Embodied energy optimization by innovative structural systems

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ABSTRACT: Motivated by the first oil-crisis in 1973 most countries have implemented building codes for insulation standards, resulting in a massive saving of energy for operation – heating, cooling and domestic services. Technological development in HVAC-systems and sealing methods has enabled a decrease in buildings' operational energy consumption to very low levels up to the extend known as passive-house projects. These changes have induced the relevance of widening the scope of energy saving from a former exclusive focus on operational energy in the use phase to the inclusion of embodied energy. The reduction of the embodied energy means an optimized utilization of materials and related energy during their entire life cycle.

In this respect this contribution focuses on a latest development for large span floor solutions, the "Composite Slim-Floor Beam" (CoSFB). Slim-Floor construction is characterized by integrating the principle steel beam into the floor with the advantages of low construction height as well as quick erection due to the use of prefabricated slabs. The new development, the CoSFB, combines the advantages of Slim-Floor with the ones of composite construction - stiffness, robustness, durability, easy erection and large spans - leading to high flexibility and multifunctional buildings. The span of traditional non-composite Slim-Floor Beams is limited to +/- 8m; with the CoSFB clear spans up to 14m with a beam distance of 10m and an overall construction height of only 40cm are achievable. In addition to enlarged spans and a reduced use of raw materials the CoSFB incorporates an integrated fire resistance due to the composite design. The fire resistance class R120 can be achieved without passive fire protection measures like board claddings, reactive (intumescent) fire protection systems or spray protection. Further the innovative CoSFB is ending up in less columns and larger spans and offers more flexibility in use and re-use. In addition, less construction weight leads to additional benefits as reduced column sizes, smaller foundations and less material transports to job site. In this paper the sustainable benefits of the CoSFB system are proven by design examples for typical grids (ULS and SLS design) including the verification of the vibration comfort. By explicitly presenting the gain in reduction of embodied energy consumption it is outlined, how the use of high performance materials and high quality engineering can contribute to reducing CO_2-emissions and primary energy consumption and to achieve the goals set in the Kyoto protocols.

1 LIFE CYCLE ASSESSMENT

1.1 *General*

Life cycle assessment is the analysis of the potential environmental burdens of a product or service in its production, use phase and disposal (end of life). Especially for buildings various labeling systems for the interpretation of the life-cycle assessment results in terms of ecological or even sustainable quality have been developed in the recent years [Hauke et al 2010]. They provide ratings based on the evaluation of different requirements concerning the environmental performance of the buildings. As internal benefits from an environmental assessment they promise the detection of strategic risks and environmental issues, development of sustainable products based on environmental information (Ecodesign) and the communication with politics and authorities. As external benefits the improvement of the image due to ecological considerations, the support of environmental innovations and decrease of environmental impacts as well as the competitive advantage by inclusion of the environmental aspects are listed. Overall the investor considers the life cycle assessment of his buildings to assure a sustainable and long-term value creation and investment stability.

A full Life Cycle Assessment (LCA) is a Cradle-to-grave investigation from manufacture ('cradle') over use phase to disposal phase ('grave'), including end-of-life scenarios e.g. recycling of construction materials. All inputs and outputs are considered for all phases of the life cycle. For buildings, 50 years of design life are generally imposed - so far, it has been assumed, that ca. 80% of the energy input and emission arise in this use phase (service life).

However, motivated by the first oil-crisis in 1973, most countries have implemented building codes for insulation standards, resulting in a massive saving of energy for operation – heating, cooling and domestic services. Technological development in HVAC-systems and sealing methods has enabled a decrease in buildings' operational energy consumption to very low levels up to the extend known as passive-house projects. These changes have induced the relevance of widening the scope of energy saving from a former exclusive focus on operational energy in the use phase to the inclusion of process energy – i.e. energy for mining, processing, transportation, assembly and building site operations [Hechler 2010]. Three significant challenges evoke from this perspective:

1. Sophisticated integral building management combined with high quality cladding systems as well as optimally tailored thermal mass and minimal weight for reducing the embodied energy should be designed; for this purpose advanced, cost-effective solutions combining structural steel with concrete (ca. 10-14cm concrete slab are sufficient for passive thermal activation [corusconstruction 2010]) have already been developed. Hereby the use of high strength materials (e.g. S460 steel and higher strength concrete) should be focused on.
2. Disassembly methodologies must be developed and employed in contemporary building practice in order to enable future reuse of building parts with the lowest possible consumption of energy for transformation.
3. The understanding of buildings' structures as a capital amount of embodied energy certainly includes the existing building stock, and hereby the relevance of treating construction wastes in an upgrading process similar to the processing of virgin mining resources.

In this paper the reduction of embodied energy is focused. As LCA functional unit for comparison two slab systems have been identified: grid 1) is supposed to cover the standard grid requested by the market of today and grid 2) provides a competitive and promising outlook to on the future trend in ground floor design using the potential of the latest structural technique. The life-cycle inventories used in the LCA are listed in the following chapter to allow for neutral comprehension and reproduction of the evaluation results.

1.2 *Life-cycle inventories used in the LCA*

For the LCA, Life Cycle Inventories (LCI) are required which provide information on the materials and energy flows during their entire life. In a first step, process structures are modeled in order to have a basis for assembling data. The material and energy flows are determined as input-/output-sizes for every partial process with regard to the system boundary. By connecting all partial processes, the relations between the modules and the environment are represented, and the mass/energy balance is drawn up as the inventory of the total system. All material and energy streams which pass the system borders are listed as quantities in physical units. The data refer to the functional unit. For steel, the LCI from WorldSteel [WorldSteel 2010], for concrete the inventories provided by ECOINVENT for a standard concrete have been chosen.

Hereby the following end-of-life scenario for steel and concrete products has been used based on [Hettinger 2010]:

- 99% recovery rate for structural steel whereas 1% is lost and goes to landfill;
- 35% of reinforced concrete is directly landfilled - thus embedded rebars are also 100% landfilled;
- 65% of reinforced concrete is sorted: rebars are separated from concrete - it is assumed, that 100% of the sorted rebars are recycled;
- For concrete, it has been considered that after the sorting plant, 15% of concrete is valorised and 85% is disposed.

The Global Warming Potential impacts resulting from Life Cycle Inventories used within this study are detailed in Table 1.

Steel and concrete elements are assumed to be transported by truck only, either regular truck for steel elements and prefabricated concrete, or mixer truck for ready mixed concrete. The consumption linked to transportation is calculated taking into account partial load and empty return trips [INRETS]. Steel elements are supposed to be transported on an average distance of 1000km, and prefabricated concrete on 500km. Concerning on-site concrete, a short transport distance of 50km for the ready-mixed concrete is assumed. The origin of the different parts (cement, water granulates, etc.) has not been taken into account for the analysis.

Other information (fuel production, emissions linked to transportation, etc.) is provided by the models of the consulting group PE International [PE 2006].

Table 1. List of data and sources for steel products.

Process	LCI associated	Data source	GWP Production [kg CO_2-eq/t]
Production and recycling of steel profiles	WO-Sections – 99%	[WorldSteel 2010]	930
Production and recycling of shear studs	WO-Rebars – 99%	[WorldSteel 2010]	830
Production and recycling of steel end plates	WO-Plates – 99%	[WorldSteel 2010]	1073
Production and recycling of reinforcement	WO-Rebars – 65%	[WorldSteel 2010]	1348
Production of concrete	"Concrete, normal, at plant"	[ECOINVENT 2007]	112
	and "concrete exacting, at plant"	[ECOINVENT 2007]	135
	Linear regression for 350 kg/m3		128
Production of diesel	Diesel, at refinery	[PE / ELCD 2003]	375
Emissions - fuel combustion	truck-trailer 28-34to total / 22to payload / EURO3	[PE 2006]	3183
Separation of concrete and reinforcement	disposal, building, reinforced concrete, to sorting plant	[ECOINVENT 2002]	61
Landfill of reinforced concrete	disposal, building, reinforced concrete, to final disposal	[ECOINVENT 2002]	67
Landfill of sorted concrete	disposal, concrete, 5%water, to inert material landfill	[ECOINVENT 1995]	7
Valorization of crushed concrete	gravel, unspecified, at mine	[ECOINVENT 2001]	3

2 SUSTAINABILITY OF MODERN SLIM-FLOOR CONSTRUCTION

2.1 *Demands on modern floor systems*

Sustainability is not only of environmental nature (climate effects, wastes (= landfill), energy consumption, raw material consumption, recycling). In addition economic (life cycle costs, maintenance, value preservation, functionality, flexibility, reusability = reconstruction) and social demands (health and safety, comfort, aesthetics, urban redevelopment) are to be considered and assessed.

Consequently sustainable floors need to fulfill the demands for ecologic, economic and social sustainability [Maydl, Passer, Cresnik 2007]. Thus modern floor design is more than designing for sufficient load bearing resistance at room temperature and in fire situation only. A floor has to be also designed for today customer requirements – especially vibration comfort and heat and sound insulation. Nonetheless a floor has to be economic and cost-effective in construction due to quick erection and availability in short delivery time. The high degree of prefabrication assures further increases safety on the construction site during erection and in the final state due to quality control in the shop.

Besides modern floor design has to take into account future use. As we are normally not able to predict the future, the floor construction (and ground floor design) must be easy adaptable to future customer expectations – with this flexibility and reuse potential the investment itself becomes sustainable. Further maintenance and enhancement of e.g. installation services, should be feasible and as easy as possible.

These additional demands are requesting the design of enlarged spans and reduced column quantity in conjunction with slender slabs with few limitations for service installations. In the following chapter, a floor system is presented fulfilling all the above described criteria: the combination of slim-floor construction with composite beam design – the CoSFB. It is representing a sustainable, re-usable and economic floor system with an enormous future potential in sustainable construction.

2.2 *State-of-the-art in slim-floor construction – the CoSFB*

Slim-floor construction is characterized by the integration of a steel beam into the slab. The steel section consists of a hot rolled beam with a welded plate. To facilitate the erection, the width of the plate is larger than the flange of the hot rolled section, so the slab elements can easily be placed. The SFB (slim-floor beam) can be combined with any kind of slab. Prefabricated or partially prefabricated concrete slab fits perfectly to SFB; a safe and quick erection is assured. By using this construction system the construction thickness of the floor is reduced and thus the overall height of the building or, by keeping the building height as constant, the total quantity of floors can be increased. The technical installations (e.g. heating and cooling devices) are installed very quickly due to the absence of down standing beams. Therefore both processes are also independent in the designing phase. However, because of the small beam height, the design of a slim-floor beam is governed by the stiffness of the system and thus spans are limited.

A nice example of Slim-Floor construction is the 11000m^2 office building “Espace Pétrusse” in Luxembourg (EPL) designed by the architect Marc WERNER, built from CDC in 2006, see Figure 1 to Figure 3. The main arguments to choose the SFB solution have been: reduction of the overall building height, decrease of the foundation reaction forces (the building was built above an existing underground parking – 2 additional floors could be constructed because of the “light” system), increased erection speed (1000m^2/month) and fire resistance w/o passive protection (R90).


Fig. 1: EPL

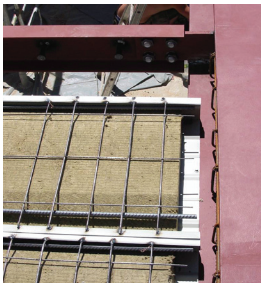


Fig. 2: EPL – SFB and Cofradal


Fig. 3: EPL – Ground floor design

For this application, the potential to use composite action in slim-floor construction has been evaluated for the first time – although SLS design has only been focused. Based on the experience by this project it has been identified, that to increase the stiffness and fulfill the demand to large spans, a new slim-floor beam needed to be developed - the CoSFB, see Figure 4. The CoSFB combines the advantages of composite construction (stiffness, robustness, durability, easy erectable, large spans) with the advantages of slim floor construction (low construction height, quick and safe in erection due to the use of prefabricated slabs). The aim is to assure the composite action without increasing the construction height. Therefore the use of standard shear studs welded on the upper flange is not appropriate, horizontal studs welded on the flange of the section activates not enough shear resistance. The innovative CoSFB solution, developed by ArcelorMittal in close cooperation with the University of Stuttgart/Germany, therefore uses concrete dowels to achieve a controlled shear transmission between the steel section and the concrete chord, see Fig, 4. These dowels are openings in the web penetrated by reinforced concrete. The resistance of the dowel is depending on the projection area of the compressed steel surface from the opening in the concrete chord and the 3-dimensional stress state concrete resistance activated. Concrete dowels are ductile and able to transfer 100% of the shear forces between concrete and steel without increasing the overall construction height. For the design of the dowel and further information it is references to [Hechler, Braun 2010].

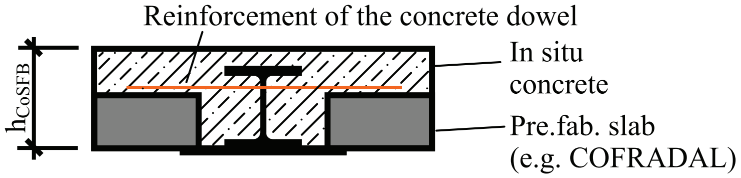


Fig. 4: Typical CoSFB section

Thanks to the increased stiffness, large span slim-floor construction is possible by respecting the deflection limitation and the vibration comfort. The typical application range for CoSFB is beam span from 8m up to 14m with a beam distance between 4m and 10m. The typical slenderness (span CoSFB / h CoSFB) of CoSFB construction is 35. Main advantages of the CoSFB construction are:

- quick and safe in erection,
- less columns and larger spans offer more flexibility in use and re-use,
- less construction weight leads to additional benefits as columns size, smaller foundations, fewer material transports to job site.

In addition CoSFB has an excellent behavior under fire conditions. The fire resistance class R120 can be achieved without passive fire protection measures (e.g. intumescent paint, spray protection or fireproof board).

CoSFB leads to an economic and flexible construction and fulfils the requirements for sustainable structures with efficient use of raw material in combination with light and slender members.

3 LIFE CYCLE ASSESSMENT OF GROUND FLOOR DESIGNS

3.1 *Introduction*

The structural performance of the CoSFB has been proven to be significantly improved compared to conventional slim-floor construction, thus leading to more economic and slender slab systems [Hechler, Braun 2010]. Further the overall flexibility completes the requested demands on economic and social sustainability. Although the environmental performance has not yet been assessed for the CoSFB system. To complete the integral sustainability assessment this paper consequently focuses on the life-cycle assessment of the CoSFB slim floor solution. As LCA functional unit for comparison two slab systems have been defined: 1) grid 8.1m x 8.1m (chapter 3.2) and 2) grid 12m x 8.1m (chapter 3.3). The grid 1) is supposed to cover the standard grid requested by the market of today. Grid 2) provides a competitive and promising outlook on the future trend in ground floor design using the potential of the latest structural technique. Grid 2) has been chosen with specific view on the demands listed in chapter 2.1.

For evaluation, results of the life-cycle assessment of the CoSFB solution are compared to results of cast in-situ flat concrete slab solutions. The related calculations for each grid and the outcome of the study are summarized in the following.

3.2 *Grid 8.10m x 8.10m*

To evaluate the environmental performance of the CoSFB + Cofradal 260 system, the Global Warming Potential (GWP = CO_2 equivalent) and the Primary Energy Consumption (PEC) for a typical 8.10m x 8.10m grid (functional unit) is calculated, see Fig. 5 and 6. The most important design results are presented in Fig. 7 (L = Beam Span; a = Beam Distance; DL = Dead Load; LL = Live Load).

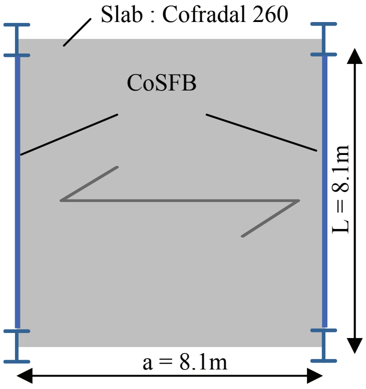
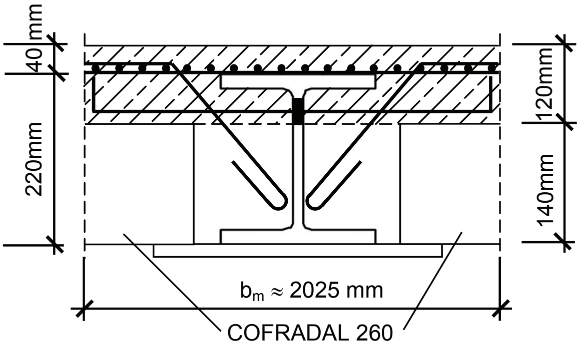
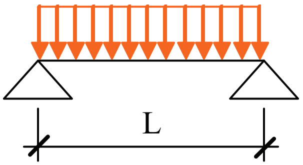


Fig. 5: Grid 8.10m x 8.10m



Steel section – HE220B, S355M + Plate 400x20, S355
In situ concrete C30/37

Fig. 6: Section CoSFB



DL slab = 2.80 kN/m^2
Additional DL = 1.70 kN/m^2
LL (cat. B) = 2.50 kN/m^2
Partition wall = 1.00 kN/m^2

Bearing Resistance, ULS: $q_d = 98.5$ kN/m
$M_{Ed} = 810$ kNm < $M_{pl,Rd,red,CoSFB} = 880$ kNm
($M_{pl,Rd,red,SFB} = 350$ kNm)

Deflection and natural frequency, SLS: $q_k = 69.8$ kN/m
$I_{y,0,CoSFB} = 43900$ cm^4, effective width $b_{eff} = L/4 \approx 2.00$ m,
Deflection $\delta_0 = 4.2$ cm ≈ L/200,
Natural Frequency $f_0 = 3.3$ Hz > 3 Hz
Fire resistance of the CoSFB: R60 (w/o add. measures)

Fig. 7: Application Example – CoSFB + Cofradal 260

The GWP and PEC of the CoSFB system above is compared to a cast in-situ flat concrete slab (slab thickness 27cm + 5cm floating screed, C30/37, reinforcement ratio 41.5kg/m^2), see Fig. 8. The calculation is performed with the AMECO software [CTICM 2010]. AMECO Software calculates environmental impacts of buildings and bridges made of steel and concrete. GWP and PEC are expressed for production phase as well as for transportation and End-of-Live.

Cast in-situ flat concrete slab	
Total volume of concrete:	21.0 m^3
Total mass of concrete:	50.8 to
Total mass of reinforcement:	2.85 to

CoSFB + Cofradal 260 slab	
Total volume of concrete:	7.55 m^3
Total mass of concrete:	18.3 to
Total mass of reinforcement:	1.11 to
Total mass of the C260 sheet:	0.79 to
Total mass of the CoSFB:	1.09 to

Life Cycle Assessment - Synthesis

Impact of ..	GWP [to Co_2-eq]	PEC* [GJ]	GWP [to CO_2-eq]	PEC* [GJ]
Production	10.04	83.82	6.99	64.46
Transport	0.26	4.840	0.17	3.260
End of Life	1.18	21.64	-0.77	-1.530
Total	**11.49**	**110.3**	**6.38**	**66.19**

Fig. 8: GWP and PEC comparison – Key figures
* Only non renewable energy mix has been taken into account.

3.3 *Grid 12.00m x 8.10m*

The CoSFB system is flexible to be combined many different slab products. This example shows the combination of CoSFB with a typical steel shuttering, the Cofraplus 220. Design results, GWP and PEC values for a 12m x 8.10m grid are given in the following.

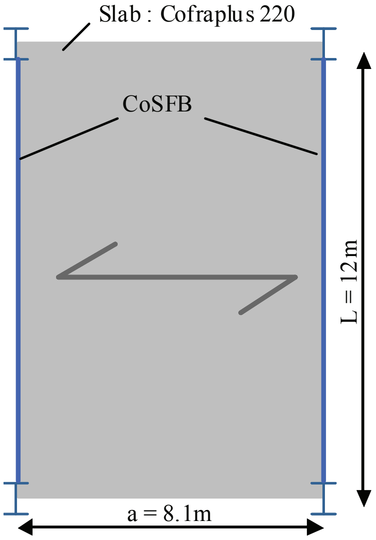
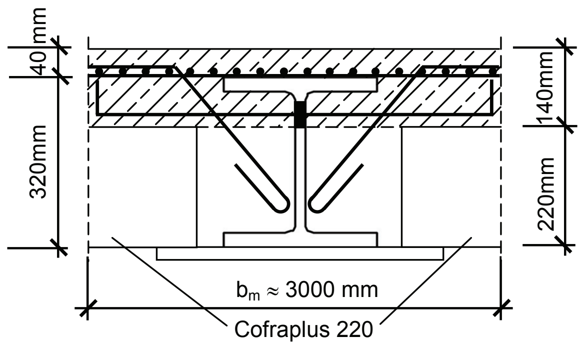
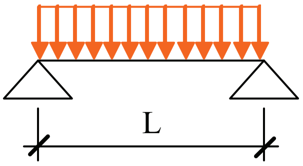


Fig. 9: Grid 12.0m x 8.10m



Steel section – HE260B, S355M + Plate 500x30, S355
In situ concrete C30/37

Fig. 10: Section CoSFB



$L = 12.00$ m, $a = 8.10$ m
DL slab = 2.80 kN/m^2
Additional DL = 1.70 kN/m^2
LL (cat. B) = 2.50 kN/m^2
Partition wall = 1.00 kN/m^2

Bearing Resistance, ULS: $q_d = 116.5$ kN/m
$M_{Ed} = 2097$ kNm $< M_{pl,Rd,red,CoSFB} = 2300$ kNm
($M_{pl,Rd,red,SFB} = 910$ kNm)
Deflection and vibration, SLS: $q_k = 83.2$ kN/m
$I_{y,0,CoSFB} = 162400$ cm^4, effective width $b_{eff} = L/4 = 3.00$ m,
Deflection δ_0 – camber = 5.4 cm ≈ L/220,
Natural Frequency $f_0 = 2.6$ Hz < 3 Hz
⇒ check of OS-RMS$_{90}$ value [Feldmann et al 2008]
⇒ OS-RMS$_{90}$ = 2.20 < 3.20 = class D
⇒ Comfort for office use is assured!
Fire resistance of the CoSFB: R60 (w/o add. measures)

Because of a modal mass of more than 36.000 kg, the velocity and the acceleration of vibrations induced by normal walking are absolutely within the acceptable range for office use!

Fig. 11: Application Example – CoSFB + Cofradal 260

The GWP and PEC of the CoSFB system above is compared to a cast in-situ concrete slab supported by concrete beams (slab thickness 30cm, C30/37, reinforcement ratio 35kg/m^2). The calculation is performed with the AMECO software [CTICM 2010].

Cast in-situ flat concrete slab		**CoSFB + Cofraplus 220 slab**	
Total volume of concrete:	30.6 m^3	Total volume of concrete:	16.4 m^3
Total mass of concrete:	74.1 to	Total mass of concrete:	39.7 to
Total mass of reinforcement:	3.67 to	Total mass of reinforcement:	2.22 to
		Total mass of the C220 sheet:	1.59 to
		Total mass of the CoSFB:	2.94 to

Life Cycle Assessment - Synthesis

Impact of …	GWP [to Co$_2$-eq]	PEC* [GJ]	GWP [to CO$_2$-eq]	PEC* [GJ]
Production	14.04	114.3	15.09	139.8
Transport	0.50	8.482	0.26	5.910
End of Life	1.66	30.77	-1.60	-2.787
Total	**16.19**	**153.5**	**13.76**	**142.9**

Fig. 12:GWP and PEC comparison – Key figures
* Only non renewable energy mix has been taken into account.

4 ASSESSMENT RESULTS AND CONCLUSIONS

The environmental impact of CoSFB slab systems and traditional slab systems has been quantified for two grids, 8.1m x 8.1m and 12m x 8.1m. The subsequent LCA of both grids and systems clearly outlines the outstanding environmental performance of the CoSFB system hereby. Compared to the traditional concrete solution a reduction of the GWP by 40% can be achieved. Detailed cost analysis further showed, that even the costs for CoSFB slab systems are lower than for traditional slabs [Birarda et al 2011]. In fact, the combination of CoSFB with partially prefabricated slabs is a very good answer to customer needs and expectations, today and in the future. Because of ongoing discussions about the fire safety of pre-stressed hollow core slabs, they are however excluded in this assessment - even though it has to be stressed, that the CoSFB can achieve the fire resistance class R120 without passive fire protection.

Further to the reduced embodied energy in the building, steel structures are built with a high degree of prefabrication/offsite manufacture with quality control in the shop. Thus, construction sites are optimized with an enhanced safety, reduced lead times, transportation, neighborhood nuisance and environmental impact (dust, water). In design and service life the slenderness for both, columns and beams with long spans, are a major advantage for steel construction. Moreover, with slim-floor systems, shallower construction height result in either higher floor space indexes associated with less land use and/or less façade surface area achieving less heat emission and therefore reduced energy consumptions of the building. The benefit of long spans is the creation of versatile spaces capable of change over time and the adaption to user's requirements. With the CoSFB slim-floor system the construction is even able to be adapted to changes in the service installations. Further steel structures are prefabricated systems from components which incorporate an ease in maintenance and the flexibility to be extended or modified. The comfort and well-being of the user therefore depend only on the thermal design of the façade and the interior design of the floors, provided with a long-lasting aesthetics as steel is environmentally inert and a durable material. In the end-of-life phase steel structures are easy to dismantle; the steel components are either reusable or recyclable economically indefinitely without quality loss.

Overall it is concluded, that the embodied energy in the construction materials is and will be even more influencing the environmental performance of buildings. Therefore reduction on mass thus lighter buildings will generally lead to more sustainability. Here the use of high performance materials and high level of engineering is of major importance. Today and in the future, engineering will make the difference – the CoSFB herefore provides an evidence.

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