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Concrete floors: multi-criteria analysis of conventional and novel solutions

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Abstract. As floors account for a significant share of a building's embodied carbon, designing low-carbon floors is crucial to mitigating construction's environmental impact. This research presents a multi-criteria comparison of four concrete floor systems: two widely used conventional systems —flat concrete slabs and timber-concrete composite slabs—and two novel systems —concrete thin shells and systems reusing concrete and steel elements. Six qualitative and quantitative criteria (embodied carbon, total depth, self-weight, waste use, deconstruction ease, supply ease) are used to compare the systems. Additionally, the study examines the sensitivity of key embodied carbon parameters such as material selection and transportation distance. Compared to flat slabs, the novel systems and timber-concrete composite slabs achieve embodied carbon reductions of up to 80 % and 40 %, respectively. While no system outperforms all criteria, the novel solutions surpass flat slabs in all aspects except supply ease and total depth. Since embodied carbon is not yet restricted in Swiss construction, flat slabs remain advantageous and largely prevalent due to their slenderness and ease of construction. To meet carbon reduction targets, the authors call for further supply-chain and business-model investigations and optimisation of the novel systems.

1. Introduction

Building floors, predominantly made of reinforced concrete, typically account for between 50 % (1) and 75 % (2) of the embodied carbon in load-bearing systems. Therefore, lowering their embodied carbon is crucial to reducing buildings' overall embodied carbon. Research in recent years has explored innovative solutions to achieve this, investigating two main strategies: (a) minimising material use through structural optimisation and (b) replacing conventional materials with lower-carbon ones.

Early explorations of structural optimisation in concrete floors date back to the advent of modern reinforced concrete (RC). In the late 19th century, ribbed slab systems emerged to reduce costs by minimising material use. However, with globalisation and the relative drop in material prices, structural optimisation was gradually abandoned, superseded by the construction ease, speed and simplification of structurally less optimised designs. In Switzerland, the use of solid flat RC progressively became predominant, and their thickness gradually increased.

More than a century later, climatic emergency has reignited interest in structural optimisation. Recent progress in digital construction – such as 3D printing, robotics, and

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computational optimisation- has enabled the development of new slab systems that require significantly less material than conventional ones (3–6). A notable example is the Hi-Lo floor, an unreinforced ribbed funicular concrete system (7,8). This system uses only one-third of the material needed for a conventional concrete flat slab (7,9). Another promising approach is thin shells. This system can halve material consumption compared to conventional flat slabs (10–12).

The second strategy aims to replace Portland cement concrete with lower-carbon materials. Timber has gained increasing attention, with well-documented environmental benefits (13–15). Although timber is often combined with a concrete slab to meet acoustic requirements (16,17), this hybrid approach is still reported to reduce carbon dioxide emissions by about 50 % (18,19). Another possibility for lower-carbon materials is using cement with a reduced clinker content compared to CEM I (minimum 95 % of clinker). CEM II (65 to 79 % of clinker) and CEM III/A (35 to 64 %) are cement types with lower embodied carbon per kilo than CEM I. In Switzerland, CEM II/B is the most used cement (63 % of sold cement), followed by CEM II/A (27 % of sales) (20). The sales of CEM III are below 1 %, as clinker-substituting blast-furnace slag is not produced in Switzerland (20,21).

Low-carbon materials also include other promising geo-based alternatives. One is reusing RC elements carefully extracted from structures deemed for demolition. Reusing RC elements differs from recycling concrete: recycled concrete follows the *crushing* of RC structures into aggregates. These aggregates then replace a share of the natural aggregates in so-called "recycled concrete mixes" that still require the same amount of sand, water, and cement as new concrete mixes, thus resulting in comparable carbon emissions (22). Conversely, reusing RC elements follows a *careful deconstruction* of structures, where entire structural elements, such as slab portions or beams, are extracted typically using circular saws. Unless in poor conditions (23), these salvaged elements can be directly reused and reassembled into new structures.

Concrete reuse is not an entirely new construction approach: over 50 applications have been identified in Europe since the late 1960s (24). However, most of these cases reused precast elements, as the clear delimitation between precast elements and their assembly methods ease their reuse. As cast-in-place concrete is more prevalent than precast concrete in some territories, such as Switzerland, recent research has been undertaken to develop design approaches to reuse cast-in-place concrete. One of them developed floor systems that reuse RC elements extracted from cast-in-place slabs (25). The system can cover long spans if the RC elements are placed on top of girders, such as new or reused steel girders. Expected average embodied carbon reductions are estimated at around 80 % compared to a conventional solid flat RC slab (25). The construction of a 30-m^2 confirmed the technical feasibility of the reused-RC system (26).

Despite their potential to significantly reduce embodied carbon, novel floor systems have challenging drawbacks, such as limited material or component availability and increased structural depth, thus calling for a multi-criteria analysis. Furthermore, previous research on novel floor systems investigated solutions mainly separately.

This paper provides a multi-criteria comparison of conventional and novel concrete floor systems, including thin shells and reused-concrete systems, addressing the drawbacks of these innovative systems. As construction habits, design standards, and industrial networks vary locally, the scope of the study is limited to Switzerland.

2. Methods

The paper compares a set of concrete floor systems, including conventional and novel solutions, through a multi-criteria analysis. The floor system design brief, the selected floor systems and their corresponding design solutions are introduced in Section 2.1. The set of evaluation criteria and their corresponding metrics are introduced in Section 2.2.

2.1. Load-bearing floor systems

The study compares design options for the load-bearing floor systems of an office building spanning over a regular column grid of 5x6 meters in Switzerland. The set of design alternatives includes two common floor systems in Switzerland - i.e. poured in situ flat RC slabs (**S1**) and poured in situ concrete slabs on timber beams and joists (**S2**), and two novel systems – i.e. textile-reinforced concrete thin shells (**S3**) and reused RC slabs over reused steel girders (**S4**) (**Figure 1**). The following paragraphs provide more details on these systems and introduce variations of these systems used to test the sensitivity of selected parameters, listed in **Table 1**.

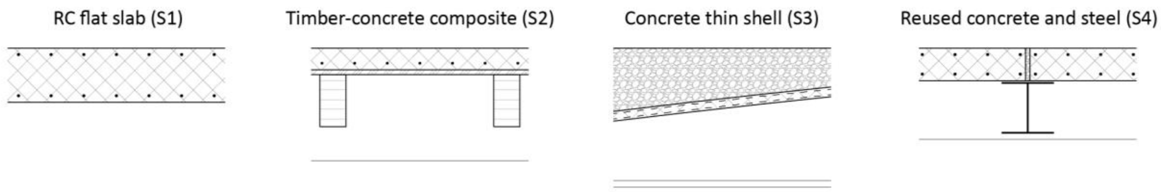

Figure 1. Sections of the compared load-bearing floor systems.

Table 1. Floor systems and list of sub-system alternatives with varying parameters

System		**System alternative**				
Code	Description	Code	Parameter 1		Parameter 2	
S1	Flat RC slab	**S1.a**	Cement type	CEM II/B	Recycled-aggregate content	0 %
		S1.b		CEM II/B		25 %
		S1.c		CEM III/A		0 %
S2	Timber-concrete composite	**S2.a**	Timber product	Glulam	Market	Swiss market
		S2.b		Glulam		Swiss production
		S2.c		Mass		Swiss market
S3	Concrete thin shell	n/a	n/a	n/a	n/a	n/a
S4	Reused concrete and steel	**S4.a**	Distance from donor site to local storage [km]	100	n/a	n/a
		S4.b		200		
		S4.c		500		

The first floor system (**S1.a**) is a flat RC slab, Switzerland's most common floor system. The slab height is 25 cm, which represents conventional designs used by the local industry. A concrete C30/37 is taken, and the cement type considered is CEM II/B - the most commonly used in the country (20). Two additional variations of this floor system are considered. In the first variation (**S1.b**), recycled aggregates replace 25 % of the natural aggregates, while in the second variation (**S1.c**), a CEM III/A cement is considered (with 100% virgin aggregates).

The second floor system (**S2.a**) is a typical concrete-timber solution used in Switzerland, where a thin concrete slab is poured on a 22-mm lost triply formwork supported on timber beams and joists. The C25/30 concrete slab is 10 cm thick and reinforced with two layers of 8-mm-diameter steel reinforcement bars. The 6-m-long beams are 12-cm wide, 24-cm high, spaced at 80 cm, and of glue-laminated timber. The joists are 5 m long, with 40-cm squared sections. Alternatives with glue-laminated timber produced in Switzerland (**S2.b**) and mass timber are also considered (**S2.c**).

The third floor system is a textile-reinforced concrete thin shell (**S3**). This construction system is a state-of-the-art solution for sustainable new-concrete floor construction. An extended description of the system design and analysis of test specimens were published in 2019 and 2020 (10,12). The floor system involves four main materials: fine-grained concrete, textile reinforcement, steel ties, and filling material (recycled concrete aggregates). The dimensions are taken from existing design tables (27). The thickness of the concrete shell is 46 mm.

The fourth system (**S4.a**) involves a novel design solution made of reused RC slabs spanning between reused H-shaped steel profiles. The design method of this system was published in 2024 (25). A 30-m^2 prototype was also built at EPFL, and details on the design, structural verifications, material-testing procedure and reused-element sourcing process can be found in (26). The design involves four reused 15-cm thick RC elements of 2.5 by 3.0 meters spanning over a grid of reused steel beams. Prestressed threaded bolts in the slab corners ensure the transfer of the lateral loads between the concrete and steel elements. The design conservatively assumes no composite action between the RC slabs and the steel beams. The connection presents the advantage of being fully dismantlable. The transportation distance from the deconstruction site to the local storage is assumed to be 100 km in **S4.a**. 200 and 500 km distances are used for alternatives **S4.b** and **S4.c**, respectively.

2.2. Comparison criteria

The floor systems are compared among each other using six criteria, which include environmental, architectural, engineering, and project-management aspects:

1. *Embodied carbon*: greenhouse-gas emissions related to stages A1 to A3 according to ISO14040(28) (cradle to gate – material supply, transport to manufacturer, manufacturing) for constructing one square meter of the compared load-bearing systems, using a cut-off approach. Impact factors are taken mainly from the ecoinvent-based KBOB database and concrete tables (29,30) and partly completed with (10) for S3. The impacts of the formworks are neglected, as they are considered designed to be reused multiple times.
2. *Self-weight*: the weight of the compared load-bearing systems.
3. *Total depth:* the total maximum depth of the load-bearing systems.
4. *Waste use:* the weight of the construction waste recycled or reused by the load-bearing systems.
5. *Deconstruction ease:* the degree of operation complexity to deconstruct the load-bearing system. The criterion differentiates between prefabricated and dry-assembled systems and in-situ systems requiring more complex deconstruction operations. This criterion qualitatively and relatively assesses the efforts required to dismantle the systems carefully.

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6. *Supply ease:* the ease with which construction components and elements can be supplied, considering current supply chains in Switzerland. This criterion qualitatively and relatively assesses the difficulty needed to obtain the materials, including delay and overall availability.

The analysis does not include the non-load-bearing parts of the floor systems, such as suspended ceilings, lighting, and flooring. Similarly, it focuses solely on the floor systems, thus excluding other parts such as columns, facades, etc. This analysis does not include costs, as sufficient data from operations larger than prototypes are not yet available for novel systems.

2.3. Assessment method

For each criterion, the value is assessed quantitatively (criteria 1, 2, 3 and 4) or qualitatively (criteria 5 and 6). Then, criterion values are normalised between 0 (the worst value among the floor systems) and 1 (the best value). For quantitative metrics, the normalisation is set using the following relationship for a performance metric *i* and a floor system *j* (for a criterion that must be minimised, such as the embodied carbon):

$$a_{i,j} = \frac{value_{i,j} - \min(value_i)}{\max(value_i) - \min(value_i)}$$

For qualitative metrics, the value is directly given between 0 and 1 for each floor system. The qualitative performances are assessed based on knowledge of the construction industry, deconstruction experience, and discussions with designers. It is acknowledged that these evaluations depend on actors' perspectives and experiences.

The set of selected systems impacts the normalisation results, as different upper and lower values would influence the normalised results. Additionally, it is acknowledged that using a different normalisation technique would influence the results too.

3. Results and discussion

3.1. Floor-system performances

Assessments of performance criteria for each floor system are shown in **Table 2** and **Figure 2**. Overall, no system outperforms across all criteria. The reused system performs best in the following performance criteria: embodied carbon, waste used, and deconstruction ease, while the thin shell is the most performant for the self-weight criterion and performs second for embodied carbon, waste used and deconstruction ease. The flat slabs deliver the best supply-ease and total-depth performances. RC flat slabs feature two main advantages for the construction industry: their slenderness and excellent availability. These assets are the reasons behind their prevalence despite their embodied carbon being up to 80 % larger. Flat slabs are also outperformed by the timber-concrete composite floor in terms of embodied carbon (- 40 %) and self-weight. Still, flat slabs remain slender and slightly easier to supply, depending on the timber used. The following paragraphs discuss each criterion and system in detail.

Starting with supply ease, the reused element system generally faces the most significant supply challenges. Indeed, conventional demolition—a fast, cost-effective, wide-stream process in which materials are crushed—still largely prevails over careful deconstruction, in which elements are selectively extracted and stored before reuse. Today, design teams must make significant efforts to identify potential soon-to-be-demolished structures and negotiate their careful deconstruction. In addition, the volumes of demolished—and thus possibly reused—materials are below that of material demand in Switzerland (31).

Table 2. Normalised results of the six assessment criteria: the colour gradient shades away from the highest normalised value (1, in blue) to the lowest (0, in grey). Absolute values for quantitative criteria are indicated in *italic*.

		Embodied carbon		Self-weight		Waste used		Total depth		Decon-structio n ease	Supply ease
		[kgCO2,e/m2]		*[kg/m2]*		*[kg/m2]*		*[m]*			
Flat RC slab	**S1.a**	*70*	0,00	*599*	0,00	*0*	0,00	*0,25*	1,00	0,30	1,00
	S1.b	*70*	0,00	*599*	0,00	*90*	0,22	*0,25*	1,00	0,30	0,90
	S1.b	*57*	0,23	*599*	0,00	*0*	0,00	*0,25*	1,00	0,30	0,40
Timber-concrete composite	**S2.a**	*42*	0,50	*282*	0,99	*0*	0,00	*0,52*	0,31	0,00	0,90
	S2.b	*40*	0,54	*282*	0,99	*0*	0,00	*0,52*	0,31	0,00	0,90
	S2.c	*41*	0,54	*282*	0,99	*0*	0,00	*0,65*	0,31	0,00	0,70
Concrete thin shell	**S3**	*24*	0,82	*278*	1,00	*169*	0,41	*0,65*	0,00	0,70	0,50
Reused concrete and steel elements	**S4.a**	*15*	1,00	*413*	0,58	*409*	1,00	*0,41*	0,60	1,00	0,00
	S4.b	*22*	0,87	*413*	0,58	*409*	1,00	*0,41*	0,60	1,00	0,10
	S4.c	*44*	0,46	*413*	0,58	*409*	1,00	*0,41*	0,60	1,00	0,20

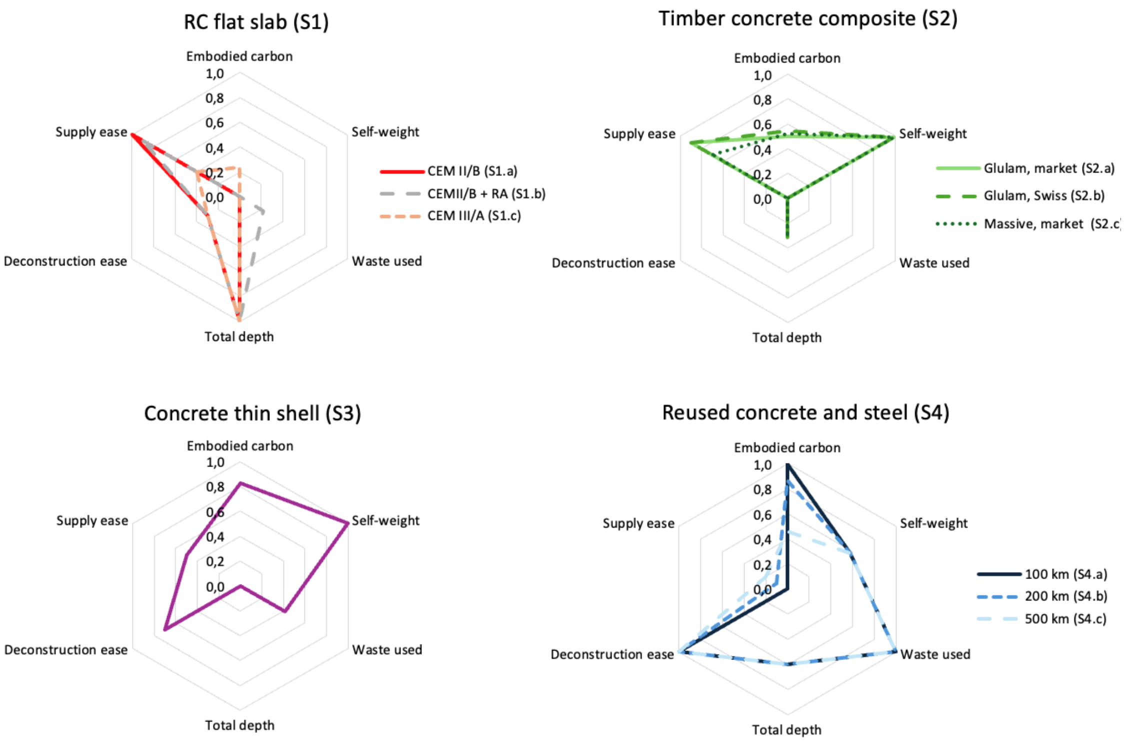

Figure 2. Graphical representation of the normalised results for the four systems and their alternatives. The highest score (1) corresponds to the best relative performance; the lowest score (0) corresponds to the poorest relative performance.

The concrete thin shell has moderate supply ease. While it uses widely available materials, its fabrication process (hand application of concrete layers (12)) differs from standard industrialised methods and may not yet be easily handled by conventional prefabrication plants.

The timber-concrete composite system currently has a good supply ease. However, longer fabrication delays are needed if mass timber is used, as these members are costumed-produced.

If timber construction significantly increases in the future, the supply of Swiss timber may become constrained by industry capacity and resource availability. In 2023, nearly 5 million cubic meters of Swiss timber were harvested, and this volume should not exceed 7 to 10 million cubic meters for sustainable exploitation, according to the Swiss Federal Office for the Environment (32).

The CEM-II/B flat RC slabs are the easiest to supply, as they are one of the most used construction systems, and there are no immediate supply challenges. However, using CEM III/A is more constrained, as blast-furnace slag production is a byproduct of the iron industry. Furthermore, blast-furnace slag is not produced in Switzerland (21).

Regarding circular material use, the deconstruction-ease criterion assesses the level of technical and planning ease to conduct a careful deconstruction of the systems. Careful deconstruction is more trivial and generally faster for systems made of distinct, prefabricated elements with dry assemblies than monolithic, built-in situ systems. The system that is easiest to deconstruct is the reused concrete and steel one, as it is made of distinct elements assembled with reversible connections, except for some low-strength mortar in the joints. The system considered the second easiest to deconstruct is the thin shell. This system is made of distinct, dry-assembled components (the shell, filling materials, and ties). Nevertheless, removing the 6x5 m shell will likely require special lifting and transportation processes. The in-situ RC solid slab would require the development of a sawing and lifting plan but with less complexity than for the timber-concrete composite system, which is constrained by the beams and joists.

In this analysis, the total depth of a system is measured. This metric does not account for variations in height within the same system or other volumetric specificities. For example, the thin shell –the deepest system, allows HVAC tubes to run in the space filled with recycled aggregates over the shell. Similarly, the space between beams could be used for technical appliances in the timber-concrete composite and reuse systems.

3.2. Embodied-carbon sensitivity analysis

Figure 3 depicts the embodied carbon for the considered systems and their variations between floor-system alternatives. Overall, the flat RC slabs have the highest embodied carbon. Comparing S1.a and S1.b, replacing a share of the natural aggregates with recycled aggregates (S1.b) does not reduce the carbon footprint—around 70 $kgCO_{2,e}/m^2$—as the same amount of cement is needed, corroborating existing literature (33). However, using CEM III (S1.c), which has a lower clinker content, reduces the carbon footprint by nearly 20 %.

Timber-concrete composite floors have embodied carbon footprints of around 40 $kgCO_{2,e}/m^2$—about 40 % lower than those of CEM-II flat RC slabs. The choice of locally produced glulam or mass timber has little influence on the footprint, as most emissions stem from concrete production. Biogenic carbon storage was not accounted for in the calculation, but considering the values available (29), its sequestration potential would slightly exceed emissions from timber harvesting and processing.

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The novel systems have the lowest embodied carbon footprint. The thin shell has a footprint of around 25 $kgCO_{2,e}/m^2$, while the reused system has a footprint that varies between 15 and 22 $kgCO_{2,e}/m^2$, for 100 and 200 km transportation, respectively. The sensitivity analysis on transportation distance demonstrates that if the reused components are transported over 500 km, then the embodied carbon footprint slightly exceeds that of the concrete-timber composite (44 vs 42 $kgCO_{2,e}/m^2$) but remains lower than that of a flat RC slab. Although transportation distance significantly impacts the reused system embodied carbon, long transportation distances can still lead to a lower footprint than conventional floor systems. Additionally, transportation costs and practical aspects will likely restrict distances even more than embodied carbon considerations would.

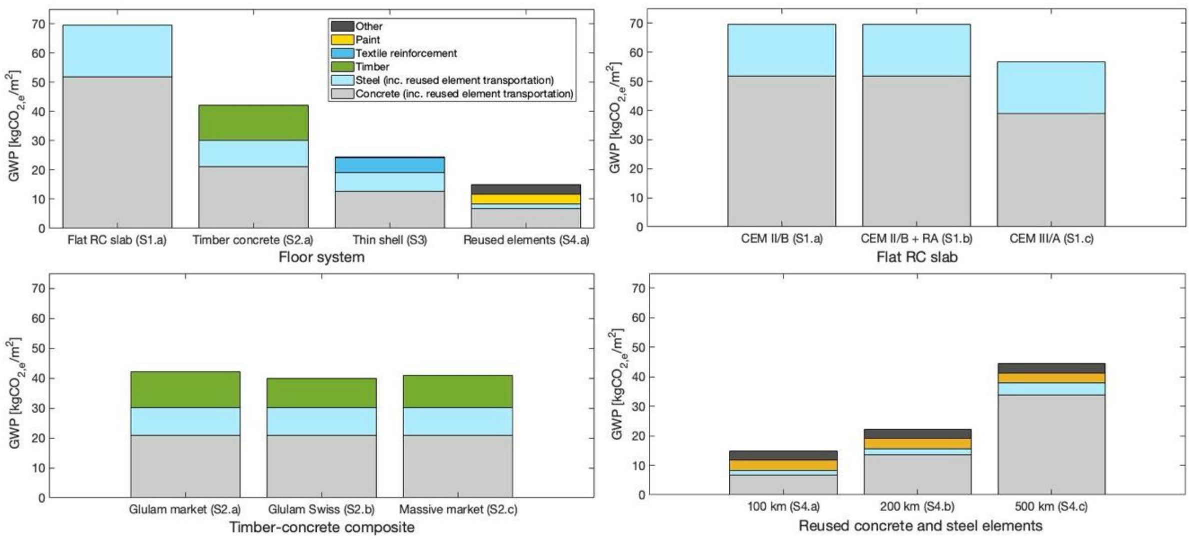

Figure 3. Embodied carbon of the floor systems and sub-system alternatives.

3.3. Discussion

Overall, concrete-timber composite systems (S2) are light, which is an asset when adding stories to an existing building. In addition, this system still allows for a consequent reduction of the embodied carbon footprint compared to RC flat slabs. Although probably the most used timber-concrete system in Switzerland, this system still requires beams and joists, which add depth to the system. To overcome this, researchers from ETHZ and the Bern University of Applied Science have developed the TS3 system, which has layered column heads that eliminate beams for floors on a column grid spaced up to 8 meters. This system has already been implemented in housing buildings (34) and could be investigated in future work.

Concrete thin shells (S3) perform well across several criteria, particularly in reducing embodied carbon and self-weight. However, challenges remain in the disassembly and fabrication processes. To address this, the research group that initiated this system has developed a new segmented version featuring interlocking prefabricated panels produced via automated concrete spraying. While this enhances fabrication and disassembly, it requires more liquid and, thus, more carbon-emitting concrete mixes (11). This new version of the system is not part of the analysis due to a lack of available design tables.

The reuse system presents the lowest embodied carbon footprint and excellent deconstruction ease. Total depth could be further optimised by developing new configurations where slabs align with girders. While the supply of reused components is a well-known challenge, increasing research analyses new business opportunities and needed industrial ecosystem modifications, for example (35,36).

While no single system excels across all criteria, the choice of floor system ultimately depends on project-specific priorities and constraints. Given the absence of mandatory embodied carbon regulations in Switzerland, flat slabs continue to dominate due to their slenderness and ease of construction. As the climatic crisis calls for more ambitious sustainability policies, a shift toward lower-carbon alternatives is already possible with timber-concrete solutions. The large-scale adoption of novel systems still requires investigating and developing robust supply chains.

Future research could expand this analysis with a broader set of systems, spans, and support conditions and integrate decision-maker preferences and scenarios within a multi-criteria decision analysis.

4. Conclusion

This study compared conventional and novel concrete floor systems through a set of six criteria. While no system excels across all criteria, the analysis leads to the following conclusions:

- Flat slabs remain the most industry-friendly option due to their low thickness and availability despite their high carbon footprint and large self-weight.
- Timber-concrete composite slabs offer a balanced alternative. They reduce carbon emissions by 40% while being compatible with established industrial methods.
- Novel floor systems significantly reduce embodied carbon, with up to 80% savings compared to flat slabs. Total depth and supply complexity remain limiting factors for the large-scale implementation of these low-carbon floor systems.

Considering the novel system advantages and limitations, future research avenues include investigating supply chains, business models, and local optimisation to support carbon-emission reduction targets.

5. Acknowledgements

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