Građevinski materijali i konstrukcije
Building Materials and Structures
journal homepage: www.buildingmaterialsstructures.com

https://doi.org/10.5937/GRMK2600018M

Original scientific paper

Comparative environmental assessment of conventional and designed for deconstruction steel-concrete composite floor structures

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Article history

Received: 29 April 2026
Received in revised form: 23 May 2026
Accepted: 01 June 2026
Available online: 18 June 2026

Keywords

steel-concrete composite floor,
design for deconstruction,
reuse,
environmental impact,
LCA

ABSTRACT

Design for deconstruction and reuse is a design strategy that can effectively contribute to circular economy goals in the building sector. However, its potential to reduce the environmental impact of steel and concrete building structures has to be assessed using scientific-based methods, like life cycle assessment (LCA). In this study, the environmental impacts of two steel-concrete composite floor structural solutions of a typical office building were assessed and compared: conventional (not demountable) and designed for deconstruction (DfD) solution. Both solutions were designed to provide two subsequent 50-years life spans of the building with the same spatial layout, where second building was built at different location. Composite floor in the relocated building in the conventional case was made of new materials, while in DfD alternative it was made of reused elements from the first use cycle. Chosen impact category indicators were calculated for both cycles together using LCA system expansion. The assessment was performed for two scenarios that differed in the anticipated steel production route for the second building structure. In scenario S1, current average European steel production technology mix (combined BF-BOF and scrap-EAF) was assumed, while in scenario S2 it was 100% scrap-EAF route for all structural steel. The results showed that material production (steel and concrete) phase was by far the largest contributor to overall indicator values, ranging between 85% and 95% for both solutions and both scenarios. Environmental benefits of DfD solution depended significantly on the assumed steel production technology. Low energy- and emission- intensive scrap-EAF route assumed for the second building in the scenario S2 led to decrease of DfD indicators reduction (compared to conventional solution): from around 37% in the scenario S1 to 16% - 24% in the scenario S2, which proved the importance of including future technology development in LCA.

1 Introduction

The construction industry's activities, especially in the buildings sector, generate significant impact on the environmental, economic and social aspects of sustainability. According to [1,2], buildings are responsible for 40% of all waste generated (by volume), 40% of all material resource use (by volume) and 33% of all human-induced emissions globally. As much as 11% of global greenhouse gas (GHG) emissions originate globally from the manufacturing of construction materials [3]. Within the linear economy concept (take-make-use-dispose) it can only be expected those figures to rise due to the population and urbanization growth. Based on the trends of global migration from land to cities it is forecasted that by 2050 almost 75% of the world's population will be urbanized [4]. This can potentially lead to increase of the demand for global construction (expected 70% increase over the next 10 years [4]) which puts a tremendous pressure on the already depleted world's resources.

Historically, the use phase of buildings has been shown to be the highest contributor to the environmental impacts [5] due to large consumption of energy during the building operation. In the recent decade, many policies were put in action with a goal of improving the energy performance of buildings and decarbonizing their energy consumption [6]. However, as buildings become more energy efficient and electricity grids more decarbonized, the embodied environmental impacts (from production, construction, maintenance and disposal of building materials) represent an increasing share of buildings total environmental burden [7]. For instance, it is estimated that 25% of global buildings GHG emissions are embodied carbon [8] but that their share will rise from the current 25% to nearly half by 2050 [9].

Structural components are major contributors to embodied environmental impacts of buildings [10–12].

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Although non-structural elements have shorter service lives and generally need to be repaired/replaced within the building's life span, structures are the most material- and energy-intensive parts of the buildings. Therefore, with constantly reducing the impacts of operational energy, design and construction of buildings load-bearing systems become important target in achieving the sustainable goals of this sector.

In order to reduce the environmental burdens, preserve natural resources and minimize the waste generation, circular economy (CE) agenda in buildings sector has been intensively promoted recently [13,14]. The basic CE principles include slowing loops (prolonging the service lives), closing loops (recycling and reuse) and narrowing loops (reducing resource use) of products and processes [15]. Reuse of construction products is much more effective in retaining the product's value compared to recycling, if additional processing can be kept at minimal level. For instance, it is estimated that the value of the reinforced concrete (RC) wall element is some 50 times higher per ton than the value of the aggregates into which it is recycled when building is demolished [4].

1.1 Design for deconstruction (disassembly) of steel-concrete composite floor structures

Design for deconstruction (DfD) is a design strategy that can efficiently contribute to CE, and more broadly, sustainability goals in the building sector. DfD enables downstream reuse, i.e. the building (structural) elements are designed to be reused in future with minimal transformation, over multiple life cycles of the building. To accomplish this goal, structural elements should be ideally prefabricated (even better if they are modular) and connected with dry joints, which enable easy dismantling without damage to connected structural elements. Therefore, instead of welded and chemical connections (in the case of RC structures cast-in-place concrete with additional reinforcement), easy assessable mechanical connections are required.

Steel-concrete composite floor structures are characterized by high structural efficiency, as composite action reduces the required quantities of both concrete and steel, resulting in lighter structures. Furthermore, compared to non-composite systems, longer spans can be achieved. However, conventional steel-concrete composite structures, in which shear connections between steel beams and solid or composite concrete slabs are typically realized using welded headed studs, do not allow for demountability. Consequently, significant research efforts over recent decades have focused on the development of effective demountable shear connections, which are the crucial detail in the design of reusable steel-concrete composite floor structures [16,17]. The majority of proposed demountable shear connections include the application of various types of bolts, with the most common being bolts with embedded nuts [18,19], friction-grip bolts [18,20–22] and bolts with a coupler system [22,23]. Nevertheless, some solutions with headed studs were proposed as well, such as threaded studs [24,25] and a connection combining welded studs and bolts [26].

The primary requirement for demountable connectors is to provide high stiffness and shear resistance while ensuring rapid, straightforward disassembly and reassembly. Connectors should be designed to leave both the steel profile and the concrete slab undamaged, facilitating their reuse in subsequent life cycles. Furthermore, the ability to secure connectors within the slab or remove them entirely is advantageous, since it minimizes the risk of connector damage during structural transport and on-site handling.

While existing connector designs often exhibit high load-bearing capacities, the critical challenge lies in preventing initial slip within the bolt holes of the steel flange [27]. If left unaddressed, this slip increases beam deflections, as composite action is only achieved once the bolt-to-hole clearances are closed. The issue is compounded by the fact that standard bolt-to-hole clearances of 1-3 mm are insufficient for application along the entire beam length, as they do not provide adequate execution tolerances for simple and rapid floor structure assembly [27,28]. To balance assembly efficiency and structural stiffness, two approaches are used: bolt preloading to provide slip resistance or injecting epoxy resin to eliminate clearances [22,29]. The epoxy resin should effectively fill bolt-to-hole gaps while remaining easily removable, therefore enabling the connector to be withdrawn without causing damage to the steel or concrete components, and facilitating their reuse in next life cycles.

Design provisions for reusable steel–concrete composite structures are still not included in current standards, although certain directions could be found in guidance publications [29]. As previously noted, connector stiffness should be considered when assessing serviceability limit states and beam deflections. Another important aspect of composite beam design with demountable connectors is their limited ductility. Although such connectors often exhibit slip at failure exceeding 6 mm [17,29], they are not considered ductile, and this characteristic should be explicitly accounted for in design. Furthermore, to prevent plastic deformation of the shear connectors and to ensure their successful reuse at the end of the first life cycle, the slab-to-beam end slip should be appropriately limited for serviceability loads.

1.2 Scope and objectives

In order to explore the environmental benefits of DfD reuse, two composite floor structural solutions of a typical office building were assessed with LCA: conventional, not demountable and DfD solution. Both solutions for the composite floor were designed to provide two subsequent 50-years life spans of the building with the same spatial layout, but at different locations. The system expansion LCA method was applied, i.e. chosen impact category indicators were calculated for both use cycles together. Comparison between alternatives showed the potential of DfD solution to reduce the conventional solution's environmental impacts in this specific case study.

2 State-of-knowledge

LCA is standardized [30] and well recognized method for calculating the environmental impacts of products and services during their whole life cycle. However, LCA faces several challenges when applied to modelling of DfD structures. Firstly, more than one cycle should be included in the assessment, which poses the question on the allocation of impacts between them. Secondly, there is a large uncertainty about the distant future technologies. The future processes avoided by reuse of structural elements will probably be more environmentally sustainable compared to the current once.

Generally, the universal consensus on the LCA modelling approach in the reuse case (multiple use cycles) is lacking. There are two possible approaches in LCA: the expansion of

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system boundaries to include all use cycles, and partitioning into separate use cycles in which case some type of allocation between them is required. In the former case, results are obtained for all cycles together and there is no need for allocation. In the latter case, results are obtained for each cycle but are sensitive to the chosen allocation type. As shown by De Wolf et al. [31] and Eberhardt et al. [32] the allocation method can have a significant impact and therefore introduce a bias into results and conclusions and inconsistencies between different studies.

As for LCA of steel-concrete composite floor structures, several studies compared conventional with novel DfD solutions [33–35]. None of them included the future technology development in the assessment.

Eckelman et al. [33] compared the DfD floor system consisting of precast concrete planks and steel beams connected using clamping connectors with traditional composite floor made of cast-in-place RC slabs on steel deck connected to steel beams via headed shear studs. The authors investigated three scenarios assuming 0-3 reuses. In DfD cases, environmental impacts were calculated as an average of the original building and subsequent buildings incorporating reused components impacts. This means that the higher the number of reuses, the lower impacts of a building are. For three reuse cycles, the impacts per building were reduced by on average 60–70% compared to traditional design. Authors also showed that, if not reused, DfD structural solutions could lead to increased environmental impacts compared to traditional design of a building with the same configuration, because of the higher production impacts in DfD case.

Brambilla et al. [34] compared demountable steel-concrete floor made of precast concrete slabs and steel beams connected using pretensioned High-Strength Friction-Grip bolts with several conventional composite floor designs. Unlike Eckelman et al. [33], for LCA modelling authors applied EN 15978 [36] which enables including several use cycles in the system boundaries by adopting the reference study period equal to duration of all included use cycles. In the specific case study of an office building, the authors adopted the reference study period equal to two design service lives of structural elements (typically 50 years for office building). The system boundaries therefore included the first building and the relocated one, i.e. the first and second use of structural elements in the demountable case. A 100% reuse rate was adopted as a best-case scenario. In the conventional case, the relocated building (second 50 years) was assumed to be completely built with new materials. Authors reported savings of at least 80 kg CO_2-eq/m^2 in GHG emissions and at least 800 MJ/m^2 of primary energy resources compared to the conventional structural systems.

3 Methods

3.1 Conventional (reference) and DfD composite floor structural solution

The analysis included two steel-concrete composite floor structural solutions of a typical office building designed and constructed using two approaches: (i) a conventional, non-demountable, composite floor structure, and (ii) a reusable and demountable composite floor structure designed according to the DfD principles. The overall geometry of the analyzed composite floor structures, as shown in Figure 1, with inter-column spans of 7.5 and 10 m, ensures adaptability to different future uses across life cycles, accommodates diverse functional requirements and enhances reuse potential. Figure 1 presents a symmetrical view of the building layout. The left side shows a traditional non-demountable design featuring a monolithic composite slab with profiled steel sheeting that spans the whole floor. The right side illustrates the alternative demountable system,

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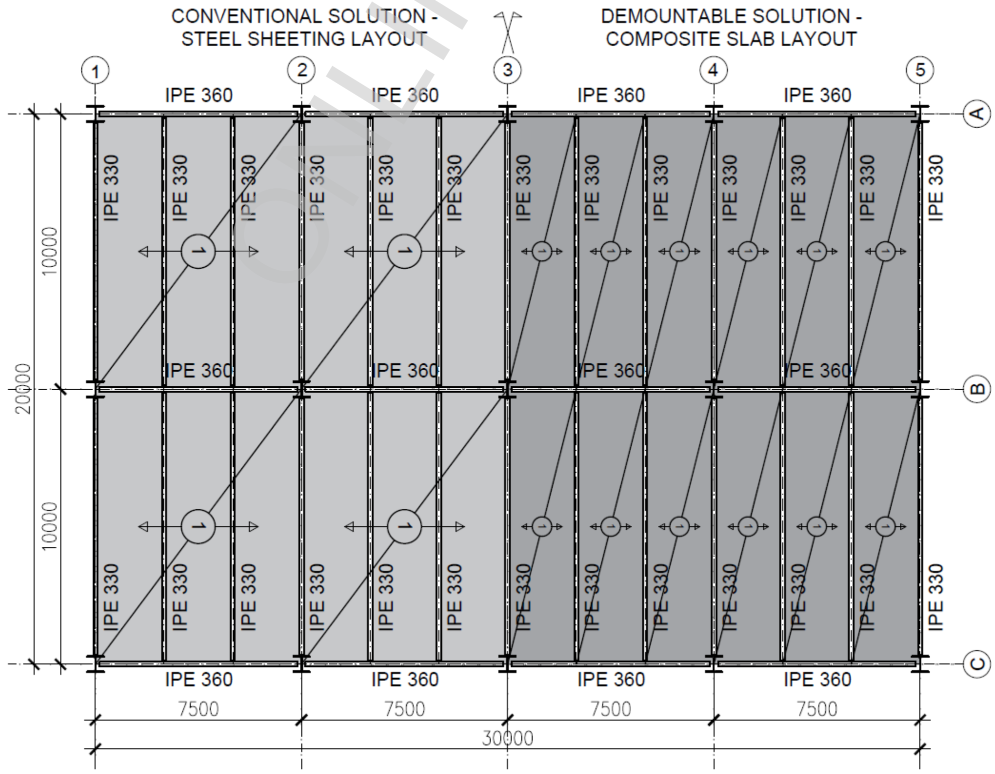

Figure 1. Composite floor structure layout

using 2.5 x 10 m slab segments. These segments are supported individually by the steel beam grid, and there are no connections linking the adjacent slabs to one another. The building's vertical load-bearing elements, which support the analyzed composite floors, comprise a system of steel columns and vertical steel bracing elements designed to maintain structural integrity and facilitate horizontal load distribution. The vertical supporting structure of the building was not part of the subject LCA analysis, but only the horizontal supporting structure, i.e. steel-concrete composite floor structure. The floor structure was designed according to the provisions of standards EN 1994-1-1 [37], EN 1993-1-1 [38], EN 1992-1-1 [39], and EN 1993-1-8 [40], to meet all requirements regarding ultimate and serviceability limit state conditions.

To design two comparable structural solutions for conventional and reusable floor structures, the following criteria were established: (i) the analyzed steel-concrete composite floor structure has overall surface of 600 m^2; (ii) a system of steel-concrete composite elements, consisting of a steel-concrete composite slab and primary and secondary steel-concrete composite beams, provides the structural spanning for the floor area; (iii) the span of composite slab is 2.5 m; (iv) the span of all secondary composite floor beams is 10.0 m, and the span of all primary composite floor beams is 7.5 m; (v) temporary propping is not used during the construction of the composite slab and beams; (vi) composite slab and beam elements are designed as simply supported; (vii) the vertical loads on the composite floor structure are adopted according to standard EN 1991-1-1 [41], for surface category B (characteristic live load value of 2.5 kN/m^2 and concentrated load of 4.5 kN).

The composite floor slab spans 2.5 m, corresponding to the spacing between the secondary floor beams that provide its support. In the conventional, non-demountable solution, the slab is cast continuously over the secondary beams across the entire floor area. In contrast, in the reusable solution, the slab is discontinuous over the supporting beams, and it is constructed from segments of a width of 2.5 m. Despite these structural differences, both options are treated as simply supported slabs in the design calculations. This complies with EN 1994-1-1 [37], which permits this approach even for continuous slabs as long as the minimum required reinforcement is provided. Overall depth of the composite floor slab is 120 mm for both structural solutions, conventional and reusable. Slabs are constructed using 58 mm deep trapezoidal profiled steel sheeting Cofraplus® 60 (thickness 1.25 mm) [42] with a 62 mm thick concrete layer above the sheeting. Concrete is adopted as a three-fraction concrete mixture with class C30/37. Both reusable and conventional solutions require the same amount of mesh reinforcement, as the governing criterion for the adoption of slab reinforcement is the control of longitudinal shear in the concrete slabs. Steel reinforcement B500 with an area of 503 mm^2/m (ϕ8/100 mm) in both directions is placed above the profiled steel sheeting.

Secondary floor beams are constructed as steel-concrete composite beams with a span of 10.0 m, built from steel hot-rolled section IPE 330 and constructional steel grade S355. Beams are simply supported by primary floor beams in the inner spans (between axes 1-2, 2-3, 3-4 and 4-5) and by columns in axes 1, 2, 3, 4 and 5, as shown in Figure 1. The secondary floor beams are designed as steel-concrete composite members supporting a composite slab with profiled steel sheeting on their upper flanges. Primary floor beams with a span of 7.5 m are also designed as steel-concrete composite floor beams, with a composite slab on their upper flanges. Those beams are built from hot-rolled steel cross-section IPE 360 with constructional steel grade S355 and simply supported by steel columns in axes A, B and C, as shown in Figure 1. They represent a support structure for the secondary floor beams at every 2.5 m.

Nominally pinned joints are provided between all steel-concrete composite floor beams, as well as between floor beams and columns, as shown in Figure 2. These joints are designed with a connecting plate (fin plate) of overall dimensions 110x10x250 mm, and four M16 bolts, grade 8.8. The same joint design is applied in both conventional and reusable structural solutions.

The key difference between the two analyzed design solutions, conventional and reusable, lies in the floor structure demountability and the design of the longitudinal shear connection. In a conventional floor structure, longitudinal shear transfer between the steel-concrete composite slab and primary and secondary steel beams is accomplished using a common solution of welded headed studs with a diameter of 19 mm and a height of 100 mm. For secondary floor beams, where the trapezoidal sheeting ribs are oriented transversely to the beam axis, two welded headed studs are provided in each rib within the width of the beam flange. In contrast, for primary beams, which are oriented orthogonally to the secondary beams, the sheeting ribs run longitudinally to the beam axis. In this case, welded headed studs are arranged at 200 mm spacing along the beam length, with two studs provided in each cross-section. The adopted connection is illustrated in Figure 3.a.

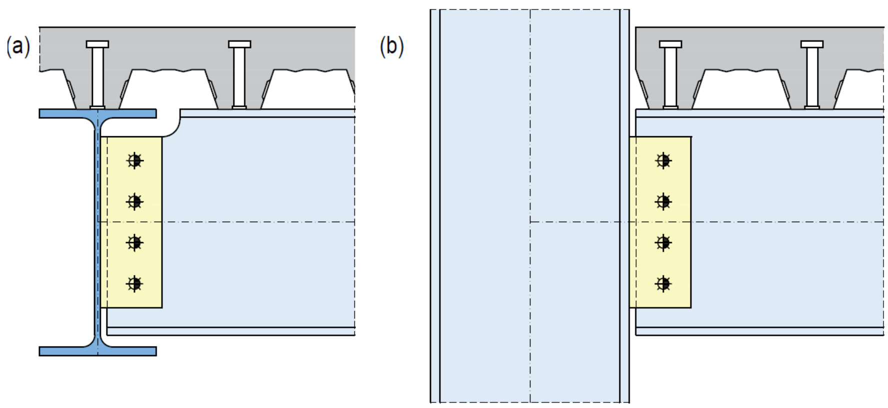

Figure 2. Nominally pinned joints: (a) between steel-concrete composite floor beams, (b) between secondary floor beams and columns

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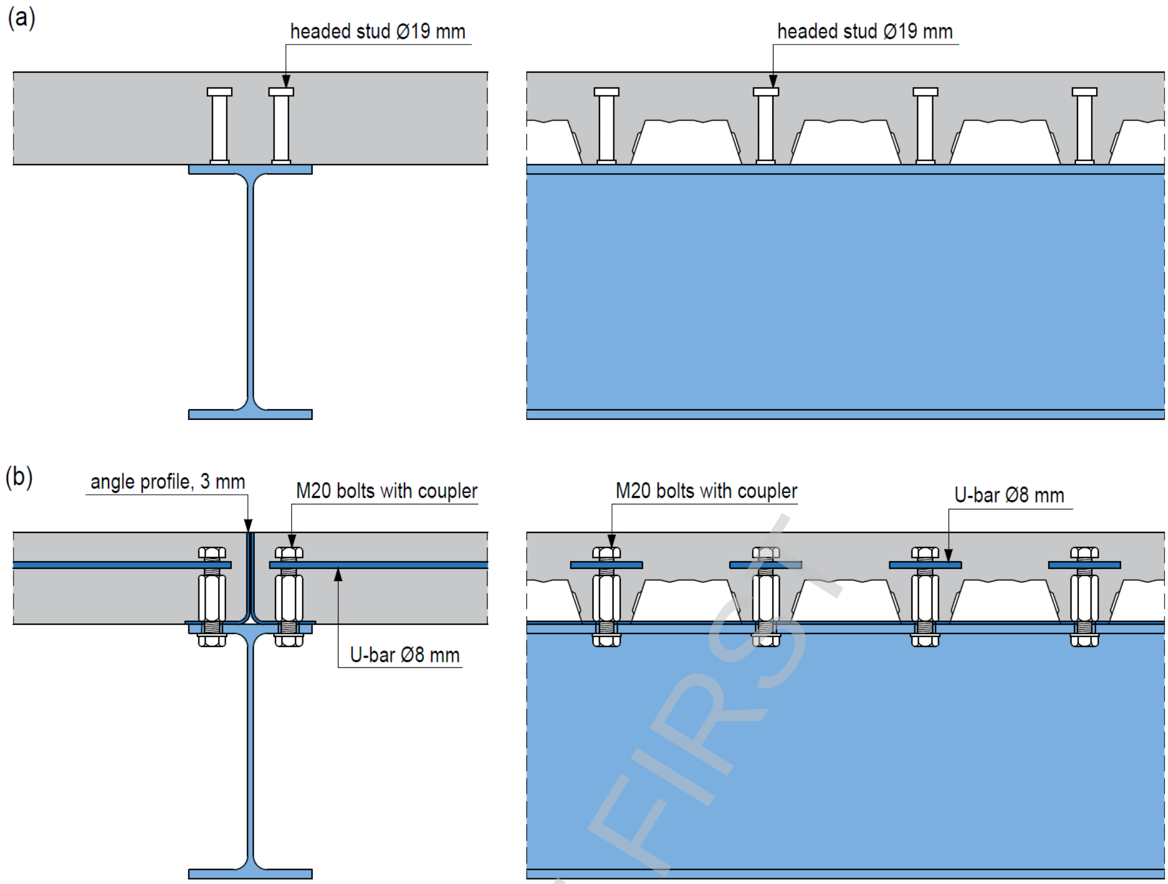

Figure 3. Shear connection: (a) non-demountable, (b) demountable

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Demountability of the floor structure is achieved through a demountable longitudinal shear connection between the composite floor slab and steel beams. The adopted connection design is based on the solution proposed and investigated by Kozma et al. [22], consisting of two bolts connected by a coupler. This configuration enables demountability by unbolting the lower steel bolt from the coupler at the underside of the steel beam flange, while the coupler and the upper bolt remain embedded within the composite slab. Such an arrangement is convenient for on-site handling and transport during structure relocation, as parts of the connectors are either embedded or completely removed, thereby reducing their susceptibility to damage. To prevent the bolt slip within the holes in the beam flange and the associated reduction in shear connection stiffness, the lower bolts are pretensioned during installation. The adopted solution, presented in Figure 3.b, utilizes M20 bolts and couplers of grade 10.9. In addition, a 3 mm thick cold-formed angle profile is provided at the slab edge, along its full depth. This profile acts as permanent formwork during concrete casting and remains integrated within the composite cross-section. It also protects slab edges during disassembly and contributes to increased connector resistance, while reducing the risk of concrete splitting failure [26]. Furthermore, U-bars with a diameter of ϕ8 mm are arranged around the embedded bolts and couplers to strengthen the connection zone and the slab edge additionally.

Total material consumption for the conventional and reusable steel-concrete composite floor solutions is presented in Tables 1 and 2, respectively. While concrete consumption remains identical in both analyzed cases, steel consumption is higher in the demountable solution due to the more complex longitudinal shear connection between the steel profile and the composite slab. Consequently, reinforcement consumption increases by nearly 17%, while the total steel consumption (including connectors, sheeting and profiles, but excluding reinforcement) is higher by 14% in the reusable solution compared to the conventional one.

Table 1. Material consumption for the conventional steel-concrete composite structure

Concrete		[m^3/m^2]	0.085
Reinforcement		[kg/m^2]	8.68
Profiled steel sheeting		[kg/m^2]	14.22
Steel profiles		[kg/m^2]	29.85
Beam-to-beam and beam-to-column pinned joints	Bolts, nuts and washers	[kg/m^2]	0.09
	Fin plates	[kg/m^2]	0.27
Beam-to-slab longitudinal shear connection	Headed studs	[kg/m^2]	1.28

Table 2. Material consumption for the reusable steel-concrete composite structure

Concrete		[m^3/m^2]	0.085
Reinforcement		[kg/m^2]	10.15
Profiled steel sheeting		[kg/m^2]	14.22
Steel profiles		[kg/m^2]	29.85
Beam-to-beam and beam-to-column pinned joints	Bolts, nuts and washers	[kg/m^2]	0.09
	Fin plates	[kg/m^2]	0.27
Beam-to-slab longitudinal shear connection	Bolts, couplers and washers	[kg/m^2]	3.00
	Angle profiles	[kg/m^2]	4.71

3.2 LCA model

3.2.1 Goal, scope and system boundaries

The goal of this study was to compare environmental impact of conventional (REF) and DfD structural solution of steel-concrete composite floor described in Chapter 3.1. The functional unit (FU) was one square meter of the floor's area that can provide two 50-years use cycles of the office building with the same configuration and loads, but at different locations. Since conventional floor cannot be disassembled, the floor in the relocated building (in the second life span) was made of new materials, while in DfD alternative floor was made of reused elements from the first use cycle, where 90% reuse rate was assumed (10% of elements were damaged and not reused).

The LCA system expansion was adopted as modelling approach to avoid allocation between assumed two use cycles. The use phase was excluded from the assessment for two reasons. Firstly, type of structure doesn't influence the operational energy consumption. Secondly, structures are commonly designed to have working life equal to a life span of a building and therefore no replacement of the structure is anticipated in the use phase.

LCA was performed for two scenarios, which differed in the first building's End-of-Life (EoL) phase and steel production route for the second building. In both scenarios, concrete was produced with cement from conventional kilns and mix design was taken from previous work [43], Table 3. The production of plasticizer was neglected as its mass was lower than 2% of the concrete mass (0.3%).

- Scenario S1 - at the EoL of the first use cycle (first building) structural elements of the composite floor were disposed of in a landfill. All of them in the reference case, and 10% of them in the DfD case. The average European production technology route, a combined BF-BOF (63%) and scrap-EAF (37%) was adopted for the structural steel and reinforcement production in both buildings [44]. In the reference case, all floor structural elements for the second building were produced from new materials, while in the DfD case only 10% were newly produced. At the EoL of the second building disposal of all elements was assumed in both cases.

System boundaries in the scenario S1, for REF and DfD composite floor, are presented in Figures 4 and 5, respectively.

Table 3. Concrete mix proportion and compressive strength

Mixture components [kg/m^3]				Compressive strength f_{ck} at 28 days [MPa]
Cement CEM II/A	Water	River aggregate	Plasticizer	
320	162	1911	8.3	35

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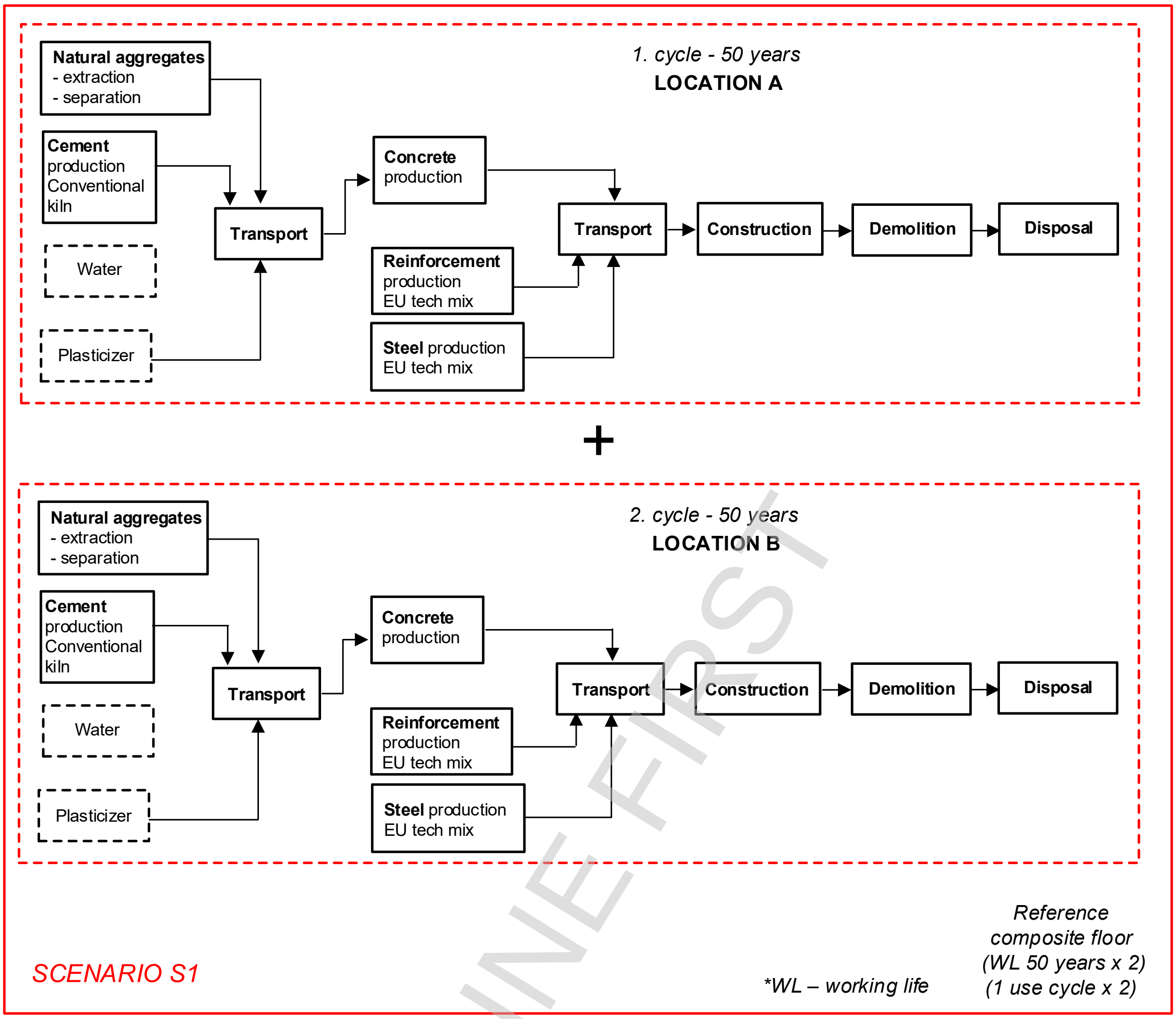

Figure 4. Reference composite floor, scenario S1

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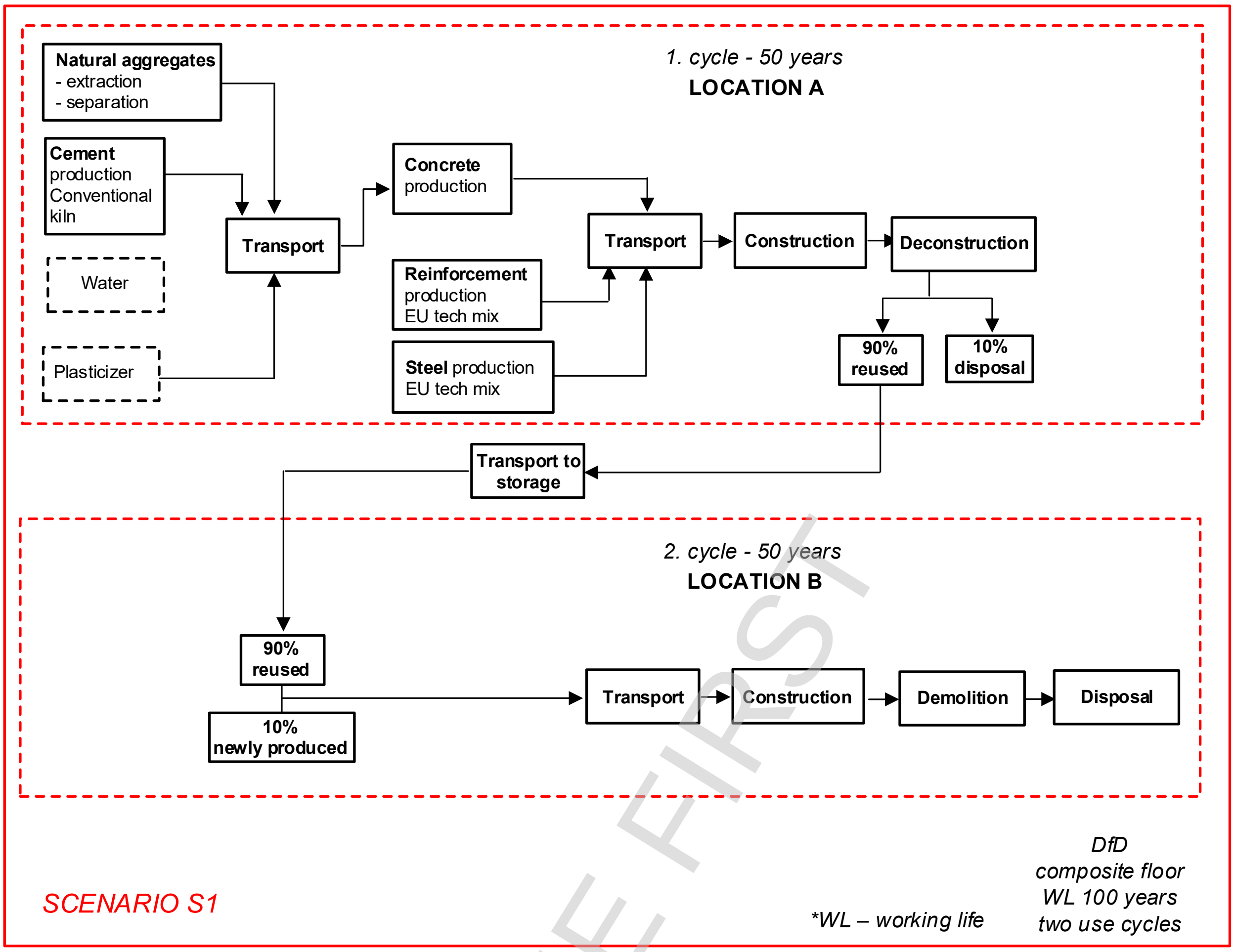

Figure 5. DfD composite floor, scenario S1

- Scenario S2 - at the EoL of the first use cycle (first building) structural steel of the composite floor was recycled, while reinforced concrete was disposed of in a landfill (the contribution of the eventual concrete recycling was neglected). In the REF case, 90% of the structural steel was recycled and 10% disposed of, while in the DfD case, all non-reusable steel (10%) was assumed to be recycled. Scrap obtained in that way was used for the structural steel production in the second building (with added amounts of scrap required for the production). This made a major difference to scenario S1 since scrap-EAF route was the only production route for new structural steel in the second building. At the EoL of the second building, similar to scenario S1, disposal of all elements was assumed in both cases.

System boundaries in the scenario S2, for REF and DfD composite floor, are presented in Figures 6 and 7, respectively.

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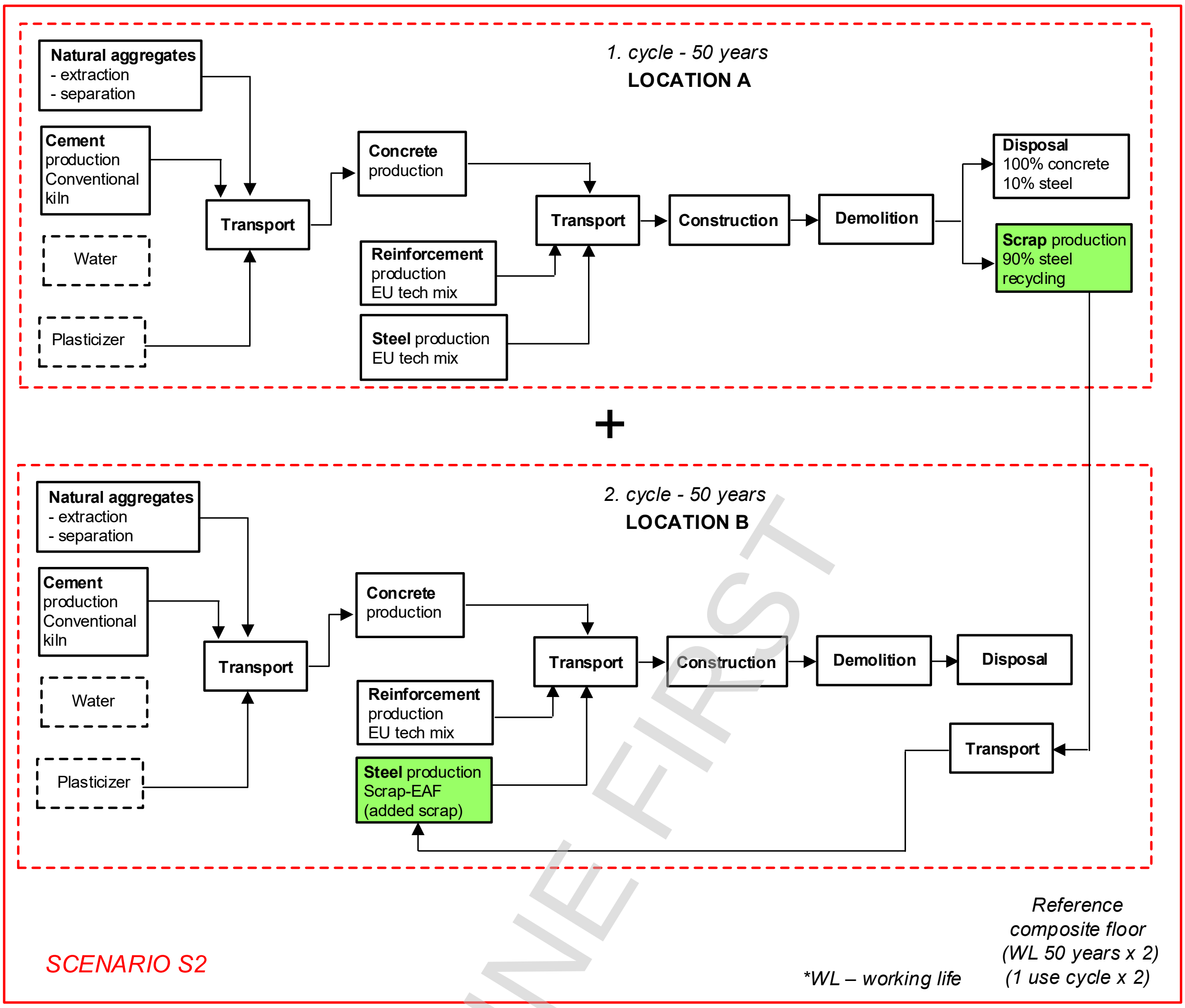

Figure 6. Reference composite floor, scenario S2

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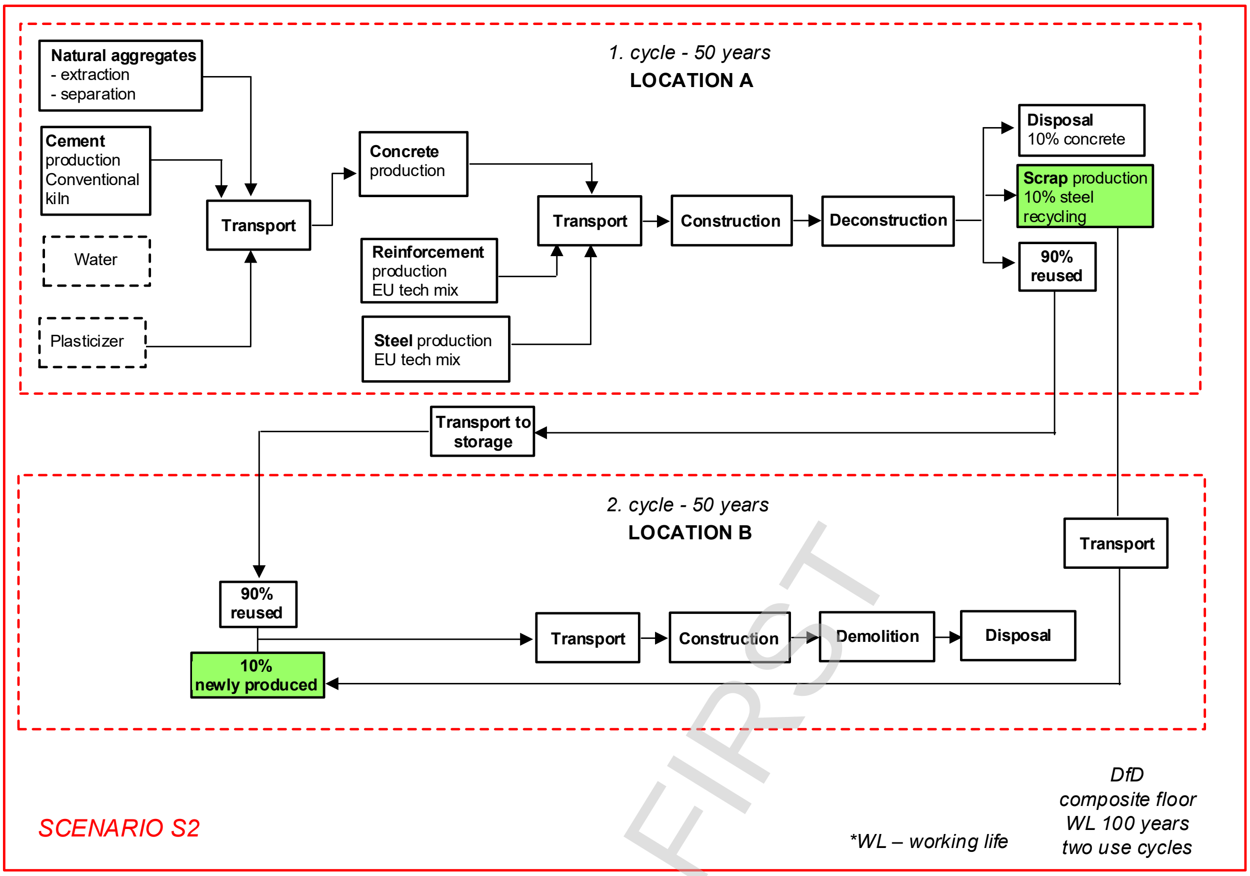

Figure 7. DfD composite floor, scenario S2

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3.2.2 Life cycle inventory (LCI)

Required LCI data were taken from ecoinvent v2.1 database [45] as EU average data wherever possible, Table 4.

In both scenarios, transport distances and types were adopted as typical for the construction site located in Belgrade, capital of Serbia, Table 5. Transport distances were doubled to account for the return route of transport vehicles.

Table 4. Sources of LCI data

Type of data	Source (file name in ecoinvent v2.1)	Geography
Energy		
Coal mining and distribution	ecoinvent (hard coal, at regional storage/kg/EEU)	EU average
Diesel production, distribution, and usage	ecoinvent (diesel, at regional storage/kg/RER) (diesel, burned in building machine/MJ/GLO)	EU average
Natural gas production, distribution, and usage	ecoinvent (natural gas, high pressure, at consumer/MJ/RER) (natural gas, burned in industrial furnace >100kW/MJ/RER)	EU average
Electricity	ecoinvent (electricity, medium voltage, production RER, at grid/kWh/RER)	EU average
Concrete		
Cement production	Industry	Serbia
River aggregate production	ecoinvent (gravel, round, at mine /kg/CH)	estimated as EU average
Concrete production	(Kellenberger et al. [46])	estimated as EU average
Reinforcement		
Reinforcement production	ecoinvent (reinforcing steel, at plant/kg/RER)	EU average

Steel		
63% BF-BOF route 37% scrap-EAF	ecoinvent (steel, low-alloyed, at plant/kg/RER)	EU average
Scrap-EAF route	ecoinvent (steel, electric, un- and low-alloyed, at plant/kg/RER)	EU average
	ecoinvent (iron scrap, at plant/kg/RER)	
Construction/deconstruction	Ökobaudat [47]	estimated as EU average
Demolition	ecoinvent (disposal, building, reinforced concrete, to recycling/kg/CH)	estimated as EU average
Transport		
Road and river	ecoinvent (transport, lorry 7.5-16t, EURO5/tkm/RER) (transport, lorry 16–32t, EURO5/tkm/RER) (transport, barge/tkm/RER)	EU average

Table 5. Transport distances and types

Material	Route		Transport distance (km)	Transport type
	From	To		
River aggregate	Place of extraction	Concrete plant	100 x 2	Barge 10000 t
Cement	Cement factory	Concrete plant	100 x 2	Truck 16–32 t
Concrete	Concrete plant	Construction site	15 x 2	Truck 7.5–16 t
Reinforcement	Reinforcement plant	Construction site	100 x 2	Truck 16–32 t
Structural steel	Steel plant	Construction site	100 x 2	Truck 16–32 t
Waste	Demolition/deconstruction site	Landfill	15 x2	Truck 16–32 t
Scrap	Demolition/deconstruction site	Steel plant	50 x 2	Truck 16–32 t
Reused elements	Deconstruction site	Storage	15 x 2	Truck 16–32 t
Reused elements	Storage	Construction site	15 x 2	Truck 16–32 t

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3.2.3 Life cycle impact assessment (LCIA)

The impact category indicators were calculated using the well-established CML (The Institute of Environmental Sciences of the Faculty of Sciences of Leiden University) baseline methodology [48]. In this work, Global warming potential (GWP), Eutrophication potential (EP), Acidification potential (AP), Photochemical oxidant creation potential (POCP), and Abiotic depletion of fossil fuels potential (ADPFF) were presented. The ADPFF was calculated using the following heating values of fossil fuels: 19.1 MJ/kg of hard coal, 8.8 MJ/kg of soft coal, 42.0 MJ/kg of diesel, and 39.0 MJ/m^3 of natural gas. An original Excel-based software was used for the life cycle inventory and the life cycle impact calculations.

4 Results and discussion

Impact category indicators for both floor structural solutions, REF and DfD, in scenarios S1 and S2 are presented in Figure 8. The environmental benefits from DfD solution and 90% reuse rate in scenario S1 are clearly displayed across all indicators. Brambilla et al. [34] obtained similar reductions, although for different DfD floor solution and different LCI data (based on Environmental Product Declarations).

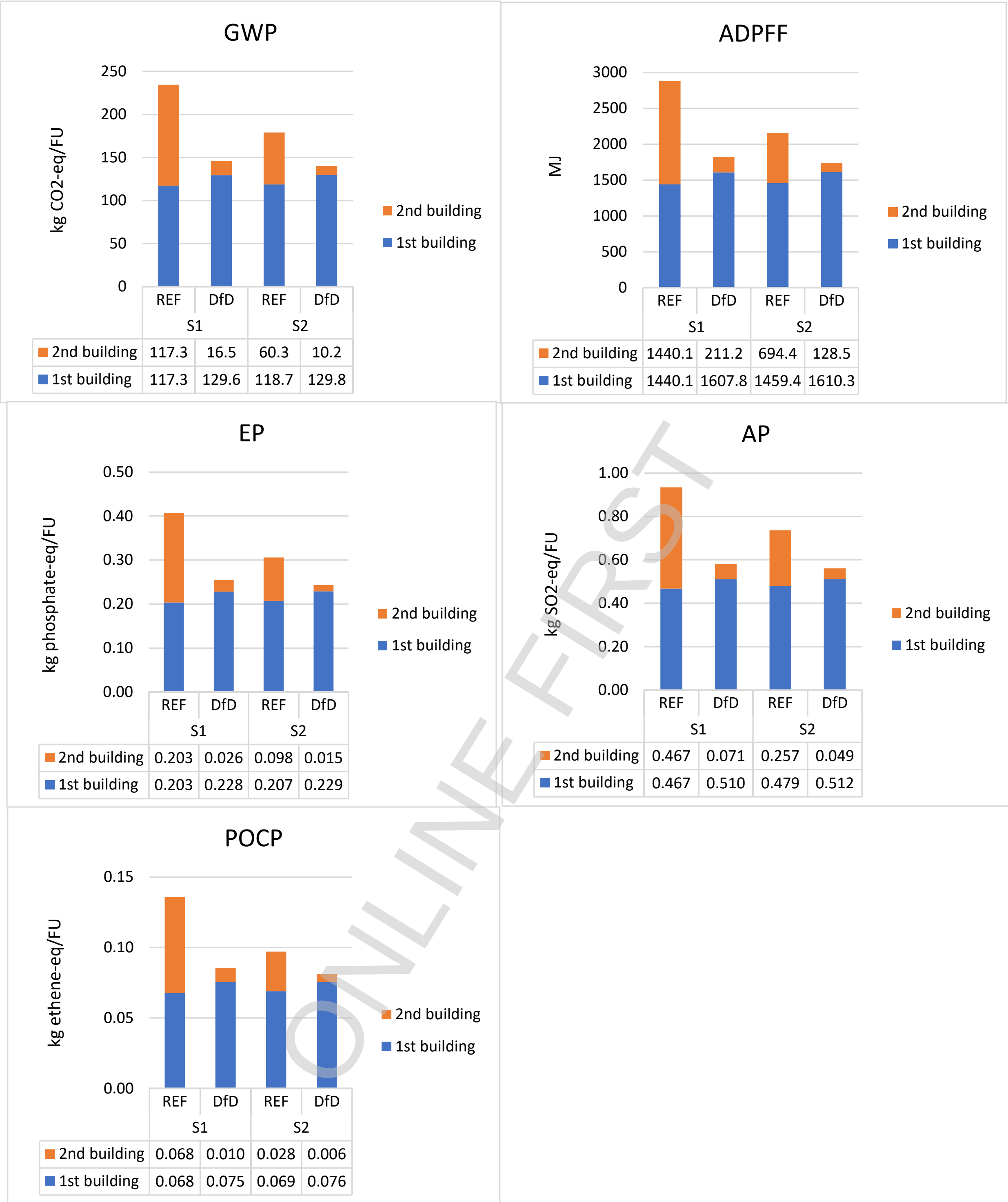

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Figure 8. Impact category indicators in the 100 hundred years life cycle of the REF and DfD composite floor in scenarios S1 and S2

In scenario S2 however, benefits from DfD floor solution are lower. Figure 9 shows the reduction of DfD floor indicators compared to REF floor indicators for both scenarios. In the scenario S1, DfD floor indicators present about 63% of the REF's (reduction about 37%). In scenario S2, DfD floor indicators range from 76% to 84% of the REF's, i.e. reductions range from 16% to 24%, depending on the indicator.

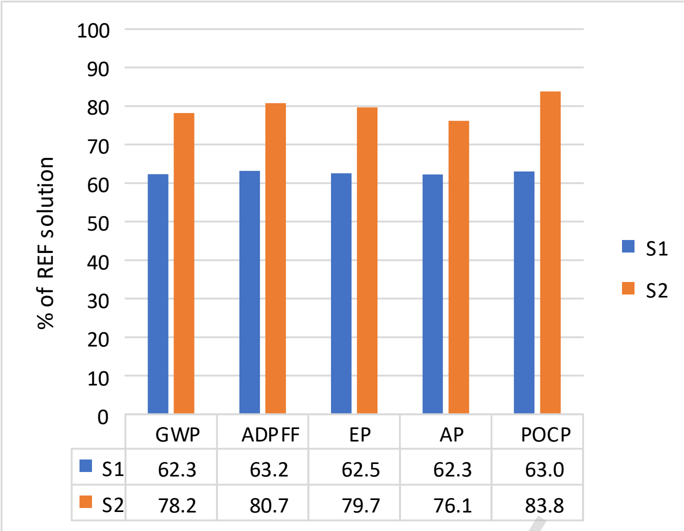

Figure 9. DfD composite floor impact category indicators reductions in scenarios S1 and S2

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The main reason for decrease of the DfD floor environmental benefits in scenario S2 is the structural steel production route. In scenario S1, same combined production route was assumed in both use cycles, i.e. both buildings. In scenario S2, structural steel was produced only via scrap-EAF route in the second use cycle (second building). This caused a significant difference in the second building indicators in the REF case, while difference was much smaller in the DfD case since only 10% of structural elements were newly produced in the second building.

The BF-BOF and scrap-EAF steel production routes differ a lot regarding the emissions intensity according to required energy and type of fuels used. While the BF-BOF route is highly energy intensive and reliant on coked coal, the scrap-EAF route is fully reliant on electricity. For instance, BF-BOF emits an average of 2.1 tons of CO_2 per ton of crude steel [49]. On the other hand, CO_2 emissions in the scrap-EAF route are highly dependent on the carbon intensity of the electricity supply but are on average 0.5 t CO_2/t crude steel [49]. It should be kept in mind however that the scrap utilization is limited by its availability. The scrap availability is currently significantly lower compared to demand for the new steel: contribution of scrap in the total steel charge is currently at 34% globally, and could eventually grow to 45% in 2050 if scaled strategies to drive more efficient production, use, and recycling of steel are introduced [49]. Therefore, scenarios S1 and S2 present in fact the worst- and best-case scenarios for the REF floor solution if current steel production technologies were anticipated in the future. The assessment results that would fit the current real practices lie within these limits. The impact of the EoL treatment and more importantly, structural steel production route is low in DfD case because only 10% of the structural elements were newly produced in the second building.

Contribution analysis showed that by far the largest contributor to all indicators was steel production, in both scenarios and for both REF and DfD floor solution, Figure 10. The structural steel production contribution to overall indicator values ranged from 65% to 77%, depending on the indicator. The reinforced concrete production (concrete + reinforcement) contributed to the overall indicator values with approximately 19% to 27%, depending on the indicator. Therefore, 90%-95% of the impact category indicators originated from the material production phase, regardless of the floor structural solution. Within the rest 5%-10% (apart from the material production phase), transport had the highest contribution, ranging from 3% to 7%, depending on the scenario and floor structural solution. Only in the scenario S2 and REF floor solution, the material production contribution was slightly lower due to lower contribution of steel production in the second building, equal to approximately 85%-90%.

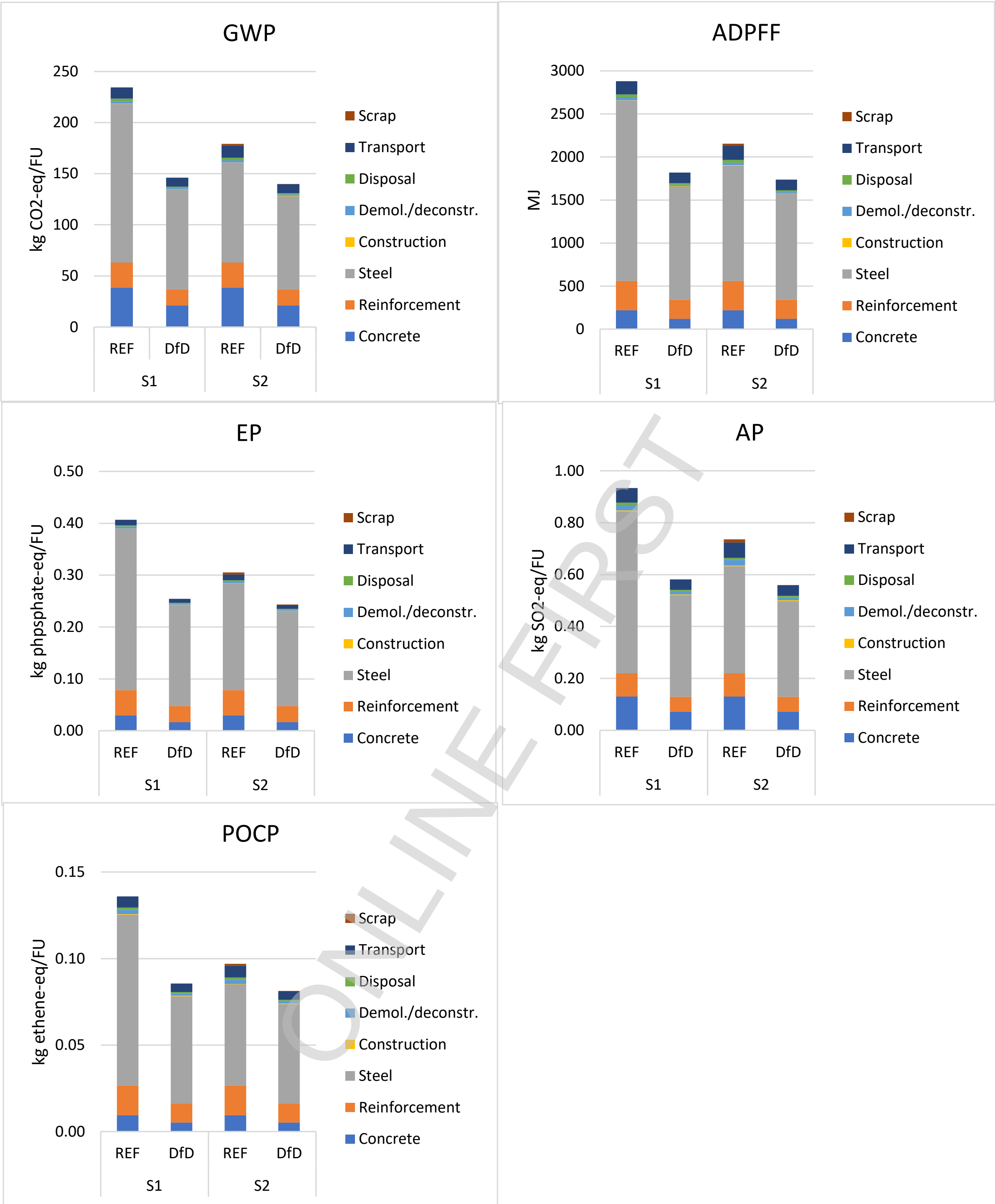

Figure 10. Contribution of various phases in the 100 years life cycle of the REF and DfD composite floor in scenarios S1 and S2

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As already mentioned, it was assumed that all structural steel for the second building was produced via scrap-EAF route in Scenario 2. This assumption was used only as an upper limit to obtain the range of possible values, not as a prediction of future. Currently around 45% of European steel is manufactured using the scrap-EAF route, but at the same time, Europe exports 20% of its collected scrap [50]. The rise of this technology deployment can certainly be expected in Europe, especially with growing efforts to decarbonize the electricity production in which case it becomes a near-zero technology. According to some estimates, the contribution of scrap-EAF in Europe is projected to increase to roughly 57% of the total steel charge by 2050 [51], but further in future it will probably be limited by the steel scrap availability. The year of interest in this study is 2076 - predictions on technologies' development so far in the future are highly uncertain.

Figure 11 shows the ratio between the reduction of the DfD solution's GWP (compared to REF's) and the scrap-EAF participation in the steel production. It can be seen that for estimated 60% participation in 2050, DfD's GWP is 69% of the REF's GWP, i.e. reduction is about 30%. However, it should be noted here that the current average European scrap-EAF route inventory was employed. In the case of fully decarbonized electricity production which is one of the European Union net-zero emissions targets, the GHG emissions from this route would be significantly lower and therefore GWP savings from the DfD enabled reuse would be lower as well.

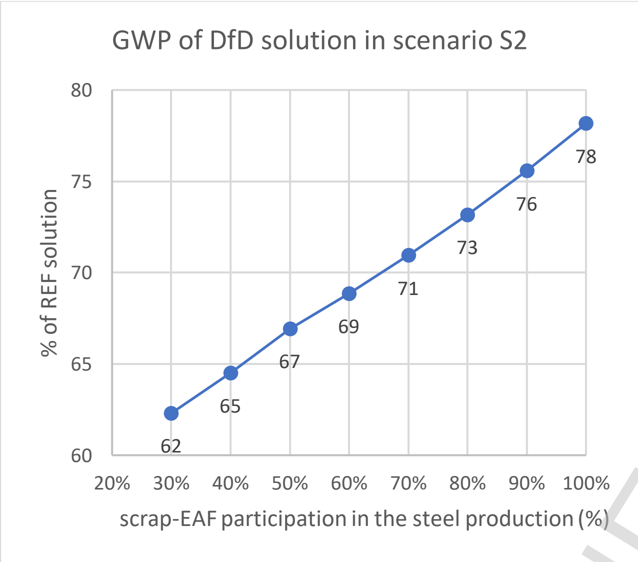

Figure 11. GWP of DfD solution compared to REF solution versus scrap-EAF route participation in the steel production

5 Limitations

As with any case study, results should not be generalized into definitive conclusions on the subject. The results are valid for the assumptions made in the whole process, which are many as we commonly face in each LCA. In this case, the results are most sensitive to the chosen steel production routes, and therefore for the assumptions different from those in scenarios S1 and S2, results would be different. The important parameter is the reuse rate as well. 90% was assumed in this work, but the benefits of DfD enabled reuse would be smaller for the lower reuse rates. Sensitivity analysis on the reuse rate should be performed to assess the impact of this parameter on the overall indicators results. The limitation factor is the assumption that current production technologies will be used 50 years in the future, which is not likely to happen. Transport distances and types are uncertain parameters that do not change significantly the results and conclusions in this case study – there contribution to overall indicators is less than 7%. Under different assumptions however, their contribution may be higher and therefore more significant.

6 Conclusions

In this study, comparative environmental assessment of two different floor structural solutions in a typical office building was performed: conventional, non-demountable, and designed for deconstruction solution, intended for reuse in one more use cycle (second relocated building). It was assumed that 90% of the floor structural elements were reused in DfD case, while the second building's floor structure in the conventional case was completely built with new materials (steel and concrete). The assessment was performed for two scenarios, which differed in the second building, therefore future, steel production route. In scenario S1, it was the current average European technology mix (37% scrap-EAF and 63% BF-BOF). In scenario S2, steel was produced solely by scrap-EAF route using scrap obtained from steel recycling at the EoL of the first building.

The assessment results of this case study showed:

- DfD floor solution showed clear environmental advantage across all calculated impact category indicators in both scenarios.
- The material production phase was the largest contributor, ranging from 85% to 95% of the overall indicator values, depending on the solution and scenario. Steel production made about 70% of the material production phase' impacts.
- Environmental benefits of DfD floor solution however depended on the assumed future steel production technology. The reductions of DfD floor's indicators were significantly lower in scenario S2, 16% - 24% compared to about 37% in scenario S1. It was the result of less energy- and emission - intensive steel production technology assumed for the second building in the REF case.

The results of this study are valid only for the assumptions made regarding several parameters. Regardless of that, study showed that material production technologies anticipated in future had significant impact on the results and therefore on the estimates of the DfD solution potential to reduce the structures' environmental impact. In order to attain broader understanding and support for decision-making, this aspect of future technology development should be taken into account in the prospective LCA – environmental benefits of designed for deconstruction and reuse structures are not guaranteed per se.

CRediT authorship contribution statement

Snežana Marinković: Conceptualization; Methodology; Data curation; Formal analysis; Writing. Isidora Jakovljević: Formal analysis; Visualization; Writing. Nina Gluhović: Formal analysis; Visualization; Writing. Milan Spremić: Supervision; Writing – Review & Editing.

Declaration of competing interest

Authors declare no conflict of interest.

Acknowledgments

Research was not supported by other persons or institutions.

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