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LCA of tall buildings: Still a long way to go

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ABSTRACT

Tall buildings are often looked at as unsustainable, energy-voracious buildings. Although this may have been true in the past, modern tall buildings have to meet the same energy-conservation standards of all other buildings. In some cases, outstanding results have been obtained, which are now seen as the exemplary examples of sustainable design. Although the design and usage of buildings is now controlled by norms and codes, minimal studies have examined tall buildings holistically, from a life cycle perspective.

The present paper analyzes the state-of-the-art of research on the life cycle assessment of tall buildings, analyzing the evolution of the discipline applied to this specific building type.

1. Introduction

Studies on the energy consumption of buildings became more and more common after the 1974 energy crisis. Concerns were predominantly driven by economic (for owners, tenants and architects) and geopolitical (for policymakers) considerations, while environmental concerns were still relatively marginal. Nonetheless, pressure to tackle the issue for the sake of the environment was rapidly growing among public opinion, with the Brundtland definition of sustainable development arriving in 1987.

It would be counterproductive to reproduce here the endless list of studies done worldwide on the energy performance of buildings, as a result of code requirements or to reduce the energy bills of new and refurbished buildings. However, the cumulative result of all energy-saving actions adopted by countries cannot be denied. Most nations have recorded a significant increase in the energy efficiency of buildings as a whole, or of most of their subcomponents (HVAC in particular), which continues today.

2. Background

Despite the development of innovative sustainable tall building theories (inspired by the work of architectural visionaries such as Kenneth Yeang) and the construction of a few sporadic game-changing buildings (SOM's 1984 National Commercial Bank in Jeddah and Foster's 1997 Commerzbank in Frankfurt, just to name a couple) that set the basis for a new tall building vernacular [1], the high-rise industry has not been in the lead on this topic. On the contrary, tall buildings have actually responded to the call for sustainability at a slower pace than have other building types.

Nonetheless, tall buildings have also benefited from a general improvement of their energy efficiency; modern tall buildings are characterized by overall improved energy efficiency [2]. The progress towards efficiency has evolved along with radical changes to architectural and technical characteristics, resulting in modern energy-efficient tall buildings that look completely different from their older predecessors [3].

The true environmental performance of tall buildings is still a heavily debated topic, with certification protocols now being adapted to fit with the specific challenges of tall buildings [4]. Energy-rated tall buildings are becoming ubiquitous in many countries, with certifications sought by developers to increase or retain the market value of their properties [5].

In the past few years, researchers worldwide have started to focus their attention on another aspect of the environmental sustainability of buildings: the construction phase.

In fact, as a consequence of the decreased energy consumption for their daily functioning, the energy required to construct such buildings and to produce the materials that comprise them is gaining relative importance from a life cycle perspective. Also, the so-called “energy-efficient buildings” require more materials than conventional construction (extra layers of thermal insulation, repeated elements such as double-skin facades, more complex mechanical equipment, etc.), and therefore they also require more energy to produce, transport, and assemble such materials [6].

A paper by R. Stein appearing in the very first issue of *Energy*

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and Buildings in 1977 [7] already pointed out the potential relevance of the issue, invoking the need of more precise data. Citing rough figures, the paper suggested that the embodied energy of buildings is approximately one-fifth of the operational energy consumption of buildings, and one-sixth of that figure if residences are excluded. Reading through this study today, it seems as if 40 years of research have somehow been lost, as the questions and doubts raised back then are still largely unanswered.

The energy spent during the construction phase of a building is usually called "embodied energy," and the associated impacts in terms or carbon emissions, pollution, etc. are referred to as "embodied impacts." Embodied energy includes all the energy inputs necessary to complete operations from the A-1 (Raw Material Supply) through A-5 (Construction) stages, as described by the European Norm EN 15,978 (Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method).

Studies on the embodied energy content or on the entire life cycle of buildings are now common, with papers comparing buildings according to function, type, location, material, performance, etc. Again, it has to be noted that the tall building community reacted to this trend with a significant delay, but interest in researching the life cycle sustainability of tall buildings is now gaining momentum at industry conferences and in industry-specific publications. However, sporadic and inconsistent data are still available in the literature today, generating confusion around the actual importance of the embodied energy / embodied impacts of tall buildings when compared to the other phases of their life, and preventing a comparison of the different results achieved [8].

3. Literature review

Acknowledging the scarcity of publications on this problem, the authors have tried to collect and review the best of the scientific production on the environmental implications of tall building construction.

While much of the attention is now dedicated to carbon emission of industrial processes and their impact on climate change, the main focus here is also dedicated to the embodied energy content of tall buildings. The authors in fact acknowledge that the greenhouse emissions of industrial processes are certainly connected to the efficiency of the production processes being examined (i.e., manufacturing of materials, construction, etc.), but recognize that a more important role can be due to the local conditions of the energy market.

For instance, the production of aluminum from bauxite has a very similar level of embodied energy in all countries, because the production process requires the same amount of electricity everywhere. However, according to the energy mix of each country, greenhouse emissions are often very different. Aluminum production is virtually carbon-neutral in countries where electricity is provided by nuclear, hydro, wind or solar plants, while it is highly carbon-intensive where electricity is generated by coal-, bio-mass or oil-fueled power plants.

The present selection of papers dedicated to the LCA and Embodied Energy of tall buildings begins with the previously cited 1977 "***Energy Cost of Building Construction***" by Richard Stein [7]. Though not specific to tall buildings, this paper, written almost 40 years ago, is probably the most relevant paper of that period, even as it only scratches the surface of this still largely unexplored research topic.

Dario Trabucco's paper "***Life Cycle Energy Analysis of Tall Buildings: Design Principles***" [10] shows how LCA can be used to assess the environmental consequences of alternative building designs, in terms of both structural material and curtain wall technologies. The paper also provides tips on how the design team of a tall building can have an impact on its embodied energy.

The paper "***Life Cycle Analysis: Are We There Yet? "*** by Donald Davies and Ron Klemencic [11], examines the impact on two case study buildings of one of the earliest commercial tools to provide "real-time" LCA information to the designer. When embedded in CAD and BIM suites, this and similar products can significantly contribute to the quality of environmental information used to guide the design of new tall buildings.

The structural system plays a major role in the design of a tall building, due to its complexity, cost, and overall importance, in terms of both strength (safety) and stiffness (serviceability). In engineering terms, "optimization" could be seen as a synonym of "sustainability" and "embodied energy reduction strategies." In fact, the "optimization" of a tall building structure can be defined as "efforts to make best use of the strength properties of the materials with which a tall building is built, thus reducing their quantities." Cost, market availability, and ease of construction are usually the driving forces behind optimization decisions, and these arguments are considered carefully by developers. However, with the increased marketing appeal of sustainability, the embodied energy and embodied carbon of structures can become additional parameters to be considered in the equation.

With this in mind, structural engineers can play a major role in defining the life cycle sustainability of tall buildings by evaluating and showcasing the carbon and energy consequences of structural design choices. Inventories of building materials are jealously kept confidential by building designers, and only a few published papers explicitly describe the material quantities needed for tall building structures [9] Steel and reinforced concrete are the two primary materials used for tall building structures, and the environmental consequences of these options are being assessed by CTBUH, thanks to an extensive two-year research project that is due to complete soon [12].

Alternative steel design options are studied in the paper "***LCA application in the optimum design of high rise steel structures***" [13]. The analysis is limited to four different steel scenarios derived from a real building located in South Korea that is actually built with concrete. Results indicate how structural optimization can lead to important material savings, and consequently to a reduction in the embodied energy due to steel production. High-strength reinforced concrete construction of tall buildings is assessed from an LCA perspective in the paper "***Life cycle CO_2 evaluation on reinforced concrete structures with high-strength concrete***" [14], demonstrating the benefits of using higher-strength concrete for the possible reduction of the necessary concrete quantities and the amount of reinforcing bars.

Based only on an academic exercise, a comparison of alternative design options both for vertical structures and for flooring technologies is presented in "***Sustainable structural design of tall buildings based on embodied energy***" [15]. This paper underlines the important role played by floor systems in a tall building's inventory of materials, and thus in its environmental impact.

The most extensive study to date on the LCA of the structural components of tall buildings is the research report "**Life Cycle Assessment of Tall Building Structural Systems"** [16] which examines at a detailed level all the phases of a tall building life, from the procurement of materials to the demolition of the building structure.

When real buildings are considered, and an actual inventory of materials is available, the scientific problem is often shifted to the selection of the appropriate accounting methodology [17] for the embodied energy related to production of materials and construction. This is because alternative methods exist that can lead to slightly different results, or because the researchers want to assess the impact of height on materials in real buildings [18].

Direct input-output systems to derive embodied energy data are used in "***Life cycle energy assessment of a typical office building in Thailand***" [19], and the results are therefore based on national industry-wide average values, referenced to Thailand"s production processes.

"***The embodied energy and emissions of a high-rise education building: A quantification using process-based hybrid life cycle inventory model***" [20] assesses the environmental impacts of a tall residential building in China, by using an input-output hybrid approach, which adapts the nationwide average values, calculated with input-output matrices to reflect more specific product-based information.

In "***Analysis of embodied energy use in the residential building of Hong Kong***" [21] environmental impact data from different literature sources are used to assess the embodied energy of two 40-story residential buildings in Hong Kong. The benefit of using recycled material rather than raw materials is also considered, and the effects on the embodied energy of the building are described.

A different approach is used by Philip Oldfield in "***Embodied carbon and High-Rise***" [22], to assess the expected growing importance of embodied carbon against the future decrease of the United Kingdom"s electricity carbon intensity on a per-whole-building basis.

Other studies, not included in this selection, describe the relative importance of tall buildings for their role in the city [23,24], single-building components such as the internal layout and furniture [25], or the internal organization and net-to-gross floor area ratio [26].

One of the challenges when compiling – and publishing – an LCA analysis is the use of proprietary information regarding the environmental values of industrial products and processes involved. Publicly accessible database exist but are limited in variety and quality of data.

4. Summary and conclusions

The papers mentioned above represent, to the knowledge of the authors, the state of the art in the LCA analysis of tall buildings that is, as previously mentioned, a largely unexplored research field.

The tall building industry and the researchers working on this unique building type need to cooperate in order to fill a fundamental gap in the pathway to constructing more sustainable buildings.

In particular:

1. Designers and developers should make available to the public exhaustive bills of materials, where both the quantities and the prices of the purchased materials and services are detailed. This will allow the creation of a database of average quantities, as well as facilitate comparative studies of LCA results, obtained through the application of the different accounting methodologies.
2. Building owners and building managers should release detailed information on the real energy consumption of their buildings, so as to compare this easily calculated figure with the result of embodied-energy and embodied-carbon studies, in order to understand the real relevance of both from a life cycle perspective.
3. Researchers and environmental consultants should create precise, user-friendly software to enable tall building designers to look at LCA as a design-assisting tool, rather than as an appraisal method to evaluate, post-facto, a completed building.
4. Producers of materials should invest energy and resources to produce and made available to the public the Environmental Product Declarations (EPDs) of their products, so as to enable more accurate and updated analysis from LCA practitioners.

The authors hope these selections will inspire additional, and much-needed, research on this topic.

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