CTBUH Research Report

Life Cycle Assessment

of Tall Building Structural Systems

Dario Trabucco, Antony Wood, Olivier Vassart, Nicoleta Popa, and Donald Davies

Council on Tall Buildings and Urban Habitat

ArcelorMittal

Council
on
Tall Buildings
and
Urban Habitat

Research Funded By:

ArcelorMittal

Bibliographic Reference:
Trabucco, D., Wood, A., Popa, N., Vassart, O. & Davies, D. (2015) *Life Cycle Assessment of Tall Building Structural Systems*.
Council on Tall Buildings and Urban Habitat: Chicago.

Principal Research Investigators: Dario Trabucco, Antony Wood, Olivier Vassart, Nicoleta Popa & Donald Davies
Additional Researchers: Meysam Tabibzadeh, Eleonora Lucchese, Mattia Mercanzin & Payam Bahrami
Editorial Support: Jason Gabel
Layout: Mattia Mercanzin & Marty Carver

Published by the Council on Tall Buildings and Urban Habitat (CTBUH) in conjunction with ArcelorMittal

Printed and bound in the USA by The Mail House

Library of Congress Cataloging-in-Publication Data
A catalog record has been requested for this book

ISBN: 978-0-939493-48-7

Council on Tall Buildings and Urban Habitat
S.R. Crown Hall
Illinois Institute of Technology
3360 South State Street
Chicago, IL 60616
Phone: +1 (312) 567-3487   Fax: +1 (312) 567-3820
Email: info@ctbuh.org
www.ctbuh.org
www.skyscrapercenter.com

ILLINOIS INSTITUTE
OF TECHNOLOGY

CTBUH Asia Headquarters Office
College of Architecture and Urban Planning, Tongji University
1239 Si Ping Rd, Yangpu District, Shanghai, China 200092
Phone: +86 21 65982972
Email: china@ctbuh.org

CTBUH Research Office
Iuav University of Venice
Dorsoduro 2006, 30123 Venice, Italy
Phone: +39 041 257 1276
Email: research@ctbuh.org

Università Iuav
di Venezia

Front Cover: Image sources; Clockwise from top left: FreeImages.com/Bo de Visser; Marshall Gerometta, (cc-by-2.0) U.S. Army Materiel Command, mzacha via RGBStock, FreeImages.com/steph poitiers

Principal Researchers / Authors

Dario Trabucco, *Research Manager, CTBUH / Iuav University of Venice*
Antony Wood, *Executive Director, CTBUH / Illinois Institute of Technology / Tongji University*
Olivier Vassart, *Head of Global R&D Long Carbon, ArcelorMittal*
Nicoleta Popa, *Senior Research Engineer, ArcelorMittal*
Donald Davies, *Principal, Magnusson Klemencic Associates*

Additional Researchers / Contributors

Eleonora Lucchese, *CTBUH Research Office, Venice*
Mattia Mercanzin, *CTBUH Research Office, Venice*
Meysam Tabibzadeh, *CTBUH Research Office, Chicago*
Payam Bahrami, *CTBUH Research Office, Chicago*

Contributors / Project Steering / Peer Review Panel

Mark Aho, *McNamara / Salvia*
Peyman Askarinejad, *Arabtec*
Martina Belmonte, *CTBUH/IUAV*
Joseph Burns, *Thornton Tomasetti*
Luis Simoes Da Silva, *University of Coimbra*
Edward DePaola, *Severud Associates*
Chukwuma Ekwueme, *Weidlinger Associates*
Paul Endres, *Endres Studio*
David Farnsworth, *Arup*
Rolf Frischknecht, *Treeze*
Erleen Hatfield, *Buro Happold*
Ben Johnson, *Skidmore, Owings & Merrill*
Leif Johnson, *Magnusson Klemencic Associates*
Makoto Kayashim, *Taisei*
Raffaele Landolofo, *University of Naples*
Dennis McGarel, *Brandenburg*
Declam Morgan, *Buro Happold*
Levon Nishkian, *Nishkian Menninger*
Tatsuo Oka, *Utsunomiya University*
Arif Ozkan, *Arup*
Stefano Panseri, *Despe*
John Peronto, *Thornton Tomasetti*
Dennis Poon, *Thornton Tomasetti*
Christopher Rockey, *Rockey Structures*
Ronald Rovers, *RiBuilIT*
Tim Santi, *Walter P Moore*
Allen Thompson, *WSP*
Robert Victor, *Brandenburg*
John Viise, *Thornton Tomasetti*
Wolfgang Werner, *Urban Fabrick*
Yong Wook Jo, *Arup*
Nabih Youssef, *Nabih Youssef & Associates*

Contents

Preface

Despite the history of the skyscraper spanning well over a century, and the fact that the world is now constructing tall buildings in excess of 1,000 meters in height, with the exception of the events of 9/11, we have never actually demolished or dismantled a building taller than 187 meters. That building was the Singer Building, a 187-meter tower in New York City that was demolished in 1968 to make way for 1 Liberty Plaza. The reality is that we are now building many hundreds of skyscrapers – in addition to those already in existence – with little idea about their real longevity, what variances and experiences they will have during their whole life cycle, and what will happen to them at the end of that life cycle.

These are massively important issues that should influence the design of all skyscrapers from the very outset (i.e., how to design buildings for multiple changes in function, an indeterminate future, or even perpetual existence?), but the industry does not even have a template for assessing the relative implications – energy or otherwise – of the different stages of a building's life. In the sustainability realm, emphasis has been placed on the reduction of operational energy at the expense of all other facets. While the reduction of operating energy is vitally important, it is far from the complete picture. Reducing the embodied energy of the materials in the building itself is equally important. As technologies increasingly allow buildings to move towards carbon-neutral operation (though we are still far away from that holy grail), embodied energy will become the main energy consumer, and thus it is the most critical area for further consideration now. In short, the true environmental impact of the full life cycle of tall buildings is a significantly unknown quantity.
This is the point of departure for this guide, and the three-year research project that underpins it. A Life Cycle Assessment (LCA) is a methodology that gauges the consequences of human actions by analyzing the flow of materials used in a product or a building and traces the environmental impacts linked to each stage of its life cycle. An LCA thus begins by analyzing the effects of material extraction and processing, accounting for the specific pieces of equipment used and the energy needed to turn raw materials into a final product (in this case, a building). The assessment also evaluates the impacts of manufacturing, transportation, and on-site construction activities, taking note of both power consumption and carbon emissions during each process. Finally, operational activities, demolition, and end-of-life recycling are considered. When information from each stage is combined, a holistic picture of environmental impacts can be formed for a given product, one that acknowledges the various actions that are required to bring a single entity into existence through contemporary means.

The true benefits of the LCA methodology are realized when numerous assessments are performed for different versions of a product. This allows researchers to compare alternatives along various impact categories, and provides a basis for making informed decisions that produce the greatest environmental benefits over time. Given this fact, it is clear that Life Cycle Assessment is largely the missing piece in the sustainable puzzle for tall buildings.

This research, which was undertaken by the CTBUH Research Division and sponsored by multinational steel manufacturer ArcelorMittal, identifies and compares the life cycle implications for multiple comparative structural systems found in 60- and 120-story buildings. Structural systems are by no means the entirety of a tall building, and an LCA of the components that are more likely to change over time (façades, MEP systems, interior fit out) would also be extremely valuable. However, the means to evaluate life cycle energy is still in its infancy and is an especially complicated subject. Thus, for this first study, focusing on the structural systems of a building – which accounts for a large share of the material inventory and has major impacts on all aspects of building performance – seemed a sensible choice.

This report thus represents the first-ever full LCA on tall building structural systems ever performed, and represents a "first stab" at environmentally quantifying the decisions made in the design and engineering process of skyscrapers. Using the results found herein, industry professionals and researchers can recognize the performance of these systems along two key impact categories: Global Warming Potential (GWP) and Embodied Energy (EE). Global Warming Potential is measured by calculating the amount of carbon (or carbon equivalent) that is released over the course of a structure's life cycle, allowing impacts on climate change to be determined. Embodied Energy was selected as an indicator for natural resource depletion, since the amount of energy consumed over the lifetime of the structural systems and their materials has direct implications for the consumption of electricity, fossil fuels, and natural gas.

In addition to this report's ability to serve as a reference in the design process, it also serves as a launching point for further research into the life cycle of tall buildings. Indeed, as is typical with undertakings of this nature, more questions tend to arise than answers. From the outset, it was the Council's goal to explore this topic with an emphasis on finding where further investigation is needed. Suggestions for further research are thus provided at length in the final section of the report.

As evidenced in this study, the CTBUH Research Division plays a very important role, not only in achieving the Council's mission of disseminating information on tall buildings to professionals and stakeholders around the world, but to engage in the global debate on sustainability that has relevance far beyond the industry itself. The CTBUH is well-positioned for research such as this due to its intermediary role between a diverse set of professionals, with members and contributors ranging from architects, engineers, material specialists, owner/developers, city planners, construction companies, and equipment suppliers. The Research Division is one of the ways that the Council uses these resources to address the research gaps identified in the *Roadmap on the Future Research Needs of Tall Buildings*, a 2014 CTBUH publication that lists and prioritizes topics that are in greatest need of further exploration. By focusing the efforts of the CTBUH in this way, attention is brought to often ignored or underrepresented aspects of tall buildings, mobilizing individuals to obtain a more complete understanding of the industry.

The daunting complexities of life cycle research require the collaboration between numerous individuals within varying specializations. This LCA alone drew on the support and expertise of numerous companies, all of whom are acknowledged on page 178. Thus, this project is truly an indication of concern for many in the tall building industry regarding the "big picture" of sustainability for our cities. So let this report serve not only as a plunge into an emerging field of study, but a call to action that emphasizes the importance of looking at the consequences of our choices, from beginning to end.

Antony Wood
Chicago, USA

Dario Trabucco
Venice, Italy

1.0 Tall Buildings Today

The Council on Tall Buildings and Urban Habitat (CTBUH) recognizes three different ways of defining a tall building. According to the CTBUH, tall buildings exhibit some element of "tallness" in one or more of the following categories:

- Height Relative to Context: a building is taller than those in the surrounding area with respect to a prevailing urban norm;
- Proportion: a tall building has a slender appearance made evident by a relatively small base in comparison to its height;
- Tall Building Technologies: a building contains technologies which may be attributed as being a product of its height (e.g. specific vertical transport technologies, structural wind bracing as a product of height, etc.).

In addition to the above criteria, there are two definitions that establish universal height thresholds for tall buildings: the CTBUH defines "supertall" buildings as those over 300 meters in height, and "megatall" buildings as those over 600 meters in height. Although great vertical strides are currently being achieved by an increasing number of tall buildings every year, there are only 93 supertall and three megatall buildings completed and occupied globally as of June 2015.

The birthplace of the tall building typology is still a heavily debated topic among experts. However, it is commonly agreed that the first tall buildings in history were found in New York and Chicago (Barr, 2014).

An early observation by Fryer (Fryer, 1891) mentions three basic elements that contributed to the birth of skyscrapers:

Figure 1.1: Home Insurance Building, 1885, Chicago, generally accepted as the first tall building because of its curtain wall construction on a steel frame.

Figure 1.2: Equitable Life Building, 1870, New York, considered by some to be the first tall building in history due to its exploration of the potentialities offered by the passenger elevator
Source: (public domain) Emerson7

the modern passenger elevator, the invention of iron/steel structures (see Figure 1.1), and the terracotta flat arch element to protect horizontal iron beams from fire. Rem Koolhaas (Koolhaas, 1978), almost one century later, also cites steel frameworks and the passenger elevator as the elements that made the construction of tall buildings possible.

Both of the above definitions exclude several notable examples of buildings that, despite having a load bearing masonry wall system (such as the 1893, 17-story Monadnock Building in Chicago), can clearly be considered a tall building (Leslie, 2013).

Considering this argument, the elevator is the only remaining determinant for a tall building. In this case, the Equitable Life Building (see Figure 1.2), completed in New York in 1870, would be the first tall building in the history due to its exploration of the potentialities offered by the passenger elevator (Weisman, 1970).

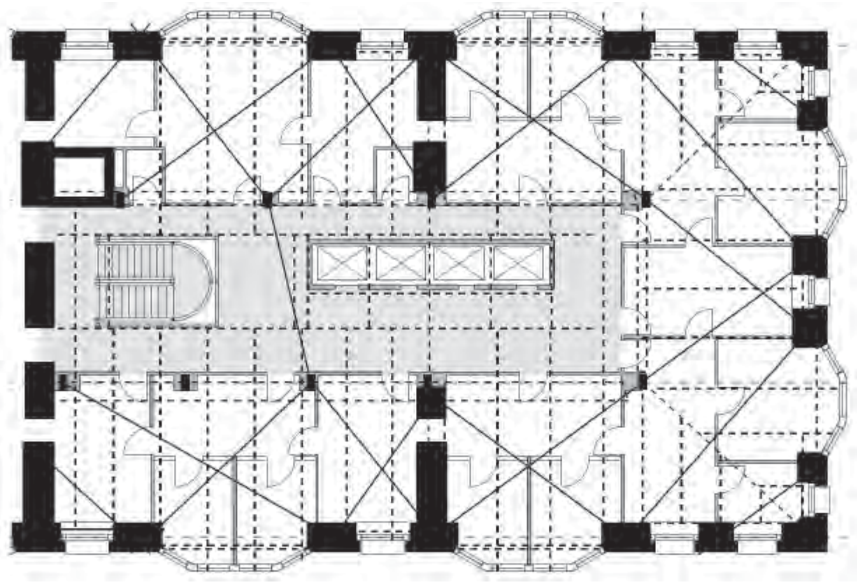

Figure 1.3: Load bearing wall system for skyscrapers Monadnock Building, Chicago, (Floor Plan)
Source: Leslie, Thomas (2013), "The Monadnock Building, Technically Revisited" CTBUH Research Paper, 2013 Issue IV, pp 29. Redrawn by CTBUH

The increased heights and different shapes that New York skyscrapers adopted as a result of the 1916 Zoning Resolution, which also affected the design of tall buildings in all other American cities (Willis, 1986), did not alter the basic structural schemes used since the birth of the skyscraper typology. In fact, from a structural perspective, all skyscrapers built before the Second World War are quite similar, and were based on the principle of a rigid frame, with required stability against lateral loads provided by the stiffness of beam-column connections (Ali & Moon, 2010) as well as the natural bracing effect provided by the solid façade panels. The solid decorated urban blocks used in early skyscrapers evolved since the 1950's toward a more neat and transparent style that spread all over the world in a movement known as the "International Style." Even if virtually all tall buildings have a façade freed from any load bearing or structural function, the International Style marked an evolution in the performance of tall buildings. Fully glazed and sealed façades, introduced for the first time in buildings such as the Lever House in New York and the Commonwealth Building in Portland, Oregon, dramatically reduced the thermal inertia of buildings.

This lead to an increase in the reliance on mechanical air conditioning and ventilation systems, together with the thermal inertia of the internal structure and surfaces. Glazed façades also significantly reduced the weight of tall buildings, while also taking away the solid walls punctuated by small windows that provided bracing against lateral loads.

As a consequence of this, and of the increasing height and slenderness of tall buildings, bracing functions were later transferred toward the interior by creating braced trusses around the elevator core. Thus, using these new features, the modern tall building typology was born. One of the earliest examples of these features can be found in the Seagram Building in New York.

Since the end of the Second World War, tall buildings have spread from their country of origin, the United States of America, to become a global symbol of modernity and

2.0 Sustainability and Tall Buildings

Figure 2.1: Integrated wind turbine example: Bahrain World Trade Center, 2008, Manama Source: (cc-by-sa) Ayleen Gaspar

Skyscrapers are often accused of being a non-sustainable building typology because they require a greater amount of energy to operate compared to a normal building, they require increased quantities of materials for their structures as a consequence of their height, and they involve a higher amount of embodied energy used to produce these materials. Indeed, tall buildings require more structural materials than lower buildings and they utilize additional features (such as elevators) that are not needed in shorter buildings.

The environmental sustainability issues of tall buildings became evident in 1973-1974 when the first energy crisis caused a rise in oil and energy prices in western countries. During the years following 1974, extensive analyses were carried out in North American cities to determine the actual energy performances of tall office buildings (Stein, 1977), while technical innovations were introduced to decrease their overall energy consumption (mostly in the field of mechanical ventilation and internal illumination), thus creating a new generation of efficient tall buildings. Since then, tall buildings have undergone major transformations that have changed not only the energy needed for their daily operations, but their architectural appearance as well.

> ***"Sustainability has clearly become a major driver of change in tall building development..."***

Sustainability has clearly become a major driver of change in tall building development, and the integration of "green" solutions has resulted in a whole new family of towers (Yeang, 1996) that have inspired the introduction of a new vernacular for tall buildings (Wood, 2007) (Yeang, 1996). However, green architectural features have been used sporadically, and only a few tall buildings with extensive use of "visible" sustainable principles exist today. This is mainly due to the increased construction and management costs associated with developing such buildings, which need to be addressed by drivers beyond basic design factors. In fact, most high performance buildings have been built using less visible – but nonetheless effective – measures, rather than bold, outstanding innovations with very high capital costs. Thanks to the use of modern curtain wall systems, the exploitation of natural ventilation, energy efficient elevators, combined heat and power units, and intelligent building control systems (Ali & Armstrong, 2008), buildings consume far less energy than their 1970s predecessors (Oldfield, et al., 2009).

With a decrease in the energy consumption of tall buildings, a new issue arose, requiring the renewed attention of building experts and professionals: life cycle thinking. In fact, buildings consume energy and cause emissions, not only during use, but throughout their entire lives. From material production, construction, and maintenance, to demolition and the recycling of building materials (or disposal into a landfill), they consume energy as well as emit gases and substances into the environment. All of these phases have an impact on the total life cycle performance of a tall building, and one should make sure that the benefits of an energy reduction strategy (such as the use of a double skin façade) are carefully studied, so as not to create bigger drawbacks for other environmental characteristics; for example, by augmenting the initial embodied energy that offsets the benefits created in daily energy consumption.

2.1 Energy Consumption of Tall Buildings

The energy consumption of tall buildings evolved significantly over the past 100 years, reaching a maximum before the first energy crisis and then diminishing remarkably (Oldfield, et al., 2009). The theoretical limit of 90 kWh/m^2 per year mentioned by Raman (Raman, 2001) excludes the presence of on-site energy generation. Thanks to the exploitation of renewable sources such as photovoltaic cells or wind turbines, tall buildings can be not only efficient in consuming energy, but also in producing it.

Figure 2.2: Photovoltaic façade example: Palazzo Lombardia Building, 2011, Milan Source: Dario Trabucco

Figure 2.3: Integrated wind turbine example: Pearl River Tower, 2013, Guangzhou Source: Tansri Muliani

Photovoltaic panels are being installed on a number of tall building's rooftops, such as the Euro Tower in Rome, or façades, as on the Palazzo Lombardia in Milan (see Figure 2.2), but their effect is limited to the surface of their external envelopes, which are quite limited when compared to the building's usable floor area. Therefore, their energy production rate is small when compared to the high energy consumption of the whole building.

Only a few tall buildings with integrated wind turbines have been built; the Strata Tower in London, the Bahrain World Trade Center in Bahrain, and the Pearl River Tower in Guangzhou (see Figure 2.3) are probably the most relevant examples. Generally speaking, renewable energy production systems are not as effective as expected, and cause many drawbacks to the comfort of a tower's inhabitants (noise, vibrations, etc.). These drawbacks prevent their full exploitation and require mitigation measures (Killa & Smith, 2008) in the use of such systems, which have to be carefully assessed from a life cycle perspective.

3.0 Life Cycle Assessment

Developed during the 1990's, Life Cycle Assessment (LCA) is a methodology aimed at assessing the environmental consequences of human actions, particularly the production of goods. In the past two decades, LCA analysis has become more and more popular in all disciplines, including architecture and engineering. Despite the fact that LCA has been used for thousands of research projects analyzing the environmental characteristics of materials, components, and even entire buildings, and is widely described in books and scientific publications, doubts and criticisms still exist in the scientific community about the effectiveness and accuracy of LCA methods in accounting for all environmental characteristics of buildings and the built environment (Lenzen, et al., 2004) (Zamagni, et al., 2008).

There are three main methodologies found in literature for performing a LCA (Treloar, 1998):

> ***"...Life Cycle Assessment (LCA) is a methodology aimed at assessing the environmental consequences of human actions, particularly the production of goods."***

1. Process-based LCA: In a process-based assessment, the process to be analyzed is divided into all of its sub-processes. The inputs and outputs of each sub-process are quantified and the process analysis is repeated on all of the inputs, tracing the processes back to a "cradle," where raw materials are excavated or harvested. This method has several problems, most notably concerning the arbitrary process of defining the boundaries of the analyzed system (to decide which processes are to be included or excluded from the analysis) and the availability and reliability of information regarding upstream processes. It is also a very time consuming and complex method. On the other hand, the process-based analysis is notable for its specificity and precision when it comes to detailed product studies.

2. Input-output LCA: In input-output assessment, all production inputs are converted into economic factors using industry-aggregated data on economic interchanges. All of the infinite material and non-material upstream inputs are included in the analysis using a mathematic algorithm. This method has been adapted from the environmental analyses that emerged from the research developed by Nobel Laureate W. Leontief in the 1940s. The problem with this method is that it uses industry-wide average data, and therefore is not specific to a single product, site, or country, and the production processes and technologies for the same product can be very different in different parts of the world. The positive aspect of this method lies in its ability to assess the seemingly infinite upstream processes with a quick, simple calculation method.

3. Hybrid LCA: Hybrid systems can either be based on an input/output analysis or on a process analysis. Such systems try to take advantage of the positive aspects of the two main methods by combining them to perform a quick, comprehensive, and detailed LCA analysis. Hybrid systems are still relatively under development but they seem to be very promising for the future (Zamagni, et al., 2008).

For the purposes of this study, a process-based analysis was adopted, as described in the International Reference Life Cycle Data System Handbook (JRC, 2010), a handbook released by the European Union's Joint Research Centre, Institute for Environment and Sustainability, to guide users through the steps described in more general terms by ISO Norm 14044:2006.

3.1 Explanation of ISO LCA

ISO Norms 14040:2006 and 14044:2006 are the reference standard for the LCA. According to ISO 14040:2006 (see Figure 3.1), a LCA is composed of four phases:

- Goal and scope definition: the definition of a study goal indicates whether the analysis is meant to simply provide a data set for a process – thus a Life Cycle Inventory (LCI) is its main deliverable – or a complete LCA analysis in which the Life Cycle Inventory is interpreted and compared to similar results for other processes or goods. The goal definition also identifies the intended purpose of the study (i.e., comparison of similar products) and the target audience. In the scope definition, the subject of the analysis is identified and described in line with what was stated in the goal definition. This includes the identification of the system boundaries and the functional unit; the analysis on the consistency of the methods; assumptions and data; and finally, the declaration of the results' reproducibility.

- Inventory analysis: during this phase, all inputs and outputs of the process are acquired and described in line with the goal and scope definitions. It is usually the most time-consuming phase of a LCA, as it requires collecting and measuring a large quantity of data, which often comes from external sources. It is from the accuracy and completeness of the LCI that a LCA study gains its quality.

- Impact assessment: The Life Cycle Impact Assessment (LCIA) is the phase in which all inputs and outputs to the process collected during the LCI phase, are converted into impact indicators. Impact indicators are the tools that measure the impact of an analyzed process on target categories such as human health, the natural environment, and natural resources.

- Interpretation of results: The interpretation of results is often the most interesting and "proactive" phase of a LCA, as it gives recommendations on how to improve a process or selects the better process when two processes are compared.

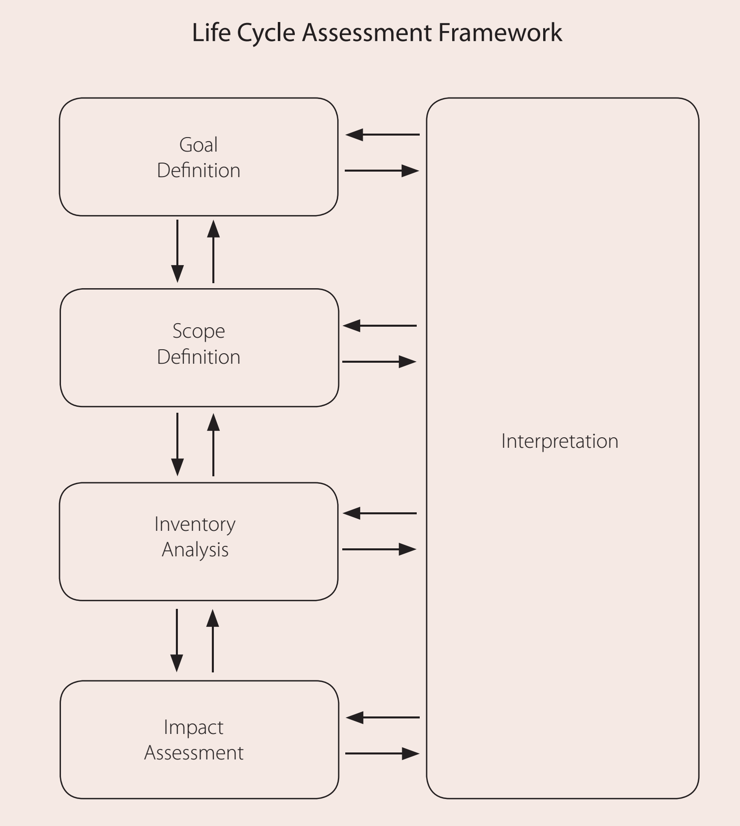

Figure 3.1: Life Cycle Assessment Framework from ISO 14040:2006
Source: CTBUH

3.2 Definition of the Goal of the Study

The intended application of this study is to inform the community of professionals and researchers specializing in tall buildings on the environmental performance of the most common structural systems (reinforced concrete, steel and composite structural alternatives) by providing the most accurate, up-to-date analysis on two key impact categories: Global Warming Potential (GWP) and Embodied Energy (EE). The limitations of this study are represented by the fact that only two impact categories (GWP and EE) are considered here, while other impact categories may lead to different results. Similarly, the obtained results are influenced by the quality of the information used, both in terms of environmental data (i.e., the "quality" and representativeness of the environmental data contained in the international databases used in the study) and data completeness (for example, environmental data on the end-of-life of tall buildings simply doesn't exist, and had to be collected specifically for this research). The studied scenarios are representative of the most common structural systems for buildings of the height here considered.

This research is a complete Life Cycle Assessment of structural systems for 60- and 120-story buildings.

The main reason to conduct this study is that there is a lack of reliable and comprehensive information on the environmental impacts of various structural systems and materials for tall buildings, as well as the impacts of the construction phase on such projects. Also, a comparison on the relative importance of selecting various structural materials and structural systems for a tall building is needed. The intended audience of this public study is the community of tall building experts involved in the

4.0 Steel: Cradle to Grave

Steel is a highly demanded product used for many purposes, including buildings and automobiles. The use of steel as a structural element in buildings goes back to the mid-18th century, when the industrialized production of steel was made possible. It is a metal product with the unique ability to withstand both compression and tension forces, making it a great candidate for building structures.

As the construction of tall buildings became a trend in the 20th century, steel framed structures have become very popular. Their light weight in comparison to concrete or masonry structures, their capability of holding large forces (both horizontal and vertical) over wide spans, and relatively small profile (which results in more space efficiency) are the qualities that gave rise to the popularity of structural steel products.

4.1 Steel Production

Steel is produced using a complicated and energy-intensive process: it is produced through the carbonation of iron (pig iron or cast iron made of iron ore). This initial production procedure is done in blast oxygen furnaces (Yellishetty, et al., 2011).

A Blast Oxygen Furnace (BOF) uses iron ore, oxygen blast, and coke, heating the compounds to make pig iron (see Figure 4.1). The produced iron pellets then get carbonated to make steel. The steel is then molded and rolled into the desired shape (Yellishetty, et al., 2011).

There are only a few integrated BOF mills in the United States that are able to produce large amounts of high-grade steel, a material mainly used in big steel profiles such as large structural steel sections and sophisticated steel products such as high-strength steel or alloy steel.

As steel is a highly recyclable material, a significant part of the new steel produced in the industry, especially in Europe and North America, is made out of recycled steel scrap. This production method utilizes Electric Arc Furnaces (EAF). Unlike

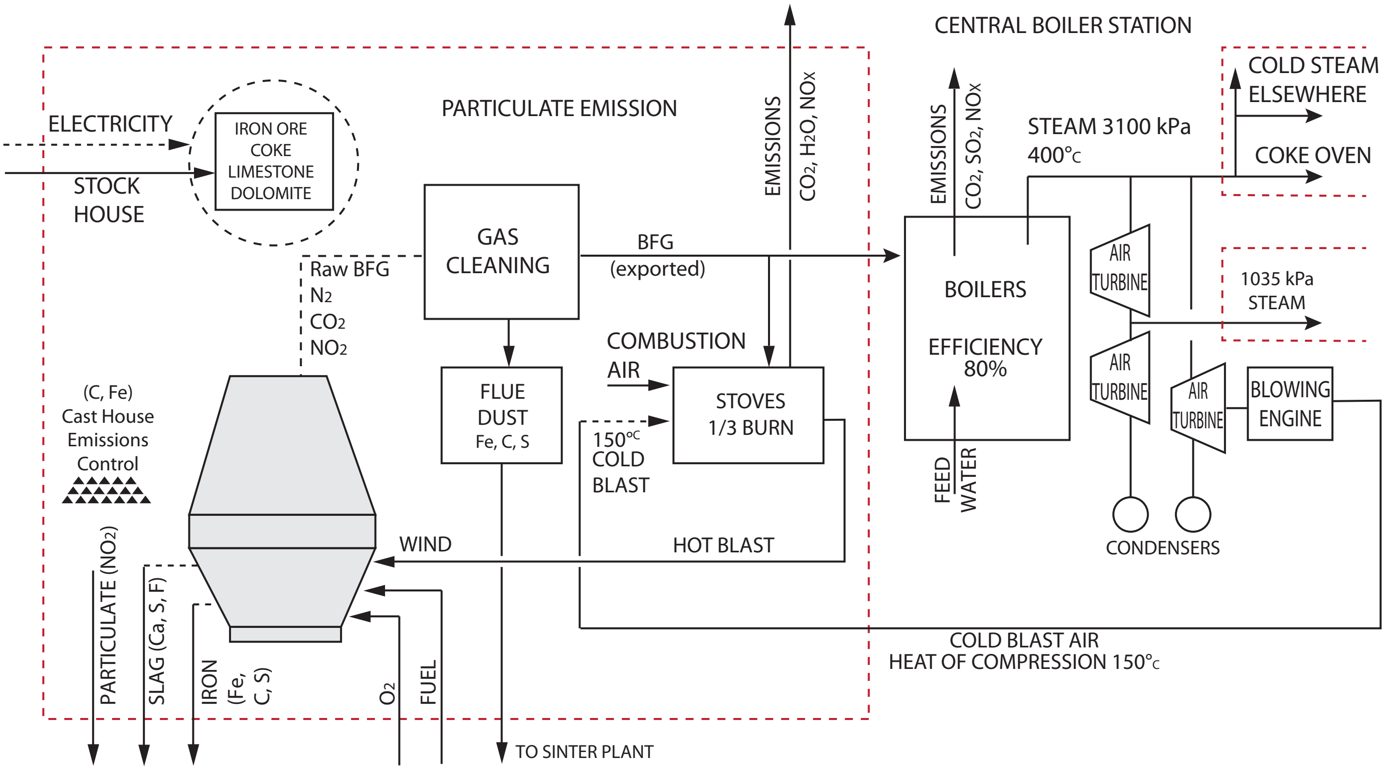

Figure 4.1: Schematic of a Blast Oxygen Furnace
Source: Yellishetti et al, 2011, redrawn by CTBUH

blast oxygen furnaces, EAFs use electrical energy to melt steel scrap and form the molten steel back into various shapes though molding and rolling (Yellishetty, et al., 2011) (see Figure 4.2). In 2014, 60% of steel in the EU was produced with the BOF method, while the remainder came from EAFs. In the US, the above mentioned percentages were inverted, with 40% coming from BOFs, and 60% from EAFs (WorldSteel, 2014).

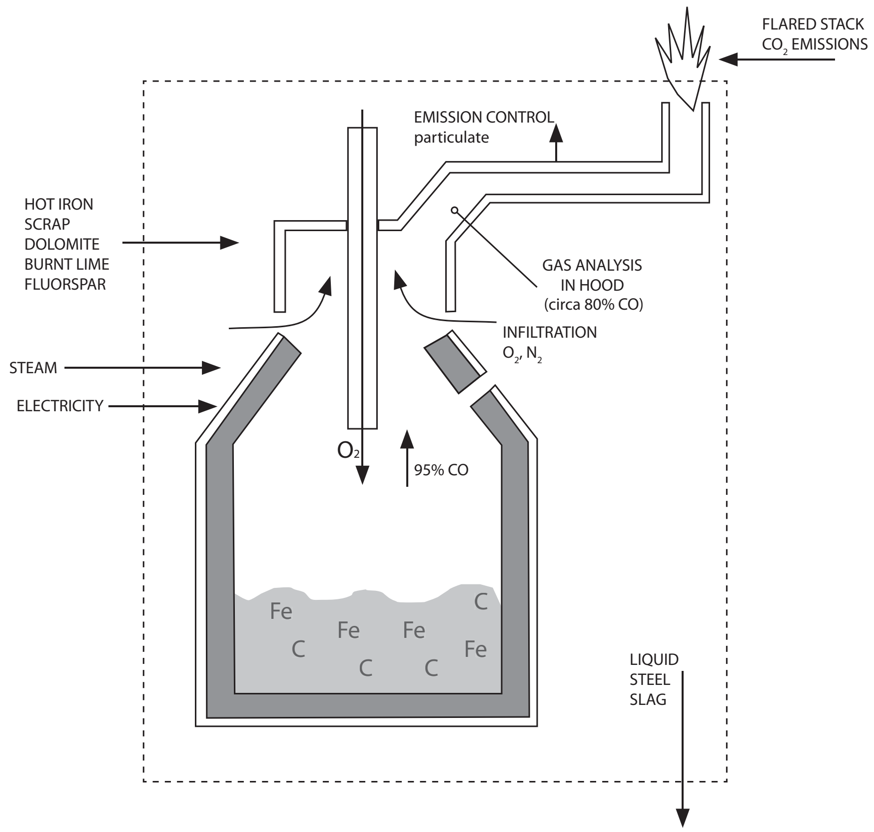

Figure 4.2: Schematic of an Electric Arc Furnace
Source: Yellishetti et al, 2011, redrawn by CTBUH

Although the BOF method uses mostly virgin iron and the EAF method uses mostly scrap as the raw material, there is still scrap used in the BOF steelmaking process (about 25% scrap is used in BOF furnaces) and some virgin iron is needed in EAFs (5% virgin iron on average). The steel made in combination mills, which use a combination of EAFs and BOFs, thus contain an average amount of steel scrap based on the proportion of each production route in the overall number of steel products (Briggs, et al., 2010). Production data for steel typically utilizes an average of these routes, on both national and international levels.

The steel products from EAF mills are usually smaller in size and sometimes lower in grade compared to the steel from integrated BOF mills. Steel rebar and other reinforcement steel products are mostly produced using the EAF method and thus contain significant scrap content, while structural steel sections are produced using both EAF and BOF routes (Yellishetty, et al., 2011). The actual scrap ratio of various steel products may differ based on the location of their source and, consequently, the environmental impacts associated with steel production can vary by production process. The coke-making and iron-making processes in a BOF mill contribute much more to the environmental impacts of steel than the electricity used in EAF mills (Briggs, et al., 2010), although the impact of steel production in EAFs also vary based on the energy source used to generate the required electricity.

Although most new steel mills use electricity as their power source instead of burning coal or natural gas (ATHENA Sustainable Materials Institute, 2002), the average carbon footprint (1.77 kg CO_2/kg average) and embodied energy (24.4 MJ/kg average) of steel products is on par with the average of the world's combined production processes (Hammond & Jones, 2008).

There are two grades of steel used in the tall building structures considered in this research; normal-strength (50 Ksi/345 MPa) and high-strength (65 Ksi/450 MPa).

Although normal-strength and high-strength steel are not very different in terms of embodied energy and CO_2 emissions (Stroetmann, 2011), the use of high-strength steel in tall building structures helps reduce the environmental impacts of steel by using a smaller quantity of steel profiles.

Although the high-strength steel used in steel structures is mostly limited to

5.0 Concrete: Cradle to Grave

Various types of concrete are used in high-rises: normal and lightweight (especially for floor systems); and conventional and high performance (with higher strength, durability, and workability). These are often integrated in the technologies adopted in tall buildings, which can vary from traditional Reinforced Concrete (RC) to post-tensioned systems that use high-performance concrete.

Although in some recent studies (Weisenberger, 2010), where the benefits of structural steel frames have been demonstrated (reduced column sizes, high strength-to-member-size benefits), concrete systems have gained great acceptance and the material has been widely used by designers, especially since the 1970s. This is partially related to the fact that the concrete wall is the stiffest element currently in the structural engineer's tool kit when conceiving tower framing systems. Tall building design is often controlled by stiffness more that strength. Also, concrete can be poured into different shapes, even under extreme weather conditions and temperatures, and is easily delivered to job sites (concrete plants tend to be conveniently located, even to city centers and busy metropolitan areas). Aggressive environmental conditions are countered with additives that are able to significantly enhance the durability of the material.

As a consequence of the increase of concrete use, the environmental impact of concrete production is growing. Concrete production is considered to be responsible for up to 10% of global CO_2 emissions (Ochsendorf, 2005), including infrastructure construction.

5.1 Cement Production and Transportation

Cement consists of a controlled chemical combination of calcium oxides, silicon, aluminum, iron, and other ingredients.

The most common manufacturing process for cement is a dry method. After quarrying raw materials including limestone, shells, and chalk (or marl), they are crushed in several stages using crushers and hammer mills. Crushed rock is then combined with other components such as shale, clay, slate, blast furnace slag, silica sand, and iron ore. The mixture is fed into a cylindrical steel rotary kiln that heats the ingredients to about 1480°C, powered by burning powdered coal, oil, alternative fuels, or gas under a forced draft. This heating and mixing process releases both clinker and gasses. Clinker (see Figure 5.1) is brought down to handling temperature in coolers. In order to increase burning efficiency and save fuel, heated air is returned to the kilns. The cooled clinker is then mixed with small amounts of gypsum and limestone, then ground to a fine powder commonly known as cement.

Among all concrete production procedures, cement production is responsible for the greatest amount of CO_2 emissions: on average, every ton of cement produces 0.9 tons of CO_2. Although cement industries have focused their efforts on reducing CO_2 emissions related to the thermal energy of clinker production, little can be done to reduce the carbon released from limestone decomposition, unless the amount of Portland cement is minimized in the design mix.

In fact, it is important to note in the equation below, CO_2 is not released just as a consequence of the fossil fuels burnt to heat the mixture in the kiln, but also as a by-product of the chemical reaction that transforms the limestone in clinker, with the following percentages (Kestner, et al., 2010): 40% from the production of clinker;

Figure 5.1: Cement clinker
Source: (cc-by-sa) Amit Kenny

60% from the decomposition of limestone under high temperatures (above 1370°C).

Simplified chemical reaction of cement production:

$CaCO_3 + Heat \rightarrow CaO + CO_2 \uparrow$

Considering that 15% to 20% of cement is used in conventional concrete mixes, replacing 50% of cement with fly ash or other substitutes can lead to a significant reduction in CO_2 related to the "carbonation" of cement. A good concrete mix design is one that meets the required levels of workability, strength, and durability for every building. However, in order to meet more stringent sustainability requirements, the designer may consider using non-cement binders and recycled aggregates.

The cement industry produces about 7% of global manmade CO_2 emissions (Ochsendorf, 2005), of which 60% arises from the chemical process, and 40% from burning fuel. Emissions from cement production plants, apart from CO_2, include dust, nitrogen oxide (NO_x), sulphur oxide (SO_x), as well as some micro-pollutants (World Business Council for Sustainable Development, 2002). Heavy metals (Tl, Cd, Hg, etc.) are often found as trace elements in common metal sulfides. Pyrite (FeS_2), zinc blende (ZnS), and galena (PbS) are present as secondary minerals in most of the raw materials.

In terms of energy consumption, cement production requires 4 GJ of energy per ton of clinker produced (Kestner, et al., 2010). Typical primary fuels used in clinker production are fossil fuels such as coal and petroleum cokes, as well as natural gas and oil. It is possible to use selected waste that meets strict specifications for combustion in a kiln, partially replacing fossil fuels. This waste often contains not only recoverable calorific value, but also useful minerals such as calcium silica, alumina, and iron; therefore, it can be used as raw material in the kiln. However, the distinction between alternative fuels and alternative raw materials is not always clear, since some of them are characterized by both recoverable calorific value and useful minerals. Organic substances as well as alternative fuels can be used for this purpose, since the high temperatures of the kiln gasses destroy the toughest organic substances.

Sustainability is not an empirical property of materials, since the choice of suitable materials cannot be based on numerical parameters, as is done in the process of selecting materials for their strength and elasticity characteristics. Therefore, in assessing the sustainability of building materials it is necessary to compare and quantify the environmental impacts as well as identify the context in which the material will be applied.

Cement leaves the cement plant and is transported to either a distribution terminal or a final customer, such as a concrete production plant or a ready mix plant. Transportation and distribution occurs via boat, train, or truck. Cement transportation requires special care in order to avoid: contamination by residues or previous cargoes; solidification, if cement is exposed to humidity and wet conditions; and dust released during loading (dust can react with water and harden, damaging the transportation tools). Transportation by ship is particularly difficult: specialized ships called cement carriers are available with different capacities. More advanced technologies include cement carriers equipped with self discharging systems.

As the commodity cost is quite low, transportation cost is a key factor in competitively supplying customers with cement.

5.2 Cement Substitutes

The American Concrete Institute's Building Code Requirements for Structural Concrete (ACI318-11) defines a High Performance Concrete (HPC) as a special engineered concrete in which one or more specific characteristics have been enhanced through the selection of components. Thus, the concept of HPC has been evolving since the 1970s. For this reason Mehta (Mehta, 2004) suggests that the term "high performance" should be applied to the entire family of concrete mixtures that offer higher strength, higher durability, and higher workability. One of the engineered processes of HPC production is the partial substitution of Portland cements in mix

> ***"...Cement substitutes ...reduce the carbon footprint, embodied energy, material waste in landfills, extraction of virgin materials and the environmental impacts related to manufacturing Portland cement clinker..."***

8.0 The End-of-Life of Tall Buildings

The CTBUH Skyscraper Center database (Council on Tall Buildings and Urban Habitat, 2015) shows that only seven buildings taller than 150 meters have ever been demolished to date (see Table 8.1). However, this list includes the two tallest buildings ever demolished, the World Trade Center Twin Towers, which collapsed as a consequence of the terrorist attacks of September 11, 2001, together with Seven World Trade Center that collapsed at the same time. Excluding these three cases, only four buildings taller than 150 meters have ever been voluntarily demolished, with the 187-meter Singer Building (demolished in 1969) holding the title of the tallest building ever dismantled, followed by the 1965 demolition of the Morrison Hotel in Chicago. Interestingly, the Deutsche Bank building in New York City and the One Meridian Plaza in Philadelphia (respectively the 6th and 7th tallest in the list) have been demolished, though not as proper demolition projects, but as a result of consequences suffered during two catastrophic events (9/11 for the former, and a fire occurring in 1991 for the latter).

Except for a few demolitions that cleared the way for the construction of bigger towers during the 1970s, one could say that significant tall buildings are almost never demolished. A number of options exist to rejuvenate old towers (Trabucco & Fava, 2013) and demolition is typically not the preferred response to the evolution of market needs, but more demolitions will likely take place in the future as many tall buildings are now approaching the end of their service lives.

Fast growing economies are putting ever increasing pressures on city centers, with a continuous demand for new offices, luxury hotels, and trophy residences. While nobody argues that many iconic buildings are likely to grace a city's skyline for centuries, evidence shows that typical tall buildings suffer from a much faster aging processes, not in terms of structural and material obsolescence, but in terms of functional obsolescence. One of the most striking examples may be the 142-meter Ritz-Carlton hotel in Hong Kong that was demolished a mere 16 years after construction to be replaced with a taller office tower as a consequence of Hong Kong's booming office market.

8.1 High-Rise Demolition Techniques

Implosions are the most dramatic way to demolish buildings and they have been adopted in a number of cases (Liss, 2000), especially in the US. At 125-meters, the Great Hudson Store in Detroit is the tallest building ever imploded. Though this system is still widely used, it is being banned in most downtown areas due to the heavy impact it has on the city in terms of dust and pollution. Even where it is allowed, assurance liabilities and preparative mitigation works on nearby buildings make this system unsuitable for large-scale tall buildings in dense urban environments. On February 2013, the 116-meter AfE Turm in Frankfurt, Germany was imploded, making this the second-tallest building ever demolished with explosives, though it likely had a bigger volume than the Great Hudson Store.

A slight variation of the implosion system is the controlled collapse system, which has been applied at its largest scale on a 14-story residential block in Vitry-sur-Seine, France. With this method, the load bearing structural system of the building is weakened in a convenient location

Building Name	City	Height	Year of Demolition	Reason for Demolition
One World Trade Center	*New York City (US)*	*417 m*	*2001*	*Uncontrolled collapse due to terroristic attack*
Two World Trade Center	*New York City (US)*	*415 m*	*2001*	*Uncontrolled collapse due to terroristic attack*
Singer Building	New York City (US)	187 m	1968	Demolished to make room for 1 Liberty Plaza
Seven World Trade Center	*New York City (US)*	*174 m*	*2001*	*Uncontrolled collapse due to terroristic attack*
Morrison Hotel	Chicago (US)	160 m	1965	Demolished to make room for the First National Bank Building (now Chase Tower)
Deutsche Bank	New York City (US)	158 m	2011	Irreparable damages caused by previous terroristic attack
One Meridian Plaza	Philadelphia (US)	150 m	1999	Irreparable damages caused by fire

Table 8.1: Recent Cases of Demolished Tall Buildings (italics denote buildings demolished through catastophic events)
Source: CTBUH

through pull-cables or hydraulic rams until the tower collapses on itself. The weight of the falling structure above the collapse point crushes the lower portion with an effect similar to the use of explosives. Though this system is less dangerous in some ways, it creates the same problems as explosives and is therefore unsuitable in dense urban environments.

Deconstruction (or dismantling) is a less-invasive demolition method that can be applied to any kind of structure and is the most widely adopted system for tall buildings. Deconstructing tall buildings is a long term task that sometimes requires more time than was needed for the construction of the tower (see Table 8.2). Before demolition starts, the building must be protected with scaffolds to prevent falling debris. The scaffolding system can be "traditionally" supported from the ground (and attached to the main structure) or suspended from the roof of the building and jacked down as deconstruction proceeds downward. The latter option was extensively covered by the media in two very recent cases: the demolition of the 74-meter UAP Tower in Lyon, France as well as the 140-meter Grand Prince Hotel Akasaka and the Otemachi Financial Center, both in Tokyo (Kayashima, et al., 2012).

Deconstruction requires the use of small excavators and other machines hoisted to the roof of a building. Structural elements are demolished through shears, torches, saws, and crushers. The limiting factors of this method is the load bearing capacity of the floor system (that needs to be able to carry heavy equipment and building debris), and the actual floor plan that may prevent the presence of multiple machines. Debris must be lowered with a crane and cannot usually be dropped via gravity into empty elevator shafts as this will cause vibrations, danger for the

Figure 8.1: Kajima Demolition Method applied at the Kajima HQ, Japan
Source: Kajima Corporation

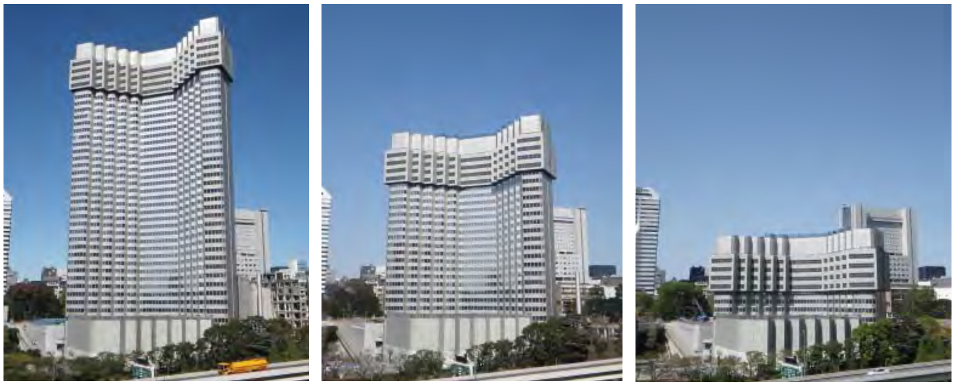

Figure 8.2: Taisei Corporation's Ecological Reproduction System (Tecorep) applied at the Grand Prince Hotel, Japan
Source: Taisei Corporation

Building Name	Height	Duration of Demolition Works	Notes
Deutsche Bank, New York	158 m	48 months	Actual duration of 47 months, demolition halted for 9 months due to a fire
One Meridian Plaza, Philadelphia	150 m	24 months	-
Ritz-Carlton, Hong Kong	142 m	12 months	Small floor plate
Hennessy Centre, Hong Kong	140 m	18 months	-

Table 8.2: Duration of Demolition Projects
Source: CTBUH

We now find ourselves in an age where "green design" is at the forefront of many tall building projects around the world, where it seems that every year brings new technologies and innovations that are touted as the be-all and end-all for a long-term sustainable future. But these solutions tend to only reduce the environmental impacts of a building during its operation phases, with the stages before and after this period often neglected. This is perhaps best illustrated by the fact that the world is currently constructing tall buildings in excess of 1,000 meters in height yet we have never demolished a building of even 200 meters in height through conventional means. Despite this reality, our cities continue to be filled with myriad skyscrapers, most of which are not given full considerations for their entire life cycle, or end-of-life.

Through the Life Cycle Assessment (LCA) methodology, we can gauge the environmental consequences of human actions by analyzing the flow of materials used in a building and trace the environmental impacts linked to each stage of its life cycle. When information from each stage is combined, a holistic picture of environmental impacts can be formed for a given product, one that acknowledges the various actions that are required to bring a single entity into existence through contemporary means.

This research identifies and compares the life cycle implications for the structural systems found in 60- and 120-story buildings. It is intended to inform the international community of professionals and researchers specializing in tall buildings on the life cycle environmental performance of the most common structural systems by providing the most accurate, up-to-date analysis on two key impact categories: Global Warming Potential (GWP) and Embodied Energy (EE). In doing this it presents interesting research results, and also lays down a methodology in this emerging field for others to follow.

ISBN 978-0939493487
9 780939 493487 >

Council
on
Tall Buildings
and
Urban Habitat

Research Funded by:
ArcelorMittal