ENVIRONMENTAL ASSESSMENT OF OPTIMIZED STRUCTURAL SYSTEMS IN TALL BUILDINGS

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Abstract: Building structures are considered as major contributors to global energy consumption (30-40%) and they are responsible for the 40-50% of greenhouse gas emissions. Due to huge energy consumption and material use, tall buildings have drawn particular attention with reference to their environmental impact. The influence of structural systems on the environmental performance of tall buildings is studied in this work, calculating the embodied energy and CO_2 emissions of construction materials. In this direction, characteristic structural systems of tall buildings are considered in order to compare their environmental behavior and to account for their differences on the amount of construction materials used for their formation. In order to achieve this comparison, the structural systems are material-cost optimized using the optimization computing platform (OCP), developed by the authors for solving real-world structural design optimization problems. The results of this research provide valuable findings for the significant role of structural optimization in sustainable design of tall buildings as well as in limiting the production of construction materials.

Keywords: Design optimization; structural systems; tall buildings; life cycle assessment; environmental performance.

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1 INTRODUCTION

Augmented environmental issues encountered in modern times have drawn the attention of the scientific community worldwide. Over the last decades, climate changes are rapidly amplified, thus mitigating the environmental problems arising from the modern way of life. In the matter of construction industry, buildings are responsible for 40% of primary energy consumption and according to IEA [1] they are projected to grow their energy demands by 2035, hence, it is imperative that buildings be sustainably designed in order to diminish their impact on the environment. Given that construction industry generates 50% of the global output of greenhouse gas (GHG) emissions and consumes 3 billion of raw materials [2], it is highly important to design structures towards the attainment of sustainable development. For this purpose, an interdisciplinary approach is adopted that includes reducing energy usage, recycling building materials and controlling GHG emissions. Life cycle assessment (LCA) is the most well known approach, which contrives to deal with the environmental problems that buildings cause. Whereas buildings are accused of abundant environmental problems, tall buildings are considered as principal consumers of global energy and prodigious emitters of CO_2 because they demand immense quantities of materials and variety of environmentally harmful operations. In major urban centers, trying to exploit the urban airspace, the first tall buildings were constructed in early 1900s, based on overengineered solutions, by utilizing large quantities of unnecessary building materials. The last decades, the development of structural analysis software helped the transition of the conceptual design of tall buildings into more sustainable structural systems, utilizing less building materials. The upcoming step of development in tall buildings is determined by limiting their environmental impact towards more sustainable structures [3].

Implementing LCA as a tool for designing environmentally acceptable buildings, the impacts produced during the construction phase are referred as “embodied”, while those during the use-phase are called “operational”. The demolition phase of building’s life cycle is often ignored as it is estimated to contribute less than 1% in the total life cycle [4]. In the matter of tall buildings, the enormous quantities of materials utilized for their construction have established LCA as a precious evaluator of their sustainable behavior. Comparing downtown high-rise living in Chicago with suburban low-rise living, Du *et al.* [5] indicated that high-rise living is about 25% more energy intensive, accumulating both embodied and operational demands. According to Sartori and Hestnes [6], embodied and operational energy demands are relatively important for limiting the energy consumption of buildings. Trying to reduce the operational energy demands, more energy intensive materials and technological implants are used leading to increase the embodied energy. Hence, the embodied energy content of buildings have drawn the attention of research, as well as the embodied carbon emissions, derived from industrial processes of building materials. Except for embodied energy, Luo *et al*. [7] calculated embodied CO_2 emissions per unit area of super-high-rise buildings 1.5 times that of multi-story buildings, highlighting the importance of embodied component of high-rise building's life cycle. Additionally, Chau *et al.* [8] estimated the embodied energy usage in two typical high-rise buildings in Hong Kong, revealing the energy intensive elements whose energy production could be potentially reduced, while Gan *et al*. [9] proposed a method, based on LCA, for analyzing the embodied carbon in high-rise buildings. In the case study, they illustrated a 60-story building in Hong Kong in which they examined the influence of recycled structural materials. Utama and Gheewala [10] investigated the influence of material selection for buildings' envelope and they measured their contribution in the total life cycle of Indonesian high-rise buildings.

From structural engineering viewpoint, designing tall buildings consists of numerous processes and generates particular complexities compared to typical structures. In order to configure their structural system, numerous structural elements have to be combined so as to accomplish an efficient design. A structurally efficient design utilizes less materials under the observation of design regulations and, consequently, produces more economic structures. This work underlines that structural optimization can also contribute to diminish energy demands and the environmental footprint of buildings by limiting the material usage; this can be clearly observed from a recent study by the authors [11]. Given that tall buildings accumulate enormous quantities of materials, optimizing their structural behavior can lead to more environmentally friendly high-rise structures. The significant role of structural optimization in lessening the building material usage is highlighted by Cho *et al*. [12] which minimized the weight of four different steel structural systems, resulting into material savings, so to embodied energy reduction. According to the review study by Trabucco and Wood [13], life cycle analysis in tall buildings have engendered the interest of structural engineers and it has been implemented in order to optimize their structural systems in the matter of their environmental behavior. Park *et al*. [14] minimized the cost and the CO_2 emissions of composite columns in high-rise buildings using genetic algorithms and claimed that using higher strength concrete than steel and higher lead to more economic and environmental design. In similar way, Foraboshi *et al*. [15] defined the structural design decisions minimized the embodied energy of structural systems in tall buildings. They underlined the criticality of flooring systems’ embodied content and they stated that steel usage is more energy intensive than reinforced concrete (RC). In the study by Yeo and Potra [16], a typical building’s was cost optimized, providing an abatement of 5 to 10% in CO_2 emissions. The authors stated that their optimization algorithm could lead to a more significant reduction of footprints if it was implanted in tall buildings. After re-designing a super tall building, [17] suggested that using high-strength concrete entails a reduction of both concrete and reinforcement bars. The life cycle carbon emissions were decreased by 15% in relation to the initial design, thus the utilization of high strength materials lead the structural design towards sustainability.

Overall, structural efficiency, economy and environmental behavior comprise the most dominant criteria of structural design. Upon tall buildings, these components of structural design become more complicated than normal structures and make their optimal configuration more valuable. In this work, a parametric study is performed, aiming to select the most efficient environmentally structural system for tall buildings. The implementation of the parametric study relies in structural optimization and may contributes to a more sustainable approach of structural engineering, alleviating the environment from deleterious impacts. Moreover, the authors underline the benefits of structural optimization in reducing the production of energy intensive materials, as well as mitigating GHG emissions due to building sector’s operations. This study explores the environmental approach of structural design in tall buildings by cost optimizing their structural systems. In particular, five characteristic structural systems of tall buildings, implemented in real structures, are analyzed in order to perceive their load-resisting behavior. Two of them correspond to RC building structures and three to steel ones. Structural analysis software ETABS was used for simulating the five systems and the optimization computing platform (OCP) [18] was implemented for solving the optimization problem

2 LIFE CYCLE ASSESSMENT

2.1 The framework

Growing concern on environmental issues has established the LCA framework as an important tool for assessing the impact of products arose from their manufacturing process to consumption. LCA commences by acquiring raw materials from the earth, it continues with manufacturing and use of materials and it ends up with their disposal and recycling. This procedure is referred by the International Standardization Organization (ISO) [19] as "*cradle to grave*"; while, detailed implementation framework of LCA consisting of four phases has also been developed by ISO. The first phase denoted as "*goal and scope definition*" includes description of the product, formation of the framework and definition of system boundaries. "*Inventory analysis, LCI*" constitutes the second phase and involves capturing and recording life cycle data, required to reach the goal of the analysis. The third phase of LCA, called "*Life Cycle Impact Assessment (LCIA)*", is related to the assessment of significance of environmental impacts and in the last phase, the so called "*Interpretation*" one, the results are analyzed and evaluated in order to define the products and services that reduces the environmental impacts. In buildings, there is a plethora of productive-industrial procedures, implemented during their life cycle, which make them responsible for a large proportion of environmental impacts. Thus, it is essential to accumulate the impacts derived from every aspect of building's life cycle. This study foresees on the product stage of the building and uses as system boundaries, the cradle to gate approach that considers raw materials supply, transport and manufacturing [20].

2.2 Embodied energy and CO_2 emissions analysis

The environmental impact of buildings is evaluated in terms of energy or CO_2 emissions. Life cycle energy analysis (LCEA) and life cycle carbon emissions analysis (LCCO$_2$A) constitute the basic assessment tools of the environmental behavior of buildings in their life cycle [19]. LCEA is divided into three sections according to the phases of the building's life cycle:

embodied, operational and demolition energy. Embodied energy aggregates the energy content of materials considering the cradle to gate approach, the energy at the construction site during erection and its renovation, usually referred as recurring. Operational part consists of the energy utilized during operation-phase of the building for controlling the conditions of internal environment and demolition corresponds to the energy required to transport waste materials in the recycling center [21].

This study aims at evaluating and comparing tall buildings' energy behavior among different structural systems. On the grounds that the energy assessment of a structural system is correlated with the embodied energy of the building, the diversification of the structural systems depends on the quantity of materials required for the construction of structural elements. Therefore, comparative purposes of this paper require the estimation of the embodied energy's variation between the structural systems.

Embodied energy is divided in two parts: initial used for construction and recurring used for rehabilitating the building. Structural elements are included in the initial embodied energy as well as covering materials, which are identified likewise in the recurring embodied energy of the building. The embodied energy is expressed through the following equation [22]:

$$\begin{aligned} EE(\mathbf{s}) &= EE_i(\mathbf{s}) + EE_r(\mathbf{s}) \\ &= \sum_i m_i(\mathbf{s}) M_i + \sum_i m_i(\mathbf{s}) M_i \left[\frac{L_b}{L_{m_i}} - 1 \right] \end{aligned} \tag{1}$$

where $EE_i(\mathbf{s})$ is the initial embodied energy of design ***s***; $EE_r(\mathbf{s})$ is the recurring embodied energy; $m_i(\mathbf{s})$ is the quantity of building material; $M_i(\mathbf{s})$ is the energy content of the i^{th} material per unit quantity; L_b is the life span of the building; and L_{m_i} is the life span of the material (i).

Eq. (1) defines the portion of the embodied energy, which varies between differed structural systems of tall buildings. The quantity of embodied energy derived from technical installations, architectural details and energy used at site for construction are not considered as this is not related to the configuration of structural system. In the matter of LCCO$_2$A [4], embodied CO$_2$ emissions consist of two parts: fossil carbon emissions, produced throughout the combustion of fossil fuels, and process carbon emissions during chemical reactions in the manufacture phase.

$$CO_2^{Embodied} = CO_2^{Fossil} + CO_2^{\mathrm{Process}} \tag{2}$$

Based on the work by Chau *et al*. [4], embodied CO_2 emissions are estimated using the carbon emissions databases, which include not only the carbon emissions produced from material production (raw materials extraction and manufacture) but also the carbon emitted throughout the transportation of materials.

$$CO_2^{Embodied} = \sum_i CO_{2,i}^{Embodied} \tag{3}$$

$$CO_{2,i}^{Embodied} = CO_{2,i}^{extraction} + CO_{2,i}^{manufacture} + CO_{2,i}^{transportation} \tag{4}$$

3 STRUCTURAL SYSTEMS

3.1 Design criteria

Tall buildings' structural systems are designed to resist primarily against lateral loads, which are developed due to extreme exposure mainly to wind, contrary to conventional buildings in which vertical loads are critical. Earthquake loads augment accordingly to the building mass, while wind loads increase according to the building height. Given that height as the most distinctive feature of tall buildings, wind loads provoke extreme lateral sway, therefore they are more critical than earthquake.

The structural design of tall buildings satisfies the requirements of strength and stability through the design codes (i.e. Eurocode, ACI, etc.) as well as the serviceability of the building, limiting the lateral displacements. By virtue of extreme wind loads, tall buildings are vulnerable to swaying, appointing lateral drift as a fundamental design criterion. According to Choi [23], the maximum allowed lateral roof drift of the top story is defined between $H/500$ and $H/800$, where H is the building height. In addition, human comfortability is another crucial aspect of design that should be secured by mitigating the micro-accelerations of the higher stories up to 10-25 mg (milli-g). Except for lateral stress, gravity loads (dead and live) are also taken into account.

3.2 Characteristic structural systems

The particular requirements in the structural design procedure of tall buildings have led to the configuration of unique structural systems. Ali and Moon [24] tried to classify these systems based on the structural efficiency in correspondence with their height. This classification comprises the typical structural systems, implemented to the most famous tall buildings. The evolution of structural systems is correlated with the design goal of reaching extreme building heights. To this effort, structural developments in tall buildings lean on the fulfillment of design criteria that become more demanding as the building rises higher. Handling lateral strain due to wind effect is the dominant design goal of tall buildings. Three lateral resisting systems (rigid, shear wall and braced frames) are used for the design of structural systems as well as a combination of them in the most advanced structural forms.

Rigid frames consist of moment resisting connections of beams and columns that allow development of bending and shear forces making frame capable of resisting both vertical and lateral loads. In case of shear wall frames, limiting the lateral displacements is achieved using shear walls. Their efficiency relies on the augmented structural stiffness along the loading direction thus, they are used in both directions. The third approach of lateral resistance is the formation of braces as structural elements that provide increased stiffness. Bracings are used in order to abate the lateral displacements and assist the implementation of larger openings. In order to explain their structural role, when tension occurs in one of the brace elements, it is presumed that the other brace buckles due to compression force. For this reason, X-bracing and K-bracing constitute the most efficient arrangements of diagonals. The lateral load resisting systems described above are initially developed and combined for the configuration of more complicated structural systems [25].

For the purposes of this study, five advanced structural systems are chosen to be optimized and compared with reference for their environmental impact. They are selected based on the diversity of both structural systems and height efficiency as well, in order to achieve a successful comparison. Toward the attainment of realistic results, Table 1 contains five representative real-world tall buildings the structural systems of which adopted for the needs of the current study. According to the classification of Ali and Moon [24] in which the structural systems are commensurate with the number of stories that they are efficient for, the five distinct structural systems selected to strictly exceed the 60 stories’ efficiency. Subsequently, a comprehensive presentation of their structural functions is presented further below [26], [27].

3.2.1 Braced Tube - Steel

"*Braced Tube*" structural system comprises a combination of framed tubular system with exterior mega cross braces. The framed tube consists of columns located in the circumference of the building spaced from 1.5 to 4.5 meters between them and spandrel beam depths spaced from 0.6 to 1.2 meters. In order to magnify the openings of the building, diagonal bracings were added to the structural system, connecting the columns, reducing their bending stress. On the gist, the braces equilibrate the differences between load stresses in highly and less highly stressed columns throughout their axial stiffness. In addition, they are used as inclined columns contributing to the transfer of gravity loads through axial pressure. The supplementary braced frames in the tubular framework support the system against shear lag, helping the augmentation of height limit.

3.2.2 Braced Tube - Concrete

The "*Braced Tube*" structural system is implemented not only in steel structures but also in RC buildings. Instead of the mega diagonal braces, shear walls are arranged between the columns in the perimeter of the building. They are located into a diagonal pattern and they transfer the gravity loads, operating as inclined columns. Except for carrying vertical loads, these elements participate in the lateral load resistance, taking advantage of their increased stiffness of their strong axis. Their location in both directions of building's perimeter, provides the building against lateral loading.

3.2.3 Tube in Tube - Concrete

"*Tube in Tube*" is another structural system that comprise a structural development of tubular framework. The basic particular characteristic of this system is the augmented strain in the corner columns in comparison to the rest of circumferential columns owing to shear lag effect in which the stresses are distributed in non-linear way to both directions of the building. The optimized structural design consists of the abatement of shear lag effect and the implementation of cantilevered behavior. The adjunct of an internal tube that participate in the resisting system of the structure possess a dominant role to the vertical and lateral loads collection. In concrete structures, the inner tube is simulated as a system of shear walls in both directions of building.

3.2.4 Diagrid - Steel

The label "*Diagrid*" is composed by the words "diagonal" and "grid" and constitutes a development of framed tube with the characteristic substitution of vertical columns with diagonal structural elements. The main diversification of the system occurs in the use of axial stiffness in order to resist the shear forces from lateral loads, while there is no use of bending stiffness to the structure. The configuration of the system has been implemented in various shapes for rectangular or circular floor plan views. The diagonal structural elements are made of steel, they use only their axial stiffness and they compose a spaced netting around the building, which carries vertical and lateral loads simultaneously.

3.2.5 Outrigger - Steel

Synthesized as an expansion of shear frame with the addition of internal structural elements in the core of the building, the "*Outrigger*" system is the basis of the structural design for the most progressive structural designs of super-tall buildings in modern times. The key feature of the system's efficiency is the configuration of belt trusses provided to distribute the forces from the core of the building to the exterior frame columns. The core of the building represents the principal component of the building that in case of steel structures is made of steel braced elements and mega-columns. This system constitutes a smart design choice as its stability is based on internal structural elements that connect with limited exterior columns by the aid of belt zones. Mega-columns are also located in the circumference of the building in order to create larger openings to the structure. It is notable to be adduced that "*Outrigger*" system was inspired from sailing ships whose masts help resist the wind forces.

3.3 Simulation of structural systems

The structural systems used to simulate tall buildings behave as vertical cantilever beams where wind pressure is applied as distributed loading along their height. Besides lateral loading, structural systems need to carry vertical loading like gravity loads, the combined effect of which defines the design purpose of structural system as the best combination of axial and bending stiffness. To this effect, structural systems have rapidly evolved during the last century, aided also by pioneering structural analysis software. For the purposes of this study, the five structural systems described previously were simulated using ETABS structural analysis software in the environment of which, OCP [18] operates as a plugin.

The simulation was implemented under specific conditions, which create an appropriate application framework in order to secure the export of realistic results. For assessing and comparing the environmental behavior of differed structural systems, it is imperative that constants be established for the simulation process. Table 2 contains the design constants, about the geometry of the building, its materials, the loading conditions and several structural details as well. The simulation procedure was also regulated by creating a constant environment in which a possible structure would be erected. In the matter of geometry, the 3,600m^2 floor plan, the number of 64 stories and the 192m height are restricted in all models, similarly to real configurations of tall buildings. For the floor plan of the building, a quadrangular plan view was considered for every structural system apart from the “Diagrid” system, whose floor plan view is varying according to building’s height. The configuration of floor plan view’s shape as symmetrical, in both directions, was considered in order not to affect the accuracy of simulation by reason of lateral loading. The loading combinations were applied according to the regulatory provisions of Eurocode-1, excluding the combinations which contained the seismic loads. The models should, also, be imposed under certain structural restrictions taking into account the optimization procedure. The slabs are excluded from the structural design, as their role is to transfer the same vertical loads to the structure, given that all systems consist of the same plan view. In order to include slab’s loads in the simulation, they were applied as distributed loads on the beams located parallel to the plan view. In addition, the beams whose structural purpose is the same among the differed structural systems are defined as secondary. The slabs were configured to have approximately 25.0m^2 area and 20cm thickness and the secondary beams with an approximate 7.5m length. In the matter of structural elements’ cross sections, the columns are simulated as quadrangular sections, while beams and trusses as I-sections.

4 STRUCTURAL DESIGN OPTIMIZATION

4.1 Problem formulation

Most of structural optimization problems can be expressed in standard mathematical terms as a non-linear programming problem that in general form can be defined as follows:

$$\begin{aligned}
&F(\mathbf{s}) \rightarrow \min \\
&\mathbf{s}_{\mathrm{d}} = [\mathrm{s}_{\mathrm{d},1},\ldots,\mathrm{s}_{\mathrm{n_d}}]^T, \mathbf{s}_{\mathrm{c}} = [\mathrm{s}_{\mathrm{c},1},\ldots,\mathrm{s}_{\mathrm{n_c}}]^T \\
&\mathbf{s}_{\mathrm{d}} \in D^{n_d}, \mathbf{s}_{\mathrm{c}} \in C^{n_c} \\
&g_j(\mathbf{s}) \leq 0,\ \mathrm{j}=1,2,\ldots,\mathrm{m}
\end{aligned} \tag{5}$$

where $F(\boldsymbol{s})$ is the objective function to be optimized, $\mathbf{s} = [\mathbf{s}_d, \mathbf{s}_c]^T$ is the vector of the design variables, $g_j(\boldsymbol{s})$ is the j^{th} behavioral constraints imposed to the structural design, while D and C are the discrete and continuous design sets of size n_d and n_c, respectively.

Given that the environmental impact of buildings is related to the quantities of construction materials, the structural systems of tall buildings problem at hand is formulated as sizing optimization. The size of structural elements' cross-sections determines the quantity of material used for configuring the structural systems and, by extension, the cost of materials. Thus, the material cost comprises the objective function of the optimization problem to be minimized. The behavioral constraints of the problem are imposed by design codes or specific design criteria such as lateral displacement restrictions. In particular, Eurocode regulations and drift restriction comprise the constraints of the optimization problem. The upper and lower bounds of design variables are specified for the dimensions of structural elements by purpose of limiting the research area of the algorithm during the optimization process.

4.2 Optimization Computing Platform

The structural optimization part required by the current study is solved by means of the optimization computing platform, which is a specially tailored design tool developed to provide optimized design solutions of structural simulations in the category of structural analysis software. OCP design tool was developed by the Institute of Structural Analysis and Antiseismic Research (ISAAR) of the National Technical University of Athens (NTUA) [18] aiming to contribute to the global goal of designing safe and simultaneously economic structures. The current version of OCP is equipped with three state-of-the-art search algorithms, while two objective criteria to be optimized (either minimized or maximized) are supported. The basic assumptions for calculating the two objectives along with a short description of the three algorithms are provided below.

Material Cost: stands for the cost of material quantities used for the construction of the structural system under investigation. For the case of RC structures this cost is calculated as the sum of concrete cost (volume times concrete unit cost) plus the reinforcement cost (weight of longitudinal and transverse reinforcement times unit cost), while for the case of steel structures this cost is calculated as the sum of structural steel cost (weight of steel times unit cost). *Construction Cost*: stands for the cost of the construction of the structural system under investigation. Where in addition to the cost of material the labor cost is also considered. Labor and material costs are different entities, with two commonalities. Both types of costs can be deducted, and both are used to deliver the product to the customers. Both costs are calculated during the budgetary process and are typically considered when determining the amount to charge for the end product. The labor cost is calculated based on the unit costs where the productivity rates are provided for three group of elements (beams, columns and slabs). The productivity rates refer to time required for the construction of unit volume or weight for the concrete, steel reinforcement, construction steel and/or aluminum. The labor cost for each group of elements (beams, columns and slabs) is calculated as the sum of concrete volume times the corresponding productivity rate plus the reinforcement weight times the corresponding productivity rate plus the weight of the structural steel for this type of elements times the corresponding productivity rate. Then this sum that corresponds to working time (hours) is multiplied by the labor unit cost (currency/hour).

4.3 Search algorithms

OCP design tool is integrated with three algorithms, belonging to two categories: Probabilistic and Deterministic search. In probabilistic search Differential Evolution (DE) algorithm is available together with a pure random search (RS) one that is based on Latin hypercube sampling (LHS). In deterministic search the projected quasi-Newton (PQN) algorithm is provided.

RS algorithm ensures that all portions of the search space are properly represented into N samples. According to RS algorithm, the uniform distribution function for each variable is divided into a number of segments of equal marginal probability. These segments are randomly selected for each variable and randomly shuffled among different variables to define the samples. According to RS a sample is constructed by dividing first the range of each of the D variables into N non-overlapping equal segments, and then a sample with dimension D is created by randomly pairing the values of all parameters. Thus, the D-space is partitioned into N_D segments and a single value is selected randomly from each cell, producing a set of size D. The values from the N_D space are randomly matched to create N samples.

PQN algorithm is suggested for the case of with high order models in terms of finite element (FE) simulation (many degrees of freedom) therefore, PQN is used for the needs of the current study. PQN is a steepest descent algorithm for noisy optimization problems and it is intended for problems with non-convex landscapes (i.e. with many local minima). PQN is a hybrid algorithm combining a projected quasi-Newton or Gauss-Newton algorithm for nonlinear least squares problems and a deterministic grid-based search algorithm. The gradients for the quasi-Newton method and the Hessians for the Gauss-Newton iteration are approximated with finite differences, and the difference increment varies as the optimization progresses. The points on the difference stencil are also used to guide a direct search. PQN is based on a sampling method that controls the progress of search procedure by sampling the objective function of feasible solutions. Sampling methods do not require gradient information, but may, as PQN does, attempt to infer gradient and even Hessian information from the sampling.

DE is a stochastic population-based evolutionary algorithm (EA) for global optimization. DE follows the outline of EAs with some differences on mutation and selection operators. DE algorithm is based on two parameters, the mutation factor and the crossover probability. The fundamental idea behind DE is the use of vector differences by choosing randomly selected vectors, and then taking their difference as a means to perturb the parent vector with a special kind operator and probe the search space.

5 TEST EXAMPLES

In this study, five real-world structural systems for the case of tall buildings are considered for assessing their environmental efficiency. First, the five structural systems were optimally designed in order to create a basis of comparison for them. The material cost (i.e. the material quantities) was considered in the optimization problem formulation as the objective function to be minimized while the constraint functions considered are those imposed by the design codes. Subsequently, the optimized designs are compared with reference to their environmental performance.

In the case of the steel structural system, all structural elements are made of structural steel, while in the case of the concrete ones they are comprised of reinforced concrete (i.e. concrete combined with steel reinforcement bars). Non-structural elements such as architectural and mechanical installations do not participate in the formulation of the optimization problems; however, they are quantified evenly in all structural systems examined. For the solution of the five design optimization problems PQN algorithm is used. The computer hardware platform that was used for the optimizations runs performed in this study consists of a 2-node Intel Core i7-950 quad-core PC cluster. The number of finite element analyses (FEAs) and computing time required for performing the optimization runs for each model are provided in Table 3. The computing time required was about 1 to 2 days, therefore it can be said that performing real-word optimization studies with the aid of next generation computational tools (e.g. OCP [18]) is not prohibitive.

As far as it concerns the environmental behavior of the structural systems, life cycle assessment was applied to calculate the embodied energy and CO_2 emissions derived from the construction of the five tall buildings. In order to compare the structural systems of tall buildings over their environmental efficiency, it is essential to encompass all the structural elements. Although slabs do not participate in the optimization problem formulation, they are considered in the total material quantities of structural systems' environmental impact together with all fundamental elements of structural systems. More specifically, besides the quantity of concrete considered for slabs, steel reinforcement was taken into account as the 1.0% of the total slabs' concrete quantity. For estimating energy and carbon emissions ICE-DATA v2.0 Inventory of Carbon & Energy (ICE) database is used, developed by the University of Bath [28]. ICE-DATA inventory includes energy and CO_2 emissions intensity for different construction materials, the unit values that were taken into consideration are: 1.0 MJ and 0.141 $kgCO_2$ per kg of concrete, 17.4 MJ and 1.31 $kgCO_2$ per kg of steel rebar and 21.5 MJ/kg and 1.42 $kgCO_2/kg$ per kg of structural steel.

The reference designs of both concrete and steel structural systems have been configured under certain criteria: (i) The general purpose of the configurations adopted was to create representative models based on existing tall buildings structures (i.e. on the buildings listed in Table 1). (ii) In order to export comparable results, all models should comply with the design constants described in Table 2. (iii) For the formulation of the optimization problem, the structural members are divided into groups having the same cross-sectional properties and are the same for the five structural systems. The groups have been defined according to the type of members, their location in the plan view and the story in which they belong to. The structural elements have been classified into columns, beams, walls and braces depending on their role into the structural systems, while their cross-sectional dimensions constitute the design variables of the optimization problem.

5.1 Concrete structural systems

The structural members of the concrete structural systems are labeled either as columns, shear walls or beams. The beams transfer the vertical loads from the slabs to the columns and the shear walls. Taking into account that beams transfer the same load values in every story of the buildings, they have been divided into two groups, depending only on their location in the interior or exterior of the plan view. On the contrary, columns and shear walls resist both to the vertical and lateral loads. Given that vertical loads are inversely proportional to the story height, four groups (every 16 stories for the 64 stories) have been considered. The columns of the concrete structural systems have also been divided into three categories based on their location in the plan view (i.e. interior, exterior and corners), while the shear walls located in the core of the “Tube in Tube” structural system and in the peripheral of “Braced Tube” they are divided into one category. Overall, twelve groups have been defined for the columns, two groups for the beams and four groups for the shear walls in both concrete structural systems, as they are presented in Tables 4 and 5.

5.1.1 Tube in Tube - Concrete

The structural characteristics of the system shown in Figure 1a were borrowed from “Tube in Tube” type of systems in conjunction with those of an existing system (i.e. the “181 West Madison Street” tall building). The structural system shown in Figure 1a is basically supported on the internal and external tubes, which justifies the name of the system. The external tube is designed with seven equally spaced exterior columns (7.5m distance) and four corner columns, while shear walls located in both directions of the plan view constitute the internal tube. The arrangement of the shear walls was also guided by architectural criteria such as the installation of the elevators. The 3D model and the plan view of the structural system are shown in Figure 1a. For the formulation of the optimization problem, the design variables considered are the eighteen cross-sectional dimensions of the structural elements according to the groups described in Table 4 in which their limits are also provided, both for the cross section of the structural elements and their longitudinal and transverse reinforcement. The optimized design saved a large amount of CO_2 emissions and lessened the energy consumed during its construction phase; in particular the optimized “Tube in Tube - Concrete” structural system consumes 626 TJ of energy and emits 68 thousand tonnes of CO_2 during its construction.

5.1.2 Braced Tube - Concrete

Similar to the previous test example, in order to define the structural system, all its characteristics together with the design constants have been considered. The “780 Third Avenue” concrete building represents an existing application of the “Braced Tube” system and was considered as the basis for developing the reference design. The model developed in order to simulate the “Braced Tube - Concrete” system is shown in Figure 1b. The most significant aspect of this structural system is the simulation of diagonal braces, usually adopted for the case of steel structures, by means of diagonal arrangement of shear walls between the columns in the circumference of the building. In order to compare the optimized structural system with those of the rest, the plan view of the model was designed according to the design constants of Table 2, while the same number of design variables are used; i.e. twelve for the columns, four for the beams and four for the shear walls.. The main difference with the former concrete structural system constitutes the location of the shear walls in the structure, which are located in the exterior of the building instead of its core. The dimensions of the optimized structural system are presented in Table 5 as well as their bounds applied in the optimization process. The optimized structural system during construction emits 53 thousand tonnes of CO_2 and consumes 548 TJ of energy.

5.2 Steel structural systems

Structural steel is the construction material used for the next three test examples, while columns, beams and braces structural elements have been considered for their configuration. The main design difference of the steel structural systems compared to the concrete ones is the configuration of steel braces that are used instead of concrete shear walls. Similar to the concrete systems, the groups of structural elements have been defined taking into consideration the systems' structural performance. Real-world representatives of the steel tall buildings can be found in Table 1 and the design constants adopted are provided in Table 2. More details about the groups of the structural elements adopted for the steel structural systems, as well as the design optimization process, are presented subsequently.

5.2.1 Braced Tube - Steel

The most significant characteristic of this structural system constitutes the exterior mega cross braces; they provide the system with additional stiffness and they resist both to vertical and lateral loads. The so-called "John Hancock Center" tall building represent an existing implementation of the steel brace tube structural system. The system is primarily supported by an external tubular framework composed of seven exterior columns, four corner columns and the exterior beams. The tubular pattern has been configured by the same way in all structural systems in order to produce comparable results. The interior of the structural system comply with the restrictions of Table 2, likewise to the other structural systems for comparability purposes. More design details are provided in Figure 1c with its plan and 3D model views. Concerning grouping, the columns have been divided into three categories according to their location at the corner, exterior or interior of the plan view, while braces are located only in the exterior of the building. For the reasons described previously the stories of the building are divided into four zones, as described in the Table 6. Consequently, eighteen groups have been defined, the dimensions of which constitute the design variables of the optimization problem. The optimized design results to a more economical and environmentally friendly design, mitigating the CO_2 emissions up to 101 thousand tonnes and the energy consumption up to 1,324 TJ.

5.2.2 Diagrid - Steel

For the case of the "Diagrid – Steel" system, the first ten stories have been configured on the basis of the tubular framework, while the rest fifty-four stories simulate the "Diagrid" system's particular characteristics. In general, the structural system has been designed with reference to the "Hearst Building" which is made of both concrete and steel (see Table 1). In order to develop the steel structural system, the concrete part was simulated using steel-framed tube for the first ten stories. Five groups were defined in order to design this tubular framework; three corresponding to the interior, exterior and corner columns, while two for the interior and exterior beams; the interior beams belong to the same group for all stories. The rest fifty-four stories have been divided into three zones, while the tubular framework is composed by a spaced grid of braces, which resist both to vertical and lateral loading, using only their axial stiffness. These structural elements have been divided into three groups from the 11th to the 64th story, as shown in Table 7. As presented in Figure 1d, the system's grid led to different configurations of the plan view, the peripheral and corner beams are of different length and consequently, they have been grouped into four different categories each. The design variables of the system are shown in Table 7 and they are formed according to the cross-sectional dimensions of the structural elements. The optimized design of "Diagrid system" required 85 thousand tonnes of CO_2 and 1,124 TJ of energy for its configuration.

5.2.3 Outrigger - Steel

The tall building considered as reference example for the case of "Outrigger – Steel" system is the "Taipei 101" composed of composite structural elements. In this work, the model developed to describe the "Outrigger" system's characteristics is configured by steel structural elements only. For the grouping procedure, the building has been divided into four zones from the 1st to the 64th story; one zone every sixteen stories. The system is primarily buttressed on a core-structure, consisted of steel braced elements and mega-columns. Four mega-columns have been formatted, each one consisting of four core-columns elements; connected with core beams. Another key feature of "Outrigger" system constitutes the formulation of four belt zones, one every sixteen stories, which connect the core of the building with the exterior frame. More specifically, each belt zone is designed among three stories in which the dimensions of connecting beams are amplified. The belt zones are also reinforced by diagonal braces, placed at the exterior of the building. In order to simulate all these features, twenty-one different groups have been defined, the dimensions of which constitute the design variables of the optimization problem. The formulation of the "Outrigger" structural system is presented in the Figure 1e, while the grouping is shown in the Table 8. The columns of the structural system have been divided into four different groups according to their location at the core, the corner, the exterior or the interior. The beams connecting the mega-columns into the core of the building have been grouped as "core beams", while the beams in the stories of belt-zones have been included into a distinct group. The other two groups of beams include the rest beam-elements in the interior and the exterior of the building. The braces considered for the formulation of belt zones, both in the core and the exterior of the zones, have composed two additional groups. In the Table 8, there are also included the total amount of construction cost, CO_2 emissions and energy consumption of the initial and the optimized design. As a result of the optimization procedure, the environmental footprint of the system reduced to 107 thousand tonnes of CO_2 and the energy consumed for the system's erection is 1,460 TJ.

5.3 Commenting on the results

In general, it can be said that the cost-optimization procedure that was initially applied has created the basis of comparison between the designs of the five structural systems with respect to structural elements' material requirements. Consequently, it is possible to compare their environmental performance both in terms of CO_2 emissions and energy consumption. The results of the five optimized structural systems are analytically presented in the bar chart of the Figure 2. In order to understand the importance of these results, worth noticing that 30 thousand tonnes of CO_2 are emitted annually by 6,500 passenger vehicles [29], while 300 TJ of energy is consumed by 300 Boeing 747 when crossing Atlantic Ocean [30].

With regard to concrete structural systems, "Braced Tube - Concrete" system appeared to be more environmentally friendly than "Tube in Tube - Concrete" one, resulting into differences of 15 thousand tonnes of CO_2 emissions and 78 TJ of energy consumption. Among steel structural systems, "Diagrid - Steel" system required 26 thousand tonnes of CO_2 and 200 TJ of energy less than "Braced Tube - Steel" one; accordingly, 32 thousand tonnes of CO_2 and 336 TJ of energy for the "Outrigger - Steel" system.

Comparing concrete and steel structural systems it can be observed that the later ones require almost double energy and emit double quantities of CO_2 compared to concrete ones. These noticeable differences between steel and concrete configurations are justified as a result of height efficiency. It seems that from environmental point of view, the use of concrete for tall buildings of about 60 stories is the proper choice.

6 CONCLUSIONS

The major objective of this study was to establish the environmental assessment as an influential part of tall buildings' structural design. In order to achieve that, first optimization algorithms were implemented in five representative structural systems of tall buildings in order to diminish the differences between their initial designs. Through the optimization procedure, a mutual base was created for comparing the different structural systems examined in the study. The life cycle assessment (LCA) methodology was utilized as the environmental tool for evaluating the structural systems, taking into account the construction materials used. Structural steel and reinforced concrete used as construction materials, so, the results of the study could also contribute to extract information about the environmental identity of construction materials. LCA methodology was implemented in terms of CO_2 emissions and energy consumption, taking into consideration the part of buildings' life cycle that refers to the construction phase.

The structural optimization part was performed by means of the optimization computing platform (OCP) developed at the Institute of Structural Analysis and Antiseismic Research of the National Technical University of Athens. Through the results of this study, structural optimization is proved to be a key factor in order to design sustainable structural systems. Although, the environmental footprint and the energy consumed during the construction phase of buildings is about 10% of the building's life cycle, this percentage becomes greater (about 20-30%) when it comes to tall building. Thus, since tall buildings are voracious consumers of energy and large emitters of CO_2, already from the construction phase, it is comprehensive that tall buildings are the subject of this study. Taking into consideration the enormous contribution of structural materials in the environmental problems of the modern era, minimizing the construction materials used for buildings' erection alleviate the environmental problems, arisen during the construction phase.

Modern engineers should combine structural efficiency, construction cost and environmental performance in order to lead buildings into sustainable development. Even though, the operational phase of buildings remains responsible for the largest fraction of CO_2 emissions and energy consumption, the construction phase should be taken into consideration as responsible for environmental problems and further research could contribute to their mitigation. The noticeable differences between steel and concrete configurations are considered as a result of height efficiency that seems to promote from environmental view the use of concrete for tall buildings of about 60 stories. Through this study, we realized that construction materials strength in combination of tall buildings' height constitute significant parameters for the optimization of structural efficiency with a great influence on the results. It would be of great interest to integrate these parameters in a future research. Moreover, recycling materials usage could be another one field of research interest that has to be examined to move the structural design in the direction of sustainability.

ACKNOWLEDGEMENTS

This research has been supported by the OptArch project: “Optimization Driven Architectural Design of Structures” (No: 689983) belonging to the Marie Skłodowska-Curie Actions (MSCA) Research and Innovation Staff Exchange (RISE) H2020-MSCA-RISE-2015.

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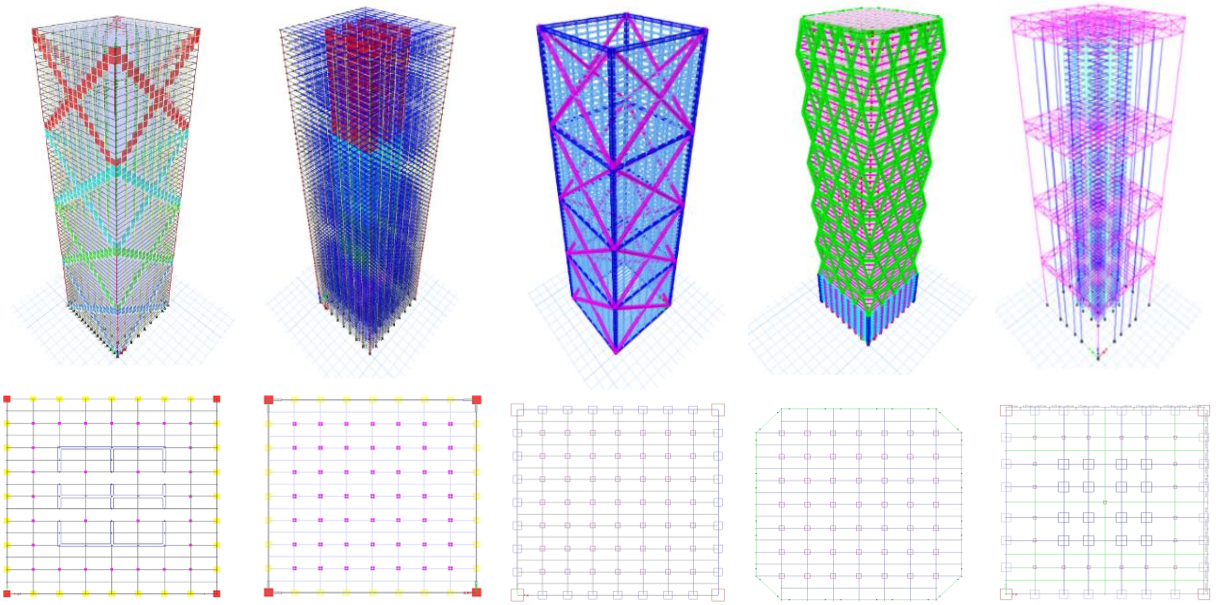
FIGURES



(a) (b) (c) (d) (e)

Figure 1. 3D models and plan views of the five structural systems: a) Tube in Tube - Concrete, b) Braced Tube - Concrete, c) Braced Tube - Steel, d) Diagrid – Steel and e) Outrigger - Steel.

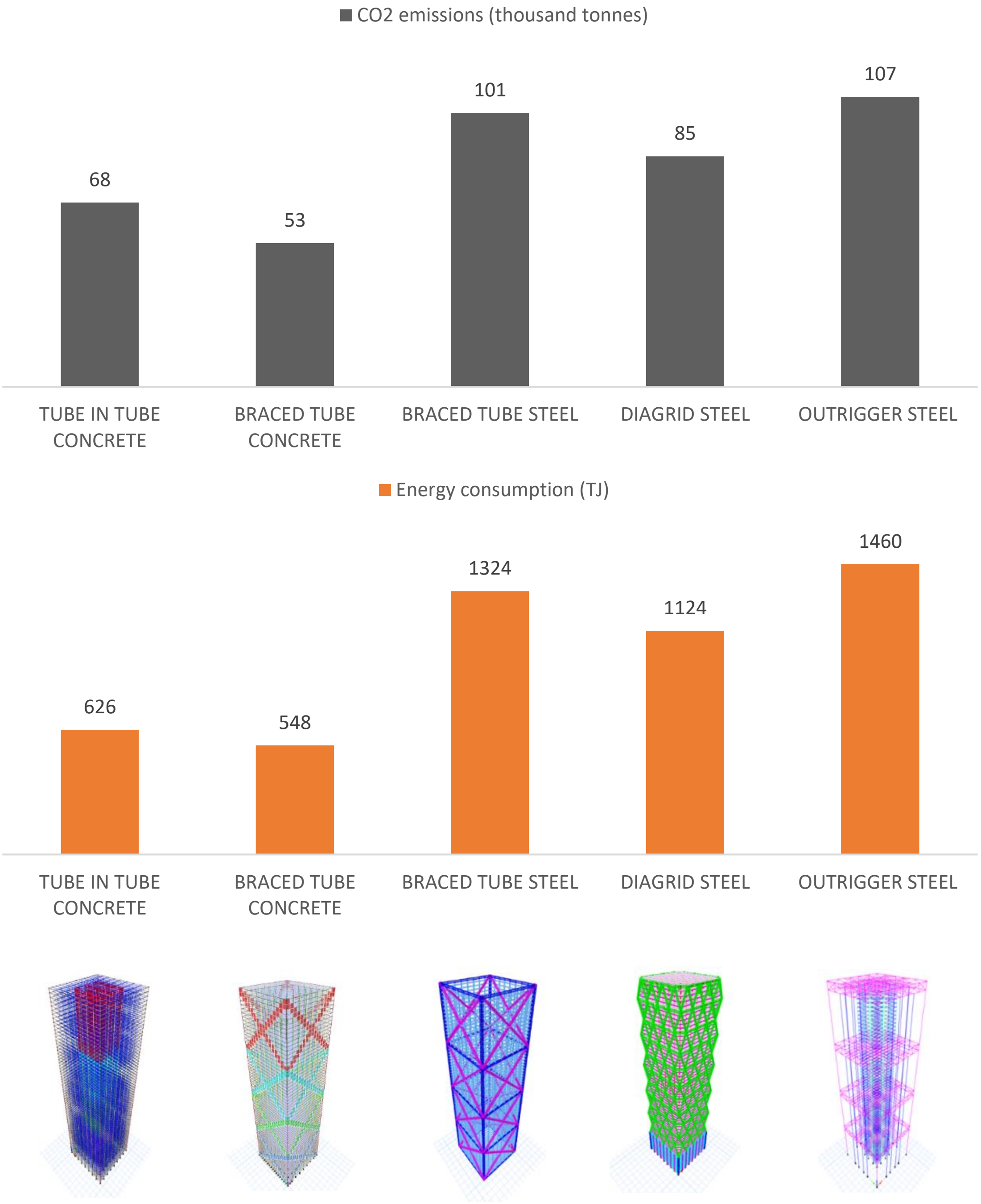


Figure 2. Energy consumption (in TJ) and CO_2 emissions (in thousand of tonnes) for the five structural systems.

TABLES

Category	Material	Building example	Location
Braced Tube	Concrete	780 Third Avenue	New York, USA
Braced Tube	Steel	John Hancock Center	Chicago, USA
Tube in Tube	Concrete	181 West Madison Street	Chicago, USA
Diagrid	Steel	Hearst Building	New York, USA
Outrigger	Steel	Taipei 101	Taipei, Taiwan

Table 1. Realistic applications of structural systems in existing tall buildings.

Category	Design constant	Configuration details
Geometry	Floor Plan	60 × 60=3,600m^2 Quadrangular floor plan due to wind effect
	Number of stories	64
	Stories height	3m
	Building height	192m
Loads	Vertical	Eurocode-1 (dead, live, super dead)
	Lateral	Wind loads commensurate with height increase and seismic loads negligible
	Combinations	Eurocode-1
Materials	Concrete	C40/50
	Reinforcements bars	B500C
	Structural steel	S450
Structural	Cross section of columns	Quadrangular section
	Cross section of beams	I – section
	Cross section of trusses	I – section
	Slabs	Excluded from the structural design 0.20m thickness and 25.0m^2 slab-element's area
	Length of a secondary beam	7.5m

Table 2. Design constants of simulation.

Category	Total time
Braced Tube	1d 20h 57min
Braced Tube	2d 13h 41min
Tube in Tube	2d 2h 45min
Diagrid	1d 14h 49min
Outrigger	2d 16h 38min
Computer specifications	
Processor	Intel Xeon CPU E5-1620 v3 @ 3,50GHz
Installed memory	16.0 GB
Operating system	64-bit, x64-based processor

Table 3. Total computing time and computer specifications.

Structural elements	**Location**	**Storey**	**Bounds / Step**	**Optimized Cross-sections**
Columns	Corner	1 to 16	*1050 mm ≤ DV_i ≤ 2750 mm (i=1, ..., 4) step=50mm*	2250 × 2250 (1)
		17 to 32		2200 × 2200 (2)
		33 to 48		2200 × 2200 (3)
		49 to 64		2150 × 2150 (4)
	Exterior	1 to 16	*900 mm ≤ DV_i ≤ 1950 mm (i=5, ..., 8) step=50mm*	1300 × 1300 (5)
		17 to 32		1300 × 1300 (6)
		33 to 48		1250 × 1250 (7)
		49 to 64		1150 × 1150 (8)
	Interior	1 to 16	*450 mm ≤ DV_i ≤ 2350 mm (i=9, …, 12) step=50mm*	1300 × 1300 (9)
		17 to 32		1200 × 1200 (10)
		33 to 48		1000 × 1000 (11)
		49 to 64		900 × 900 (12)
Beams	Exterior	1 to 96	*200 mm ≤ DV_i ≤ 1850 mm (i=13, ..., 16) step=50mm*	850 (13) × 550 (14)
	Interior	1 to 96		950 (15) × 350 (16)
Shear Walls	Core	1 to 16	*550 mm ≤ DV_i ≤ 1950 mm (i=17, …, 20) step=50mm*	1050 (17)
		17 to 32		900 (18)
		33 to 48		800 (19)
		49 to 64		650 (20)
Slabs		1 to 64	-	200
GHG emissions (thousand metric tonnes of CO_2)				**68**
Energy consumption (TJ)				**626**

Table 4. "Tube in Tube - Concrete" optimization results: CO_2 emissions, energy and cost of structural elements (cross sectional dimensions in mm, numbers inside the brackets indicate the design variables).

Structural elements	**Location**	**Storey**	**Bounds / Step**	**Optimized Cross-sections**
Columns	Corner	1 to 16	$1050\ mm \leq DV_i \leq 2750\ mm\ (i=1, ..., 4)\ step=50mm$	2050 × 2050 (1)
		17 to 32		1900 × 1900 (2)
		33 to 48		1750 × 1750 (3)
		49 to 64		1600 × 1600 (4)
	Exterior	1 to 16	$900\ mm \leq DV_i \leq 1950\ mm\ (i=5, ..., 8)\ step=50mm$	1350 × 1350 (5)
		17 to 32		1350 × 1350 (6)
		33 to 48		1350 × 1350 (7)
		49 to 64		1350 × 1350 (8)
	Interior	1 to 16	$450\ mm \leq DV_i \leq 2350\ mm\ (i=9, ..., 12)\ step=50mm$	1500 × 1500 (9)
		17 to 32		950 × 950 (10)
		33 to 48		700 × 700 (11)
		49 to 64		700 × 700 (12)
Beams	Exterior	1 to 96	$200\ mm \leq DV_i \leq 1850\ mm\ (i=13, ..., 16)\ step=50mm$	900 (13) × 350 (14)
	Interior	1 to 96		500 (15) × 300 (16)
Shear Walls	Exterior	1 to 16	$150\ mm \leq DV_i \leq 1250\ mm\ (i=17, ..., 20)\ step=50mm$	640 (17)
		17 to 32		460 (18)
		33 to 48		340 (19)
		49 to 64		230 (20)
Slabs	-	1 to 64	-	200
GHG emissions (thousand metric tonnes of CO_2)				**53**
Energy consumption (TJ)				**548**

Table 5. "Braced Tube - Concrete" optimization results: CO_2 emissions, energy and cost of structural elements (cross sectional dimensions in mm, numbers inside the brackets indicate the design variables).

Structural elements	Location	Storey	Bounds / Step	Optimized Cross-sections
Columns	Corner	1 to 16	*$1850\text{mm} \le DV_1 \le 3950\text{mm}$ step=50mm* *$50\text{mm} \le DV_i \le 290\text{mm}$ (i=2, ..., 5) step=10mm*	2250×2250 (1) × 130×130 (2)
		17 to 32		2250×2250 (1) × 120×120 (3)
		33 to 48		2250×2250 (1) × 120×120 (4)
		49 to 64		2250×2250 (1) × 80×80 (5)
	Exterior	1 to 16	*$900\text{mm} \le DV_6 \le 2850\text{mm}$ step=50mm* *$30\text{mm} \le DV_i \le 150$ mm (i=7, ..., 10) step=10mm*	1050×1050 (6) × 35×35 (7)
		17 to 32		1050×1050 (6) × 35×35 (8)
		33 to 48		1050×1050 (6) × 35×35 (9)
		49 to 64		1050×1050 (6) × 45×45 (10)
	Interior	1 to 16	*$500\text{mm} \le DV_{11} \le 2250\text{mm}$ step=50mm* *$10\text{mm} \le DV_i \le 100$ mm (i=12, ..., 15) step=10mm*	800×800 (11) ×20×20 (12)
		17 to 32		800×800 (11) ×20×20 (13)
		33 to 48		800×800 (11) ×20×20 (14)
		49 to 64		800×800 (11) ×20×20 (15)
Beams	Exterior	1 to 64	$150\text{mm} \le DV_i \le 750\text{mm}$ (i=16, ..., 19) step=10mm *$10\text{mm} \le DV_i \le 60$ mm (i=20, ..., 23) step=5mm*	320 (16) × 260 (17) × 25 (20) × 10 (21)
	Interior	1 to 64		540 (18) × 240 (19) × 25 (22) × 10 (23)
Braces	Exterior	1 to 16	*$1050\text{ mm} \le DV_i \le 4950$ mm (i=24, ..., 31) step=50mm* *$30\text{mm} \le DV_i \le 180$ mm (i=32, ..., 39) step=5mm*	2700 (24) ×1900 (25) × 70 (32) × 55 (33)
		17 to 32		2450 (26) × 1750 (27) × 70 (34) × 55 (35)
		33 to 48		2200 (28) ×1750 (29) × 60 (36) × 55 (37)
		49 to 64		2000 (30) × 1550 (31) × 60 (38) ×55 (39)
Slabs	-	1 to 64	-	200
GHG emissions (thousand metric tonnes of CO_2)				**101**
Energy consumption (TJ)				**1,324**

Table 6. “Braced Tube - Steel” optimization results: CO_2 emissions, energy and cost of structural elements (cross sectional dimensions in mm, numbers inside the brackets indicate the design variables).

Structural elements	**Location**	**Storey**	**Bounds / Step**	**Optimized Cross-sections**
Columns	Corner	1 to 10	*$850mm \leq DV_i \leq 5250mm$ (i=1, 2, 3) step=50mm* *$60mm \leq DV_i \leq 380mm$ (i=4, 5, 6) step=5mm*	2450×2450 (1) × 55×55 (4)
	Exterior	1 to 10		1600×1600 (2) × 35×35 (5)
	Interior	1 to 10		850×850 (3) × 30×30 (6)
Beams	Exterior	1 to 10	*$150mm \leq DV_i \leq 1450mm$ (i=7, …, 14) step=10mm* *$10mm \leq DV_i \leq 70mm$ (i=15, …, 22) step=5mm*	1070 (7) × 540 (8) × 65 (15) × 30 (16)
	Interior	1 to 64		460 (9) × 180 (10) × 25 (17) × 10 (18)
	Peripheral	11 to 14 & 16 to 18, …, 61 to 64		650 (11) × 350 (12) × 25 (19) × 10 (20)
	Corner	11 & 19, …, 64		500 (13) × 400 (14) × 25 (21) × 15 (22)
Braces	Exterior	11 to 25	*$100mm \leq DV_i \leq 1950mm$ (i=23, …, 28) step=50mm* *$10mm \leq DV_i \leq 75mm$ (i=33, …, 38) step=10mm*	1050 (23) × 600 (24) × 35 (33) × 25 (34)
		26 to 50		900 (25) × 550 (26) × 30 (35) × 30 (36)
		50 to 64		850 (27) × 450 (28) × 25 (37) × 30 (38)
Slabs	-	1 to 64	-	200
GHG emissions (thousand metric tonnes of CO_2)				**85**
Energy consumption (TJ)				**1,124**

Table 7. "Diagrid - Steel" optimization results: CO_2 emissions, energy and cost of structural elements (cross sectional dimensions in mm, numbers inside the brackets indicate the design variables).

Structural elements	Location	Storey	Bounds / Step	Optimized Cross-sections
Columns	Core	1 to 16	$650mm \leq DV_1 \leq 2950mm$ *step=50mm* $20mm \leq DV_i \leq 100mm$ *(i=2, ..., 5) step=10mm*	1000×1000 (1) × 35×35 (2)
		17 to 32		1000×1000 (1) ×25×25 (3)
		33 to 48		1000×1000 (1) ×25×25 (4)
		49 to 64		1000×1000 (1) ×25×25 (5)
	Corner	1 to 16	$1800mm \leq DV_6 \leq 3750mm$ *step=50mm* $50mm \leq DV_i \leq 250 mm$ *(i=7, ..., 10) step=10mm*	2450×2450 (6) ×160×160 (7)
		17 to 32		2450×2450 (6) ×80×80 (8)
		33 to 48		2450×2450 (6) ×75×75 (9)
		49 to 64		2450×2450 (6) ×75×75 (10)
	Exterior	1 to 16	$650mm \leq DV_{15} \leq 1650mm$ *step=50mm* $15mm \leq DV_i \leq 160mm$ *(i=12, ..., 15) step=10mm*	1110×1110 (11) × 60×60 (12)
		17 to 32		1100×1100 (11) ×40×40 (13)
		33 to 48		1100×1100 (11) ×35×35 (14)
		49 to 64		1050×1050 (11) ×35×35 (15)
	Interior	1 to 16	$450mm \leq DV_{16} \leq 1850mm$ *step=50mm* $20mm \leq DV_i \leq 100 mm$ *(i=17, ..., 20) step=10mm*	550×550 (16) × 15×15 (17)
		17 to 32		550×550 (16) × 15×15 (18)
		33 to 48		550×550 (16) × 15×15 (19)
		49 to 64		550×550 (16) × 15×15 (20)
Beams	Core - Belt zone	14 to 16 & 30 to 32 … & 62 to 64	$100mm \leq DV_i \leq 1800 mm$ *(i=21, ..., 30) step=50mm* $10mm \leq DV_i \leq 100 mm$ *(i=31, ..., 40) step=5mm*	1200 (21) × 650 (22) × 30 (31) × 20 (32)
	Core	1 to 64		780 (23) × 600 (24) × 30 (33) × 20 (34)
	Exterior	1 to 64		550 (25) × 250 (26) × 25 (35) × 10 (36)
	Interior	1 to 64		550 (27) × 300 (28) × 15 (37) × 10 (38)
Braces	Exterior - Belt zone	10 to 12 & 22-24 …		850 (29) × 450 (30) × 30 (39) × 15 (40)
Slabs	-	1 to 64	-	200
GHG emissions (thousand metric tonnes of CO_2)				**107**
Energy consumption (TJ)				**1,460**

Table 8. “Outrigger - Steel” optimization results: CO_2 emissions, energy and cost of structural elements (cross sectional dimensions in mm, numbers inside the brackets indicate the design variables).