Title:	**Life Cycle Analysis: Load-Bearing Structures Of High-Rise Buildings in Western Europe**
Authors:	
Subjects:	Building Materials/Products Conservation/Restoration/Maintenance Construction
Keywords:	Concrete Life Cycle Analysis Steel Structure Sustainability
Publication Date:	2019
Original Publication:	CTBUH Journal Issue III
Paper Type:	1. Book chapter/Part chapter 2. **Journal paper** 3. Conference proceeding 4. Unpublished conference paper 5. Magazine article 6. Unpublished

Life Cycle Analysis: Load-Bearing Structures Of High-Rise Buildings in Western Europe

Authors

Gerran J. Lankhorst, Structural Engineer, Industry & Buildings
Janko Arts, Associate Director and Consulting Engineer, Industry & Buildings
Royal HaskoningDHV
George Hintzenweg 85
Rotterdam 3068 AX, the Netherlands
t: +31 88 348 22 23
e: gerran.lankhorst@rhdhv.com
royalhaskoningdhv.com

Karel C. Terwel, Assistant Professor, Structural Design and Safety
Henk M. Jonkers, Associate Professor, Sustainability Group, Materials & Environment, Civil Engineering and Geosciences
Delft University of Technology
Delft, the Netherlands
t: +31 15 27 81 512
t: +31 15 27 86157
e: communication-CiTG@tudelft.nl
tudelft.nl/en

Gerran Lankhorst is a Structural Engineer at Royal HaskoningDHV and former DUT student in Building Engineering, Structural Design. During his studies and internship at Nikken Sekkei in Tokyo, he developed skills and interests in tall building design, parametric modeling and sustainable structural design. Lankhorst aims to tackle structural design challenges with new computational technologies and a multi-disciplinary approach.

Janko Arts is Associate Director and Consulting Engineer at Royal HaskoningDHV. He has performed design activities for a broad range of buildings including high-rise buildings in Rotterdam (the Red Apple and First Rotterdam), Feyenoord City, large naval projects in India and metro stations in Qatar. As Associate Director, he manages a structural design and engineering team of 25-35 people. Arts carries the qualification of registered structural engineer (RO) in the Netherlands.

Karel Terwel is Assistant Professor Structural Design and Safety at DUT and Consulting Engineer/Project Leader at IMd Raadgevende Ingenieurs and has performed design activities for various types of buildings, including two governmental towers of 146 meters in The Hague. His PhD thesis (2014) focused on human and organizational factors influencing structural safety. Terwel is vice-chair of TG5.1 "Forensic Structural Engineering" of IABSE.

Henk Jonkers is Associate Professor of the Sustainability Group within the Materials & Environment section of the faculty of Civil Engineering and Geosciences at DUT. Jonkers obtained his PhD in Marine Microbiology at Groningen University and currently researches the development of innovative-, bio-based- and sustainable construction materials, such as self-healing concrete. Furthermore, he is scientific advisor of the DUT spinoff company Basilisk Concrete.

Abstract

The choice of structural system has a big influence on the environmental impact of structural materials in tall building design. This paper provides a comparison of the environmental impact of several structural systems for high-rise buildings. The environmental performance for relatively slender buildings in the range of 150 to 250 meters in Western Europe is analyzed for five different types of structural systems in cast-in-situ concrete, precast concrete, and steel. The cradle-to-gate environmental impact was determined by using environmental cost, an assessment method including 10 impact categories. Compared to tube structures, diagrid structures reduced the impact by 17-33% for the concrete models and 28-41% for the steel models, due to reduction of material use. By using non-conventional structural systems such as diagrids, reductions in environmental impact can be achieved relatively easily.

Keywords: Sustainability, Materials, Life Cycle, Carbon

Introduction

The built environment is a key contributor to global greenhouse gas emissions (Oldfield, 2012), and buildings account for 30-40% of all primary energy used worldwide (UNEP, 2007). Therefore, the industry is researching possible ways to reduce its environmental impact. High-rise buildings have proven to be a potential solution for reducing the environmental impact of construction (Trabucco & Wood, 2016).

Most of the research conducted to date on improving sustainability of buildings has been focused on reducing operational energy (OE), used for heating, cooling, hot water, ventilation, etc. (Oldfield, 2012; Sarkisian, 2016; Trabucco & Wood, 2016). As future buildings will be designed to net-zero energy standards, the impact of embodied energy (EE), used for production, construction, maintenance and demolition of materials, will represent a significantly increasing part of the total impact (Trabucco & Wood, 2016; Webster, 2004; Yohanis & Norton, 2002), possibly increasing up to 100% (Sarkisian, 2016). The biggest part of EE is caused by the predominant structural materials used in tall buildings: concrete and steel (Kaethner & Burridge, 2012; Oldfield, 2012). Figure 1 shows an overview of the life cycle stages of a building with definitions per European standard EN 15804.

Research Objective and Scope

Research into the environmental impact of a wide range of stability systems for high-rise building structures is limited. It is uncertain whether the research by Trabucco et al. (2016) is applicable in Western Europe. First, the average height of high-rise buildings in Europe is typically lower than in North America and Asia. Second, regulations and local conditions are different. For example, a rule regarding daylight penetration in the Netherlands restricts the depth of office floors to approximately 9 meters, resulting in slender buildings. Also, poor soil conditions in many parts of Western Europe result in building deflections caused by rotation of the foundation structure. Additionally, material production industries differ from those in North America, resulting in different environmental impacts due to the ratio of fly-ash in cement or the ratio of blast to electric-arc furnaces in steel production.

The goal of this paper is to provide a comparison of the environmental impact of

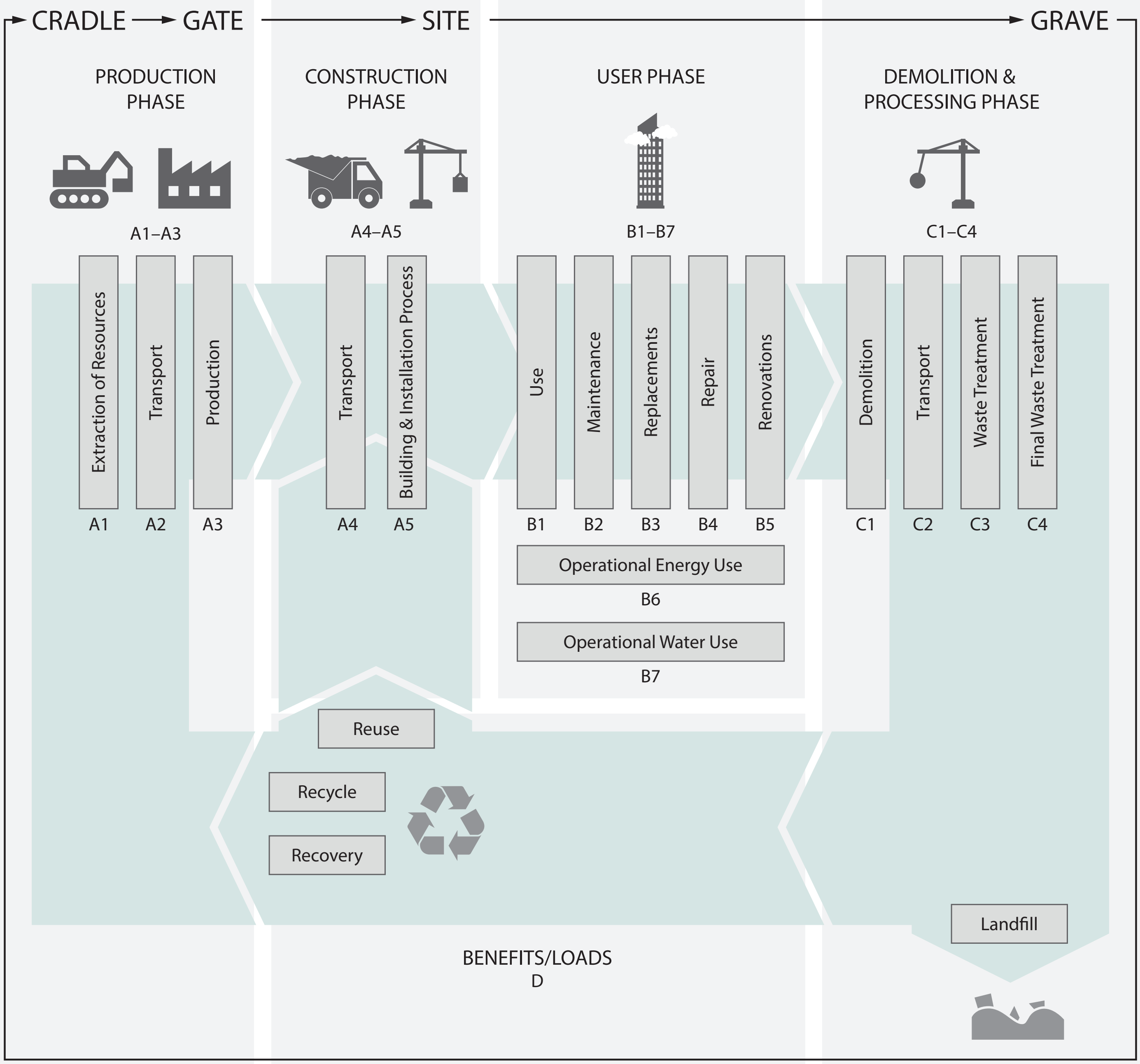

Figure 1. Life cycle stages of a building, including the life cycle phases, represented by A1-D, according to EN 15804.

several structural systems for high-rise buildings in the range of 150-250 meters located in Western Europe. Five different stability systems and three floor systems were designed in cast-in-situ concrete, precast concrete and steel for three fictitious office buildings in Rotterdam. All models contained a concrete core, and the foundation structure was excluded from the study. The environmental impact was calculated and analyzed according to the cradle-to-gate principle (production phase only, A1-A3) for 10 different impact categories, using environmental cost (EC) as the common indicator.

> “Differences in daylight penetration standards, soil conditions, material production techniques, and generally lower heights suggest the importance of independently studying European skyscrapers’ environmental impact, beyond prior research conducted on North American and Asian buildings.”

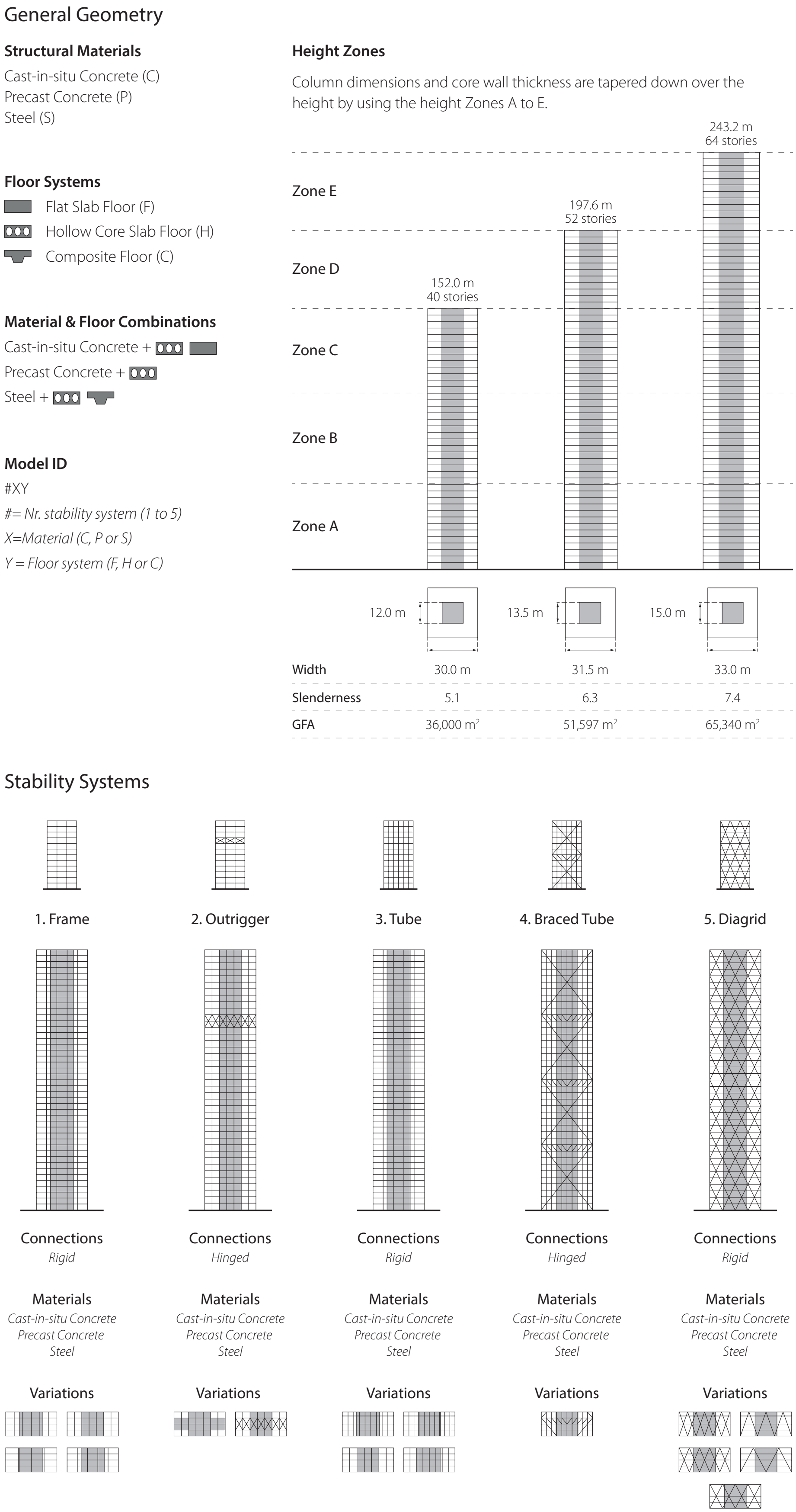

Figure 2. Overview of the used building geometry, floor systems, structural materials, stability systems, variations and considered cases.

Methodology

Structural Design

Three different building geometries were considered with heights of 150, 200 and 250 meters. The depth of the floors, 9 meters, was based on daylight-entry regulations in the Netherlands. For these three building geometries, five different stability systems were designed, based on the classifications by Ali & Moon (2007): 1, rigid frame structure; 2, outrigger structure; 3, tube structure; 4, braced-tube structure and 5, diagrid structure (see Figure 2). The stability systems contained up to five sub-variations in column spacing or diagrid configuration, resulting in 15 different building structure cases per height. All the modeled building cases contained a structural concrete core, since it also provides significant advantages for multiple functionalities.

Three floor types (flat-slab floor, prestressed hollow-core slab floor and composite floor), and three different materials (cast-in-situ concrete, precast concrete and steel) were used, resulting in five possible material cases for each possible building structure case.

Structures were designed according to the Eurocode. Only wind loads were considered, as there is no meaningful seismic activity in the area. The influence of the foundation structure on the global stiffness was included by assuming that the foundation structure was responsible for half of the total building deflection at the top.

A total of 146 models were assessed. Due to the high number of repetitive models, a parametric and automated workflow was developed and implemented. The workflow consisted of linked models in Grasshopper, Karamba and Excel for generating the geometry, performing the structural analysis, optimizing the geometry, cross-sections and reinforcement, and performing the life cycle analysis (LCA) respectively. Structural optimization of the geometry was achieved by generating and comparing several sub-variations (such as varying column spacing or selecting a diagrid configuration) on their environmental impact. Outrigger locations were optimized for minimum global deflection using algorithms. Cross-section dimensions and reinforcement quantities were optimized for both local and global strength, and for stiffness, aiming for unity checks of 0.8-0.9 in the ultimate limit state.

Life Cycle Analysis

The Fast Track LCA method was used in this study, as it is considered advantageous for comparing design alternatives. It uses the data that is produced by a classical LCA (the environmental impact of different materials) as an input. The impact of the final product can then be determined by quantifying the used materials in the product, and scaling upward to determine their individual impacts.

The environmental impact in this research was quantified using EC, which is a Dutch assessment method containing 10 environmental impact categories (see Table 1) and the following formulas. Each impact category is assigned a factor, in euros, which represents the fictional cost (shadow price) required to bring its impact to a sustainable level.

$$EC_{total} = \Sigma(m_{material;i} \cdot SP_{material;i})$$

$$SP_{material;i} = \Sigma(m_{impact;i} \cdot SP_{impact;i})$$

EC_{total}: total environmental cost of considered structure [€]

$m_{material;i}$: mass of material i in considered structure [kg]

$SP_{material;i}$: shadow price of material i per kg material [€/kg]

$m_{impact;i}$: mass of equivalent of impact category i per kg material [kg/kg]

$SP_{impact;i}$: shadow price of equivalent of impact category i per kg equivalent [€/kg]

The functional unit of this research is the main load-bearing structure of the building. The structures have the same function and are designed according to the same

Impact Categories & Corresponding Shadow Prices

Impact Category	Unit	Shadow Price / kg Equivalents (€/kg)
Abiotic Depletion	kg Sb eq	€ 0.1600
Global Warming (GWP100)	**kg CO_2 eq**	**€ 0.0500**
Ozone Layer Depletion (OCP)	kg CFC-11 eq	€ 30.0000
Human Toxicity	kg 1,4-DB eq	€ 0.0900
Fresh Water Aquatic Ecotox	kg 1,4-DB eq	€ 0.0300
Marine Aquatic Ecotoxicity	kg 1,4-DB eq	€ 0.0001
Terrestrial Ecotoxicity	kg 1,4-DB eq	€ 0.0600
Photochemical Oxidation	kg C_2H_4 eq	€ 2.0000
Acidification	kg SO_2 eq	€ 4.0000
Eutrophication	kg PO_4^{3-} eq	€ 9.0000

Impact Categories & Corresponding Shadow Prices
Example: Steel (S355)

kg Equivalents / Impact Category (kg/kg)	Shadow Price / Impact Category (€/kg)
x 5.21E-03	= € 0.0008
x 9.08E-01	**= € 0.0454**
x 1.55E-08	= € 0.0000
x 3.33E-02	= € 0.0030
x 3.02E-03	= € 0.0001
x 6.34E+00	= € 0.0006
x 4.68E-04	= € 0.0000
x 3.30E-04	= € 0.0007
x 3.38E-03	= € 0.0135
x 3.74E-04	= € 0.0034 +
Shadow Price S355	= € 0.0675

Materials & Corresponding Environmental Impacts

Material	Shadow Price Material (€/kg)
C20/25	€ 0.0073
C35/45	€ 0.0075
C45/55	€ 0.0082
C55/67	€ 0.0090
FEB500	€ 0.2471
PT Steel	€ 0.6568
S355	**€ 0.0675**
Steel Sheet	€ 0.1675
Fire Safety Material	€ 0.0692

Example
200 m building using steel outrigger and hollow-core slab

Mass Material (T)	Environmental Cost per Material (€)
x 7,028	= € 51,457
x 12,798	= € 95,987
x 15,892	= € 130,912
x 0	= € 0
x 742	= € 183,276
x 194	= € 127,148
x 4,155	= € 280,446
x 0	= € 0
x 428	= € 29,668 +
Total Environmental Cost	= € 898,894
Total Gross Floor Area (GFA)	= 51,597 m^2
Total Environmental Cost per Square Meter GFA	= 17.42 €/m^2

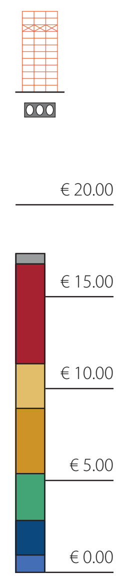

Table 1. Explanation of the shadow price concept, showing the different environmental impact categories, an example calculation of the shadow price for steel, the used shadow prices for each material, and an example calculation for the environmental impact of one model.

Eurocode criteria regarding strength and stiffness, which make them comparable with each other. The single indicator used was environmental cost per square meter of gross floor area (EC/m^2 GFA). This enables comparison of the impacts of the different building height cases.

The system boundaries are represented by the cradle-to-gate principle (production phase only, A1-A3). This is mainly due to the choice of using EC as indicator, since there is no suitable or sufficient data of the impact of the other life cycle phases. Further research is required to identify the environmental impact of these phases for all 10 impact categories. End-of-life phase is excluded because high-rise buildings are rarely demolished.

Data about the environmental impact of the materials was mainly obtained from the Dutch National Environmental Database (NMD) (Stichting Bouwkwaliteit, 2014). An exception was made for steel sections and sheets, which were retrieved from Bouwen

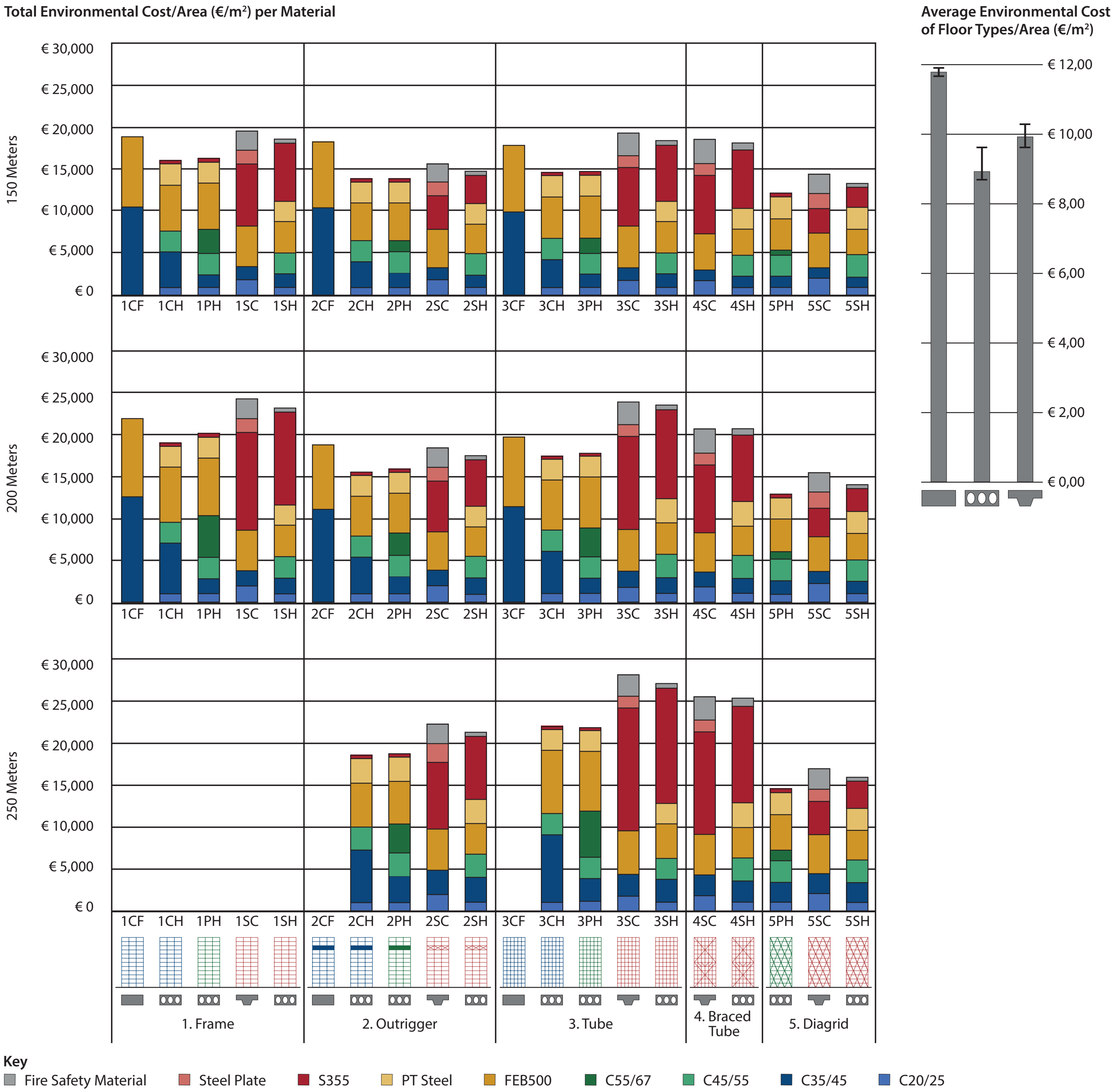

Figure 3. Results of the life cycle analysis for each case, broken down by impact per material, in environmental cost per square meter GFA, including the average environmental impact of the three floor systems. Model IDs are explained in Figure 2.

met Staal (BmS), a Dutch steel branch organization (MRPI 2013a and 2013b). In fact, any European database can principally be used for recalculation of the environmental impact. The material quantities were automatically determined within the parametric workflow.

Results and Discussion

Figure 3 shows the results and indicates the share of each material in the environmental impact of each model.

Figure 4 and Table 2 show the results only for the models containing hollow-core slab floors, and indicates the share of each element type in the environmental impact of the model. Evaluating the results of the models with the same floor system enables comparison of the environmental performance of the different stability systems and structural materials.

Steel models generally score 6-35% higher in environmental impact than the corresponding concrete models with the same stability system. The steel models have a lower weight than the concrete models, but the higher shadow price of steel yields a higher total EC. The impacts of the cast-in-situ concrete and precast concrete models are relatively similar.

Floor systems comprise the biggest share in the total environmental impact of the building structure. Depending on the efficiency of the stability system, floors are responsible for 32-73% of the total environmental impact. Flat-slab floors show the highest environmental impact, composite floors are situated in the middle,

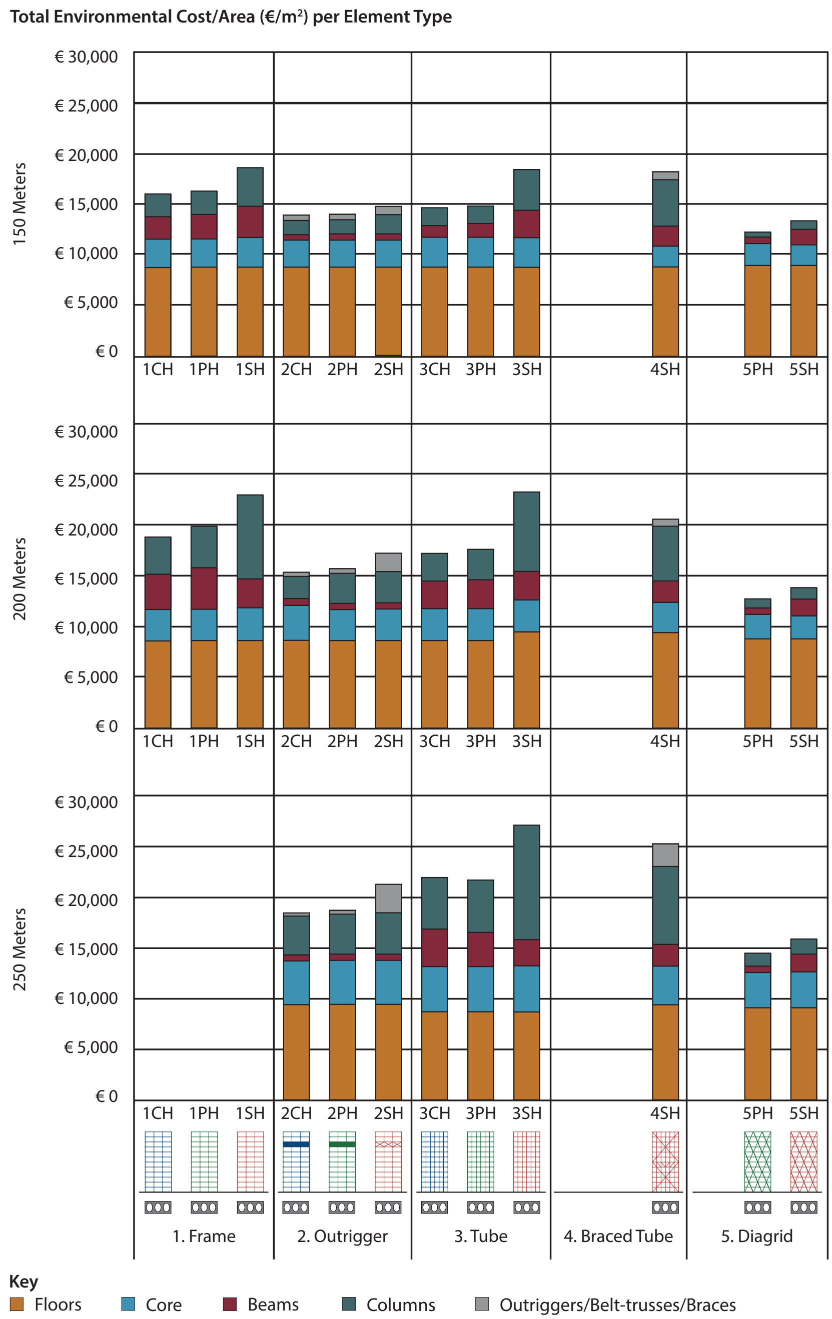

Figure 4. Results of the life cycle analysis, limited to cases with hollow-core slab floors, broken down for their impact by element type, in EC/m² GFA. Model IDs are explained in Figure 2.

and hollow-core slab floors have the lowest impact. This indicates that using a lighter floor system does not necessarily lead to a lower environmental impact, which was also a finding by Foraboschi, Mercanzin & Trabucco (2014).

When comparing the different stability systems, the frame structures have the highest environmental impacts. At 250 meters, it was impossible to design a frame structure that would fulfill the strength, stiffness and design criteria for the determined building geometry and soil conditions.

Using a tube structure resulted in a reduction of impact for the concrete models of 5-11%, compared to the frame structures. This is due to better material distribution for global stiffness. Long rectangular cross-sections are used for columns in the tube structures, instead of the square sections used in frame structures. For the steel tube structures, the environmental impact remains the same compared to frame structures. The tube structures are taken as a reference for further comparisons between different stability systems, as shown in Table 2.

The braced-tube structure only reduces the environmental impact of the models of 200 and 250 meters by 7-12%, compared to the tube structures. This is due to the use of heavy belt trusses to transfer vertical loads horizontally to the corner columns. Changing the design regarding vertical load distribution, e.g., increasing the floor areas supported by the corner columns by increasing column spacing, might lead to a higher material efficiency, and therefore a lower environmental impact.

The two best-performing stability systems are the outrigger and diagrid structures. The environmental impact of the concrete outrigger structures is 5-16% lower than that of the tube structures. For steel outrigger structures, the reduction is 20-26%. The diagrid structures show the lowest environmental impact in both concrete and steel for each height. The reduction for the concrete models is 17-33%, and for the steel models is 28-41%, compared to the tube structures in the same material.

The better environmental performance of the outrigger and diagrid structures can be explained by mechanics. When subjected to wind forces, structural elements in the rigid frame and tube structure are loaded in bending to provide lateral stiffness. However, within the outrigger and diagrid structure, the elements are predominantly axially loaded. The axial stiffness of a structural element is significantly higher than the bending stiffness, which therefore results in a lower amount of required material and a lower environmental impact.

Moreover, the results show increasing differences in environmental impact between the different stability systems when building height and slenderness increase. This indicates that the choice of stability system has an increasing influence on the environmental performance of the building structure as the building's structural behavior becomes less stiff. Consequently, a decreased foundation stiffness due to poor soil conditions might have a magnifying effect on the differences in environmental impact between the different stability systems. This is caused by more strict deflection criteria, because the foundation is already responsible for a significant part of the permissible deflections.

Relative Results per Structural Material

		1. Frame	2. Outrigger	3. Tube	4. Braced Tube	5. Diagrid
150 Meters	C	110%	95%	100%		
	P	110%	95%	100%		83%
	S	101%	80%	100%	99%	72%
200 Meters	C	109%	89%	100%		
	P	113%	89%	100%		72%
	S	99%	74%	100%	88%	60%
250 Meters	C		84%	100%		
	P		86%	100%		67%
	S		79%	100%	93%	59%

Table 2. Relative performances of structural systems, showing the (in)efficiency of each, on the basis of its structural material, compared to tube structures using the same material.

Factors of Influence

A brief sensitivity analysis was performed on the shadow prices of concrete, reinforcement steel and structural steel for the 200-meter models. Fluctuations in shadow prices can occur due to several circumstances, e.g., using different material suppliers, different concrete mix designs, etc. An increase/decrease of 25% of the shadow prices of these materials leads to an increase/decrease of the gap between concrete and steel models, but does not lead to a scenario where the environmental impact of the steel models becomes the lowest.

Using older steel shadow prices originating from the NMD instead of BmS resulted in an enormous increase of 52-124% in the environmental impact of the steel models. This shows that the Fast Track LCA method is a relatively simple, yet sensitive way to determine the environmental impact of building structures. More transparency is required from material suppliers and databases to make fairer comparisons.

Reusing structural elements after building demolition for construction of new buildings has a high potential of reducing the environmental impact of building structures. Steel has a significant advantage over concrete in this regard, since it has a great potential for reuse. Considering reuse of steel elements could lead to scenarios where the steel models would become more favorable over the concrete models in terms of environmental impact. This would require developing demountable high-rise building structures and special demolition techniques.

The foundation (or substructure) is responsible for a large part of the environmental impact of the structure. Oldfield (2012) estimated this to be 28% for 30 St. Mary Axe, London. The weight of the building generally plays a major role in the foundation design: heavier buildings require heavier foundation structures. This could be beneficial for steel buildings, since these are lighter than concrete buildings, but rotation stiffness of the foundation is a major factor and can govern strength in design. Therefore, it is unknown to what extent the gap between steel and concrete models could be reduced by inclusion of the foundation structure.

The construction phase (A4-A5) is accountable for approximately 10% to 25% of the total EC (Sarkisian & Shook, 2014). One of the aspects within the construction phase is transportation to the building site (A4). A sub-study was performed for the 200-meter outrigger model, where the impact of transportation was determined. Default distances of 150 kilometers were used, except for cast-in-situ concrete and reinforcement steel, where 30 kilometers was used. The results showed that for the cast-in-situ concrete and steel models, transportation was accountable for 3.5% and 2.4% of the total environmental impact (A1-A4), respectively. For the precast concrete model, transportation was accountable for 9.0%, due to the heavy weight and large transportation distance.

The impact of the construction phase (A5) depends on several project-specific factors (Cole, 1999). These factors also relate to building erection speed. Construction of a building with prefabricated concrete or steel elements is generally faster than constructing a cast-in-situ concrete structure, which might have a positive influence on the environmental impact. According to Sarkisian, on average, the impact of the construction phase is twice as high for reinforced-concrete buildings as for steel buildings (10% vs 20% of the total impact) (Sarkisian & Shook, 2014). The construction phase has a significant influence on the total environmental impact of the structure. It is likely that the differences in environmental impact between the steel and concrete models will be reduced by inclusion of the construction phase into the LCA.

Comparison with Literature

A comparison is made with the 60-story models of the research by Trabucco et al. (2016). These models have a gross floor area of 141,600 square meters and are 246 meters in height. Due to the large differences in geometry (significantly lower slenderness), it was chosen to only compare the all-steel diagrid from Trabucco with the 250-meter steel diagrid models with composite floors from this research. Global warming potential (GWP) was used as the only indicator, as EE is not listed in the NmD.

The total impact (A1-A5) of the all-steel diagrid model of Trabucco is 243 kg CO_2/m^2, whereas the impact (A1-A3) of the 250-meter steel diagrid models of this research range from 185 to 212 kg CO_2/m^2, which is 13-24% lower. This difference in impact has several explanations. Trabucco's results include the construction phase, which is accountable for 10-25% (Sarkisian & Shook, 2014). Also, the model in this research contains a concrete core, which reduces the amount of required steel for lateral stiffness. Finally, the GWP values for steel used by Trabucco are 33% higher in this research.

Trabucco et al. concluded that for the 60-story scenario the concrete models had the highest scores regarding GWP, while all-steel scenarios had the highest EE. When only considering GWP as indicator in this research, similar observations can be made as described above: the steel models have a higher GWP than the concrete models. This contradicts the conclusion by Trabucco that concrete models have the highest GWP values.

One possible reason for this contradiction is that the models in this research are significantly slenderer than those in Trabucco's study. This means that structural elements are often designed for global stiffness instead of strength capacity, emphasizing the differences in stiffness of the stability systems. Poorer soil conditions have a similar effect, causing additional lateral deflection due to decreased rotational stiffness of the foundation. Another reason can be found in the mix design of the concrete. The average GWP values for concrete used by Trabucco are 50-90% higher than values used here. The concrete mix designs used in the Netherlands are generally based on low-clinker-content cements (typically 30-50% clinker and more fly-ash, plus 50-70% ground granulated blast-furnace slag), which reduces the GWP significantly. Another discrepancy might lie in Trabucco's inclusion of transportation, construction and demolition, which could have an equalizing effect between the impacts of the steel and concrete models.

Conclusions

Steel models have a 6-35% higher cradle-to-gate impact (A1-A3) than the corresponding concrete models. It is likely that inclusion of the construction phase and foundation structure in the LCA leads to a decrease in the gap between the environmental impacts of the concrete and steel models. Regarding cast-in-situ versus precast concrete, no clear winner can be appointed yet, as the environmental impact scores are close.

Floor systems are responsible for the largest part, 32-73%, of the total environmental impact of high-rise building structures. Decreasing the impact of the stability system increases the significance of reducing the impact of floors. Using a lighter floor system leads to a decreasing demand of material but does not necessarily lead to a lower total environmental impact, due to the floor itself having a big share of the total impact.

In terms of stability systems, the frame and tube structures lead to the highest cradle-to-gate environmental impacts (A1-A3) for all heights. The outrigger and diagrid structure result in the lowest environmental impacts for all heights. Using an outrigger structure decreases the impact by 5-16% for concrete and 20-26% for steel models, compared to the tube structure. The diagrid structure has the lowest impact for all examined heights and reduces the impact by 17-28% for concrete and 28-41% for steel models, compared to the tube structure.

Structural designers and engineers already have options for making a difference in reducing the environmental impact of high-rise buildings. This research showed that the choice of a structural system plays a major role compared to the choice of a structural material when seeking to reduce the environmental impact of tall building structures in Western Europe. More importantly, by using less-obvious but already existing design solutions for the considered height range of 150-250 meters, like the diagrid structure, reductions in impact can be achieved relatively easily. ■

Unless otherwise noted, all image credits in this paper belong to the authors. Some images have been redrawn by CTBUH.

References

ALI, M. & MOON, K. S. 2007. "Structural Developments in Tall Buildings: Current Trends and Future Prospects." ***Architectural Science Review***. 50(3):205–223. doi: doi:10.3763/asre.2007.5027.

COLE, R. J. 1999. "Construction of Alternative Structural Systems." ***Building and Environment.*** 34:335-348.

FORABOSCHI, P.; MERCANZIN, M. & TRABUCCO, D. 2014. "Sustainable structural design of tall buildings based on embodied energy." ***Energy and Buildings.*** 68:254–269. doi: 10.1016/j.enbuild.2013.09.003.

KAETHNER, S. C. & BURRIDGE, J. A. 2012. "Embodied CO_2 of structural frames." ***The Structural Engineer***. May (5):33–40. ISSN 14665123.

MRPI. 2013a. "MRPI® sheet for heavy steel construction products." ***SGS INTRON-rapport R20110677, MRPI® van constructiestaal.*** January 2012.

MRPI. 2013b. "MRPI® sheet for light steel construction products." ***SGS INTRON-rapport R20110677, MRPI® van constructiestaal.*** January 2012.

OLDFIELD, P. 2012. "Embodied Carbon and High-Rise." ***In CTBUH 2012 9th World Congress, Shanghai***. pages 614–622.

SARKISIAN, M. 2016. "Designing Tall Buildings, Structure as Architecture." ***Routledge.*** New York, 2nd edition.

SARKISIAN, M. & SHOOK, D. 2014. "Embodied Carbon in Structures and Cities." ***37th IABSE Symposium Madrid***. Volume 102, pages 3166–3173.

STICHTING BOUWKWALITEIT. 2017. ***Nationale Milieudatabase.*** Version 3.3, 2017

TRABUCCO, D. & WOOD, A. 2016. "LCA of tall buildings: Still a long way to go." ***Journal of Building Engineering.*** 7:379–381. doi: 10.1016/j.jobe.2016.07.009.

TRABUCCO, D. et al. 2016. "A Whole LCA of the Sustainable Aspects of Structural Systems in Tall Buildings Paper Type." ***International Journal of High-Rise Buildings.*** 5(2):71–86.

UNITED NATIONS. 2001. "Future World Population Growth to be Concentrated in Urban Areas." ***United Nations Population Division Report, March.***

YOHANIS, Y. G. & NORTON, B. 2002. "Life-cycle operational and embodied energy for a generic single-storey office building in the UK." ***Energy.*** 27:77–92. doi: 10.1016/S0360-5442(01)00061-5.

WEBSTER, M. D. 2004. "Relevance of structural engineers to sustainable design of buildings." ***Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE)***. 3:181–185. doi: 10.2749/101686604777963874.

> "For the cast-in-situ concrete and steel models, transportation was accountable for 3.5% and 2.4% of the total environmental impact, respectively. For the precast concrete model, that figure was 9.0%."