹³ Including I9 with an actor from STEP2.

¹⁴ Small and medium-sized enterprises (SME).

The interviews were conducted between 20.06.2025 and 26.08.2025. In the end, the interviews lasted from 40 minutes (shortened version¹⁵) to 1 hour 46 minutes. Nine of the interviews were conducted via MS Teams, as this was more suitable for the interviewees¹⁶. The six on-site interviews were held in office spaces or conference rooms. The following table summarises the interviewees' aliases, their roles in NEST, and the interview details, including duration, language, location, and date.

Table 1: Overview of interviewees (own illustration).

Alias	Role	Unit	Duration	Language	Place	Date
I1	Management ¹⁷	HiLo	01:03:50	Swiss German	On-site	20.06.2025
I2	Spin-off	HiLo	00:54:04	English	On-site	30.06.2025
I3	Architect	Sprint	01:45:58	Standard German	MS Teams	01.07.2025
I4	Management	UMAR	00:47:52	Swiss German	On-site	03.07.2025
I5	Industry actor	HiLo	00:55:44	Swiss German	MS Teams	09.07.2025
I6	Architect	UMAR	00:54:48	Standard German	MS Teams	09.07.2025
I7	Research	HiLo	00:48:09	Standard German	On-site	10.07.2025
I8	Public authority	NEST	01:01:37	Swiss German	On-site	17.07.2025
I9	Industry actor	NEST	01:03:44	Swiss German	MS Teams	18.07.2025
I10	Industry actor	HiLo	00:39:55	Swiss German	MS Teams	22.07.2025
I11	Industry actor	HiLo	00:40:42	Swiss German	MS Teams	28.07.2025
I12	Industry actor	UMAR	00:43:57	Swiss German	MS Teams	29.07.2025
I13	Industry actor	NEST	00:46:32	Swiss German	MS Teams	11.08.2025
I14	Architect	HiLo	00:55:45	Standard German	MS Teams	11.08.2025
I15	Research	HiLo	00:53:16	English	On-site	26.08.2025

One to two days before an interview, a reminder was sent via email to the interviewee. Attached to this e-mail was the privacy policy, asking for permission to audio-record the interview while ensuring the interviewee's anonymity in the transcripts and quotes used for this master's thesis (see attached in chapter 10.2). This privacy policy was either already signed and returned before the appointment or discussed shortly before the interview.

With the interviewee's permission, the interview was audio-recorded with at least two devices. Following the interview, a postscript was created, either in written form (Word document) or by briefly recording thoughts in an audio file (memo). These postscripts contain information about the interviewees and surprising or striking thoughts from the interviews.

¹⁵ Requested by the interviewee.

¹⁶ One interview with an actor from outside Switzerland.

¹⁷ Standing for Empa's and their personal point of view.

5.4 Data Analysis

5.4.1 Ethical Considerations and Challenges

Anonymising interview data is a fundamental aspect of this research to ensure participants' confidentiality and trust. Preserving experts' identities is critical, as it allows interviewees to feel comfortable sharing more sensitive or candid information without fear of repercussions. Since interviewees may discuss their roles or the actions of other actors within the construction industry, anonymity becomes even more significant. To achieve this, I had to carefully consider how to anonymise the data, including personal and company names, hierarchical positions, and other identifiable details. Managing this data securely - including storage protocols - is equally essential. Throughout this process, transparency was a guiding principle. Communicating the research process to interviewees fosters trust and ensures they understand how their information will be used and protected. Potential conflicts of interest must also be acknowledged, as hidden or unknown competition between actors could influence the information provided during interviews. Power dynamics within the construction industry might lead interviewees to withhold details, selectively disclose information, or align their responses with company narratives. Another critical challenge relates to bias or conflicts of interest among actors. For example, information shared during interviews may be shaped by an interviewee's ties to industry stakeholders or certain lobbies. This raises an important methodological question of how to evaluate and incorporate data that might be biased.

5.4.2 Transcription

To transcribe and later analyse these interviews, MAXQDA24 was used. As many of the interviews were held either in Swiss German or German, the fee-based app 'Schweizerdeutsch Übersetzer' helped with the transcription. Powered by AI, this app can directly transcribe interview audio from a dialect into Standard German. Depending on the interview and dialects used, this app was more or less precise with its proposed transcripts. Therefore, every interview needed to be error-checked in a second step and adjusted where needed. For the two English interviews, the transcription software MAXQDA24 (also fee-based) and noScribe¹⁸, both AI-based, were used. Again, the interview needed error-proofing.

Furthermore, the first few interviews were transcribed word-for-word, including the interviewees' responses and my comments or disfluencies, such as "umm", "okay", "yes", etc. During transcription, I decided on an easy scheme using punctuation characters for each of these comments (see chapter 10.4). As these comments lacked any specific meaning and were intended solely to draw the interviewees' or my attention, the following interviews were transcribed without including them. To further simplify the transcripts, I gave myself the alias "A". To then anonymise the interviewee's names during the transcription process, the aliases of I1 to I15 (I = interviewee) were used.

If an interviewee was quoted directly for this thesis, some rules were applied. First, all non-English quotations were translated into English. Here, an effort was made to keep these translations as close to the originals as possible. Secondly, care was taken to make the quotations as anonymous as possible by removing all references to companies, positions, or similar.

5.4.3 Coding and Content Analysis

After transcribing the interviews, the next step was to develop a coding scheme. The final coding scheme was revised a few times before it was applied to the individual interview transcripts, using an inductive-deductive approach (see Mayring, 2022). To this end, the first two interviews were coded twice to refine the coding scheme and standardise the procedure. Some interviews were also revised later to ensure coding was as consistent as possible. The overall aim was to develop codes

¹⁸ Vers. 0.6.1.

that help with answering the research questions, while keeping the theoretical concepts and interview questionnaires in mind (deductive category development). During the analysis, more codes were added or merged (inductive category development) (Kuckartz & Rädiker, 2022; Mayring, 2022). The final coding scheme is attached in the annexe (see chapter 10.3).

To address the research questions, the interview data were coded into categories such as geographical scale, system resources, actors, and NEST units. Text segments were often assigned multiple codes to capture overlaps and thereby highlight interrelations and contextual meaning. In addition, analytical codes, such as couplings or similar, were applied to emphasise and capture the topics mentioned by the interviewees.

In a subsequent step, the coded segments were reviewed to identify relevant overlaps for selected themes – for instance, between geographical scales and specific units. For this, the MAXQDA24 function “near” was used, showing segments only if they had been mentioned within the same segment, as defined by me. This approach enables a more detailed understanding of the respective influences in the results and relationships, which were then differentiated by unit and analytical dimension in the results section.

5.5 Reflection of the Methodology

For this thesis, a total of fifteen interviews were conducted for two thematic focuses. However, the number of interviews per focus was uneven, with twice as many interviews for the HiLo unit. Since the overall number of actors in HiLo is larger, this may be difficult to avoid within the scope of this thesis. Additionally, almost all the interviews involved individuals directly engaged with the units or were identified through snowball sampling. This could affect the later generalisation of results, as most interviewees may share similar (positive) perspectives or at least demonstrate motivation to participate in a project like NEST.

6 Results

The following chapters present the analysis of the interview material and actor statements based on the methods outlined in the previous chapter (chapter 5). The structure of the sub-chapters follows the three research questions, organised by unit focus (UMAR, Sprint, and HiLo), and concludes with a summary presented in table form. It should be noted that some interviewees discussed only one unit, while others mentioned multiple units. Firstly, the formation of the four system resources – knowledge, market formation, financial investment, and legitimacy – is explored (chapter 6.1). This is followed by a breakdown of the geographical scales of impact (regional/national and international) (chapter 6.2). Finally, the multi-system interactions within the respective NEST units are assessed (chapter 6.3).

6.1 System Resource Formation

The following examines the results from the perspective of the four key GIS system resources (knowledge and technology development, market formation, investment mobilisation, and technology legitimisation), divided into two subject areas across three units. To conclude the chapter, there is a summary in table form, alongside a focus on regulatory frameworks, a topic covered throughout.

6.1.1 Urban Mining and Recycling

Knowledge and Technology Development

In NEST's UMAR and Sprint units, **knowledge creation** comprises diverse elements (e.g., shared visions, knowledge spill-over, multi-actor interactions, or scaling of solutions) (I3, I4, I6, I10, I12). In general, knowledge was **exchanged** among a wide range of actors within the units. Significantly, actors and disciplines from **across the value chain** were involved, including perspectives of craftspeople such as electricians.

“(...) all actors are involved – all disciplines across the value chain, including planners, architects, clients, material producers, and contractors. Everyone across the value chain needs to be engaged in a research project or platform” (I12, 29.07.2025, Pos. 39)

Networks of NEST partners developed over time, **sharing knowledge** and gaining greater **expertise** within the thematic fields of their respective units (e.g., recycling concrete, circular economy, reuse). Also, actors were assigned partner companies from Empa's existing network, sharing knowledge and support (I3). Nevertheless, some interviewees mentioned a **lack of knowledge**, which could hinder a wider diffusion (I3).

Offering **visitors** the opportunity to take part in guided tours, including students and experts, is an **additional spill-over** of knowledge. Here, the solutions presented in UMAR and Sprint stand in contrast to the “ready-made” products offered by the construction industry. Moreover, “sharing knowledge” is closely linked to a concern for the **education** of a “new” generation of academics. Besides, NEST actors provide **information and assistance** to external industry actors to promote future implementation of the solutions (e.g., architects) (I3).

In general, solutions in UMAR and Sprint are not ‘alien’ to the market but are well **known**. These units **supply a theme** – not a technological solution. As I6 explains, the products used in these two units are not necessarily novel, but their practical applications are. While topics like ‘reuse’ are known in the industry (“ancient history”), NEST is taking a **pioneering role** in applying **the products or technology** in question. Hence, many of the products entering UMAR and Sprint have already **completed development**, so that NEST actors primarily exchange knowledge (I4).

„With UMAR and Sprint (...), nothing was actually developed. There was nothing done there that had not already existed in some form before. There is no novel concrete slab or innovative climate system (...). These units were really about managing and showcasing a theme, and that is an important distinction.” (I4, 03.07.2025, Pos. 94)

Nevertheless, **long-term impacts** of solutions like reuse are also challenged. Especially with novel solutions, architects might only seek a “good” story that could benefit from lax regulations. One interviewee even cautioned against celebrating sustainability too quickly, emphasising the need to remain critical and to avoid creating future problems with today’s supposedly ‘sustainable’ solution (I3).

Market Formation

As I6 detailed, solutions for urban mining and recycling are **no longer niche**. Overall, the ideas have become **widespread** across the construction sector, accompanied by an **interest** and **awareness** of how to put them into practice (I4, I6). As I3 adds, **architects** seem particularly interested in novel solutions for reuse and recycling. However, more players are needed to strengthen the industry as a whole (I3). In parallel, there are **stark contrasts** even within individual units – some solutions are less successful, while others “explode” due to increased demand (I3, I4).

“At the moment, I have the feeling that the demand is greater than what we – or those who are on the market – can actually deliver, right?” (I3, 01.07.2025, Pos. 30)

“Yes, they [topics] have arrived. Their target, after all, is to bring the topic into the market. And yes, we have succeeded. With UMAR, absolutely. A very clear ‘yes’.” (I4, 03.07.2025, Pos. 96)

Moreover, products used in UMAR and Sprint are not entirely unfamiliar to the market; instead, they represent the **reuse or reapplication of conventional elements** (I6). Whether industry actors will take concrete measures or put their acquired knowledge into practice is another question. To a certain extent, some actors already do (I3). Furthermore, having more **references** and **pioneering actors** who actively discuss and illustrate successfully implemented approaches is essential (e.g., how certain building materials can be reused) (I3).

„Not everything that was implemented in the unit had an entirely new character. (...) Perhaps it had not been used this way before or had been used for something else. So, in that sense, it is not completely foreign to the market. (...) You simply cannot build entirely on something completely new, can you?” (I6, 09.07.2025, Pos. 41)

At the same time, UMAR and Sprint units are **places** within NEST, where **novel technologies or products** come into the world. Because of NEST’s characteristics, the units are **ideal places** for product launches or ‘kick-offs’ (I3, I6). Being a **lighthouse**, general conditions differ from the ‘free market’ (‘Freier Markt’ in German), allowing a ‘relatively great freedom’ (I6). Exceptions might include complying fully with norms or regulations and instead planning with “100 per cent sustainability” in mind (I3). The latter might conflict with the economic efficiency of such a ‘sustainable’ solution when introduced into practice. On a related note, I3 characterises NEST as a **bubble** in which interests are distinctly oriented towards greater ecological awareness, climate-adaptive solutions, and overall emission reduction. However, such objectives may at times overlook practical realities and risk becoming partially **unrealistic** or even **idealistic**.

“Because NEST has these special conditions and frameworks, different from what you would find in the private sector. The move from a demonstrator to the private sector is obviously smaller than from pure theory. But you shouldn’t forget that there is still another step to consider in terms of spatial impact.” (I6, 09.07.2025, Pos. 3-4)

“You can create the most amazing things, but if no one can afford to pay for them, it will remain a bubble, right? Or just a luxury segment. And for people who have a lot of money, the topic is probably too... I am inclined to say ‘unsexy’...for them to want to build exclusively like that.” (I3, 01.07.2025, Pos. 56)

UMAR and Sprint’s market formation faces multiple **challenges**, one of the most significant being the lack of **value chains linking** individual actors for core products or the reuse of building materials. After I3, establishing value chains goes hand in hand with achieving long-term economic efficiency. Here, a (current) **lack of demand** is challenging the successful introduction of thematic solutions presented in NEST (I4). This lack of demand is closely linked to (too) **prohibitive costs**, which impede the introduction of concepts such as reuse.

More so, the **scalability** of innovative solutions remains limited, as the absence of economies of scale and the often customised or **labour-intensive production** – unlike in industrial processes – inevitably keeps costs high (I6). Here, the **lack of profitability** led, in practice, to the absence of concepts like reuse. When leaving the LH, the idea of reuse and urban mining becomes “impractical” for some (I12).

„(...) I believe the demand must be so high that we could establish corresponding production lines, which would then be utilised permanently. It’s somewhat understandable, isn’t it? (...) On the one hand, we were quite enlightened, thinking: ‘Wow, there’s already so much out there’. And at the same time, we were again disappointed. When you then say: ‘It’s actually already possible, but we just can’t do it right now, we can’t make [reuse] economically viable yet’.“ (I3, 01.07.2025, Pos. 14)

For reuse to become economically viable, the existing building stock must adopt a more modular design, while current technologies for deconstructing and reprocessing building materials remain insufficiently adapted to support this aim (I12). Additionally, I6 describes the ‘**market**’ as **distorted** because the extraction of primary raw materials remains too cheap. Ultimately, a **trade-off** between cost efficiency and ecology seems to emerge – but as I3 emphasises, ecological value cannot be equated with monetary value.

Investment Mobilisation

Investments in NEST’s two units, UMAR and Sprint, depend primarily on the individual actors involved in the projects. Here, NEST, as the **host**, acts both as an **investor** and a “**financier**” of novel solutions (I3). Furthermore, I6 emphasised the underlying **network** and **participation** across NEST, maintaining the investments in UMAR and Sprint to remain “stable”. Overall, the ease with which diverse actors can establish themselves within NEST varies, partly due to **differing investment capabilities** (I1). **Start-ups**, for instance, must begin from scratch and seek external capital, whereas **established companies** are often able to allocate resources directly to specific areas of development. **Larger NEST partners** tend to conduct **internal research and development (R&D)** before joining NEST, meaning that significant financial investments have already been made (I4, I6). For these actors, R&D investments remain consistent both before and during the project. Also, in their own product development, their goal is to bring a commercialised product to market (scaling up) and reach clients and the wider industry.

“In the end, it [Sprint] was not even expensive. It was actually a low-cost project.” (I3, 01.07.2025, Pos. 54)

“(...) If you have enough resources, you can speed things up. But at some point, you have to decide what you’re actually going to do and where you have the money. Otherwise, you end up trying to solve the entire system.” (I1, 20.06.2025, Pos. 38)

Besides, I6 noted that reuse itself can constitute **value storage**. Constructing with reuse/modular/circular building methods could be a way to “store” a material’s value in the long term, with the potential to recover it.

“You practically secure the value of the material you build with. (...) Meaning that you have the potential to recover this material and its value again. So, it’s not only a question of investment costs, but also, in the long term, of storing or building up value.” (I6, 09.07.2025, Pos. 25)

A key **challenge** in advancing (reuse) solutions lies in the **relationship between the methodological approaches** and their **economic efficiency**, including issues of pricing, market demand, and overall acceptance. Here, interviewees made the **value of reuse** apparent. For some, reuse – in contrast to the recycling of building materials – currently makes **little economic sense** (I12). At present, reuse is not economically viable and is unlikely to change significantly in the future, even with the introduction of CO₂ certificates. Therefore, the reuse of elements such as steel beams is considered “pointless”, whereas the reuse of objects like toilet bowls or balcony railings can be reasonable. Thus, it is necessary to distinguish between distinct types of objects and, presumably, the effort required to reuse them (I12). Thus, the **distinction between reuse and recycling** is crucial, given the solutions

introduced and their potential future development. The resource of **financial investment** is therefore frequently linked to questions of **profitability** (cf. market formation) and cost. The **notion of value** associated with reuse – almost a fundamental question within the UMAR and Sprint units’ thematic scope – was also raised. I12 reinforced this argument by noting that many such projects are financed through “**business angels**”, meaning that they often have little in common with real-world implementation (“**reuse bubble**”).

“That is the difficulty, making it economically viable. It all comes back to economics. Many things are difficult to implement. But a lot of people do not want to acknowledge that because they are financed from elsewhere.” (I12, 29.07.2025, Pos. 37)

Certain actors, therefore, need to be “brought back down to earth” (I12). Such **external financing** can bias the picture, as it allows some actors to disregard whether their solutions are actually viable in the market. Profitability and financial investment are therefore closely linked: If external funding shields actors from the ‘downside’ of reuse, they can stay within their bubble; however, if this funding fails, they may face problems such as limited economic returns, which can impede broader scaling prospects.

Technology Legitimation

As I13 pointed out, one of NEST’s greatest strengths is its role as a “**neutral**” **platform**: it provides a space where provocation and experimentation outside strict regulatory frameworks and norms in construction are possible without the fear of losing clients – something familiar to many NEST partners (I13). Here, Empa acts as the host, offering a ‘protective space’ for experimentation, which is a rare and vital role within the national and international research environment and industry (I12). Furthermore, different actors experience **freedom** and **security** outside of ‘normality’ as key **values** provided by the LH. For I6, a LH is about unlocking **potential** and trying something new initially. Additionally, actual impacts and measures should include **reflections**, as these are equally important as the construction itself. All these elements together give **meaning** to measures like reuse in the built environment (I6). Moreover, NEST allows actors to explore proposed solutions, build **confidence** in the subject, advance their work, and ultimately develop a **proof of concept** (I3, I4, I6). Presenting innovative solutions in UMAR and Sprint also enhances visibility, **credibility**, and **trustworthiness**. Overall, research and industry actors connect within NEST and become “closer” (I6). Their strong relationships highlight the practical relevance of the solution, for instance, for universities such as ETH and UZH. Therefore, not only is new knowledge generated within the LH, but ideas are also legitimised through diverse contributing factors – such as high credibility, the research institute’s visibility, or factual evidence. Nonetheless, NEST as a LH operates within a specific **field of tension**. While it may present counterexamples and demonstrate alternative pathways, its solutions are not yet fully regarded as legitimate or mainstream, and certain barriers remain (I6).

“That is the so-called killer argument – the claim that ‘something like this can’t even be built; it’s completely unrealistic.’ To that, one can respond: ‘Look, it’s standing right there’ By translating such ideas into reality, it becomes possible to counter certain prejudices – for instance, to show that a material of rather humble origin can still result in a high-quality appearance. Nevertheless, not all prejudices can be overcome. This is partly because, despite its realistic foundations, the demonstrator still occupies a special position and is not, especially in the public eye, equated with an ordinary building project.” (I6, 09.07.2025, Pos. 29)

For UMAR and Sprint, **public tours** play a significant role – both in informing and inspiring the public and planners and construction experts – and thus indirectly contribute to value shifts among key industry stakeholders. According to I6, the themes addressed in UMAR and Sprint are present and actively discussed, with a **general awareness** of these issues within society. Moreover, solutions presented in UMAR and Sprint had seen broad uptake in international **media**, both specialist and mass media (I4). Examples include a feature in the ‘50th anniversary special’ of the well-known German Children’s TV series “Mouse TV” (I4). Here, media coverage creates **transparency** on the presented solutions. Overall, how people react to it might differ, and is beyond the media’s control.

„We have a good, even excellent, media coverage – consistently. And with new units, you get another peak, you know. Overall, I think our media coverage is strong, both in specialist media and in the broader public media.” (I4, 03.07.2025, Pos. 62)

The UMAR and Sprint units are linked to **expert consensus**. After I3, more experts, such as local communities (public authorities) or architects, seek assistance to meet climate adaptation goals, without aiming for competition (I3). There is also a connection here to knowledge spillovers from NEST actors to the industry or public sector (I3). Overall, the acceptance or receptivity to “novel” solutions presented in NEST is diverging – some clients might initially be hesitant but later proud, while others declare the proposed ideas as “crazy” (I3). Besides, the **profession** of industry actors might influence their acceptance of “novel” methods – working fields closer to ‘good’ building materials (e.g., wood) might be easier to convince than others.

“Woodworkers, i.e., skilled workers who already work with ‘good’ building materials, are always more open to this. (...) Steelworkers and façade builders, on the other hand, have tended to be a bit more... very closed-minded.” (I3, 01.07.2025, Pos. 52)

As I6 adds, the underlying **“mindset” of reuse** also includes thinking about how every construction material will – eventually – age. Thus, learning how to address this topic is crucial when integrating new values (I6).

“It is about being more aware of how things age, knowing when something needs replacing, and considering the options for keeping it in good condition. (...) It is not about lowering quality standards; it is more about consciously dealing with the fact that buildings age and figuring out how best to manage that.” (I6, 09.07.2025, Pos. 43)

However, **current examples** show that solutions in UMAR and Sprint have not yet been deeply institutionalised in practice. For example, some interviewees brought up current construction **award ceremonies** (I1, I9). In the end, the award was given to a “concrete block”. Reuse, recycling, or sustainable projects in general felt “alienated” – especially when the architects in the panel/jury had a background in academia.

„Sustainability, and especially things like risk and resilience, have been moving more to the forefront for quite a while now. But if you then look at the awards that are being given out, you can see that it is still mostly traditional architecture – no judgement intended.” (I1, 20.06.2025, Pos. 42)

At the same time, interviewees ask for **additional support** to enable more innovative solutions – at least, until they naturally gain a “certain level of acceptance” (I3). Also, NEST, as the host, has to prioritise their resources, as not every idea or solution can be supported.

6.1.2 Resource-efficient and Advanced Construction Technologies

Knowledge and Technology Development

Within HiLo, **knowledge** of innovative solutions is developed in different ways. Depending on the solution implemented, they are at **various stages of development** when entering the unit. In several interviews, a continuous innovation process was described (I7, I11, I14). Here, a particular **research character or pioneering spirit** stands out, leading to constant interaction between individual researchers and industry actors. Moreover, elements such as patience, the “risk and try-out” initiative, and mutual questioning of long-standing habits are part of this knowledge creation (I7, I11). Additionally, the transition from HiLo to industry to client can pose a challenge, as they might not embrace novel solutions. Here, convincing end users is vital as they will make the final decision (I12).

“That means you do not have any experience in this area [of NEST], so it is usually something new that you want to try out. A pioneering spirit is required to a certain extent, and development work needs to be done, which means that sometimes things do not work out, and you have to go back to the drawing board.” (I11, 28.07.2025, Pos. 5)

Some innovative technologies or solutions enter HiLo as already commercialised products, others as finished prototypes, and some somewhere in between (I7, I10, I11). For some of HiLo’s industry partners, **knowledge creation** occurred with their own internal resources (R&D) and was somewhat independent of NEST (I14). In HiLo, some solutions are still in the **final stages** of development. This also includes building materials that do not really exist in the market (yet), in the sense that they are not (yet) considered in standards. Consequently, **planning and delivery periods** can differ from conventional projects and pose a challenge (I10). Nonetheless, even though some research solutions are still considered prototypes, the **technology readiness level** within HiLo is high (applied science).

“I still have huge respect for Empa and the construction companies that went along with it [the proposed technological solutions]. And in the end – and this is the funny thing – when it’s finally up, you think, ‘Well, it must have always been planned like this, right?’. It all looks so natural. But the nerves, the heart, and the soul it took to get there were really intense. For us, it is almost exclusively prototypes. Nothing like this had ever existed in this form before. And of course, that is inherently a massive risk.” (I7, 10.07.2025, Pos. 38)

Knowledge spillovers occur in HiLo in several ways (I7, I11, I14). On the one hand, spill-over from previous research projects towards NEST under the supervision of researchers/research institutions (national/international) happens (I14). Examples include the spill-over of knowledge about models, calculation methods, simulations, views on technologies/processes, and novel concepts (I7). On the other hand, industry actors share their equipment and implementation competencies with other actors in the NEST project to effectively use a product, technology or similar. This also includes an expert who understands the implemented system and can teach others to use it as well (I7, I11). In the case of HiLo, stage builders have been such specialists, transferring their knowledge to other NEST partners (I11).

“(…) At best, ideas, visions, models come together with practical experience. And then you need construction companies that are willing to get involved, maybe even go a bit further and be creative, right? The appeal for construction companies is understanding how processes might change – how building might be done in the future, with robots or certain formwork techniques and things like that (…). And I think these kinds of applications, components, and demonstrators are ideal for enabling that kind of transfer. (…)” (I7, 10.07.2025, Pos. 56)

Another vital factor in knowledge development is a **mutual interest** in creating something new and in **proactively** thinking about the future (I2, I11, I14). For HiLo, such **joint innovation** or group experience translates into an **exchange in both directions** (practice/industry and research) to bring solutions together and make them work (I7, I12). It also underlines HiLo’s characteristic as a light-house project – and its practical relevance, distinct from a mere “research project”. Moreover, researchers abandon their virtual ‘bubble’ and enter reality. Thus, HiLo becomes a space where research, industry, and other actors meet, collaborate, engage, and actively seek solutions – together

(I2, I5, I11). However, I5 noted **missing places for “casual” interactions** among diverse actors, which could also serve as presentation areas for start-ups or “innovation corners”.

“Projects like this [LH] are completely different, as things are built in the real world, theory simply becomes reality. And then questions arise (...) even if there were countless meetings and concepts, etc., that could not have been predicted. This triggers a learning process on both sides [industry and research], but I believe that everyone can benefit from it in the end.” (I14, 11.08.2025, Pos. 36)

Another key element in the **development of knowledge within HiLo** was the **work process** (I11, I14, I15). On the one hand, some interviewees described developing innovative solutions as ‘**away from the traditional approach**. Mainly, when solutions originate in a research environment, HiLo would offer a first and needed **point of contact for industry partners** such as planners or construction companies. During the work process at HiLo, a key value for researchers was the opportunity for prominent levels of integration and **leading positions** (I15).

To “make it happen”, different disciplines collaborated to address open questions (I7). As a result, a **dual learning process** was created. However, it is also important to recognise that there is a limit to how “far” innovative solutions can go while still being supported by industry players. Here, “incremental” (or gradual) innovation is preferred over “systemic” innovation (I7). Additionally, the HiLo unit advanced **computational design** while enabling less experienced actors in this field to participate (I15).

“As researchers (...), we also learn about the real-world conditions that ultimately shape innovation to some extent. (...) If I try to do things differently, I would have to rethink all the processes, and then implementation and impact are very unlikely. Rebuilding the whole industry – that is a 20-year job. So, it’s always a stretch for us: How can we combine the industry’s practical knowledge and processes with the innovations we have? (...)” (I7, 10.07.2025, Pos. 56)

On the other hand, some interviewees viewed the **development process as “normal”** and comparable to different construction projects (I10). In HiLo, actors supplying “innovative” solutions joined forces with a similar group of actors, as in the “real world”, just on a much smaller scale: architects, façade experts, metalworkers, electricians, researchers, and others. Overall, a common focus of research on sustainability, especially on “design for circularity”, brings these actors together – showing “what is possible” and that it can be “very exciting, (...) meaningful architecture” (I15).

Knowledge transfer and spill-over also occurred beyond HiLo to an **international research community** (I7, I15). Overall, there was a strong, positive feedback, centring around HiLo as a real-life implementation of science. Likewise, the research community appreciate talking, sharing, and giving insights on the realities of such “real-life” projects. This includes sharing anecdotes or talking about hindrances – the “real talk” that offers valuable insights on what did not work or could be improved in the future (I15).

“(...) The HiLo project ended up meaning 45 publications for us. So, you really do get something out of it.” (I7, 10.07.2025, Pos. 16)

According to some interviewees, the **knowledge formation** within NEST HiLo’s unit is vastly different to how things would have been done in practice. This **dissimilarity** can be caused by a **researcher’s approach to planning** the unit: Everything is modelled and highly technological to achieve an efficient, optimised outcome. With every single step being modelled, everything looks pretty theoretical (e.g., form, structural aspects, etc.). This, in turn, intensifies the metaphor of the LH as a bubble for scientists – far removed from reality.

“And these things are absolutely not done in practice, to be honest. (...) We had to learn to (...) connect how we approach things with real life. We had to also learn in general kind of the sensitivities and how different partners work so to actually also respect that not everyone works like [this].” (I15, 26.08.2025, Pos. 8)

Within HiLo, **diverse challenges** and barriers **exacerbate the creation and development of knowledge**. The challenges can be categorised into three categories: 1) Scientist and their papers, 2) too little openness about failures, and 3) challenges of everyday working life. The **first** challenge described how sure scientists tend to jump from one innovation to the next, without sticking to the “complex” problems or breaking them down (I15). Additionally, funding compounds this challenge, motivating researchers to jump to the next “shiny” thing right away. Instead, a shift towards processes and reflection is needed (I15).

“(…) That is not what you write papers [about]. In papers, we want the latest, fanciest this and that. (...) I do not even think a paper would be accepted that talks about ‘what can we learn from this for real practice or something’. I do not know [it], or people do not do it either. People also do not have that experience or that attitude. They jump from one cool thing to the next, because the funding is already with the next (...). There are maybe some traces of these kinds of learning in NEST, but what is sad is maybe there could be more reflection.” (I15, 26.08.2025, Pos. 48)

The **second** challenge then criticises the lack of openness about failures within HiLo, albeit offering invaluable insights and lessons for future projects. **Thirdly**, the challenge of everyday working life encompasses a broader range of issues, given the diversity of international teams within HiLo. As was emphasised in the interviews, it is to be expected that difficulties may arise during a project, particularly those related to (work) culture, interpersonal relationships, or, in this case, language (Swiss German, German, English). In most cases, however, these are not significant problems but merely challenges of everyday working life (I7, I11). Moreover, developing an innovative solution within the NEST “environment” itself can be a challenge, as many aspects do not really have anything to do with research in the first place, including communication, protocols, and basic technical equipment (I7).

Market Formation

During the interviews, a **contrast of market readiness** between products entering NEST became apparent. Some interviewees emphasised the trade-off between market-readiness and (yet) unattainable ecological aims (I9, I14). Moreover, there is a **clear divide** amongst already **commercialised products** that came into NEST ready to use, mostly from large, partly internationally active companies (e.g., I5, I10, I13), and spin-offs or research-based products that came into NEST as largely finished **prototypes** (e.g., I2, I7, I15). On top of this, “experienced” companies can draw on **existing toolkits** and feed in their experience in HiLo (I7, I11).

“You would rather go for a solution that is 30% better and implementable than an 80% perfect one you cannot put into practice. I do not think we delivered the very best ecological solution [at NEST]. There are many better ones, but ours is feasible. It is implementable, and we even believe it is quite practical. That is why we hope it will genuinely succeed in the market.” (I9, 18.07.2025, Pos. 33)

After HiLo, innovative solutions experienced different **scaling effects** through market mechanisms. (I4, I7, I14). The joint objective of actors in HiLo is to convert solutions into marketable products by scaling up and “conquering a larger market for themselves” – thus achieving a certain “growth” (I7, I14). As various interviewees noted, access to niche or broader markets varies considerably and is inherently tied to the innovative solution itself.

“You cannot really make a blanket statement about that. (...) Many things are not successful. Then some are niche (...). [Others] are exploding. So that is going to create a big market. (...) Some things are (...) more on the sidelines, and others that are really starting to take off now, both in terms of solutions and, above all, in terms of themes.” (I4, 03.07.2025, Pos. 24)

Moreover, HiLo also accommodates two spin-offs. One originated from the **Rippman-Floor-System** (RFS), which was **spun off** and is quite successful now (I2, I11, I14, I15). There is a **substantial interest** from professionals and other market actors (I2). Today, their innovative floors are used in large-scale building projects. Therefore, HiLo initiated follow-up projects for the spin-off to win competitions for large-scale projects currently under construction. Importantly, these follow-up

projects are “normal” buildings, not experimental ones like NEST. Consequently, this success shows the industry that innovative solutions do work effectively (I15). Moreover, **other companies emerge** from a single spin-off, such as a new manufacturer of slabs – thus there is a connected success (I14). However, challenges remain, as HiLo represents a particular **environment**, and the step into the “real world” was – and still is – a “big development phase” (I2).

Another element contributing to the development and later market access of innovative solutions is **partnerships** of (international) industry actors with (national) research actors (I7, I14). An example includes HiLo’s air conditioning and ventilation system, a research project between industry and research partners. These projects are also ongoing, even after the HiLo unit was completed. Moreover, the novel control systems and solutions were directly transferred to the producer’s systems. However, how scaling up into a market or developing new, adjusted products might look remains an open question. Furthermore, other industry actors are more critical of innovative solutions, considering them too risky (I14, I15).

“So, people did try to convince them [industry actors], but for them it was almost too uncertain or just too specialised in a way, for them to say, ‘Right, we’ll make a product out of this straight away.’” (I14, 11.08.2025, Pos. 50)

Plus, HiLo also gave room to solutions that are still a **step away from realisation** or market entry. Being a LH and experimental place, this took the pressure off having to have a successful product at once, as “you never know what will come of it” (I14).

Moreover, HiLo **pushes innovation further** than other units within NEST. Therefore, solutions seem “further away” from market actors but closer to multinationals interested in future developments within the area of studies (I7). This is connected to **challenges** faced by industry actors in foreseeing or imagining the impact of solutions beyond HiLo (I15). Additionally, as NEST offers strongly research-driven projects within HiLo, a “proof of concept” and a follow-up concept for a solution’s market entry might be lacking (I5, I14). This lack of thinking ahead is somewhat connected to a disconnect of standard building practice (I5).

“The HiLo unit is perhaps one of the NEST units that really tried to push things quite far in terms of innovation. (...) Of course, other units are closer to the market and market developments. (...) Companies always ask, ‘What’s the next incremental step in my innovation?’ And what we are doing is maybe five steps before that. (...) And that means (...) that such things are often picked up more by bigger players – multinationals, large companies (...) who want to know where things are heading.” (I7, 10.07.2025, Pos. 18)

A **significant challenge** for further scaling is the **absence of a production or functioning value chain** (I2, I5, I9, I14). If the processes needed for the implemented solution are not adapted accordingly, the solution itself cannot be properly incorporated. Construction processes typically require the **coordination** of a heap of actors. Here, conventional products have established production and value chains – and thus have an advantage (I14). Moreover, there are numerous players for the same service in the construction industry. If someone changes a single element or technology by introducing an innovative solution, “you have to think about all the ramifications of the connected elements” (I2). Currently, the “innovators” have to undertake this part, often doing it “in-house” and “not sustainable”. Eventually, this should scale up to become (cost-)efficient. This **fragmentation of the construction sector**, therefore, hinders the implementation of novel solutions to some degree (I2, I9, I14).

“They’ve [another partner] taken a different approach, the theoretical approach. 70% CO₂ was saved using as little material as possible. It is feasible, but you cannot implement the system on a construction site. (...) While they have the maximum CO₂ solution, the entire construction process in the background is not functioning properly. (...) And that is why, in the end, it is not always the best that succeeds. Rather, it is what is simple, what people understand, and can be implemented.” (I9, 18.07.2025, Pos. 33)

Finally, the **critical question** arose as to what the **real impact**, if any, HiLo’s novel solutions will have in the immediate future (I11, I15). On top of that, the significance for **market development** for

industry partners also seems to be limited (I11). Moreover, short-term revenue goals contrast with long-term sustainability goals (I7). Even though a solution is currently being implemented in a ‘real’ building project in Switzerland, I15 does not make a strong connection to acceleration of its impact.

“What can happen to accelerate or have more impact? Nothing really. (...) People now want to see it applied at multiple scales. So, for example, in Switzerland: No chance for us. (...) So, I do not think you can accelerate specifically with the NEST thing.” (I15, 26.08.2025, Pos. 54)

Investment Mobilisation

How HiLo contributed to mobilising financial investment varies depending on the individual actors or solutions involved. On the one hand, interviewees described funding for **research-based solutions** as large from the beginning. Here, **various sources of funding** are listed: public education, private investors, the ETH Foundation, competition prizes (within education), and industrial sponsorships at different scales. Besides, the private investor was a Swiss individual. Moreover, some interviewees confirmed that Empa did in fact not pay for anything (I2, I7, I15). Also, **banks** can provide additional support, sometimes through **partnerships** with educational institutions on innovation projects (I2).

Furthermore, several industry actors have **strategic partnerships** with NEST, or HiLo in this case. Thus, these actors are solely supporting HiLo through **material ‘donations’** without actively participating in the projects (I10). An initial interest might surface because NEST, as a LH, is seen as ‘innovative’, cutting-edge, and international. Hence, bigger companies “want” to be part of this, and an agreement on a “special price” that works for both parties is reached (I10). An investment in HiLo’s innovative solutions, e.g., for prefabricated materials, might also result in their **later integration** into the companies (I14).

Additionally, industry actors provide other HiLo actors with **equipment and implementation competencies**. This also includes **sponsoring** things like hardware. Furthermore, industry experts are sent to explain to research actors, for example, how the technology worked (I7).

“(…) It is a bit of a game – seeing who can join in and who you can get involved. But in the end, it all worked out.” (I7, 10.07.2025, Pos. 22)

“Even I personally had to go on a fundraising round, and (...) I needed to bridge a gap of one million at the end (...) which I did thanks to a nice private donation.” (I15, 26.08.2025, Pos. 34)

On the other hand, **start-ups** did not receive any additional financial support (I1, I5). Similarly, I1 noted that **smaller partners, such as SMEs** (de KMUs), also faced a significant challenge with financial resources (I7). I14 describes a local SME as a “perfect NEST partner” in the Step2¹⁹ unit because they were highly initiative-taking, developed everything themselves, and continue to do so. Investing themselves “several millions” of their own money in the production plant reflects their initiative and interest in the solution (I1).

“From experience, it is mostly the big companies – the ones with research budgets and can oversee these extended periods – companies that think about how the building world will change in ten years (...). And that is a bit of a pity (...) – it is a dilemma. On the one hand, we are very keen to collaborate with smaller firms too, to understand where the difficulties lie and how we can contribute. But it is just not that easy to make it happen.” (I7, 10.07.2025, Pos. 20).

In contrast, **(international) NEST partners** had vastly differing sets of resources when entering HiLo in the first place (I4, I7, I10, I14). This, unlike the quantity of available (internal) resources, also translates into a grander research and development (R&D) budget (I7, I14). With the necessary internal R&D resources, novel solutions are often developed in efficient in-house testing labs. Consequently, some of the solutions of products used in HiLo might have been evaluated, produced, or distributed internationally (I14).

¹⁹ Follow-up unit of HiLo.

Technology Legitimation

Solutions in HiLo are fostering broader legitimacy for sustainable construction in various ways. The following chapter is organised around the different components that contribute to this resource. By making solutions visible in HiLo and giving them a value, a **real impact** is created (I7, I9, I15). Moreover, having **factual proof** in the form of a LH might trigger an invaluable **conversation** about the innovative solution (I2, I7, I10, I11, I15, I15). Especially the international **research community** answered with **strong positive feedback** on HiLo's factual proofs (I7, I9, I15). The unit thus summoned the voices of scientists praising the innovations' "real-life implementations". Importantly, HiLo also builds **trust** and **credibility** for the individual solutions – for example, by using the novel Rippmann Floor System (RFS) instead of conventional floors (I14).

"These are people [like] that, if they do not see, they do not do [it]. (...) You have to see it, and then you do it. So, HiLo was extremely important because otherwise the only thing you can see is the [virtual] model that you have." (I2, 30.06.2025, Pos. 72)

Also, the element of credibility can benefit industry actors for their **own solutions and persona**. Industry partners connected to HiLo might see NEST as "beneficial", as it gives their own person or company more credibility. Additionally, being part of HiLo might lead to a long-term, trusting (industry) partnership, which is key for future projects. Besides, HiLo can be used to launch an actor's own product, benefiting from HiLo's credibility (I5, I10, I15).

"We have pushed a lot of innovative things or unique things in how we work. What for sure has come out of it is that I believe in trust. Trust can only be built when you have partnerships – trusting partnerships – and long-term". (I15, 26.08.2025, Pos. 14)

Although HiLo has gained increasing acceptance among research and industry actors, its **actual impact** remains hard to measure and judge (I15). Even with enhanced trust, credibility, visibility, and proof of concept, the transition of an innovative solution towards tangible impact remains uncertain. Moreover, NEST's **influence on market trends** is somewhat **challenged**. After I10, the innovative solutions would have their justifications within markets; however, their concrete value remains unclear. Overall, HiLo and NEST, as a lighthouse, are still perceived as **far from real-world conditions**, remaining largely within a laboratory setting with limited links to practical implementation. If a "real" project were to emerge, interest in HiLo would accordingly vanish. One important reason is the **lack of experience** from long-term residents – real buildings provide more extended and authentic data. HiLo's strong technological solutions created additional **challenges**. The development of novel technologies **pushed boundaries** far beyond those of other units, resulting in substantial structural innovations but also delays and increased uncertainties (nervosity) (I15). Moreover, the construction sector's inherent **risk awareness** constrained the willingness to experiment with novel solutions (I2, I15).

"NEST has a very rosy kind of definition of 'you bring [in] industry' – in our case, it helped to jump something off, but there was so much more work needed, and I am continuously surprised (...) because (...) we had done quite detailed prototypes before. You bring architects, colleagues, (...) clients, and so on. (...) So, then we build it in NEST and then [they] say this surely does not work, and I am like: 'But listen, acoustically, you – do you hear anything? It clearly works!' And then [they say] 'yeah, okay, but (...) you cannot make it work acoustically [like this]'. So, you have something physical where you are interacting with – and even then, there are these comments and scepticism. (...) So, you show like the most advanced structural prototypes, x prototypes – not enough. You build it in a real project – you are standing there – not enough! (...) So, it is (...) a first proof of concept – but it has nothing to do with an impact in industry quite yet." (I15, 26.08.2025, Pos. 12)

"There is a lot of kind of risk aversion – by the way, it all makes sense: Our industry does not have any margins – If anyone takes a risk and it goes wrong, you go bankrupt right? You're done." (I15, 26.08.2025, Pos. 12)

This demonstrates how industry actors might prefer sticking to the 'tried and trusted', creating what I15 calls "risk bubbles" (structural, financial, legal, insurance risks, etc.).

Education, as another key element in the acceptance of an innovative solution, has also been raised during several interviews. Visiting HiLo can introduce students to state-of-the-art research, thereby bringing together education and practical research. By offering **workshops** and integrating the innovative solution into future CAS or MAS degrees, this link to education could be strengthened (I15).

Other actors contributing to understanding how innovative solutions in HiLo are already accepted and validated are **political authorities** (I7, I14). The unit has already received frequent visits from various authorities and agencies, indicating significant curiosity.

“(…) I have always found projects like this in Switzerland to be extremely productive. (…) That is definitely one of the strengths here – the way people collaborate with the authorities. I do not know any other country where that happens. Where you are actually able to shift the boundaries together and say, “yeah, let’s give it a try.” (I7, 10.07.2025, Pos. 70)

On top of that, NEST with HiLo represent a **communication platform** (I10). Through media, HiLo can share their **latest findings** with a broader community, encompassing diverse target groups such as scientists, industry actors, public authorities, and the public (I7, I11). Examples of contributions include a TED talk, the “most general, general public thing you can do” – showing that people are curious about the innovations happening in HiLo (I2). Overall, HiLo was portrayed in the media because it was “easy to show” – but the long-term “effect” of such reports is still an open question (I11). Also, I1 hypothesised a decrease in media posts on HiLo.

“(…) I give tours to really general public, and they are so interested because they do not know [a lot] about this stuff. And it’s actually quite interesting to enter – because if you see a presentation (…) – okay, it is boring, but if you see it and it’s like: ‘Okay, I can have it in my house, and it’s sustainable’.” (I2, 30.06.2025, Pos. 24)

HiLo also has a significant role in transforming the common conception of **research as “spaceships”** (I15). The unit demonstrates the role of “research” in our society and how important people’s perceptions and acceptance of an innovative solution are. Additionally, reflecting, writing, and talking more about **hindrances** make LHs, like NEST, more tangible. Moreover, hindrances are closely associated with a **natural scepticism** towards novel solutions. There, I15 stresses the need for a very open and transparent reaction to people’s natural scepticism.

“We need to do much, much better as academics to clarify how our spaceships are actually relevant for day-to-day business and why we have done things in certain ways. It does not mean that we propose these kinds of extreme things, like in HiLo. But we do it so extreme to actually test our systems, to show that even for such complexity, you can approach it in a very controlled kind of way.” (I15, 26.08.2025, Pos. 48)

“Maybe it’s a way of being very open and transparent. (…) There is a natural scepticism of anything that looks different from other things. And so, by being maybe more transparent also of the less rosy side of things, perhaps that actually helps to adopt more.” (I15, 26.08.2025, Pos. 52)

6.1.3 Summary of results related to RQ1

Norms, regulations, and standards are closely linked to the local and global construction industries. In Switzerland, examples include SIA, ISO, EN, or “Minergie” (SIA, 2013). There are also various legally binding frameworks for defining emissions, energy consumption, and sustainability in construction. These operate at the global level (Paris Agreement), national level (SIA’s climate pathway), or regional level (Der Bundesrat, 2021; SIA, 2025; United Nations, n.d.). According to the SIA, these standards include “prescriptive publications” on knowledge of living environments – including safe construction, with a focus on “functionality, durability, and economic viability”. As a “set of rules” of legal importance, professionals in civil engineering, architecture, technology, and the environment are guided by these standards (Górecki et al., 2019). At the same time, standards should not hinder creativity and innovation (SIA, 2024). Furthermore, norms are widely accepted by the public (SIA, 2013). This key thematic issue on **regulatory frameworks** frequently appeared during the interviews and cannot be clearly linked to any of the four system resources discussed in chapter 6.1. Instead, it acts more as an element that consistently runs through statements about various system resources (for example, new material development, market access, prevailing standards as fixed rules) and is seen both as a supportive and limiting factor.

“(…) From my point of view, NEST can almost only exist here in Switzerland (…). Here in Switzerland, entrepreneurs and engineers are allowed to take on a greater degree of personal responsibility when it comes to implementing a product as a prototype in NEST. (…) Everything used in NEST still has to meet the same requirements as it would later on. Fire safety regulations apply just the same, the structural integrity has to work the same way (…). But everything concerning construction and safety must be fully complied with.” (I14, 11.08.2025, Pos. 44)

This quote exemplifies how the underlying regulatory framework takes a central role within a LH project like NEST. Therefore, regulatory frameworks are particularly relevant to the topic of this thesis, the construction sector, and were mentioned repeatedly throughout the interviews. This complements the results of Sovacool et al. (2025, p. 6), which show that institutional change can play an instrumental role in policy experimentation and eventually accelerate transitions. The results are summarised in **Table 2**, structured around contributions, limitations, and the units.

Table 2: Regulatory frameworks sectioned after contributions and limitations (own illustration).

Regulatory Frameworks
Contributions
- Public authorities in Switzerland as positive and solution-oriented, enabling innovation - One of the main tools that help to ‘break out’ of the niche and achieve economies of scale for innovative solutions - LH as a platform with partly reduced risks. NEST as ‘safe’ environment for testing - Parallel development of technology and associated standards might encourage the use of innovative solutions
Limitations
- Dependence on standards, regulations, or laws may hinder innovative solutions, potentially causing conflict or lengthy approval times if proposals push boundaries too much - Lack of political pressure, for example for instruments including incentives or CO₂ pricing

Furthermore, summarises the results presented in chapters 6.1.1 and 6.1.2 of UMAR, Sprint, and HiLo’s contributions to mobilising key system resources, such as knowledge and technological development, market formation, investment mobilisation, and technology legitimisation. Additionally, the results are categorised into contributions (with a positive connotation) or limitations (with a negative connotation) to socio-technical transitions. For this table, the qualitative findings are condensed and organised under shared thematic headings.

Table 3: Results of RQ1, organised into the four system resources (own illustration).

Knowledge and Technology Development	Market Formation	Investment Mobilisation	Technology Legitimation
Contributions			
- Place for research, knowledge exchange, and spill-over across the value chain - Research-driven and pioneering spirit - NEST is open to public, students, and external industry actors - Focus on the practical application of products. (UMAR/Sprint) - Work process as different or as comparable to conventional construction (HiLo)	- Ideas considered as widespread - Implementation of both prototypes and commercialised solutions - Reusing or reapplying conventional elements (UMAR/Sprint) - Connected to interest of available solutions - Formation of novel projects form - High readiness level of solutions (HiLo) - Experienced companies can draw on existing toolkits. - Examples of successful spin-offs (HiLo)	- Investments vary depending on the solution - Underlying networks and partnerships can provide support - Internal R&D of (international) bigger companies - Building as value storage. (UMAR/Sprint) - Large funding for research-based solutions from the beginning (HiLo) - Agreement to later integration of solutions (HiLo)	- Safe, neutral platform for experimenting, fostering reflections and engagement across diverse actors. - Proof of concept for transformative ideas - Strengthening of actors' credibility and trustworthiness. - Acceptance and validation from different experts - Broad uptake in international specialist and mainstream media - Reflection on hindrances helps to bridge research with other actors (HiLo) - Strong positive feedback from the international research community - Starting point for long-term and trust-based partnerships within the industry
Limitations			
- Sometimes unclear intentions of users - Inherent 'laboratory character' (HiLo) - Long planning and delivery periods (HiLo) - Lack of places for informal meetings within LH - Coordination of a many actors is challenging and cost/labour-intensive (HiLo). - More reflection needed to understand complex problems and underlying processes - Challenges including communication, basic technical equipment, etc.	- Innovation in NEST as a 'bubble' that is detached from practical and market realities. - Limited demand and prohibitive costs of solutions developed in NEST - Limited scalabilities hinder the transfer to real-world projects, where financial risks become decisive - Absence of established production and value chains and fragmentation of the construction sector - Lack of knowledge of potential customers (UMAR/Sprint)	- Challenges in obtaining financial resources, especially smaller companies - Limited economic efficiency of solutions - Some actors/projects would benefit from 'business angels', (UMAR/Sprint)	- Risk awareness of the construction sector - Wide-spread scepticism towards novel solutions (HiLo) - Impact on practice and market trends is questioned. - Conditions within LH "far" from real-world conditions, remaining within a laboratory setting - Lack of experience and long-term data - Delays and increased uncertainties - Current focus of construction should shift to be more impact-driven (e.g., award ceremonies) - Limited resources within NEST to be present at key events (e.g., trade fairs) - Challenges because of highly technological solutions (HiLo)

6.2 Scales of Impact

The following two chapters will shortly present the geographical impact of NEST, again divided into the two subject areas, followed by a summary in table form.

6.2.1 Urban Mining and Recycling

Regional / National

UMAR and Sprint's geographical impact is often most directly relevant at the **regional and national** scales (I1, I3, I4, I6, I12). Here, interviewees emphasised implementation projects elsewhere that directly relate to UMAR and Sprint's **thematic priority**. One example includes a project in Basel, where thousands of square meters of carpet were removed from an office building and later reused. Here, the impact was on a local scale. Another example is the application of reuse practices by other actors (architects, etc.) across Switzerland, as NEST sets an example with its UMAR and Sprint units (I12).

Additionally, specifics regarding **regulations and norms** are tied to the extent to which solutions are scaling, as solutions might be limited by regional (Swiss) permits or conditions, e.g., for sprinklers or electrical installations (I6). As I3 adds, this primary impact on a national scale might extend to other German-speaking neighbouring countries; however, I3's objective is to remain within a regional context, without any wish to expand to larger scales. After I4, UMAR also played a leading role in the introduction of the **canton of Zurich**'s 'circular economy bill' (see Kanton Zürich, 2020).

"So, UMAR did play a driving role in getting the circular economy bill introduced in the canton of Zurich, right? They even made a short film about it, where I got to say a few words, too. (...) It's recognised at the federal level too." (I4, 03.07.2025, Pos. 66)

International

Simultaneously, the **issues** raised in UMAR and Sprint are not confined to a specific region or country but are of **global interest** (I3, I6). Furthermore, the diverse international construction industries and their regulations are often comparable and interconnected across national and global levels – even though regional specificities exist (I3, I4). In particular, certifications like ISO address the concept of 'circular economy' on an international scale. As I7 states, the interest or engagement with this topic is "definitely an international concern" and not limited to a regional context.

After I3, they receive increased interest from **local communities** across **Europe**, which feel pressure to meet climate targets and are now seeking solutions. Here, reuse or building within the existing stock ("Bauen im Bestand" in German) is presented. I3 generated significant interest when presenting his work on NEST units across Europe. As I3 notes, the 'international' community must understand that reuse works (even if its concrete implementation potential is price-driven).

"There's a lot of interest. On the one hand, in what we are doing, and interestingly, primarily from municipalities that are now under pressure to reduce CO2 and more or less reach net zero by around 2050. And they are now also realising that reuse and building within the existing stock can be viable options. (...) You shouldn't give up what you have got [in building material] too easily." (I3, 01.07.2025, Pos. 30)

6.2.2 Resource-efficient and Advanced Construction Technologies

Regional / National

When discussing HiLo's geographical impact, two interviewees highlighted the **strong local nature and connection** of the Swiss construction sector (I14, I15). As I15 notes, over forty subcontractors had to be organised to 'make it work'. Here, the **geographical proximity** of actors was also important. Specifically, most construction companies were based in Switzerland and primarily located in the Zurich region (I14). Additionally, a major private investor in HiLo also had a Swiss background, underlining the strong geographical link. Furthermore, HiLo's construction phase coincided with the **COVID-19 pandemic**, further emphasising the importance of geographic proximity. Moreover, the introduction of videoconferencing also enabled actors to participate in planning processes that were previously impossible (I14).

"The geographical proximity is definitely relevant, because even with the projects we had, this whole coronavirus situation occurred during the construction phase of HiLo. After that, a lot changed in how we plan and in everyone's preparedness to plan via video conferencing or similar methods. I think a lot more became possible after that" (I14, 11.08.2025, Pos. 14)

Following the NEST project, there are ongoing larger projects, such as the high-rise office building 'CreaTower'²⁰, with more to come (I9, I15). Nevertheless, further **diffusion** beyond the current level is **limited** by Switzerland's low level of **digitalisation**, which is 'lightyears' behind international standards (I15). After I15, solutions for 'everyone' are needed to scale further and diffuse HiLo's innovative solution, without making them 'too fancy' for customers.

HiLo's roof structure has not yet widely affected **national practitioners**, although it **gained** traction in the **international scientific community** for its structural and computational design (I15). Here, a **gap** between national/international and industry/scientists became apparent: The roof is unlikely to be replicated as is, but it will inspire on a technological level. Thus, there is **no direct national** but a linked **international relevance** (I7, I15). Additionally, the unit's "untypical, not-Swiss" architecture might limit its impact in Swiss architecture curricula (I15).

"(...) [The roof] is being very inspirational for all the computational designers in the world. So, there is a lot of parametric design, complex architecture and so on. For example, the Chinese, the Indians, the Iranians are all over it, because they are just not only very good, but they are all about this kind of highly complex computational architecture. Yeah so (...) that went entirely viral, people are really impressed by it and so on, but the relevance is (...) minimal. So, in that sense also: It has inspired researchers, (...) but not necessarily practice." (I15, 26.08.2025, Pos. 12)

Participating in innovative solutions demands either financial or human resources. Smaller firms, such as SMEs, often lack the funds for projects like NEST (I7). This is also one reason spin-offs emerge and then undertake many tasks along the production chain, as "nobody [else] wants to do this" (I2). Nevertheless, in STEP2, a "follow-up" unit of HiLo, a Swiss SME, invested millions in a local production plant for an innovative floor slab, highlighting the potential for future development on a national level (I1).

²⁰ Ten-storey office building in Zug (CH), designed by Gigon Guyer architects (Gigon Guyer Partner Architekten, 2022).

International

Many of HiLo's (strategic) partner companies are **large international companies** (I7, I10, I11, I13). Overall, the diverse partners have been described as 'extremely international', with a presence in various countries and even continents. A majority of actors in HiLo have a **strong bond to Switzerland** – for example, by having their headquarters in Switzerland (I7). Again, the **geographical proximity** to Switzerland seems pivotal, even for companies with global projects (I7).

"These are companies based in Switzerland. They can also be international firms, but with a clear connection to the Swiss context. And in this case, there was also a Swiss private individual involved [investor]." (I7, 10.07.2025, Pos. 26)

"They [NEST team] knew about us, and they knew about our product. They wanted to use it because it is something genuinely innovative. We then agreed on a special price that suited both parties, which allowed us to take part. From there, it developed in a step-by-step manner. Other people at NEST saw it too, which is why we are now in three units." (I10, 22.07.2025, Pos. 17)

Additionally, foreign companies have also invested in HiLo. Especially research-focused firms, such as BASF or Mitsubishi, have contributed to these solutions. In these instances, testing, development (R&D), and production are often carried out outside Switzerland. However, international or 'non-Swiss' partners are the 'exception rather than the rule' (I14). Moreover, foreign imitators may encounter challenges due to differing legal regulations (I4). As I7 explains regarding a living lab in another country: "The current practice is simply a bit different there" (translated from German).

One notable example in HiLo is the **floors**, which are being used in various projects across **Europe** (Switzerland, Belgium, UK) and in pilot initiatives **worldwide** (India, USA) (I2). Additionally, the floors serve a very different purpose in a project in South Africa (I15). Furthermore, there is a 'mock-up' project in Germany (Stuttgart) that appears to replicate HiLo's floors (I15). However, as I7 observes, the true impact of HiLo is hard to assess, as stakeholders continue their research, leave NEST, or may not pursue the innovative solutions further (I7).

In summary, many of HiLo's innovative solutions have attracted an **international audience** (I2, I7, I11, I15) and have been implemented in real-world contexts in Switzerland and internationally. Primarily, this interest comes from a **scientific community** (I7, I15). Secondly, the **public demonstrates** its curiosity by engaging with HiLo on a more public platform, such as a TED Talk (I2). Moreover, I11 emphasises NEST's international **pioneering role**. Here, its level of awareness is closely linked to local events, such as presentations or tours.

"But from us: [they come from] anywhere. Anyone who comes and visits us for sure says, 'Can you also take us there?' (...) It keeps happening, like this unit, when was it built already? Quite a while ago (...). It officially opened (...) four and a half years ago! It was finished over Covid (...), and so that is already a while that has been there, and still big delegations come (...)." (I15, 26.08.2025, Pos. 20)

„(...) You can write a lot of papers – nobody reads them, at least not ordinary people. But once you put something out there physically, you can, of course, see how it might have an impact. The risk, and this is maybe even stronger with HiLo than with other units, is that people who visit say, 'Well, this is too far away from my reality.' (...) That is where excellent communication is essential." (I7, 10.07.2025, Pos. 36)

6.2.3 Summary RQ2

Table 4 offers an overview of how the impacts of the NEST units develop across different geographical scales, as described by the interviewees. It summarises both the types of influence seen at regional, national, and international levels and the constraints that limit these effects. At the Swiss level, the results emphasise the importance of geographical proximity, locally embedded reuse practices (UMAR/Sprint), and NEST's role as a research site (especially HiLo) – while also highlighting structural barriers such as the strong local character of the construction sector, limited digitisation, and restricted diffusion into broader industry. At an international level, the table demonstrates that themes such as reuse, circularity, and innovative construction attract widespread interest from municipalities, companies, and the scientific community (HiLo) beyond Switzerland. Also, the solutions resonate internationally through global networks, regulatory debates, and public engagement. However, the findings also reveal that regulatory differences between countries can limit the broader adoption of these solutions. Overall, the table highlights the multi-scalar nature of NEST's impact while also emphasising the structural, regulatory, and sectoral conditions that influence the extent and ways in which these innovations spread.

Table 4: Summary table for RQ2 (own illustration).

Results
Regional / National
- Reuse practices and projects with a similar thematic focus across Switzerland (UMAR/Sprint) - Many actors have a geographical proximity to NEST/Zurich/Switzerland - Important as research location (especially HiLo) - Swiss SME investing in production plants (STEP2) - Temporal overlap with Covid-19 pandemic intensified importance of geographical proximity
Limitations
- Strong locality of Swiss construction to solutions reaches of impact - Switzerland's deficient digitalization (HiLo) - Limited impact on national industry (especially SMEs) - Untypical, 'not-Swiss' architecture lessens impact on Swiss education (HiLo)
International
- Reuse and recycling are of international interest (UMAR/Sprint) - Importance of international regulations and regional distinctions - Interesting for municipalities and audiences across Europe (UMAR/Sprint) - Interest from an international audience and science community (HiLo) - Engagement from public (e.g., via TED Talk) - Many partner companies work on a larger, international scale (HiLo) - Installation of floors throughout Europe and globally (HiLo)
Limitations
- International regulations might not allow solutions

6.3 Multi-System Interactions

The following two sub-chapters examine the results and the multi-system interactions among elements in the two NEST units. For this, the sections follow the different couplings (structural, functional).

6.3.1 Urban Mining and Recycling

Continuous collaboration between diverse players is the starting point for many of UMAR and Sprint's products (I4, I12). Therefore, multi-system interactions and **organisational couplings** can be observed. Actors from architecture, engineering, and fabrication interacted with one another, at large, across disciplines **within the construction sector**.

Also, in the UMAR and Sprint units, **NEST** was described as the **bridging element** that connects people, ideas, and knowledge (I4, I6). Moreover, I12 stressed that **Empa**, as the host, would enjoy a "natural high status" – and that the solutions linked to it would have high credibility. Besides, Empa has a strong **network** of industry contacts through various **partner companies** (I3). As I3 notes, these partners in Empa's wider network would be 'ready to assist' NEST actors along the way. Furthermore, I6 mentioned the **woodworker** responsible for the base construction of the units as a central link.

„If there is one thing at NEST that really works well, it is the interdisciplinary collaboration. Everything happens on an equal footing – no one is placed above anyone else. There is an open discourse. Of course, it needs to be organised. And there have to be a few key figures who help set the direction. But because the framework is open and, at least in our project, not overly regulated, many different kinds of connections emerged, allowing everyone to contribute. Even actors who initially thought they were merely a means to an end were able to bring their own ideas and perspectives on the topic.“ (I6, 09.07.2025, Pos. 31)

“(…) I believe there is also a lot of development in the planning processes right now, but it's a very ideal environment there [in NEST], because from day one, the contractors and planners sit down together and develop the solution together“ (I14, 11.08.2025, Pos. 24)

I3 also highlights that, beyond NEST, interactions between architects and steelworkers have been gradually strengthening when working on reuse projects (strengthening of actor coupling).

Within the multi-system interactions among elements in the two NEST units, institutional couplings are significant. According to I6, **regulations** surrounding the "circular economy" **cross national borders** and meet **international interests** (e.g., ISO certification). Additionally, regional or **country-specific** regulations for circular construction exist, e.g. SIA (Switzerland), or DIN (Germany and transregional). At the regional or local level, UMAR's proximity to **public authorities** is evident in its collaboration on the new "circularity article" in the canton of Zurich (I4).

Simultaneously, UMAR and Sprint enabled actors to '**maximise**' **sustainable construction** – without the (restrictive) 'input' of any opinionator, client, or public authority. Having **Empa** as their client allowed actors to 'make mistakes' – giving them the stability to try out innovative products (I3).

However, I3 emphasises that the present legislation does not yet adequately reflect the need for change. Here, the **pressure** to implement an innovative solution could be increased by introducing CO₂ taxes, aligning the price of the conventional solution with that of the novel solution (or vice versa) (I3). Furthermore, UMAR and Sprint's solutions for circular construction and related knowledge are not always in line with demand, suggesting they may not be fully accepted by society (I3).

Apart from interactions between actors, **functional couplings** can also be observed: In UMAR and Sprint, diverse building materials have been reused or recycled to create novel solutions. As such, also 'waste materials' from industry, including plastics, have been **transformed** or **adjusted** to fit within the units (e.g., Tetra Pak, cotton, or PET bottles).

„Well, let us say waste materials, of course. I mean, if you are talking about, for example, using waste from one industry – collecting plastic packaging or certain cotton textiles, and then wanting to use them in that way [in NEST]” (I1, 20.06.2025, Pos. 50)

The interviewees also mentioned the flow of material between projects. In Sprint, for example, **carpet** was introduced as wall insulation, hitherto used as flooring (I3). Thereby, the material’s functionality was used for another purpose (functional couplings). Thus, NEST actors used a material known primarily for one purpose and introduced it to circular construction practices.

6.3.2 Resource-efficient and Advanced Construction Technologies

NEST’s HiLo unit stimulated a variety of solutions, bringing together diverse actors (**organisational couplings**). I15 emphasised this “Vielfalt” (diversity), a **fan of options**: Rather than a ‘typical’ LH, NEST resembles a **think tank** (I15). Many interviewees described the formation of **novel interactions** and NEST being a ‘**network platform**’ (hence, a site of interaction). The latter would benefit new contacts – vital for specific projects (I14). Organisational couplings were thereby established. In HiLo, for example, a stage builder applied and shared his knowledge of “spraying processes” to a completely different field, simultaneously applying building materials in a new way (I11).

“(…) What is very unique again about NEST – and kudos for whoever came up with this concept – is that you really have a broad variety of approaches and solutions there, and that makes NEST particularly exciting to bring also people [there] (…). It makes it actually quite a destination, and I think it will remain a destination of inspiration because of that Vielfalt [diversity], that kind of variety of options. So, it is kind of cool. It makes it also less black and white as a Leuchtturm [LH].” (I15, 26.08.2025, Pos. 20)

„(…) Like a networking platform. (…) What I find interesting is that people can meet there who maybe didn’t even know each other existed, and who didn’t realise they could help each other.” (I14, 11.08.2025, Pos. 40)

Overall, HiLo was an interdisciplinary working environment (I3). Interviewees noted that “everyone is on an equal footing with one another”, except key figures who are “managing” the project (I3). I14 mentioned that when research, planning, and industry sectors collaborate on innovative solutions, there is a certain potential for misunderstandings. However, the experiences have largely been positive during the HiLo project (I14). Additionally, other actors across disciplines, such as architects, industry professionals, planners, or researchers, reported positive experiences (I3). Nonetheless, some fields maintain a highly hierarchical structure, as seen with architects, who were described as the “Gods in Black” (I13). However, strong hierarchical working cultures can present challenges, especially in interdisciplinary environments like a LH, which rely on exchange between equals.

However, as I2 noted, many actor networks existed before entering NEST and are by no means “new” but rather well known. Therefore, it must be noted that specific organisational couplings were already established. As I14 points out, most actors’ interactions are not entirely novel to the construction industry, especially not within construction (e.g., robotics). Thus, it is not a completely ‘novel’ sector interaction, but rather within the construction sector, where innovative solutions appear, and the industry itself might start to shape differently. Therefore, it is a sector interaction within the construction sector, not beyond the sector’s borders (I14).

“I think it is clear to everyone that interdisciplinarity is much more important for achieving good solutions. I think many actors – especially those who are successful – understand that. I believe you have to look at where new areas of expertise exist that you can make use of to improve, right?” (I1, 20.06.2025, Pos. 48)

“Many of these collaborations were already there before we worked on the unit itself. So, it was easier to work already with friends or with people you already know.” (I2, 30.06.2025, Pos. 8)

Moreover, interviewees described the relationship among the diverse elements in HiLo as **collaborative** and characterised by **constant interaction** (I5, I7, I8, I10, I11, I13, I14, I15). More so, important insights concern **bridging theory and practice** and developing **sensitivities** for collaborating with diverse partners (I15). During the HiLo project, actors from industry, research,

architecture (national and international), and other fields were in **‘constant’ interaction** (I7, I14, I15). In HiLo, **market actors**²¹ and **researchers** came together – a crucial aspect, as this kind of collaboration had not existed to such an extent before. As I8 noted, practitioners need to see and engage with the available innovations. Also, more ‘real’ interactions and conversations happen compared to “only” drafting papers or presenting a simulation, as I7 emphasises. In this sense, NEST’s HiLo has high potential to engage market actors.

In HiLo, one objective was to **bring different disciplines**, also within research, **together** – for example, to answer questions by combining structural elements with energy and climate research (I7, I15). Eventually, collaboration and intensified interaction should benefit the **transfer of innovative solutions** to a bigger market (I7). Accompanying HiLo’s innovative solutions was a **mutual interest** in creating something new and thinking proactively about the future (I3, I11). As I8 emphasises, players who participated in the project are, regardless of their sector, **more open to innovative solutions** in the first place. Besides, HiLo brings the education/research and industry actors together by sharing knowledge or offering forms of ‘coaching’ (I5).

„By bringing the market actors together with research. That is crucial. That had not existed to this extent before. Because people from practice need to see what innovations are out there. How can I implement this in the market? That is a very decisive factor.“ (I8, 17.07.2025, Pos. 55)

Interestingly, NEST’s HiLo unit also facilitated the creation of **specialised companies** through **innovative interactions** that previously did not exist. These “linking” companies, or **“integrators”**, emerge between two unconnected sectors, bringing them together (I14). An example of such a specialised company is the spin-off MESH, which now acts as a bridge between robotics, research, and the ‘conservative’ construction industry (I14). Furthermore, when collaborating on novel solutions, companies also shared knowledge on models, calculation methods, and manufacturing techniques, for instance, through interactions or technological exchanges. I11 illustrated this with a stage builder who applied his specific expertise in a completely different field—spraying concrete. Actors like the stage builder or MESH serve as **bridging elements** between diverse sectors, potentially destabilising system entanglers such as structural lock-ins or challenging established relationships.

“It is also the case that the traditional manufacturing enterprises are interested in investing in these new technologies and integrating them into their own operations. This creates contact between two worlds that did not really interact before.” (I14, 11.08.2025, Pos. 28)

“It [the roof] is done using a cable net as a formwork. So, you stretch a cable net, and you put a tarp on top of it (...). Do you know Freitag? It is the same. So, we use that as formwork. Also, the floor (...) uses a sand-printed (...) formwork, which is commonly not used (...). So yes, there were quite a few interactions from other industries.” (I2, 30.06.2025, Pos. 88)

For some interviewees, **“everyone”** includes a bridging element (I2, I7). As I2 notes, HiLo was a **“group experience”** that lasted about two years. This offers an interesting perspective at NEST, namely that all stakeholders are somehow working together and moving in the same direction to find a new solution or material – in other words, this shared effort or vision, or desire for transition, should then lead to a solution for everyone.

Other interviewees named other actors within NEST as **bridging elements** (I2, I5, I7, I14). Firstly, one of the key elements named is the **NEST team** itself: They manage the entire process, primarily at the organisational level, bring people, or ‘the group’, together, and ensure that everyone has an interest in seeing the project succeed (I5, I7, I14). This also includes **Empa** as the client for the entire NEST project and as the responsible party in forming this group in the first place (I7). Secondly, **architects** are bringing together NEST actors by overseeing communication between actors (research and industry), filling potential knowledge gaps, and preventing actors from waiting for information – all alongside their conventional planning tasks. Here, experience in research helped the

²¹ “These are the people who make up the system, shape it and often derive income from it. They can be individuals, companies or groups. Examples include: producers, buyers, traders, processors, input suppliers, government extension agents, and policy makers” (Practical Action, 2022).

architectural team to address problems and close gaps (I14). After I2, the architect was “the glue of everything” and in the centre of the project. As I5 states, they only got together through the architect, underlying the bridging factor of architects. Thirdly, **engineers** are “more knowledgeable with numbers” and bring a lot to the process as a whole (I2).

„Actually, we were all, to some extent, bridges – we had to be. As research group leaders, and of course, always between the companies that needed to be convinced, the PhD students who eventually had to integrate it into their work, and also Empa as the client, where you had to argue why things needed to be done in a certain way. So, we all had to be at these important intersections.” (I7, 10.07.2025, Pos. 70)

Another challenge was **miscommunications** during the construction process (I15). Here, a lack of **transparency** led to mistakes in **data formats**, resulting in ‘expensive’ delays on the construction site. As I15 stresses, efficiency gains get easily lost in problems connected to communications – a bottleneck for research and other actors when collaborating in a project like HiLo. Hence, actors were “lost in translation” exchanging file formats (formal language). In HiLo, these ‘simple’ mishaps of format eventually led to mistakes like failing to fit windows on the construction site. Moreover, the digitalisation in Switzerland overall could be seen as a problem, as I15 notes.

“That is the key thing: How you exchange information. And in our case, that was the bottleneck. And even when you insist that is also again interesting: (...) Like why didn’t you say that, actually, that is how you are planning to do it? (...) It is interesting how things go wrong. Lost in translation literally”. (I15, 26.08.2025, Pos. 42)

Besides organisational couplings, interviewees mentioned institutional couplings: In HiLo, **public authorities** interact with other actors through **regulations** and **norms** (I1, I7, I14, I15). As I7 states, the collaboration between the public and research/industry sector was “extremely productive”. For I1, there was ‘**no problem**’ on the regulatory/standard side – it was not ideal, but also not preventing ‘better’ construction (I1). At the same time, HiLo pushed solutions **beyond norms**, challenging how authorities and other actors outside NEST might receive the solutions (I15).

“(…) We naturally ran into conflicts with the standards, because we wanted to try things that were not initially approved under the rules. That created a certain tension. Can a living lab break the rules to innovate, or must it comply with them? And as a result, some innovations are not possible, and certain improvements are not achievable either. (...) Because, of course, the nature of innovation is that it is not reflected in the standards. (...) You can discuss such issues with the authorities (...). [In HiLo] the focus was very much on enabling rather than preventing.” (I7, 10.07.2025, Pos. 32)

“(…) From my point of view, NEST can almost only exist here in Switzerland – at least in Europe (...). Here in Switzerland, entrepreneurs and engineers are allowed to assume greater personal responsibility when implementing a product as a prototype in NEST. But essentially, everything used in NEST still has to meet the same requirements as it would later on.” (I14, 11.08.2025, Pos. 44)

However, not all regulations support innovative solutions, especially if they mainly focus on energy-based rather than emissions-driven approaches (I1). Nevertheless, with SIA’s latest publication²², the emphasis in new building projects has shifted towards performance, enabling a more environmentally friendly use of concrete than before. Furthermore, the Swiss Committees for the Environment, Spatial Planning and Energy of the Federal Assembly (UREK) visited NEST, demonstrating their interest in the presented solutions.

Overall, the planning and construction process of HiLo was not typical – it was not driven by cost or time pressure, but by a scientific motive to ‘innovate’ (I2). Additionally, for innovative solutions in HiLo to work, **technologies** from diverse actors had to be aligned and adapted, creating

²² See the publication of the Swiss national annexe “ND” to SN EN 206 (introduced in early 2025), which enabled a more performance-oriented and environmentally friendly use of concrete. This standard promotes sustainable concrete production by reducing clinker content to lower CO₂ emissions (Dimitrios et al., 2025, pp. 3–9; Herbst, 2024).

interdependencies and **co-evolutions** between systems (I7, I10, I14, I15) (technological **couplings**). After I7, a Swiss SME provided HiLo with its technical systems, which were then incorporated into the research setups. Subsequently, there has been a direct transfer from control and regulation concepts applied in HiLo to manufacturers' systems (I7). Nonetheless, **uncertainties** in the conservative, risk-averse industry persist, preventing novel interactions between sectors from forming (I2).

“Often it is (...) a joint innovation. For example, with HiLo, it was the case that the curved ceiling was only possible because the practical knowledge of the companies came together with the geometric knowledge of the researchers. So, what was ‘exchanged’ was (...) the shape, the measurements, the calculations from our side, and from the practitioners, the way of spraying the concrete, the viscosity, the way it is applied in the process, over 30 hours non-stop. (...) That is the direction of the exchange – in both directions.” (I7, 10.07.2025, Pos. 60)

Furthermore, NEST provides **partnership models** that enable actors to decide the scope and form of their collaboration, **financing, and eventual partnerships** (functional couplings) (I11). For example, during HiLo, spin-offs and industry partners **worked** together through **shared investments** and the joint development of innovative solutions – a collaboration that went beyond the NEST project (I7). Such long-term partnerships with industry could therefore be significant for the widespread adoption of an innovative solution from the LH. After I15, HiLo became sufficiently established to secure projects with larger industry players, leading to increased interaction between research and industry. As I4 observes, research requires **funding**, and development needs research – here, NEST not only conducts research or provides coaching but also advances innovations, connecting actors within the industry. Significantly, a strong **partnership** across the **entire value chain** is essential for the success of innovative solutions: a planner, an architect, and a client willing to try something new (I12). Additionally, **other industry partners** accessible through the NEST **network**, such as building services, heating, ventilation, and electricians, also play a key role (I3).

However, not all actors or solutions were always well integrated, and some were also described as disconnected. I15, for example, mentioned that the research still remained ‘too theoretical’ and was confined to their „**bubble**“. Consequently, researchers face a steep learning curve once they leave their ‘bubble’ and start interacting with NEST actors who must operate within the constraints of business plans, employment contracts, and other practical realities.

“[The] NEST project was in no means a model of anything realistic for practice. Because there was kind of a crazy experienced and committed team that worked like 500 percent – I am exaggerating – for a really long time to make this project happen. (...) Because we are in this kind of bubble for a long time, and we go a thousand per cent for a long time. This is something I had to learn somehow: How to not expect that everyone has that passion or necessarily is allowed or available to do these kinds of things.” (I15, 26.08.2025, Pos. 8-10)

Even within HiLo, researchers remain detached from these ‘realities’, and the interactions therefore also serve as a process through which they learn to understand the construction and its practical conditions, such as sensitivities of how other partners work.

6.3.3 Summary of RQ3

The following table summarises the results of chapters 6.3.1 and 6.3.2, divided into structural and functional couplings. The structural couplings are categorised into organisational (actors), technological, and institutional couplings.

Table 5: Summary table for RQ3. Structural and functional couplings (own illustration).

Results
Structural Couplings
Organisational
- Networking platform, sharing of knowledge, described as think tank - Novel or known networks and partnerships between individual actors - Interdisciplinary working environment between diverse actors - Collaborative and constant interactions Bridging actors - NEST (and Empa) as manager, organiser, and motivator. Enjoys a high status, linked to credibility and strong network of industry contacts. - Architects overlooked the communication, filling potential knowledge gaps - Specialist companies integrate two previously unconnected sectors - Other important actors mentioned include woodworker, or ‘everyone involved’
Technological
- Highly technological design of HiLo unit. Possibly challenging for industry actors. - Challenge of incomplete digitalisation (HiLo)
Institutional
Formal - Regulations surrounding circularity (local to global level) - Actors are enabled with favourable inputs from authority’s side (and Empa) - Innovative solution ‘beyond’ norms, challenging authorities etc. (HiLo) - Lacking pressure for industry to commit to more sustainable, innovative solutions. Informal - Uncertainties and risk averse industry might prevent transition (especially HiLo) - Trends in society of consuming less. However, fear, that trend might only be temporary. (UMAR)
Functional Couplings
- Transfer of materials (for example, reuse and recycling materials like carpet in UMAR/Sprint) - Transfer of knowledge (for example, stage builder in HiLo) - Transfer of data (HiLo) - Transfer of resources, including economic resources (for example, partnership models, cooperation within units, and follow-up industry projects)

7 Discussion

In this chapter, the research findings are analysed, interpreted, and discussed in relation to the research questions. Furthermore, the main results are situated within the existing theory and academic literature. Similarities, divergences, and newly derived insights are highlighted. Finally, the limitations of this thesis are addressed and translated into recommendations for future research. The results are structured according to the two unit-specific themes but are discussed together in relation to each research question.

7.1 LH's Role in the Transformation of Carbon-Intensive Sectors (RQ1)

To answer the overarching question (RQ1), the following two sub-questions are addressed first.

Sub-question: **“How do lighthouse projects like NEST contribute to mobilising key system resources for innovation (knowledge development, market formation, investment mobilisation, or legitimacy)? What are limitations?”**

Most interviewees named NEST as an exemplary lighthouse project for Switzerland's construction sector. This becomes obvious when we trace active system-formation processes across all four resources in both units (UMAR/Sprint and HiLo). The following sections will briefly discuss these four resources. For this, the units and NEST in their entirety will be examined through a discussion of their contributions and limitations, with the results placed in the broader context of recent literature.

The first system resource is **knowledge and technology development**. In this context, NEST stands out as a unique environment for testing ideas and solutions, fostering critical reflection, knowledge exchange, and collaboration among a diverse community of scientists, industry actors, practitioners, authorities, and the public. Through this exchange, participants throughout the entire value chain are encouraged to engage and contribute to developing innovative solutions. As Feddersen et al. (2024, p. 178) note, involving practitioners in projects related to the ‘green transition’ is significant because it enables them to actively shape decisions rather than merely accept them. However, the motives of individual actors sometimes remain unclear – are they aiming for meaningful follow-up implementation, or are they perhaps using the final products only to craft a “good story”?

Additionally, actors such as start-ups face extra challenges, since there are no dedicated spaces within the LH for informal meetings among different stakeholders, including potential investors. Interestingly, some interviewees described the work process in HiLo as either markedly different (for example, researchers in leading positions) or similar to conventional construction. This again underlines the distinctive working methods within NEST, where various actors often participate in round-table discussions from the very beginning. It also highlights the role of the LH as an enabling platform that allows researchers to translate innovative ideas into practice and to oversee their implementation from concept to realisation. On one hand, researchers were able to monitor their innovative solutions and technologies closely, such as by leading planning processes. This emphasises the role of scientists in initiating pioneering projects, leveraging their research expertise, systems understanding, and networks to educate the next generation of climate innovators (Becattini et al., 2024).

Conversely, these ‘unusual’ planning horizons and delivery deadlines posed challenges for various actors, who found the process “very difficult” and endured exceptional working hours. For some SMEs, working in NEST was an additional “burden” on their daily operations. Consequently, the findings of this thesis highlight the importance of integration and communication among actors within lighthouse projects (place) to generate new knowledge or technology (see chapter 2.4). It also underscores the significance of work processes and spill-over effects between different actor types in transition and innovation processes. Furthermore, a greater focus on who exactly participates in knowledge development, including the unique aspects of regional characteristics, is noteworthy (see

Su & Yan, 2023). Within this thesis, the integration of SMEs (particularly in the Swiss context) appears crucial for a successful future transition of the construction sector.

Additionally, LHs represent a distinctly research-driven environment where innovative approaches are explored and a pioneering spirit prevails. However, this ‘lab-like character’ can resemble an innovative “bubble” detached from reality, potentially limiting a LH’s broader impact on transition. According to Kirchherr (2022, p. 171), promotion or funding might drive scientists to seek citations and recognition – for a LH, this could result in insufficient engagement with fundamental issues. Therefore, LHs must engage in even more reflection processes so that more complex problems and underlying processes can be understood, and the focus is not solely on the newest, most innovative solutions.

The second system resource contributed by both units is **market formation**. Overall, innovative solutions within NEST were described differently in terms of their market readiness and scalability potential. Depending on the units, solutions, or topics presented, interviewees decided whether they fit a niche context. In **UMAR/Sprint**, the applied products are seen as already widespread throughout the construction sector. This is because, in these units, the primary focus is on reusing or reapplying conventional elements rather than on the ‘innovation’ of entirely novel solutions or materials, as seen in HiLo. In **HiLo**, solutions were introduced that were essentially ready for market launch within the unit (‘finished prototypes’ that were not yet available commercially). Additionally, equipment, expertise, and knowledge of models or calculations were shared among the various participants.

Furthermore, two **spin-offs** linked to HiLo are now quite successful and attract substantial interest from market actors. Here, their solutions are scaled up in normal building projects. However, the interviews showed that some NEST solutions are now struggling with implementation “on the construction site”. Within the LH, solutions are, to a certain extent, shielded from external influences. However, when leaving NEST, the solutions face the broader challenge of the construction sector’s **fragmented production and supply chains** (Stubbs et al., 2024, pp. 467–469). Thus, wide market implementation of solutions might be complex because companies or producers “are often decentralised entities, relying on multiple, independent actors” (Habert et al., 2020, p. 565). This fragmentation can eventually lead to insufficient integration among actors or even to increased CO₂ emissions due to incoordination during the project (BUILD, 2024; Konrad et al., 2008, p. 1197). Also, a lack of “adequate supply chain infrastructure” currently poses one of the most significant barriers for the market entry of innovative solutions, as conventional construction machinery is often unsuitable for alternative materials (e.g., bio-based materials) (Li et al., 2025, p. 6). Moreover, primary raw materials are described as disproportionately cheap, distorting the market for alternative materials (e.g., recycling). Too innovative or “fancy” solutions from NEST risk outright rejection by conventional construction actors, calling for a trade-off between sustainable innovation and potential barriers (incl. regulatory hurdles or costly testing processes).

Finally, the path dependency of conventional materials is reinforced by industry norms, regulations, and the long lifespan of infrastructure, which creates a tendency to resist innovation (United Nations Environment Programme, 2022, p. 43). The results show that the upscaling market for NEST solutions faces a key trade-off: on the one hand, the solution must be innovative and more sustainable than conventional alternatives, but on the other hand, it must be sufficiently cost-effective. Furthermore, there also needs to be demand from more sceptical customers who perceive possible (structural or financial) risks. In summary, our results confirm insights from existing studies that LHs can play a key role in initiating new niche markets for innovative solutions (see Schelbert et al., 2023). However, the protection from market forces created by the LH also creates a “bubble” that shields actors from practical realities and economic constraints. Furthermore, after leaving the LH (where ideas are “widespread”, interest, awareness), there may be a gap, as established production or supply chains are absent, and the construction sector remains fragmented. Since a holistic view and effective functioning of the value chain are essential for successful transitions, awareness of this limitation within

the construction sector is crucial for thinking about how to increase the transformative impact of LH initiatives.

The third system resource is **investment mobilisation**. In NEST, interviewees agreed that investment capabilities varied heavily between the individual actors. Overall, underlying networks helped to secure sufficient investments across the units. Moreover, the investors had diverse backgrounds, including public, private individuals, industry sponsors, and bank partnerships. Especially bigger – often internationally operating – companies had comparatively high spending power (e.g., for internal R&D).

In contrast, raising sufficient financial and human resources for sustainable innovation was described as (too) high for smaller companies, although it is necessary for their own “long-term survival” and also to facilitate transition processes for emission reduction across the industry (Peng & Bai, 2021; Stubbs et al., 2024, p. 467). Interestingly, HiLo, as a highly research-oriented unit, had significant funding from the outset. Here, the unit is viewed by investors as innovative, cutting-edge, and internationally appealing. There was also potential for later integration of the creative solutions into the investing companies. Conversely, the solutions developed within the UMAR and Sprint units were less research-focused, mainly concentrating on the practical (re-)application of known materials. Additionally, reuse was described as a form of value storage: through modular construction methods, materials are secured within the building and, rather than being ‘lost’ at the end of the lifecycle, remain available for future use. This mindset is also shared outside the interview group (SRF Podcast, 2025).

These results highlight parts of the underinvested innovation sector, especially start-ups and SMEs, which struggle to join LHs in the first place due to limited human or financial resources. Moreover, LHs show that, within decarbonisation, some solutions receive more funding (cutting-edge vs. the application of known materials), highlighting an unequal distribution of investment. However, if an actor is heavily financed and no longer “sees” the reality of costs, misperceptions might emerge (a financial bubble). This also complements Moon’s (2022, pp. 9–10) findings, which argue that public-sector support for smaller companies can create an environment conducive to technological progress and growth. By financially supporting actors, companies can actively participate in LHs. However, this also raises the question of the competitiveness of financed solutions, which in turn calls into question the economic viability of cross-financed solutions (financial bubbles).

The fourth resource is **technology legitimisation**. Overall, NEST has a strong legitimisation function and is described as a safe, neutral platform where diverse actors (from science, industry, authorities, and the public) meet and can form long-term, trust-based partnerships. Furthermore, the NEST is widely recognised and validated by industry and political experts at the local and global levels. As a lighthouse project in the truest sense, NEST offers a strong counterargument to the high risk aversion prevalent in the construction sector (see Roijen Van et al., 2025, p. 181). Additionally, interviewees noted that presenting in NEST could enhance actors’ credibility and trustworthiness, thereby increasing clients’ perceived reliability of their solutions.

Furthermore, involving the public (e.g., through tours or education) facilitated broader dissemination of ideas and helped legitimise the move towards decarbonisation. The many examples show how lighthouse projects like NEST play a central role in legitimising innovative solutions, making them tangible, understandable, and plausible to a broad audience, which confirms findings from similar studies (Binz, Harris-Lovett, et al., 2016; Huguenin & Jeannerat, 2017). Nevertheless, in risk-averse, conservative sectors like construction, even a proof-of-concept from a LH might not be enough to change stakeholders’ perceptions or establish legitimacy for innovative solutions. Identifying which elements could speed up decarbonisation despite such barriers (e.g., risk aversion or natural scepticism, system entanglers) is vital for transition studies to consider.

Regulatory frameworks stood out as a fifth crucial element characterising an innovative solution or practice, alongside the four key system resources. Especially in the Swiss construction sector,

norms and regulations have been identified as key factors influencing innovation and transition potential. In NEST, both units showed strong dependence on rules, with different implications for the solutions presented: some solutions cannot (yet) be reflected in norms, others benefited, and others again were somewhat hindered by current regulations (see Nilimaa, 2023). As NEST was the final platform before entering the ‘real’ market, regulatory frameworks could then decide whether and how the scaling would look. Nevertheless, public authorities were described as positive and solution-oriented, very much enabling innovative solutions to develop in NEST. At the same time, norms were noted as crucial for creative solutions to work, as otherwise, few would be willing to take responsibility for low-carbon or circular solutions. In Binz et al. (2016), the regulatory and normative dimensions of legitimacy are also mentioned under technical legitimations. However, the results show that greater emphasis is needed on regulatory frameworks, as they are not yet adequately covered in the literature and appear to play a decisive role in the transition process.

Overarching question: “What role do lighthouse projects play in the (socio-technical) transformation of carbon-intensive sectors?”

Heavy-emitting industries such as the construction sector face increasing pressure to develop low-innovative solutions. In this context, Empa’s NEST operates not only as a “research and technology transfer platform” (Richner et al., 2018) but also as a lighthouse (LH) that challenges established norms by demonstrating what is technologically and organisationally possible. The uniqueness of NEST lies in their ability to allow technologies to progress at different speeds; some may scale up, while others remain exploratory. As suggested by Andersen and Markard (2024), LHs can thereby introduce “multi-purpose technologies” capable of transforming entire value chains. Examining the four key system resources sheds light on how such platforms generate, mobilise, and constrain transitions.

A central finding is that LHs serve as interaction spaces where diverse stakeholders – research, industry, public, education, and authorities – meet, exchange knowledge and co-create solutions. By assembling actors at the same table from the outset, LHs enable iterative collaboration, build long-term partnerships and foster new actor subsystems across research, planning, architecture, policy, and industry. These processes strengthen knowledge flows and increase the likelihood that research ideas reach practice (Sjöö & Frishammar, 2019, p. 331). This resonates with Huguenin and Jeanerats’s (2017) argument that LHs should not be reduced to mere innovation incubators. Instead, they are sites where new social and economic values emerge through complex processes of value co-creation, supported by policy actors who function as agents of change.

However, the distribution and mobilisation of system resources remain uneven. While LHs effectively generate knowledge and legitimacy, they are less successful in market formation and investment mobilisation. Risk aversion – particularly entrenched in construction – continues to restrict the uptake of novel solutions. Even when LHs provide proof of concept and demonstrate successful real-world performance, scepticism persists, and the willingness to adopt remains limited²³. This tension between legitimacy and adoption illustrated the deeply embedded, path-dependent structures of high-carbon sectors, where linear production chains and established procurement practices create significant barriers to transformative change.

NEST exemplifies this tension: validated technologies exist, yet actors often perceive them as risky, reaffirming the conservative nature of this sector. Nonetheless, LHs remain important places of change – platforms that inform diverse actors, challenge conventions, and inspire shifts towards sectoral transformations. The key question, however, is not whether LHs function, but rather how and where their demonstrated solutions will eventually be implemented.

²³ See also other “hinderances” (system entanglers) that prevent or slow down innovation adoption into the construction industry: Conservativeness, scepticism, risk, norms, service providing, fees, margins, (lack of) funding, segmentation, (lack of) digitalisation, (lack of) automation, closed-source, ignorance, outdated, greenwashing, green premium, governance, education (P. Block, personal communication, 28 August 2025).

The findings further highlight that participation in LHs is not equally accessible. SMEs and start-ups – which are essential economic drivers – face personnel and financial constraints that hinder participation. Since downstream actors ultimately determine whether innovations diffuse, their limited involvement reduces the transformative potential of LHs (Stubbs et al., 2024). In addition, although LHs provide a niche that simulates close-to-market conditions, solutions often remain within a “bubble”, with economic feasibility considered too late. The diffusion process depends heavily on large firms that integrate new products into their portfolios, yet successful transitions require that smaller companies use, apply, and further develop these solutions.

Structural factors further restrict scaling. Supply and production chains in construction are rigid and path-dependent, making it difficult for new materials or technologies to penetrate established value chains – a finding that echoes Mazzoni and Losacker’s (2024) finding of a knowledge bottleneck between upstream and downstream actors. Investment mobilisation reflects similar asymmetries: large companies can rely on internal R&D or research support, whereas smaller actors – despite being more integrated into the LH process – often lack the financial capacity to invest, reinforcing an underfunded innovation landscape (Moon, 2022).

7.2 Geographical impact (RQ2)

To answer the second overarching question (RQ2), two sub-questions are addressed first.

First sub-question: **“How far and where do the solutions in the LH scale and diffuse?”**

In the NEST case study, the examined units demonstrate different geographical scales of impact and diffusion. At regional and national levels, NEST’s influence is most visible in areas aligned with UMAR and Sprint. Their products and practices resonate with an increasing (though still niche-level) uptake of reuse and circular strategies in the Swiss construction sector (see Baubüro in situ AG, 2024; Buehler et al., 2025; House of Interiors AG, 2025; Switzerland Innovation Park Central, 2024). By contrast, HiLo’s technological solutions appear to have still limited influence on Swiss practitioners, particularly smaller companies. Although future projects plan to integrate elements of HiLo, interview partners questioned their potential for direct impact and market traction in Switzerland. Moreover, HiLo’s unconventional, “not typically Swiss” architectural expression was perceived as diminishing its relevance to Swiss architectural education. Nonetheless, integration of low-carbon solutions in Swiss SMEs is underway, as evidenced by the example of local production plants for innovative fabrication technologies (STEP2).

At the international level, NEST attracts a broad spectrum of actors. Municipalities and communities across Europe express interest in solutions that support climate targets, including innovations in reuse and recycling (UMAR/Sprint). Simultaneously, HiLo’s technological achievements have gained visibility among international scientists, large companies, and the broader public (e.g., via TED Talk). Its advances in structural and computational design, in particular, have received strong traction within the international research community. Many of HiLo’s partner companies also operate internationally and maintain networks beyond Switzerland while still having strong ties to the country. Depending on the specific innovation, scaling has occurred. HiLo’s floor system has been installed in several projects across Europe (Switzerland, Belgium, UK) and globally (India, South Africa, USA). The roof, in contrast, is unlikely to be replicated in its current form but may instead inspire further technological developments. As a result, its relevance lies less in national uptake and more in its contribution to international technological discourse.

Subsequently, examining a LH from a geographical perspective highlights the project’s inherent territorial embeddedness within a specific local-to-national context (here: Switzerland) (see Binz et al., 2025; Hansen & Coenen, 2015). Depending on the innovative solution or lighthouse project, this scale or impact may vary, as might the composition of the target group. In this context, the NEST case reveals a surprisingly broad and diverse set of implications that extend from the national to the global level. Meanwhile, more immediate regional effects seem comparatively limited. This pattern

aligns with NEST's primary role as an experimentation and legitimacy-building platform: it generates visibility, expectation dynamics, and discursive influence that easily transcend spatial boundaries. Given this orientation, the extensive national and international presence of NEST's solutions is therefore not surprising. What is less clear, however, are the more localised transformation dynamics related to market formation or financial investment in the surrounding region. Although some SMEs have started investing in new production capacities, these examples remain relatively isolated and do not suggest a broader regional shift. This indicates that many of the value-creation processes linked to NEST, particularly for technologically complex units like HiLo, are embedded primarily within transnational research networks and globally connected industries rather than local contractor ecosystems. Overall, the findings show that a LH's impact at the regional level currently manifests more subtly, rather than through extensive commercial adoption or structural change.

Second sub-question: “What mechanisms support or hinder the broader diffusion of solutions developed in lighthouse projects?”

In Switzerland, NEST serves as a key research hub. In units like HiLo, cutting-edge research collaborates with practitioners and industry actors to develop innovative solutions. Switzerland is described as a particularly supportive country that encourages and fosters innovation. Several regulations are viewed as beneficial rather than restrictive. The SIA plays a central role in establishing standards and regulations. By regularly updating these standards, including in response to new insights or political decisions (such as SIA's climate pathway), the SIA indirectly enables NEST solutions to access markets (Herbst, 2024; SIA, 2025).

Additionally, spin-offs operate at the crossroads of research and commercialisation, bringing solutions from the LHs outwards. Large (sometimes international) companies are also involved, offering financial, material, or collaborative support to develop solutions within the LH and later bring them to market or implement them directly. Furthermore, individual NEST actors actively share their knowledge of solutions developed within the LH, helping spread them further within their professional fields. Moreover, appearances in various media or specialist outlets can also boost the visibility of LH solutions, with the public engaging through guided tours or students becoming familiar with them. In this way, ideas are passed on from the LH.

However, the strong local focus of the Swiss construction sector may limit the influence of these solutions. This is evident in the geographic proximity of many construction actors to NEST, mainly in the Zurich region of Switzerland. Additionally, the absence of established production chains and the high prices of the developed solutions are significant obstacles to broader adoption, due to a lack of economies of scale. Moreover, solutions within LHs are created in a protected environment, sometimes forming “bubbles” that shield actors from economic realities; however, these bubbles burst as soon as the solution leaves the LH. If this issue is not addressed, it could then hinder the spread of a solution.

Overarching question: “What is the geographical reach of the impact of activities conducted in a lighthouse project?”

In summary, lighthouse projects like NEST can generate impacts at both local and global levels, albeit in different forms and through various effects. This finding supports broader debates in transition studies and geographies of innovation, which argue that sustainability transitions unfold across multiple spatial scales and follow uneven, place-specific pathways (Coenen et al., 2012b; Hansen & Coenen, 2015; Miörner & Binz, 2021).

As the construction sector moves towards decarbonisation, these scales matter in complementary ways. At the international level, climate targets, design ideas, research outputs, and innovative technologies circulate through a transnational network. In this context, NEST provides cutting-edge empirical validation and demonstrative evidence for emerging solutions. This reflects the role of global innovation systems, as described by Binz and Truffer (2017, p. 1286), which are made up of

multi-scalar actor networks and institutional contexts that collectively support (or hinder) the development and spread of an innovation.

At the same time, local industry actors translate insights from LHs into real-world applications, contributing to the local embedding of innovations within niches (see also Bakhuis et al., 2024; Finstad & Andersen, 2023; Smith & Raven, 2012). Importantly, some actors within a LH operate across these scales simultaneously: spin-offs, for example, embody what Coenen et al. (2012b) describe as multi-scalar “intermediaries”, who bridge (globally) relevant innovation with locally anchored implementation. Furthermore, local norms, regulatory frameworks, and professional cultures shape the feasibility of implementation, demonstrating the importance of institutional alignment (see also Górecki et al., 2019).

Regional diversity, therefore, becomes a crucial aspect in understanding how innovative solutions spread. As Li et al. (2025, pp. 3–6) demonstrate, effective decarbonisation demands region-specific strategies because challenges and viable approaches differ considerably across different contexts – for example, advanced material innovation in high-income countries versus low-cost, scalable methods in low-income settings. There is no universal approach; instead, strategies must be customised to geographical scale, regulatory environments, material resources, and economic capacity. This aligns with research by Binz et al. (2020), which stresses that transition pathways are fundamentally context- and place-specific.

Both local and global impacts are therefore vital – yet they serve separate functions and involve different groups of actors. Especially in the construction sector, local regulatory conditions determine which innovative solutions can be practically implemented. Meanwhile, ideas, expertise, and work processes circulate globally and can be adapted across various settings. In this way, LHs can promote meaningful interactions across various levels, linking local experimentation with global discourse and thus facilitating innovations that are both locally rooted and globally significant (Miörner & Binz, 2021).

Finally, the findings highlight that the construction sector’s high level of fragmentation and firm territorial embeddedness may help explain Switzerland’s slow decarbonisation. By examining how solutions spread (or fail to) across scales, this study provides empirical insights into these structural barriers. It enhances our understanding of the slow pace of transitions in hard-to-decarbonise, materially intensive sectors (Sovacool et al., 2025). This represents a key contribution of this thesis: it empirically demonstrates how geographical scales shape the impact of lighthouse projects and illustrates how multi-scalar mechanisms interact in a domain where local conditions and global knowledge flows are closely intertwined.

7.3 Formation of Multi-System Interactions (RQ3)

The third research question investigates how lighthouse projects cross given sectoral boundaries. On the one hand, this question examines the actors involved in this novel combination. On the other hand, it also highlights the challenges when crossing sectoral boundaries. First, two sub-questions are answered to investigate the overarching research question.

First sub-question: **“Who are the actors that are part of these novel combinations?”**

In the case of NEST, the units reveal a wide variety of actor interactions and novel combinations. Collaboratively, actors within LHs co-develop innovative solutions in areas such as urban mining and recycling (UMAR and Sprint), or energy-efficient, advanced construction (HiLo, STEP2). Chen and Li (2021) describe this as the creation of “industry interconnection[s]”, where heterogeneous technologies, competencies, and material systems are assembled into new, experiment-based constellations. Within NEST, Empa and the NEST functioned as central organising actors across all units, anchoring the innovation process and ensuring continuity throughout the project lifecycle.

Across the units, diverse actors from architecture, planning, engineering, industry (incl. fabrication), and research collaborated in multidisciplinary constellations. Notably, this convergence also occurred within research: structural engineering, materials science, digital fabrication, climate research, and energy studies intersected in ways that rarely happen in conventional settings.

A key insight from this study concerns the role of system entanglers – who connect, mediate, and weave together otherwise segmented value chains, disciplines, and innovative actors (see Löhr & Chlebna, 2023). In NEST, several types of such connecting actors were visible. The NEST management team acted as an intermediary between research, industry, and regulatory bodies, identifying suitable partners, aligning expectations, and establishing the organisational infrastructure for collaboration. Specialist companies and integrators emerged during the innovation process as well – for instance, robotics-focused spin-offs such as MESH, which served as a bridge between computational design, material fabrication, and on-site construction. These system entanglers reduce coordination barriers, translate between disciplinary languages, and help stabilise multi-actor configurations that would otherwise remain fragile. As Löhr and Chlebna (2023, p. 10) describe, they are bridging different systems, “not just in the technological but also in the organisational and institutional dimensions”. For LHs, this includes mobilising resources, aligning visions, building trust, and facilitating problem-solving – all of which are significant in the fragmented construction sector.

Overall, the actors involved in NEST do not just coexist – they are connected by a set of intermediaries and system entanglers who actively shape collaboration and enable new combinations. This highlights an essential contribution of the study: it shows empirically how lighthouse projects do not merely assemble heterogeneous actors but rely on dedicated connecting roles that bind these actors into functional socio-technological constellations, enabling experimentation in an otherwise fragmented sector.

Second sub-question: **“How does a lighthouse project like NEST bring together actors from construction and related sectors? What were the challenges in bridging sectoral boundaries when planning the units?”**

Lighthouse projects are sites of interactions for networking and knowledge exchange (organisational coupling). Novel networks and partnerships are created between research, practice, and market actors. Within these, interactions and knowledge transfer between actors are enabled and promoted (e.g., carpet use for wall insulation in Sprint, stage builder in HiLo). Moreover, NEST, with its variety of solutions, stands out as a “think tank” compared to other LHs. In general, LHs foster a collaborative, interdisciplinary working environment among actors (e.g., research and industry). Further, the mostly flat hierarchies contributed to mostly positive experiences. Also, NEST offers partnership models in which industry actors can determine the form of their collaboration, financing, and eventual participation in the project. Such partnerships might eventually go beyond the lighthouse project,

leading to ‘real’ industry projects and are crucial for innovative solutions to work. Following Konrad et al. (2008, p. 1197), NEST could be seen as a nexus that enables cross-regime learning and experimentation. Furthermore, the lighthouses platform enables actors to collaborate internationally within a globalised economy. As Lee et al. note, a needs-driven approach informed by the private sector could contribute to an overall “open innovation strategy” that would help bridge technologies and actors (Lee et al., 2020, p. 11).

Within the lighthouse, some actors stand out as bridging actors, bringing together other actors from within or outside the construction sector (system entanglers). For both units, NEST (and Empa) was such a central bridging actor, bringing people, ideas, and knowledge together in one place. Moreover, during the planning and construction process, NEST serves as a manager, organiser, and motivator, while overseeing communications. Besides, Empa would benefit from its high credibility in the research community and its strong network of industry contacts. Furthermore, architects took on the role of bridging actors by overseeing communication, filling potential knowledge gaps, and closing gaps between research and industry actors. Additionally, NEST eased the formation of specialist companies (integrators) that bridge two previously unconnected sectors (e.g., MESH spin-off that links robotics, research, and industry).

Challenges when bridging sectoral boundaries include technological challenges. When creating novel solutions, “waste” materials had to be converted into reusable or recycled materials for the UMAR/Sprint unit (e.g., carpet floors, PET, Tetra Pak). Moreover, the highly technological design of the HiLo unit was challenging for some industry actors, for example, when exchanging data (formats). In the worst case, this led to production delays or even mistakes in the finished products. Here, better communication of data or greater transparency of processes could improve future processes and make them more efficient.

Also, both units enabled actors to plan and build with maximum sustainability in mind, and to push ‘beyond’ norms. While interactions with public authorities on norms and regulations were primarily considered positive and supportive, there is insufficient pressure on actors outside NEST to adopt more sustainable, innovative solutions. This could be a challenge when trying to integrate solutions from NEST into practice.

Overarching question: “To what extent do lighthouse projects facilitate the formation of cross-sector networks?”

Lighthouse projects can be seen as sites of interaction where various actors from research, public education, architecture and planning, industry, and public authorities come together. In LH, interactions for networking, communication, and knowledge sharing among these actors, as well as for bridging sectoral boundaries, occur. Due to LH’s collaborative and interdisciplinary working methods and flat hierarchy, integrating diverse backgrounds may be easier than in traditional (and linear) building processes. Furthermore, individual actors promote sector transformation and innovative linking, for example, by managing (NEST), bridging gaps between actors (architects), or connecting sectors (specialist companies/spin-offs). Additionally, many actors involved in lighthouse projects seem highly engaged and interactive during the planning and construction phases. Moreover, LHs connect theoretical concepts (research) with practical applications, making them accessible to a broader audience and counteracting the “research as spaceships” scenario.

Furthermore, new technological solutions (such as computational design, models, and systems) are incorporated into LHs, while considering institutional frameworks (“pushing boundaries”, norms, and standards). As a result, the LH becomes a space where (innovative) multi-system couplings across different systems can be observed and studied. Next, a LH can be viewed as a site of interaction where organisational couplings emerge among a diverse set of actors, the resulting structural couplings are assessed, and conditions for future functional couplings are shaped. Thus, LHs, as sites of interaction, are spatial (institutional) hubs where multi-system interaction becomes visibly

concrete. Additionally, LHs may showcase a variety of tangible and intangible resource flows (e.g., shared ideas, visions, materials, data) (see Andersen & Markard, 2024).

Overall, decarbonisation requires the deliberate integration of previously separate sectors to form couplings (Löhr & Chlebna, 2023, p. 1). As achieving climate change mitigation involves transitioning across all systems, a lighthouse project with a multi-systems perspective helps understand the complexity of this process (Andersen & Markard, 2024). A lighthouse project, with its unique structure that brings together stakeholders from different areas of the construction sector (structural couplings), may eventually lead to technological or institutional couplings. According to Andersen and Geels (2023), cross-system funding and investment create new interdependencies, foster functional interactions, and influence system dynamics. In lighthouse projects, resource flows (e.g., financing through partnership models, or follow-up industry projects) enable functional couplings that accelerate or stabilise multi-system interactions. Simultaneously, various standards and technologies in the conservative construction sector pose obstacles that are difficult to implement at the LH level or cannot be practically translated. As Davis et al. (2018, p. 1) state, overcoming such institutional and organisational challenges is essential to achieving more rapid emission reductions. Within LHs, technological couplings establish possibilities (e.g., computational design of HiLo, use of BIM, reuse platforms). Conversely, functional couplings describe actual system-to-system interactions (e.g., data transfer from research to industry) (Andersen & Geels, 2023). A clearer understanding of multi-system interactions within lighthouse projects enhances our insight into the unfolding system dynamics in transition studies (see Andersen & Markard, 2024, p. 2).

8 Conclusion

This thesis has examined the role of lighthouse projects in socio-technical transition by analysing Empa's NEST building and its role in the decarbonisation of the Swiss construction sector. Focusing on two thematic areas (urban mining and recycling, and resource-efficient and advanced construction technologies), the three units UMAR, Sprint and HiLo served as empirical entry points. Guided by three main research questions, the thesis investigated the role of LHs in transforming carbon-intensive sectors (RQ1), their geographical impact (RQ2), and their role in forming cross-sectoral networks (RQ3). The analysis drew on transition studies (GeoST, GIS) and multi-system interaction (MSI) literature and was based on fifteen semi-structured expert interviews.

The findings show that LHs serve as interaction spaces where diverse stakeholders – from research, industry, public, education, and authorities – meet, exchange knowledge and co-create solutions. By assembling actors at the same table from the outset, LHs enable iterative collaboration, build long-term partnerships and foster new actor subsystems across research, planning, architecture, policy, and industry. These processes strengthen knowledge flows and increase the likelihood that research ideas reach practice.

However, the results also highlight the persistent lock-in in the construction sector, characterised by path-dependent structures such as linear production chains and significant risk aversion. The dominance of conventional materials and routines reflects longstanding regulatory standards, established supply chains, and the long lifespan of infrastructure, all of which reinforce resistance to change. Overcoming these structural and institutional lock-ins remains essential for enabling a sector-wide transition. Additionally, the findings emphasise that participation in LHs is not equally accessible. SMEs and start-ups – crucial economic drivers – face personnel and financial constraints that hinder participation. Since downstream actors ultimately decide whether innovations spread, their limited involvement reduces the transformative potential of LHs. Thus, LHs might indicate economic “bubbles”, structural limitations (e.g., path-dependent supply chains), or limited investment mobilisation.

The thesis further demonstrates that lighthouse projects generate impacts across multiple geographical scales (from local to global). At the regional level, enabling practitioners to adapt and apply solutions in real projects is central. Moreover, local regulatory conditions are essential in the practical implemented of solutions. At the global level, climate targets, design ideas, research outputs, and innovative technologies circulate through a transnational network. In this context, a LH provides cutting-edge empirical validation and demonstrative evidence for emerging solutions. Also, when large actors adopt lighthouse solutions, they may influence or motivate smaller firms to follow, reflecting important cross-scalar dynamics. Some actors within NEST – particularly researchers, architects, and specialist firms (integrators) – operate across several scales simultaneously, facilitating the translation of knowledge and work processes between settings.

Nevertheless, local regulatory conditions strongly shape whether innovations can be realised in practice, while global knowledge exchange continues to advance new design approaches. Lighthouse projects thus function as spatial hubs, bringing together innovations that are locally grounded yet globally relevant. The Swiss construction sector's territorial embeddedness and fragmented value chain also help explain why decarbonisation remains slow, and why the diffusion of innovative solutions varies across contexts. Viewed through a geographical lens, the thesis shows that regional diversity, regulatory environments, material availability, and economic capacity are all critical factors in shaping the impact and reach of LH-driven innovations.

A central contribution of this thesis is its analysis of how LHs facilitate the formation of cross-sectoral networks. NEST functions as an organisational site where new networks and working relationships emerge among research, architecture, planning, industry, and public authorities. Key bridging actors, such as the NEST team, Empa, architects, and specialist companies or spin-offs, play a decisive role in bringing together previously disconnected sectors and in enabling knowledge, data, and technological solutions to flow between them. The study also identifies challenges inherent in

such collaborative processes, including technological barriers related to digital data exchange, computational design, and the use of recycled or unconventional materials. NEST nevertheless provides a unique empirical setting in which structural, technological, and functional couplings can be observed, offering insight into how multi-system interactions unfold in practice. Despite their experimental and enabling character, LHs face limits to their broader transformative potential due to insufficient diffusion into the wider industry and limited external regulatory or market pressure. Overall, this research contributes to understanding how LHs act as multi-system sites of interactions (intermediaries), how cross-sectoral networks emerge, and under what conditions these networks support wider transitions.

By answering the three research questions, this thesis offers new empirical insights into transitions studies, particularly regarding geographical perspectives on socio-technical change and the spatial dynamics of multi-system interactions. The integration of the GIS framework highlighted the crucial role of regulatory frameworks as an additional, fifth element shaping transitions in the socio-technical system of the construction sector. The analysis underscores LHs as participatory and enabling infrastructures where innovative ideas move from theory to practice, where diverse actors interact, and where sector-wide transformation opportunities become empirically visible. LHs thereby generate niche opportunities, raises public and expert awareness, and validates solutions for (future) market uptake. At the same time, the thesis shows that fragmented supply chains, uneven financial resources among actors, and persistent risk aversion within the construction sector continue to pose significant barriers to the implementation of innovative practices. Even when solutions have demonstrated feasibility, their adoption remains limited, reaffirming the sector's conservative and path-dependent character.

Above all, this thesis highlights the importance of combining geographical and multi-system perspectives to understand the complexity of transitions in hard-to-decarbonise sectors. Lighthouse projects such as NEST are essential platforms for experimentation and communication, enabling connections across scales and sectors, and challenging established practices. Yet, their long-term transformative effect depends on broader systemic change within regulatory frameworks, market structures, and socio-technical regimes, as well as on the capacity of innovations to extend beyond the protected experimental environment into mainstream practice.

8.1 Limitations of Thesis

This thesis faces several methodological and analytical limitations. Firstly, it offers only a snapshot of a rapidly changing field. Research on sustainable construction, new materials, and experimental building concepts is continually influenced by emerging ideas, standards, and technologies. As a result, the findings reflect current developments but cannot fully predict future changes.

Secondly, the distribution of interviews across the three NEST units was uneven. HiLo is more prominently represented than UMAR and Sprint, which may influence the analysis's overall focus. Similarly, the roles of interviewees – research, industry representatives, architects, and other actors (e.g., SMEs, spin-offs) – are not equally represented. This imbalance could affect which viewpoints are given more prominence in the findings and subsequent discussion.

Thirdly, the choice of interview participants may introduce bias. All involved individuals have been directly or indirectly engaged with the NEST project, which is likely to have shaped their perceptions. Notably, none of the interviewees expressed strong criticism of NEST or LHs in general. As a result, the findings might present a more favourable view of these initiatives than would a more diverse sample that includes external voices or more sceptical participants. Nonetheless, this could be somewhat offset through triangulation using multiple interviews and grey literature.

Fourthly, the thesis concentrates on the Swiss context. Here, Switzerland is characterised by strong innovation policies and supportive institutional conditions. Consequently, the findings are only partly

applicable to other regional contexts with different regulatory frameworks or innovation environments.

Finally, a limitation of this work is that it focused solely on the direct scaling effects of the NEST lighthouse projects. Therefore, I was unable to critically assess whether the proposed solutions are genuinely more sustainable, fairer, or share similar qualities. The effects of such solutions or a system could, however, be critically examined, and the topic might be approached less from a technological perspective and more from an analysis of the structural causes of problems.

8.2 Outlook

Discussions on decarbonisation and climate change highlight the need for more research into challenging sectors, including construction. Given NEST's unique position at the intersection of Swiss research, policy, and society, it will likely continue to act as a platform for dialogue among diverse stakeholders and innovators. While such initiatives may help shift perspectives, the main question is whether they can enable sustained and deeper socio-technical transitions. To better understand NEST's influence on the Swiss construction sector, future research should involve more stakeholders outside NEST's network, especially SMEs and practitioners who implement these technologies in daily practice or hold critical views. Comparative analyses with other lighthouse projects in Switzerland (or worldwide) could also shed light on whether and how NEST affects subsequent initiatives.

A more focused approach could further clarify the dynamics. Focusing on a single technology or material group – such as bio-based materials or low-carbon concrete – might uncover more detailed insights than analysing multiple innovations simultaneously. Furthermore, expanding research on the role of LHs as sites of interaction could shed light on institutional linkages within the construction sector and the impact of regulations, norms, and political pressures. Given the vital role of regulatory frameworks, more detailed studies or analyses of recent regulatory changes (e.g., cement content requirements, incentives for supplementary cementitious materials) would be beneficial.

Moreover, perceived risk in the construction sector remains an interesting topic. Future work could examine how risk aversion persists even when technological performance is demonstrably proven, and how communication between actors (NEST and beyond) shapes the acceptance of innovative solutions.

Furthermore, longitudinal studies could provide additional insights. Follow-up projects that carefully track what happens once solutions “leave” the NEST environment – including how they perform in practice, how users respond to them, and which barriers appear – could offer a clearer understanding of the real impact of lighthouse projects over the long term. This might involve: assessing which innovations are actually adopted in real-world projects (in the long-term), examining personal relationships and collaboration dynamics within LHs, making the (dis)advantages of technologies more visible and experienceable for visitors, incorporating more real-time performance data (e.g., comfort studies) to inform future improvements, investigating functional linkages within and across socio-technical systems, and evaluating long-term effects and systemic influences of LHs like NEST. Collectively, such research could help develop a more complete understanding of how lighthouse projects operate, influence transitions, and shape the future of construction in Switzerland and beyond.

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10 Annexe

10.1 Interview Questionnaires (in English and German)

Interview Questionnaire

resource-efficient and advanced construction technologies (HiLo)

1 Introduction

1. **Thank you** very much for participating.
2. **Privacy Policy Document:** Before we start, I would like to shortly go over the "privacy policy" document.
 - a. If you're good with everything, could you please **sign** the document?
3. Brief **introduction** about myself:
 - a. **Master's student in Human Geography at the University of Zurich.**
 - b. Topic of my **thesis**: "*The role of lighthouse projects in socio-technical transitions*" focusing on Empa's NEST building.
 - c. I'm especially interested in understanding **how** lighthouse projects like NEST can **support the diffusion of game-changing innovation** and **contribute to a broader decarbonisation** of the Swiss construction sector.
 - d. To answer my research questions, understanding **various processes** behind NEST's innovative solutions **across sectors and space** is crucial.
4. Furthermore, the interview is divided into **six question** blocks. Do you have any **remaining questions** before we start with the interview? Otherwise / If there are no questions, I would start the **audio recording** now.

1.1 Definition of LH

1. Before we start with my questions, could you briefly **introduce yourself** / your **current responsibilities**?
2. For my work, I refer to Empa's NEST building as a "**Lighthouse Project**".
 Within my definition, NEST as an LH would be a '**safe and protective space for innovation**' aiming to create a 'proof of concept' for very innovative solutions to the public and experts. They are designed to **develop ideas** that can **be scaled up**, brought to market, and have a **wider impact** - both in the (construction) **industry and society** more widely. These projects often take place in **areas where there is still a lack of formal regulation or clear support**, making them **important testing grounds** and proofs of concept. The aim is to **demonstrate** what works, build **trust** and encourage others in the industry to **adopt and spread** successful innovations.

1.2 Knowledge and technology development

First, I would like to talk to you about how **knowledge was spread**, and **technologies were developed** through the NEST project.

1. How did you experience diverse **actors** such as enterprises and research institutions **working together** in NEST during the HiLo project?
 - a. In what way was this collaboration/teamwork **different** from other building projects?
2. Did you (have to) **acquire any new "skills" or knowledge** throughout the building process (e.g., during planning or construction)?
 - a. **Who helped** you with getting this knowledge?
3. Did you observe innovations applied in HiLo **to be used and/or further developed elsewhere**?
 - a. **If yes, where, and how?**
 - b. **If yes**, what **role** did working in the NEST unit play in **enabling this further application/innovation**?
 - c. **If yes**, can you think of **follow-up projects** such as conferences or workshops with other actors from NEST?

1.3 Market formation/access

Scale, spatial & temporal dimension, niche market

Now, I'll ask you some questions regarding **market formation**.

1. In your view, are NEST's innovations still situated in a **niche market** context?
2. To what extent have NEST's solutions been **implemented across different geographical scales** (local, regional, national, global)?
 - a. **How far** do the innovations of HiLo already reach distant markets? **In what countries have resource-efficient and advanced construction technologies entered (niche) markets?**
 - b. **Who** are the main **actors** showing interest?
Construction companies, municipalities, property owners, planners, or others?
 - c. **How** would you describe their **interests in using and buying** the innovations developed in NEST?
 - d. Are there remaining problems with **user acceptance**?
 - e. Are the current **prices** of the developed solutions an issue?

1.4 Investment mobilisation

financial resources, the combination of investments

After talking about markets, I would now shift the focus towards financial investments/support.

1. Do you know of any **additional/external financial investment that was raised** for the ideas developed in NEST (after the respective unit was built)?
 - a. **If yes**, from **where** have investments been mobilized? From **local or global** actors/networks?

- b. If **yes**, **who** were those **investors** (big companies, private, banks, venture capital, public procurement, institutional investors, real estate developers...)?
 - a. If **no**, What could be **improved** to **increase investment** in innovations/technologies developed around resource-efficient and advanced construction technologies?
2. Besides, can you think of spin-offs that formed after the NEST project (besides VAULTED AG)?
 - a. If **yes**, **who** are they? Where are they located?
 - b. If **yes**, are these **connected** to other companies or actors?
 - c. If **no**, what is limiting spin-offs from forming?
 - a. If **no**, what could be **improved** to enable **further projects**?

1.5 Technology legitimization standards/norms, (public) acceptance, values, behaviour change

Moving on, the following questions will be on how the NEST's innovations are already 'accepted' today.

1. Do you know of **new standards/norms** which developed around "resource-efficient and advanced construction technologies"?
 - a. How can a project like Empa's "HiLo" **advance standardization processes**?
2. In what ways could a lighthouse project like NEST **encourage** people in the construction industry to adopt more sustainable or innovative practices?
 - a. In what ways, do you think this project influences public **acceptance** of innovative solutions?
 - b. Do you think NEST has helped **shift mindsets** (or create new narratives) with planners, landlords, policy makers, the public, ... about how construction can be done (differently)?
3. Did you notice an **increase in media coverage** on "resource-efficient and advanced construction technologies"?
 And: Do you think **NEST's visibility in the media** has helped to **increase public or industry acceptance** of innovative approaches in **construction**?
4. Have these innovations gained any attention or support in **political discussions** or **policymaking**?

1.6 Multi-System Interactions (MSI) Multi-sectoral interactions, couplings

1. I'm interested in the **interaction of diverse sectors** involved in the project. An example:
 - To develop a **resource-saving way of building concrete walls**, actors from **research, robotics/AI, and construction** worked together.
 - Another example is the development of **adaptive PV panels**: To optimise this technology, **researchers on robotics, installation and façade experts, and architects** had to interact. The responsible start-up "Zurich Soft Robotics" is now also offering this technology to private users.
2. Thinking about the example provided, can you think of **how novel interactions between sectors** enabled innovative solution within NEST??
 (e.g., construction/engineering, research, recycling/reuse, robotics, AI, concrete sector)
 - a. **What was innovative about the solution? Which sectors/systems were linked?**
 - b. **How** was this **innovation** in NEST initially **developed**? And **who** initiated it?
 - c. What was **"exchanged"** (e.g., knowledge, skills, regulations, etc.)?
 - d. Was any **new material or technology** used from another sector? If **so**, which one?
 - e. Did you face any **difficulties** when using this material or technologies in this new situation?
 (e.g., regulatory, technical, etc.)
 - f. Did the **regulatory framework conditions or standards** hinder or drive the implementation of this innovation?
3. There are **organisations** like firms and individuals involved in your project who are especially important when working **across system boundaries / sectors**. One example is a **spin-off company**, which connects science with the market actors when translating research into products or services that meet market demand.
 - a. Can you describe who was especially important as an organisation for **HiLo**?
 - b. Have there been **actors** acting as **"bridges"** between different sectors?
 - c. Would you say that – in general – LHs function as a platform that connects otherwise separate actors and organisations?
 - d. Did you face **challenges** regarding **regulation or different working cultures** when interacting with actors from other sectors (than science)?

2 Final Questions

1. Have any of the **innovative solutions** from the HiLo project been **transferred into real-world construction** practice?
 And: Can you think of what could help innovative materials/technologies become **more widespread** in the construction sector?
2. What **potential barriers or limitations** do you see when it comes to applying the innovations discussed in practice?

3 Ending

1. We have now reached the **end** of this interview. Would you like to add anything?

Interview-Fragebogen

ressourceneffiziente und fortschrittliche Bautechnologien

1 Einführung

1. Vielen Dank noch einmal für Deine Teilnahme!
2. **Dokument zur Datenschutzerklärung:** Bevor wir beginnen, möchte ich kurz auf das Dokument «Datenschutzerklärung» eingehen
 - a. Falls Du mit allem einverstanden bist, könntest du das Dokument bitte unterschreiben?
3. Über mich:
 - a. **Masterstudentin in Humangeographie** an der Universität Zürich.
 - b. **Thema** meiner Masterarbeit: «Die Rolle von Leuchtturmprojekten in sozio-technischen (Transitionen) Übergängen» am Beispiel des NEST-Gebäudes der Empa.
 - c. Ich bin besonders daran interessiert zu verstehen, **wie Leuchtturmprojekte** wie NEST die **Verbreitung von bahnbrechenden/fundamentalen Innovationen unterstützen** und zu einer **Dekarbonisierung** des Schweizer **Bausektors** beitragen können.
 - d. Um meine Forschungsfragen zu beantworten, ist ein Verständnis der verschiedenen **Prozesse und Wechselwirkungen** von NEST in **verschiedenen Sektoren** von entscheidender Bedeutung.
4. Das Interview ist in **sechs Frageblöcke** aufgeteilt. Hast du noch irgendwelche **Fragen**, bevor wir mit dem Interview beginnen? Ansonsten / Wenn es keine Fragen gibt, würde ich jetzt mit der **Tonaufnahme** beginnen.

1.1 Definition Leuchthausprojekt

1. Bevor wir mit den Fragen anfangen, könntest du dich und deinen aktuellen **Aufgabenbereich** kurz **vorstellen**?
2. Für meine Arbeit bezeichne ich das NEST-Gebäude der Empa als «Leuchtturmprojekt» (LH).
Nach meiner **Definition** ist NEST als LH ein «**sicherer und geschützter Raum für Innovation**», der darauf abzielt, einen «Konzeptnachweis» für sehr innovative Lösungen für die Öffentlichkeit und Experten zu erbringen. LHs sind darauf ausgelegt, **Ideen zu entwickeln**, die in **größerem Massstab umgesetzt** und auf den Markt gebracht werden können. Dabei haben sie auch eine **breitere Wirkung** sowohl in der (Bau-) **Industrie** als auch in der **Gesellschaft** im Allgemeinen. Diese Projekte finden oft in Bereichen statt, in denen es noch **an Vorschriften oder klarer Unterstützung mangelt**, was sie zu einem wichtigen Ort für neuartige Konzepte macht. Ziel ist es, zu zeigen, **was funktioniert, Vertrauen** zu schaffen und **andere in der Branche zu ermutigen**, erfolgreiche Innovationen **zu übernehmen und zu verbreiten**.

1.2 Entwicklung von Wissen und Technologie

Zunächst möchte ich mit dir darüber sprechen, wie im Rahmen des NEST-Projekts **Wissen verbreitet** und **Technologien entwickelt** wurden.

1. Wie hast du die Zusammenarbeit verschiedener Akteure wie Unternehmen und Forschungsgruppen in NEST erlebt?
 - a. Inwiefern unterschied sich diese Zusammenarbeit/Teamarbeit von anderen Bauprojekten?
2. Hast du während des **Bauprozesses neues Wissen oder «Fähigkeiten»** erworben (müssen) (z.B. während Planungs- oder Bauphase)?
 - a. **Wer** hat dir geholfen, dieses Wissen zu erwerben?
3. Hast du beobachtet, dass Innovationen, die in HiLo angewandt wurden, **anderswo genutzt und/oder weiterentwickelt** werden?
Wenn ja,
 - a. **Wo** und **wie**?
 - b. Können Sie an **Folgeprojekte** wie **Konferenzen oder Workshops** denken?

1.3 Marktbildung /Zugang

Massstab, räumliche und zeitliche Dimension, Nischenmarkt

Ich werde nun einige Fragen zur **Marktbildung** stellen.

1. Sind die innovativen Lösungen, die in NEST eingebaut wurden immer noch in einem **Nischenmarkt** angesiedelt?
2. Inwieweit wurden die Lösungen von NEST auf verschiedenen **geografischen Ebenen** (lokal, regional, national, global) umgesetzt?
 - a. **Wer** zeigt hauptsächlich Interesse? (Bauunternehmen, Behörden, Immobilieneigentümer:innen, etc.)
 - b. **Wie** würdest du deren **Interesse an der Nutzung** und dem Kauf der in NEST entwickelten Innovationen beschreiben?
 - c. Gibt es noch Probleme mit der **Benutzerakzeptanz**?
 - d. Sind die **Preise** der entwickelten Lösungen ein Problem bzgl. der allgemeinen Nutzung?
Wenn ja, könnten die Preise in irgendeiner Weise angepasst/reduziert werden?

1.4 Mobilisierung von Investitionen

Finanzielle Ressourcen, die Kombination von Investitionen

Nachdem ich über die Märkte gesprochen habe, möchte ich nun den Schwerpunkt auf Finanzinvestitionen oder -unterstützung verlagern.

1. Hast du **zusätzlichen/externen finanzielle Unterstützung** in die entwickelten Ideen von NEST erhalten? Bzw. anders als bei anderen Bauprojekten, die du als Architekt betreust?
Wenn ja,
 - a. **Wer** waren diese Investoren (Grossunternehmen, Privatpersonen, Banken, Risikokapitalgeber, ...)?
 - b. **Woher** wurden die Investitionen mobilisiert? Von lokalen oder globalen Akteuren/Netzwerken?

Wenn nein,

- a. Was könnte **verbessert** werden, um die **Investitionen in Innovationen/Technologien** zu erhöhen, die im **Bereich der 'ressourceneffiziente und fortschrittliche Bautechnologien'** entwickelt wurden?

1.5 Legitimation/Akzeptanz der Technologie Standards/Normen, Akzeptanz, Werte, Verhaltensänderung

In den folgenden Fragen geht es darum, wie die NEST-Innovationen bereits heute **«akzeptiert»** werden.

1. Gibt es bereits **neue Standards/Normen**, die das Thema «ressourceneffiziente und fortschrittliche Bautechnologien» aufgreifen? Denen du immer häufiger im Alltag begegnest?
 - a. Können diese durch ein Projekt wie «HiLo» **gefördert** werden?
2. Inwiefern könnte ein Leuchtturmprojekt wie NEST die Menschen in der Bauindustrie dazu **ermutigen**, vermehrt nachhaltige oder innovativere Praktiken zu brauchen?
 - a. Inwiefern hat dieses Projekt Ihrer Meinung nach die **öffentliche Akzeptanz** (oder von Endnutzern) beeinflusst?
3. Haben Sie eine **Zunahme von Medienberichterstattung (öffentliche Akzeptanz)** zu «ressourceneffizienten und fortschrittlichen Bautechnologien» festgestellt (z. B. in Form von Zeitungsartikeln)?
 - a. Glauben Sie, dass die **Präsenz** von NEST in den Medien dazu beigetragen hat, die **Akzeptanz** innovativer Ansätze im Bauwesen in der Öffentlichkeit oder in der Industrie zu **erhöhen**?
4. Sind die Lösungen aus NEST in den politischen Diskussionen angekommen?

1.6 Multi-System-Interaktionen (MSI) Multisektorale Wechselwirkungen, Koppelungen

1. Ich interessiere mich für die **Sektoren**, die an dem Projekt beteiligt sind. Ein Beispiel dazu:
 - Bei der **Entwicklung** einer **ressourcenschonenden Methode** zum Bau von Betonwänden arbeiteten **Akteure aus den Bereichen Forschung, Robotik/KI und Bauwesen** zusammen.
 - Ein weiteres Beispiel ist die Entwicklung **adaptiver PV-Panels**. Um diese Technologie zu optimieren, mussten **Robotikforscher, Installations- und Fassadenexperten sowie Architekten** zusammenarbeiten. Das verantwortliche Start-up «Zurich Soft Robotics» bietet diese Technologie nun auch für private Nutzer an.
2. Kannst du dir anhand des genannten Beispiels vorstellen, **wie eine innovative Lösung innerhalb von NEST solche neuen Interaktionen zwischen Sektoren ermöglicht** hat?
(z. B.: Bauwesen/Ingenieurwesen, Forschung, Recycling/Wiederverwendung, Robotik, KI, Betonsektor)
 - a. **Wie** wurde diese **Innovation in NEST** ursprünglich **entwickelt**? Und **wer** hat diese Entwicklung initiiert?
 - b. Was wurde **«ausgetauscht»** (z. B. Wissen, Fähigkeiten, Vorschriften usw.)?
 - c. Wurde **neues Material** oder eine **Technologie** aus einem **anderen Sektor** verwendet? **Wenn ja**, welche?
 - d. Gab es Technologien, die angepasst werden mussten, um mit dem Gesamtsystem zu funktionieren? Wenn **ja**, wer war für die Koordinierung dieser Massnahmen zuständig?
 - e. Sind Sie bei der **Verwendung** dieses Materials oder dieser Technologien in dieser neuen Situation auf Schwierigkeiten gestossen? (z. B. rechtliche, technische usw.)
 - f. Haben die **rechtlichen Rahmenbedingungen oder Standards** die Umsetzung dieser Innovation behindert oder gefördert?
3. Es gibt bestimmte Organisationen wie Unternehmen oder Akteure, die wichtig für das Zusammenarbeiten über Systemgrenzen hinweg sind. **Bsp: Spin-off** → Es verbindet wissenschaftliche Erkenntnisse mit Wirtschaftsakteuren, indem es Forschungsergebnisse in nachgefragte Produkte oder Dienstleistungen übersetzt.
 - a. Kannst du beschreiben, welcher **Akteur** in dieser Hinsicht **wichtig für HiLo war**?
(d.h. das Zusammenarbeiten gefördert oder vereinfacht hat; Beispiele sind Partnerschaften, informeller Austausch oder Verträge)
 - b. Gab es **Akteure**, die **als «Brücken»** zwischen den Sektoren fungierten?
 - c. Würdest du sagen, dass die **LH** im Allgemeinen als **Plattform** fungieren, die ansonsten getrennte Akteure und Organisationen miteinander **verbindet**?
 - d. Standest du bei der Zusammenarbeit mit Akteuren aus anderen Sektoren vor **Herausforderungen** in Bezug auf **Vorschriften oder unterschiedliche Arbeitskulturen**?

2 Abschlussfragen (6)

1. Wurden die **Innovationen**, die im HiLo-Projekt entwickelt wurden, bereits **in der Bauindustrie übernommen**?
 - a. Fällt dir etwas ein, was dazu beitragen könnte, dass innovative Materialien/Technologien im Bausektor weiterverbreitet werden?
2. Welche potenziellen Hindernisse oder Grenzen siehst du, wenn es darum geht, die besprochenen Innovationen in der Praxis umzusetzen?

3 Ende

1. Wir sind nun am **Ende** dieses Interviews angelangt. Möchten Sie etwas **hinzufügen**?
2. Können Sie andere **Experten** vorschlagen, mit denen ein Gespräch sinnvoll wäre?

10.2 Privacy Policy (in English and German)



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Privacy Policy

Between the interviewee _____

and Claudia Tschan, master's student at UZH.

We agree to the following points:

1. Participation in the interview is voluntary.
2. Claudia Tschan is responsible for the conduct and scientific analysis of the survey. She ensures that all personal data collected during the interview is treated anonymously and analysed following the strict data protection guidelines of the University of Zurich (UZH). This also applies to short excerpts from the transcript, which may be cited anonymously in internal analyses and scientific publications.
3. The interviewee agrees to the audio recording and scientific analysis of the interview.
4. The audio recording will be treated confidentially.
5. For evaluation purposes, a transcript of the recording is produced and stored electronically in an encrypted folder.

I agree with the above terms and conditions.

Place, Date: _____

Signature (interviewee):

Signature (interviewer):



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Datenschutzerklärung

Zwischen der/dem Interviewteilernehmer/in _____

und Claudia Tschan, Masterstudentin an der UZH.

Wir erklären uns mit folgenden Punkten einverstanden:

1. Die Teilnahme am Interview ist freiwillig.
2. Verantwortlich für die Durchführung und wissenschaftliche Auswertung des Interviews ist Claudia Tschan. Sie trägt dafür Sorge, dass alle erhobenen personenbezogenen Daten des Interviews anonym behandelt und nach den strikten Datenschutzrichtlinien der Universität Zürich (UZH) ausgewertet werden. Dies gilt auch für kurze Auszüge aus dem Transkript, die in internen Auswertungen und in wissenschaftlichen Veröffentlichungen anonymisiert zitiert werden können.
3. Der/die Interviewteilernehmer/in erklärt sein/ihr Einverständnis mit der Audioaufnahme und wissenschaftlichen Auswertung des Interviews.
4. Die Audioaufnahme wird vertraulich aufbewahrt.
5. Zu Auswertungszwecken wird von der Aufnahme ein Transkript erstellt und in einem verschlüsselten Ordner elektronisch aufbewahrt.

Mit den oben genannten Punkten erkläre ich mich einverstanden.

Ort, Datum: _____

Unterschrift (Interviewteilernehmer/in):

Unterschrift (Interviewer/in):

10.3 Coding System

Code System	Frequency
Geographical Scale	3803
International	86
National	91
Local/regional	43
GIS 1 (KaTD)	0
Technology innovation / spill-over	32
Knowledge development / spill-over	111
Expertise and new skill	8
Capabilities regarding technology	5
GIS 2 (MaFo)	0
Market accessibility / pot. cust. / profitability / demand	71
Niche	11
Perception	6
Commercialisation / Scaling-up (productivity)	68
GIS 3 (invMob)	0
Financial resources for (internal) R&D	19
Material investment	11
Financial investment	43
GIS 4 (TL)	0
Acceptance and validation (st. interest)	0
General public	35
Media	14
Experts / Industry	42
Politics / Public authority	20
Emotion	7
Demonstrator / LH	17
Definition	11
Value	96
GIS Element	0
Actors	0
Industry / Construction sector	129
NEST Partner	137
KMU	49
Spin-Off / Start-Up	86
Planer / Architect / Engineer	158
Education (Public/Industry)	47
Research actor	120
Investor	26
Client / Builder	41
Policy / Public authority	46
First mover / Ambassador	9
NEST (Empa)	233
Networks	19
Institutions	0
Societal norm / trend	16
Technology standard / Regulations / Policies	95
Patent	4
MS couplings	0
Technical	15
Bridging element / System entanglers	34
Organisational / Interaction	176
Follow-up	22
Relation between elements (incl. func. coupl)	28
Topic	0
Construction sector	0
Transformation	57
Decarbonisation / NetZero / Sustainability / Climate change	40
Resource-efficient and advanced construction technologies	14
Urban mining / Re-Use / Recycling / Circularity	65
Innovative solutions	0
Design/Process	40
Prototype	5
Further application	20
Price	43
NEST	0
Communication	28
Responsibility / Tasks	24
Structure	35
Innovative Solutions	30
Learnings	0
Enabler / Impact	15
Improvement potential	41
Transformation (from learnings)	11
Units	0
HiLo	165
UMAR / Sprint	53
Step2	45
Others	14
Process	92
Barriers / Challenges / Conflict / Limitation	289
Perceived	7
Good quote	333

10.4 Encoding Key MAXQDA24

The following table shows how I initially transcribed word-for-word.

Table 6: Encoding Key for MAXQDA24 (own illustration).

Meaning	Interviewer (A)	Interviewee (I)
mhm, okay, right	&	&&
ja/jap/jup, yes/yeah/of course	J	JJ
ähm, uum	?	??
laughing	hh	hhhh
aah(a), aah right	A	AA
hmm	M	MM
pff (exhalation, sighing, clearing one's throat)	p	pp

10.5 Declaration of AI-based Tools

Several programs using AI features have been used in parts of this master's thesis. Especially for the transcription process, AI programs like 'Schweizerdeutsch Übersetzer', 'MAXQDA', and 'noScribe' have been of significant help. Additionally, primarily for translation of interview quotes or proof-checking of written texts, programs including 'DeepL', Grammarly Pro, or ChatGPT were used in this thesis.

10.6 Declaration of Authenticity

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Watt, 30 November 2025



Claudia Tschan