The Environmental and Economic Impact
of Structural Optimization

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Abstract: According to the well-known mathematician Leonhard Euler: "Nothing takes place within the universe in which the rule of maximum or minimum does not appear." The development of optimization algorithms can be traced back to the days of Kepler, Newton, Lagrange and Cauchy and the concept of minimization much earlier to the days of Euclid. However, despite these early developments, very little progress on their use was achieved until the middle of 20th century when digital computers made possible the application of the optimization algorithms and motivated further research, producing massive literature on the subject and development of new optimization techniques. Nevertheless, professional structural engineers and practitioners are highly sceptical in adopting such procedures in their professional life, while software applications implementing optimization techniques fall short of meeting their needs. Therefore, in this study the question that I will try to answer from an environmental and economic perspective is: "Is it worth performing structural optimization studies?", and aim to prove that adopting optimization based design procedures will have drastic environmental impact and contribute on the economic development in construction industry.

Keywords: Structural optimization; life cycle assessment; structural engineering practice; material usage; environmental and economic impact.

1.   INTRODUCTION

When Edison constructed the first long-lasting, high-quality light bulb in 1879; his successful design was the result of a long and effortful trial-and-error design procedure, the known as the Edisonian approach [1], targeting to identify the most filament material. Whereas Thomas Edison had no basic knowledge of how different materials resist on electric current, today's engineers are commonly armed with technical knowledge and experience concerning their domain. This enables

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them to generate good initial designs based on intuition before testing them to failure or to the design-code requirements. Design defects detected throughout the tests are then improved through the so-called make-it-and-break-it procedure.

Advances in computing power and in computer-aided engineering software packages now make it possible to produce virtual prototypes of potential designs before building and testing over-engineered physical prototypes. This reduces the cost and time needed to perform every design iteration and provides better understanding of how a design performs. However, the potential of virtual prototyping approach remains restricted by two factors. First, every iteration needs an engineer to manually develop or modify a computer model of the system. Despite ever improving software packages, this is often still a cumbersome, fallible and lengthy procedure. The second factor concerns the success of this approach that still depends heavily on the restrictions of human intuition and skills. Despite how brilliant the design team is, the human mind often cannot predict or comprehend the results of adjusting multiple variables at an equivalent time in a very complicated system. This profound barrier, let alone time constraints, severely limits the quantity and types of design iterations that can be performed. Often the result is a far-optimal solution that is a design of the team's collective expertise.

The desire to extend productivity led naturally to the automation of the design iteration procedure. Process automation software packages were introduced that might capture and execute automatically the standard manual procedure to generate and test a virtual prototype. Thus, every new design iteration can be performed much more quickly, and without worrying of manual errors. It shortly became obvious that exploration of the design space could also be automated by adding a smart iterative procedure over the design-evaluation process, and an instant market was created for all classical optimization algorithms. With the promise of reducing design time and cost whereas rising product quality, automated design optimization has tremendous potential. Starting with a sub-optimal or even random design, a numerical optimization algorithm could be used to iteratively adjust a set of pre-selected design parameters in an endeavour to realize a set of design targets.

Although since early 60's a large amount of excellent research studies have been published on the subject of optimization based structural engineering, where structural optimization was successfully been applied in various problems [2-6], structural engineering practice fall short behind of

adopting optimization based design procedures. On the other hand, various engineering professions like mechanical and aerospace engineering implement optimization procedures into the everyday profession practice. For example in automotive industry, among other car manufactures, the R&D department of BMW has developed and standardized optimization procedures in the framework of various fields of simulation when developing a new diesel engine [7]. Additionally, in aeronautic industry, Airbus adopted an optimization-based procedure for designing the wing of A380 aircraft [8].

In addition, it should be taken into consideration that: (i) The building sector is the largest contributor to global greenhouse gas (GHG) emissions; buildings use about 40% of global energy, 25% of global water, 40% of global resources, and they emit almost 30% of GHG emissions, (ii) building sector is estimated to be worth 10% of global GDP (USD 7.5 trillion) and employs more than 110 million people, while (iii) CI is expected to expand by 85% to USD 15.5 trillion worldwide in 2030, with U.S., China and India accounting for almost 60% of this growth. Bearing in mind all issues mentioned above, the main objective of the present article is to answer the question: "Is it worth performing structural optimization studies?" from the environmental and economic perspective. For this purpose the global market of structural materials is reviewed, while the environmental and economic impact is assessed accompanied by two large-scale real-world test cases of design optimization techniques into structural engineering.

2. TREND OF THE GLOBAL STRUCTURAL MATERIALS MARKET: CEMENT AND STEEL

Before performing any techno-economic analysis, the structural material quantities produced annually and those required from the demand, need to be collected and analysed. In this direction, the evolution of the global cement production for years 1950 to 2016 as reported by US Geological Survey (USGS) [9] is presented in Figure 1 (in million metric tons). The major countries in worldwide cement production for years 1967, 2000 and 2016 are presented in Figures 2(a) to 2(c), where the total production for the specific years was equal to 563, 1,200 and 4,200 million metric tons, respectively. Accordingly, for the case of steel, Figure 3 depicts the global production for years 1950 to 2016 according to World Steel Association (WSA) [10]. The production for steel worldwide by region for years 1967, 2000 and 2016 is provided in Figures 4(a) to 4(c), where the total production for the specific years was equal to 493, 850 and 1,630 million metric tons, respectively.

The material requirements for buildings currently represent one of the greatest resource use challenges in terms of mass resources used. Even though this consumption does not always manifest itself in a direct and observable problem, issues like climate change, biodiversity loss, desertification and soil erosion are all linked to extensive material use. More than 30% to 50% of total material use in Europe goes to housing that mainly consists of steel, concrete, aluminium, copper, clay, sand, gravel, limestone, wood and building stone. Concerning cement (consequently concrete) almost the total production is consumed by the Construction Industry (CI) while according to European Cement Association (CEMBUREAU), which is the representative organization of the cement industry in Europe [11], 75% of construction activity is related to buildings. Accordingly, based on Eurostat PRODCOM statistics [12] and European Steel Association [13] 28% of steel production is used in constructions, and since 75% of constructions is related to buildings, 21% of steel is used in buildings. However, based on personal communication with EUROFER, 26% of steel is used for buildings (industrial buildings included), while according to the Global Steel report for year 2014 by Ernst & Young [14], globally steel demand for constructions and infrastructures accounts for more than half of the overall steel demand; particularly, it accounts for 55% of steel demand in China and 42% in the US.

The problem of extensive material use looks set to get worse, among others due to China's booming construction industry. A growing population, as well as the rapid growth in purchasing power in emerging economies and developing countries, means that the global building floor area is expected to double by 2050, further increasing the energy demand and the GHG emissions related to construction. Figure 5 depicts projections for the future floor area for years 2030 and 2050 according to United Nations Environment Programme (UNEP) [15], where globally from 232.4 billion square meters in 2016, is estimated to become 315.5 and 415.1 billion square meters for years 2030 and 2050, respectively. Already, the cement produced is close to 2 billion tons per year, by 2050, concrete use is predicted to reach four times the 1990 level. In addition, according to WSA [16] a growing trend is also observed for the steel demand; and the estimated demand for steel worldwide by region between 2016 and 2018 is provided in Figure 6 in million metric tons where the values refer to finished steel products. The global demand for the year 2016 was equal to 1,515 million metric tons while the numbers for 2017 and 2018 are estimated to become equal to 1,535 and 1,549, respectively.

Structural materials already pilloried through their use in countless architectural eyesores, from tower blocks to car parks, concrete's environmental credentials are also now coming under scrutiny. Especially concrete is used so widely that world cement production now contributes 5% of annual anthropogenic global CO_2 production. Karen Scrivener (head of the construction laboratory at the Swiss Federal Institute of Technology) explains in the article by J.M. Crow [17] that: "*The reason there's so much concrete is because it is in fact a very low impact material.*"; while "*If you replace concrete with any other material, it would have a bigger carbon footprint. Many people have the idea that if you built in steel you'd make things better – but in fact you'd make things worse. The reason concrete has a big carbon footprint as a whole is that there are just such huge quantities used.*" Therefore, it is not an easy task to replace the existing structural materials; besides, a global transformation to a highly energy-efficient, low-carbon building sector must occur over the next decade to ensure a well below 2°C ambition. This is especially true in emerging economies, where there is a critical window of opportunity to address the largest new construction markets to avoid locking in inefficient buildings for decades [15, 17]. Thus some priority actions were set by UNEP [15], one of which is to reduce embodied energy and emissions; i.e. reduce the environmental impact of material use in the buildings & construction value chain.

3.   STRUCTURAL OPTIMIZATION AND VALUE ENGINEERING

The Latin word "optimum" means *ultimate-ideal*; accordingly, "optimus" means *the best*. Therefore, to optimize refers to try to bring something closer to its ultimate state. The history of optimization, that is the quest for finding extreme points, dates back several hundreds of years during which remarkable progress has been made in developing new and more efficient methods. Euclid (300 BC) tackled with the problem of finding the shortest distance, which may be drawn from a point to a line, while Heron of Alexandria (100 BC) studied the optimization problem of light travelling between two points by the shortest path [18]. Many years later, Fermat (1657) developed a more general principle that light travels between two points in the minimum time [19], while Cauchy (1847) presented the first minimization method (the well-known Steepest Descent method) [20]. The progress on calculus provided the basis for the development of the optimization mathematical theory. The pioneering works of Courant (1943) on penalty functions [21], Dantzig (1951) on linear programming [22], Karush (1939) as well as that of Kuhn and Tucker (1951) on optimality conditions for constrained problems [23, 24] established the modern era of numerical optimization.

The term structural optimization refers to the application of numerical optimization to the design process of engineering (load-carrying) structures, like building, automotive or aircraft structures. Prior the implementation of computer-assisted optimization procedures, structural elements (like beams and plates) were optimally designed based on the calculus of variations [25]. The presentation of the finite element method (FEM) [26] was the reason for the dominance of computerized structural analysis and allowed the application of FEM-based numerical optimization procedures to structures. Schmit in his pioneering work [27] presented the first application where a simple three-bas truss structure was used for presenting the idea of structural synthesis. During the first years of computerized structural optimization, civil engineering truss structures were used for applying the new concept, with design variables being the cross-sectional areas of the bar elements. This class of structural optimization problems refers as *sizing*. In sizing optimization problems the aim is usually to minimize the weight of the structure under certain behavioural constraints on stresses and displacements as suggested by the design codes [28-32] in case of civil engineering structures. The design variables are most frequently chosen to be dimensions of the cross-sections of the structural elements, see for example the dimensioning approach of the skyscraper shown in Figure 7(a).

More recently, structural optimization research has focused on changing the *shape* (geometry) and *topology* (layout) of the structural system. In structural shape optimization problems (associated also with the so called parametric design) the aim is to improve the performance of the structure by modifying its shape, see for example the parametric design optimization of the structural system shown in Figure 7(b). The design variables are either some of the coordinates of the key points in the boundary of the structure or some other parameters that influence the geometry of the structure. Structural topology optimization, referred also as generalized shape design problem, can be considered as a procedure for optimizing the topological arrangement of material into the design domain, eliminating the material volume that is not needed, for example the design approach of the moment resisting frame (MRF) depicted in Figure 7(c) [33]. Several combinations of the three types of structural optimization have also been proposed.

In design, construction, and maintenance of any engineering system, engineers need to take several technological and managerial decisions at many stages. The ultimate goal of these choices is either to attenuate the effort required or to maximize the profit. Among others construction and material cost reduction can be achieved consistent with the desired performance, reliability, qual-

ity and safety. Therefore, optimization is the act of getting an improved result under given circumstances. In structural engineering sizing optimization of the structural elements is considered as part of the so-called value engineering procedure when implemented in CI. Value engineering is outlined as the methodology to enhance the "value" of the product. It promotes the substitution of materials and procedures with more cost-effective alternatives, while not sacrificing practicality. Value engineering is the review of novel or existing products throughout the design stage to reduce costs and enhance functionality aiming to augment product's value.

Structural optimization problems are formulated using various objective and constraint functions that are typically expressed as non-linear combinations of the design variables. The mathematical formulation of the structural optimization problems with respect to the design variables, the objective and the constraint functions depend on the type of the application. However, most optimization problems can be expressed in standard mathematical terms as a non-linear programming problem. A mixed-discrete structural optimization problem can be formulated in the following form:

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

where $\mathbf{s} = [\mathbf{s}_d, \mathbf{s}_c]^T$ is the vector of the design variables of the optimization problem, $\mathbf{s}_d$ and $\mathbf{s}_c$ are the vectors of discrete and continues design variables respectively, while D and C are the discrete and continuous design sets of size n_d and n_c, respectively.

4. LIFE CYCLE ASSESSMENT

According to UNEP [15] GHG emissions are set to double by 2050 if CI carries on business as usual. The building sector consumes increasingly energy; since primarily newly built structures are constructed quicker than old ones are withdrawn. Figure 8 shows that buildings present the most impactful and also economical mitigation potential for GHG emissions globally [34]. Significant GHG emissions are generated through construction materials; broadly speaking, energy is consumed during the following activities: (i) manufacturing of building materials ("embedded" or "embodied" energy), (ii) transport of materials from production plants to construction sites ("grey" energy); (iii) construction of building ("induced" energy); (iv) operation of building ("operational" energy); and (v) demolition of building (and recycling of its parts).

In this direction, life cycle assessment (LCA) procedure has been established as a valuable tool for assessing the impacts of products occurred from their manufacturing process to consumption. According to the International Standardization Organization (ISO) LCA procedure is referred as "Cradle to Grave". Furthermore, ISO has developed a detailed framework [35] for the implementation of this methodology into buildings. There is a plethora of productive-industrial procedures, during buildings' 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.

In this study the significance of design optimization into CI is assessed with respect to the embodied energy of the building, since it is correlated directly with the material use and will be implemented by means of a LCA framework. In particular, the global environmental revenue annually is calculated along with two test examples, which are examined in this study by means of LCA. Therefore, the comparative purpose of this work requires estimating the embodied energy's variations of CI output and thus only structural elements are included in the initial embodied energy, which are identified likewise in the recurring embodied energy of the building. Implementing the process presented in [36], embodied energy is divided in two parts: initial and recurring; used for rehabilitating the building and it is expressed with the following expression:

$$EE(\mathbf{s}) = EE_i(\mathbf{s}) + EE_r(\mathbf{s})$$

$$= \sum_i m_i(\mathbf{s})M_i + \sum_i m_i(\mathbf{s})M_i \left[\frac{L_b}{L_{m_i}} - 1 \right] \tag{2}$$

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 ith 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).

5.   STRUCTURAL OPTIMIZATION DESIGN TOOLS

Design optimization refers to the act of generating improved designs in terms of cost, manufacturability or performance whereas not compromising safety. The implementation of optimum design formulations to real-world cases demands major computational effort, which may solely be addressed with the synergy of state-of-the-art technologies within the field. Therefore, tools developed for handling structural optimization problems primarily should serve four purposes: (i) correct numerical modelling of structural systems, (ii) reliable structural analysis for calculating

response quantities like displacements and stresses, (iii) consistent to design codes and/or the design engineers design procedure for performing the constraints checks and (iv) effective optimization algorithms for achieving improved designs that satisfy design conditions and economic, manufacturability, performance or sustainability criteria.

Structural optimization has matured from a limited topic of academic nature, wherever researchers targeted on the design optimization of small-idealized structural components or systems, to become the premise in contemporary design of complicated structural systems. In recent years, few software packages have offered these tools accessible to professional engineers, decision-makers and students outside the structural optimization research community. These software packages typically targeted to aeronautic, mechanical or naval structural systems have incorporated the optimization feature primarily as part of the basic FE software package. In particular, there are several commercial software applications on topology optimization; however all of them are integrated into mechanical and aerospace engineering mostly oriented analysis and design software, like OpiStruct by Altair [37], Tosca optimization suite by Dassault Systems [38] that works with standard FEA software (like ABAQUS and MSC Nastran), Ansys topology optimization solution [39] and recently MIDAS NFX presented its topology optimization capability [40]. However, these tools come short of meeting the requirements of professional structural engineers.

In the case of CI there are only a couple of software that offer design optimization solutions. More specifically, SCIA presented Engineer MOOT [41] which is a multi-objective optimization tool that achieves optimized structural designs using the internal forces' compliance for performing code checks and Optimization Computing Platform (OCP) [42,43] that is an holistic optimization approach in terms of final design stage for real-world civil engineering structures such as buildings, bridges or more complex civil engineering structures. These software solutions harnesses technology to drive efficiency, increase performance and reduce cost while preserving safety excellence.

6. CONSTRUCTION INDUSTRY ABSORBING OPTIMIZATION TECHNOLOGY

Engineers' main objective is to design efficient structural systems that should be as economic as possible, nevertheless strong enough to resist the foremost demanding operational requirements arising throughout their service life. The typical Edisonian design approach is not appropriate to

derive economical-sustainable designs satisfying the safety criteria as well. Structural design optimization, on the other hand, provides a numerical procedure that could replace the Edisonian design approach with an automatic one. The scientific and technical opportunities adopting optimization technology within the design practice, among others from a practitioner structural engineer point of view, are monumental. One of the goals for implementing optimization technology is to assist new generations of engineers to design safer, sustainable and economic structures within a reliable technological framework. Within the construction industry, there's constant pressure to deliver projects more effectively on multiple fronts. This is often most notable within the need to cut back project time and budget scales, whereas systematically also increasing capability and design quality. Structural optimization capabilities can provide vital else worth to the users of such design tools and instant payback.

Although there have been a huge amount of studies on structural optimization documenting formulations, algorithms etc., remains a persistent and troubling gap between the inherent value of structural optimization technology developed and the ability to be adopted by structural engineering practice effectively. This can be justified first due to the absence of specialized software for performing computerized design optimization studies in civil engineering; as it was described in the previous section, there are only a couple of such specialized software solutions worldwide. Secondly, opinion leaders of the construction industry and managers must overcome some challenges if construction companies are to absorb structural optimization technology efficiently, one of which is that the users of optimization technology are often not willing (or able) to take the responsibility for implementing the optimization technology. This is possibly because design engineers might be sceptical on the safety of the optimized structural designs. For this purpose, the developers of the specialized software need to ensure that the results obtained through structural optimization software are, directly, comparable with those used in the original design, i.e. use the same FE simulation, material properties, loading conditions, design codes etc. [43]. In order to be convinced about the efficiency of structural optimization technology, a pilot operation across the board in a large organization needs to be conducted. However, pilot application should be treated carefully since novel and exotic technologies are especially vulnerable to hype.

Last but not least, although, structural engineers are sought out as policy leaders and problem solvers in many matters of the community, while they initiate and lead the development of emerging and exponential technology; they resist changing and might not identify direct personal benefit from the use of structural optimization technology. Roughly speaking CI is composed by three

parts, the owner, the constructor and the designer; although the later one is to implement optimization technology in the design phase, only the first two parts have personal benefit from its adoption. Therefore, in order to help community earning from the outcomes of structural optimization technology, the State needs to impose its implementation through legal means.

7. WHAT IF DESIGN OPTIMIZATION PROCEDURES WERE APPLIED IN STRUCTURAL ENGINEERING PRACTICE

In this section the environmental and economic impact globally is assessed, the benefits for the structural engineers is also discussed and two indicative test examples are presented in the following parts of the section. Although the techno-economic analysis performed in the current study relies on embodied energy only; it will be shown that by means of structural optimization the environmental and economic merits are enormous.

7.1 Environmental and economic impact

Without loss of generality of the conclusions derived, the case of building structures is considered herein that represent the 75% of the construction industry activity. In order to examine the influence of design optimization procedures in structural engineering practice and thus the environmental and economic impact, some scenarios are examined: (i) assume that via design optimization procedures an average reduction on material requirements equal to 5% or 10% is achieved and (ii) assume that globally 0.1%, 0.5% or 5% of the construction industry related to the buildings market adopts optimization techniques during the design procedure.

The analysis that is presented in this section refers to year 2016; as well as to years 2030 and 2050 where based on estimates the corresponding values are calculated. The future material use (limited to concrete and steel only) for years 2030 and 2050 are derived proportional to the building floor estimates for these years. The building floor area's in billions of square meters along with the material production and the corresponding usage in the building sector of CI (in millions of metric tons) is provided in Table 1 for years 2015, 2016 and projected values for 2030 and 2050 (according to UNEP [15]). Based on these quantities of materials the environmental and economic impact is presented analytically below. For the purposes of this parametric study instead of making the calculations for cement it is performed for concrete. Typically, a concrete mix contains about 10% to 15% cement [44]; therefore, in order to derive the corresponding concrete quantities it is assumed that concrete on average contains 12.5% cement.

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Table 2 presents the reduction with respect to annual material demand for the building sector of CI (in million m^3 of concrete and million kgr of steel). Tables 3 and 4 depict the environmental impact, calculated as reduced requirements in terms of trillion BTU energy consumption (see Table 2) and million metric tons of GHG CO_2e emissions (see Table 3) when design optimization procedures are adopted. These values correspond to year 2016 based on the material consumption [15] and for years 2030 and 2050 based on predictions of CI evolution described analytically previously. These quantities are derived for explicit values for the energy and CO_2e coefficients obtained from the Inventory of Carbon and Energy of the University of Bath [45]. In particular, the energy coefficients considered are equal to 0.82 MJ/kgr for concrete and 24.35 MJ/kgr for steel (that is the mean value of 27.1 MJ/kgr corresponding to section steel and 21.6 MJ/kgr corresponding to bars & rod for the world typical with 39% recycling material [45]); the CO_2e coefficients considered are equal to 0.124 kgrCO_2e/kgr for concrete and 1.95 kgrCO_2e/kgr for steel (that is the mean value of 1.86 kgrCO_2e/kgr corresponding to section steel and 2.03 kgrCO_2e/kgr corresponding to bars & rod for the world typical with 39% recycling material [45]). The values for concrete correspond to concrete type C28/35 that is considered as a mean material category used for concrete and corresponds to 30% cement replacement with fly ash [45].

In order to underline the significance for adopting optimization procedures in the structural engineering design practice the annual GHG emissions for 24 cities (indicatively selected) around the world in million metric tons of CO_2e is presented in Table 5, obtained by the Carbon Disclosure Project (CDP) open data portal [46]. Indicatively, for the scenario that on average 5% material use reduction is achieved by the 0.50% of CI that implement optimization-based design procedures, the environmental benefit corresponds to reduction of 0.30 million metric tons of CO_2e for year 2016, it can be observed that this mass of CO_2e corresponds to the quantity that cities like Adelaide, Lausanne, Reykjavík or Udine emit annually. Accordingly, for the scenario that on average 10% material use reduction is achieved by the 5% of CI that implement optimization-based design procedures, the environmental benefit corresponds to reduction of 6.04 million metric tons of CO_2e for year 2016, it can be observed that this mass of CO_2e corresponds to the quantity that cities like Athens, Milan, Paris or Pittsburgh emit annually.

The economic impact when adopting design optimization procedures in CI is presented in Table 6, corresponding to annual profit in billion USD. The unit prices that are used for concrete and steel are equal to 200.0 USD/m^3 and 2.3 USD/kgr, respectively, which are rather conservative and correspond to material, labour and rent of equipment costs. While an interest rate equal to 0.75%

that refers to that of US economy for year 2016 according to Focus Economics [47] is used for deriving the present values for years 2030 and 2050. Before discussing the economic benefit that is achieved for the different scenarios implemented in this study, worth mentioning that the market worldwide for the year 2016 was ranging from almost USD 150 to 300 billion and is expected to range from USD 205 to 410 billion for 2030 and from USD 270 to 535 billion for 2050. More specifically, for the scenario that on average 5% material use reduction is achieved by 0.50% of CI that implement optimization-based design procedures, the cost reduction corresponds to USD 0.75 billion for year 2016. Accordingly, for the scenario that on average 10% material use reduction is achieved by 5% of CI that implement optimization-based design procedures, the cost reduction corresponds to USD 15.0 billion for year 2016; it should be underlined that this economic benefit is proportional to 50% of the Gross Domestic Product (GDP) for countries like Azerbaijan, Bulgaria, Croatia, Jordan, Luxembourg or Slovenia for 2016 according to the World Bank [48].

7.2 Real-world design test examples

In order to present the capabilities of computerized structural optimization design procedures, two real-world test examples are considered, a high-rise building and an athletic stadium. More analytical results regarding the environmental impact of design optimization procedures with reference to structural systems of high-rise buildings can be found in the recent work by Lagaros *et al*. [49], where different structural systems of high-rise buildings are compared.

(a)   High-rise building test example

In this part of the study, the high-rise reinforced concrete (RC) building shown in Figure 9 has been considered in order to perform a specially tailored structural based value engineering study. The building, that is to be constructed in the Persian Gulf area, is a 50 storey skyscraper where each storey height is equal to 10.7 meters, resulting into a total height of 535 meters and the dimensions of the building's layout are 50.0 × 50.0 square metres. Figure 9 shows the structural system that was chosen by the designers where outriggers are used every 7 to 17 storeys, i.e. more specifically in storeys 17, 25, 34 and 41. It is a real-world case that due to increased material cost the owners of the building postulated cost reduction, thus the contractors of the owners implemented a value engineering based design process for improving their initial design in terms of material requirements; we took over the structural design optimization part.

The structural system is composed by five types of structural elements: columns, perimeter beams, core shear walls, slabs and outriggers whose reference dimensions are provided in Table 7; the

optimizable dimensions are marked in bold while the rest ones are not allowed to change. Two concrete strength classes are considered depending on the cross-section, C60/75 and C90/105 (characteristic compressive cylindrical strength of 60 and 90 MPa, respectively) and A615GR60 hot rolled reinforced steel rebar (for both longitudinal reinforcement and confinement rebar) with yield strength of 400 MPa are implemented. The lower concrete class (C60/75) is used for the horizontal structural elements (beams and slabs) and the high performance one (C90/105) for the vertical ones (columns, core shear walls and outriggers). The high-rise building of Figure 9, consists of 89,688 shell elements, 32,468 beam elements, 95,211 nodes and 298,161 degrees of freedom. In addition to the self-weight of beams and slabs, distributed permanent load due to floor finishing partitions is considered. In particular, service dead load equal to 2 kN/m^2 and live load equal to 3 kN/m^2 are applied to the slabs of all storeys (i.e. storeys 1 to 50). Wind load is also considered along both horizontal directions (W_x and W_y) and is applied to the perimeter beams. The load is equal to 7.1 kN/m for storeys 1 to 17, 24.3 kN/m for storeys 18 to 34 and 41.6 kN/m for storeys 35 to 50.

The building is optimally designed to meet the ACI 318-11 [50] requirements, while an additional deformation constraint related to the roof displacement is also taken into account (roof displacement < 1.0 meter). For the formulation of the optimization problem the structural members are divided into groups having the same cross-sectional properties. Table 7 provides also information regarding the upper and lower bounds (box constraints) of the design variables (DV_i, i=1,2,…,9). The material cost is considered as the objective function to be minimized. For solving of the optimization problem the Differential Evolution (DE) metaheuristic optimization algorithm is used, as implemented in the OCP optimization software [42]. The optimized design achieved and reference one are presented in Table 7 along with the material cost, energy requirements and GHG CO$_2$ emissions. Comparing the two designs it can be seen that there are differences to almost all the design variables considered to formulate the optimization problem leading to environmental benefit of 11.2% and 12.7% with reference to the energy consumption and GHG CO$_2$ emissions, respectively; on the other hand the cost reduction achieved is of the order of 8%.

(b) *Jinan stadium test example*

The Jinan Olympic Sports Centre Stadium is a multi-use stadium within the Jinan Olympic sports centre in China. The stadium was the main venue for the 2009 National Games of China in October 2009. It had been used for the opening ceremony, soccer matches and athletics events. The structure encompasses a capability for sixty thousand spectators at a construction space of 131,000

square metres and was opened in April 2009. The stadium was designed and constructed by a consortium comprised of ARUP [51] international engineering group, Shandong Tongyuan Design Group Co. and China Construction Design International (CCDI) of Shanghai [52].

The total gross floor area of the Jinan Olympic sports centre is equal to 678,000 square metres where that of the stadium is equal to 154,000 square metres. The stadium height is 52 meters and the structural system is composed mainly by reinforced concrete elements and suspended steel truss members. The structural system is composed by five types of structural elements: columns, beams, shear walls, slabs and truss members whose reference dimensions are provided in Table 8; all dimensions are considered as optimizable. The space frame of the stadium is shown in Figure 10 and consists of 2,792 shell elements, 12,344 beam elements and 7,663 nodes resulting into a FE model with 43,224 degrees of freedom. Two concrete strength classes have been considered depending on the cross-section, C28/35 and C40/50 (characteristic compressive cylindrical strength of 28 and 40 MPa, respectively) and hot rolled reinforced steel rebar with yield strength of 400 MPa were implemented for the longitudinal reinforcement and rebar with yield strength of 235 MPa for the confinement rebar. Medium strength structural steel rods with nominal yield strength of 250 MPa are used for the truss members. Various design combinations are considered, pairing dead, live loads as well as wind and earthquake loading conditions; the latter ones as imposed by the Chinese Design codes [32,53].

The stadium has been optimally designed to meet ACI 318-14 [29] and AISC 360-10 [54], requirements. For the formulation of the optimization problem the members are divided into groups having the same structural properties, resulting into 61 design variables in total. Table 9 provides information regarding the upper and lower bounds (box constraints) of the design variables (DV_i, i=1,2,…,61). Similar to the high-rise building test example, the material cost is considered as the objective function to be minimized. For solving of the optimization problem at hand the Projected Quasi-Newton (PQN) derivative free optimization algorithm is used, as implemented in OCP optimization software [42]. The optimized design achieved and reference one are presented in Table 8 along with the material cost, energy requirements and GHG CO_2 emissions. Comparing the two designs it can be observed that solving the optimization problem led to environmental benefit of 19.2% with respect to both energy consumption and GHG CO_2 emissions, respectively; on the other hand the cost reduction achieved is equal to 19.1%.

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8. CONCLUSIONS

The objective of this work is to present the environmental and economic benefits if design optimization techniques are adopted in structural engineering practice. In this direction, the global market of the main construction material i.e. cement and steel is assessed, deriving the benefits in terms of BTU energy consumption, tons of CO_2e emissions and monetary if specific scenarios of material use reduction and structural optimization technology absorption by the construction industry were realized. In addition, a special topic is devoted related to the integration of the structural optimization by the civil engineering practice; where two real-world design test examples are used to illustrate in numbers the benefits of structural optimization.

It is emphasized that specially tailored software packages will bring optimization methods into the mainstream of structural engineering profession. Particularly, a holistic approach of the structural design optimization framework may be a potential revolution for the structural engineering community. Conveyance of the foremost advanced computational tools to applied structural engineering can facilitate transferring innovation from the research laboratory to the market. This will have a substantial impact on frontier research in the area of structural engineering and presumably act as catalyst for more advancing structural technology and educating future generations of engineers.

Although, practitioners treat new technologies with a lot of scepticism and with doubts regarding the success of their application, the scientific community along with the State need to take actions in order to force the implementation of the new technologies. The scientific community of structural optimization needs to widely act in order to fuel structural engineering practitioners' curiosity and dispel their scepticism with clear explanations and real-world applications. It is always up to the practitioners to accept new design procedures that will result to enormous benefits for the public. However, before practitioners, it is the State that needs to be convinced and force the implementation of optimization technology. The capacity to design structures, with fewer restrictions and by taking into consideration all (or as many as possible) the various factors affecting design, can result in safer, eco-friendly and further economic structures. Society at large will benefit from the implementation of such tools, not solely concerning safety and economy criteria, however mainly from an environmental point of view, since criteria associated with sustainability can also be considered in the problem formulation.

ACKNOWLEDGEMENTS

REFERENCES

1. Edisonian Approach: For more information about the Edisonian approach, visit http://edisonian.weebly.com/the-edisonian-approach.html, (last accessed December 2017).

2. Belegundu, A.D., Arora, J.S. A study of mathematical programming methods for structural optimization. Part I: Theory. *International Journal for Numerical Methods in Engineering*, **21**(9), 1583-1599, 1985.

3. Frangopol, D.M., Maute, K. Life-cycle reliability-based optimization of civil and aerospace structures. *Computers and Structures*, **81**(7), 397-410, 2003.

4. Foley, C.M., Pezeshk, S., Alimoradi, A. Probabilistic performance-based optimal design of steel moment-resisting frames. I: Formulation, *Journal of Structural Engineering*, **133**(6), 757-766, 2007.

5. Kaveh, A., Zakian, P. Optimal design of steel frames under seismic loading using two meta-heuristic algorithms. *Journal of Constructional Steel Research*, **82**, 111-130, 2013.

6. Aldwaik, M., Adeli, H. Advances in optimization of highrise building structures, *Structural and Multidisciplinary Optimization*, **50**(6), 899-919, 2016.

7. Kroiss M., Cremers L. and Evangelou V. Conceptual car design at BMW with focus on NVH performance, *5th ANSA & μETA International Conference*, June 5-7, Thessaloniki, Greece, 2013.

8. A380: http://www.altairproductdesign.com/CaseStudyDetail.aspx?id=10, (last accessed December 2017).

9. USGS, 2017, US Geological Survey - National Minerals Information Center: Cement Statistics and Information, https://minerals.usgs.gov/minerals/pubs/commodity/cement/, (retrieved 1 December 2017).

10. WSA, 50 years of the World Steel Association 1967-2017, World Steel in Figures 2017, https://goo.gl/2GGAkw, (last accessed December 2017).

11. CEMBUREAU, 2016. Cembureau-The European Cement Association, Activity Report 2016, Brussels, Belgium, https://goo.gl/AD4vg2, (last accessed December 2017).

12. Eurostat, 2017, "PRODCOM (PRODuction COMmunautaire) - Statistics by Products", Community Production for mining, quarrying and manufacturing: sections B and C of the Statistical Classification of Economy Activity in the European Union (NACE 2). http://ec.europa.eu/eurostat/web/prodcom/data/database, (retrieved 1st December 2017).

13. EUROFER, 2017, Eurofer-The European Steel Association, Annual Report 2017, Brussels, Belgium, https://goo.gl/zfQM72, (last accessed December 2017)

14. Global Steel, 2014. Planning to profit from opportunity: preparing for future demand, Ernst & Young-Building a better working world, https://goo.gl/XwrM8a, (last accessed December 2017).

15. UNEP, 2016, United Nations Environment Programme, Towards zero-emission efficient and resilient buildings, Global Status Report 2016, prepared by the GABC on the occasion of the 22nd Conference of Parties (COP22) to the United Nations Framework Convention on Climate Change (UNFCCC), https://goo.gl/oWUi3Y, (last accessed December 2017).

16. WSA, Worldsteel Short Range Outlook 2017-2018, World Steel Association, April 2017, https://goo.gl/LcNnwx, (last accessed December 2017).

17. Crow, J.M., The concrete conundrum, *Chemistry World*, 62-66, March 2008.

18. Russo, L. (2004). The forgotten revolution: How science was born in 300BC and why it had to be reborn. Springer, Berlin.

19. Veselago, V.G. Formulating Fermat's principle for light traveling in negative refraction materials. *Physics-Uspekhi*, **45**(10), 1097-1099, 2002.

20. Cauchy, A. Methode generale pour la resolution des systemes d'equations simultanees. *Comptes Rendus Hebd. Seances Acad. Sci.*, **25**, 536-538, 1847.

21. Courant, R. Variational methods for the solution of problems of equilibrium and vibrations. *Bulletin of American, Mathematical Society*, **49**, 1-23, 1943.

22. Dantzig, G. B. Maximization of a linear function of variables subject to linear inequalities. Activity Analysis of Production and Allocation, Koopman (Ed.), Cowles Commission Monograph, 13, John Wiley and Sons, New York, 1951.

23. Karush, W. (1939). Minima of Functions of Several Variables with Inequalities as Side Conditions. MS Thesis, Dept. of Mathematics, University of Chicago, Chicago, IL.

24. Kuhn, H.W., Tucker A.W. Non-linear Programming, in Neyman, J. (Ed.), Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability, University of California Press, Berkeley, CA , pp. 481-493, 1951.

25. Rozvany, G.I.N. Structural Design Via Optimality Criteria. Kluwer, Dordrecht, 1989.

26. Argyris, J.H. Energy theorems and structural analysis: a generalized discourse with applications on energy principles of structural analysis including the effects of temperature and non-linear stress-strain relations Part I. General Theory, *Aircraft Engineering and Aerospace Technology*, **27** (2), 42-58, 1955.

27. Schmit, L. A. Structural Design by Systematic Synthesis, Proceedings of the 2nd Conference on Electronic Computation, ASCE, New York, pp. 105-122, 1960.

28. ANSI/AISC 341. Seismic Provisions for Structural Steel Buildings, AISC 341-10, American Institute of Steel Construction Chicago, IL, 2010.

29. ACI 318-14. Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318M-14), American Concrete Institute (ACI) Committee, Farmington Hills, MI, 2014.

30. EC2. Eurocode 2. Design of concrete structures - part 1-1: general rules and rules for buildings. European Committee for Standardisation Brussels, Belgium: The European Standard EN 1992-1-1, 2004.

31. Committee of Steel Structure: Standard Specifications for Steel and Composite Structures (Design Edition): I General Provision, II Structural Planning, III Design, Japan Society of Civil Engineers (JSCE), First Edition, [in Japanese], December 2009.

32. Code for Seismic Design of Buildings, GB 50011-2010, National Standard of the People's Republic of China, Ministry of Housing and Urban-Rural Development of the Peoples' Republic of China, General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Beijing, [in Chinese], May 2010.

33. Kazakis, G., Kanellopoulos, I., Sotiropoulos, S., Lagaros, N.D., Topology optimization aided structural design: Interpretation, computational aspects and 3D printing, *Heliyon*, 3 (10), Article e00431, 2017.

34. IPCC (2007) Climate change 2007: synthesis report. In: Core Writing Team, Pachauri RK, Reisinger A (eds) Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, Switzerland, 104 pp.

35. ISO 14040: Environmental Management - Life Cycle Assessment-Principles and Framework, International Organization for Standardization (ISO) Geneva, Switzerland, 2006.

36. Ramesh, T., Prakash, R., Shukla, K.K. Life cycle energy analysis of buildings: An overview, *Energy and Buildings*, **42** (10), 1592-1600, 2010.

37. OptiStruct: http://www.altairhyperworks.com/product/OptiStruct/, (last accessed December 2017).

38. Tosca: https://www.3ds.com/products-services/simulia/products/tosca/, (last accessed December 2017).

39. Ansys topology optimization: http://www.ansys.com/products/structures/topology-optimization, (last accessed December 2017).

40. MIDAS NFX topology optimization capability: https://goo.gl/WHj8xs, (last accessed December 2017).

41. SCIA Engineer optimizer: Automatic Optimization of Civil Engineering Structures, https://goo.gl/PNTVKM, (last accessed December 2017).

42. OCP: The world's first optimization computing platform for structural engineering, https://goo.gl/pgkEf7, (last accessed December 2017).

43. Lagaros, N.D. A general purpose real-world structural design optimization computing platform, *Structural and Multidisciplinary Optimization*, **49**, 1047-1066, 2014.

44. PCA: America's Cement Manufacturers – How concrete is made, http://www.cement.org/cement-concrete-applications/how-concrete-is-made, (last accessed December 2017).

45. Hammond, G., Jones, C. Inventory of Carbon Energy (ICE), Department of Mechanical Engineering, University of Bath, Version 6.1, 2008.

46. CDP, 2016, Carbon Disclosure Project (CDP) open data portal - Citywide Emissions Map, https://data.cdp.net/Cities/2016-Citywide-Emissions-Map/iqbu-zjaj, (retrieved 1st December 2017).

47. Focus Economics, Policy Interest Rates for 2016, https://www.focus-economics.com/economic-indicator/policy-interest-rate, (last accessed December 2017).

48. The World Bank, World Bank national accounts data and OECD National Accounts data files, GDP in USD for 2016, https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?year_high_desc=true, (retrieved 1st December 2017).

49. Lagaros, N.D., Mavrokapnidis, D., Mitropoulou, C.C., Energy assessment of optimized high-rise buildings' structural systems, *Energy and Buildings*, to appear 2018.

50. ACI 318-11. Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary (ACI 318R-11), American Concrete Institute (ACI) Committee, Farmington Hills, MI, 2011.

51. ARUP, http://www.arup.com/, (last accessed December 2017).

52. CCDI Group, China Construction Design International, http://www.ccdi.com.cn, (last accessed December 2017).

53. Load Code for the Design of Building Structures, GB 50009-2012, National Standard of the People's Republic of China, Ministry of Housing and Urban-Rural Development of the Peoples' Republic of China, General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Beijing, [in Chinese], October 2012.

54. ANSI/AISC 360. Specification for Structural Steel Buildings, AISC 360-10, American Institute of Steel Construction Chicago, IL, 2010.

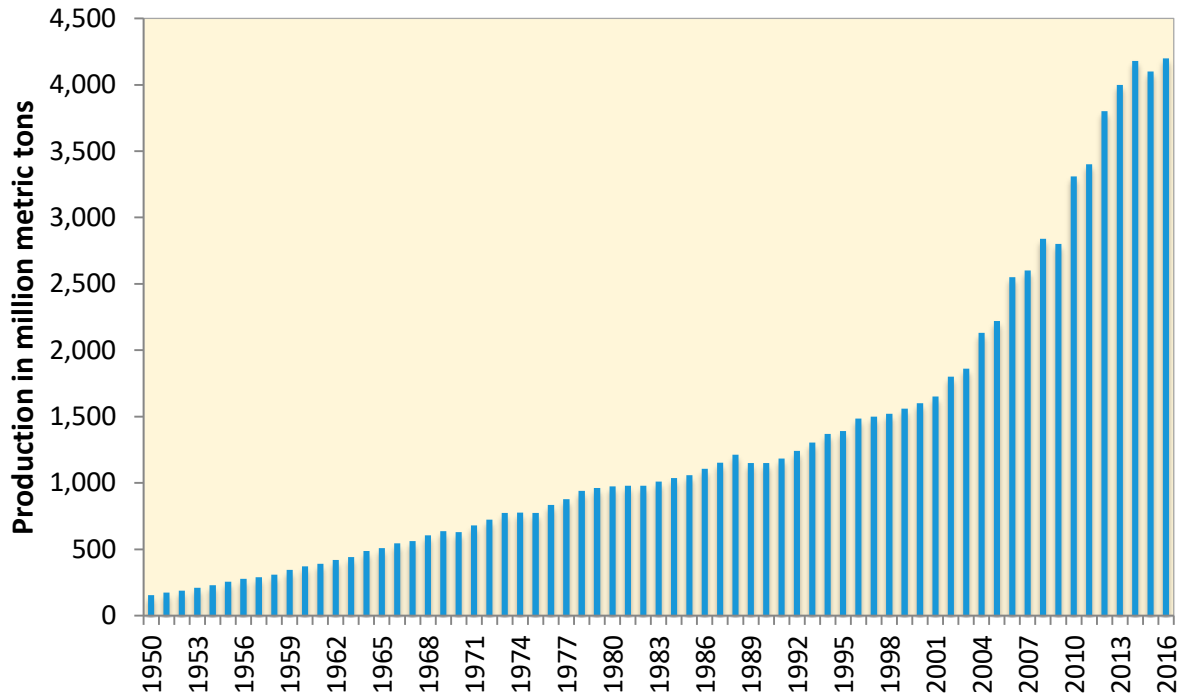**Figure 1.** Total worldwide cement production 1950-2016.

(a)

(b)

(c)

Figure 2. Major countries in worldwide cement production: (a) 563 million metric tons for year 1967, (b) 1,600 million metric tons for year 2000 and (c) 4,200 million metric tons for year 2016.

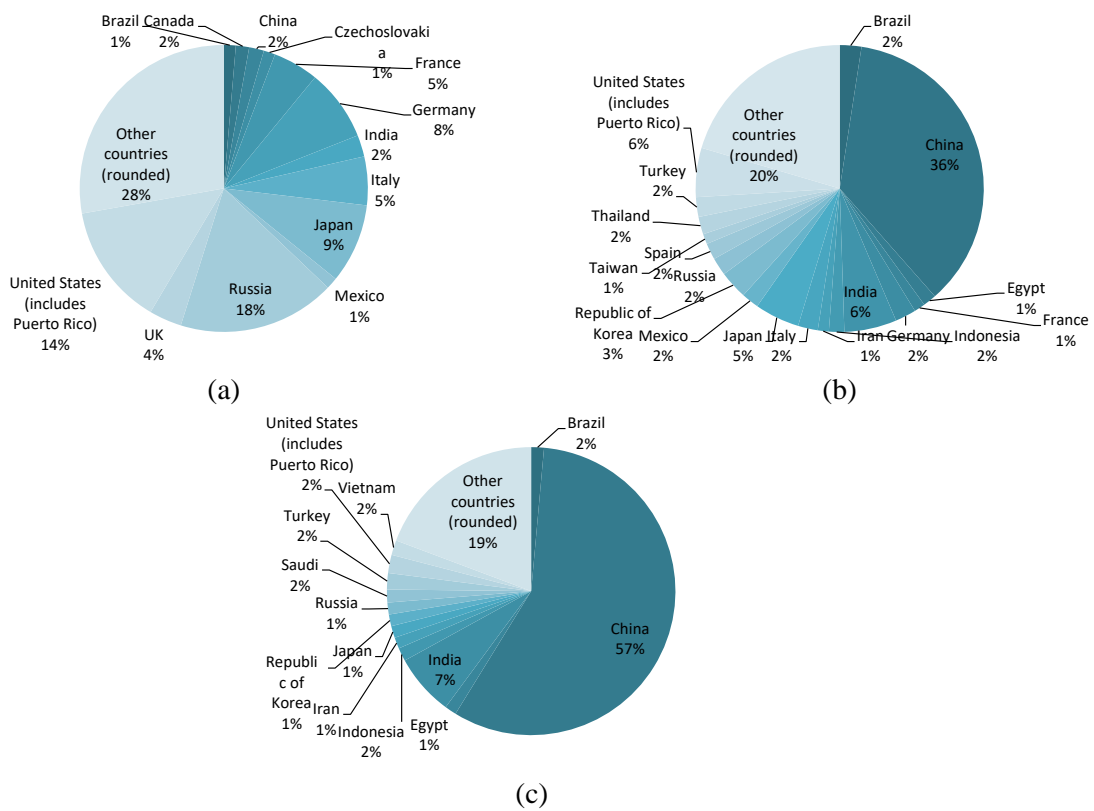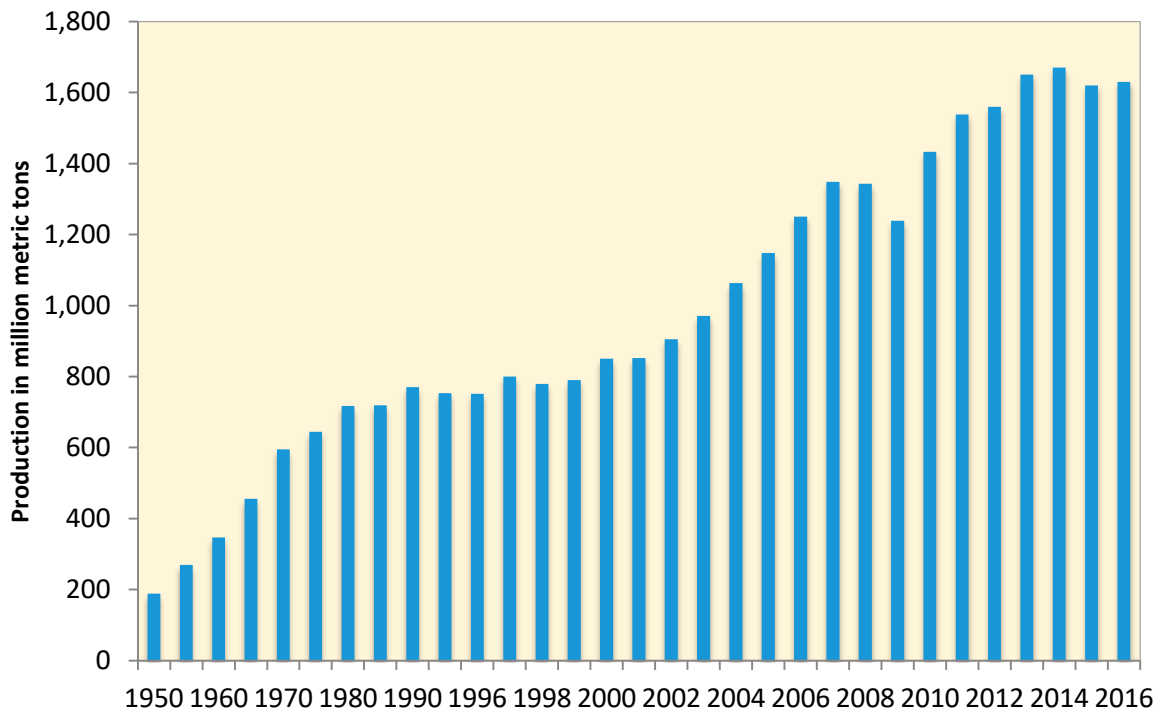**Figure 3.** Total worldwide steel production 1950-2016.

(a)

(b)

(c)
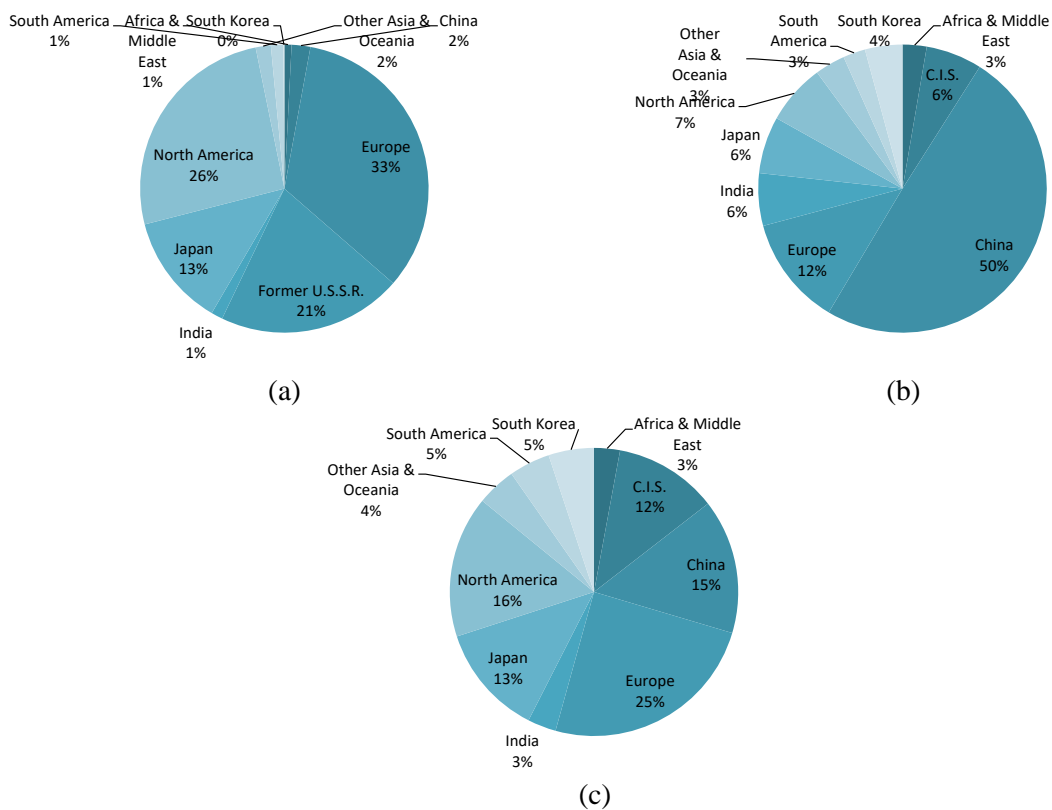
Figure 4. Major countries in worldwide steel production: (a) 493 million metric tons for year 1967, (b) 850 million metric tons for year 2000 and (c) 1,630 million metric tons for year 2016.
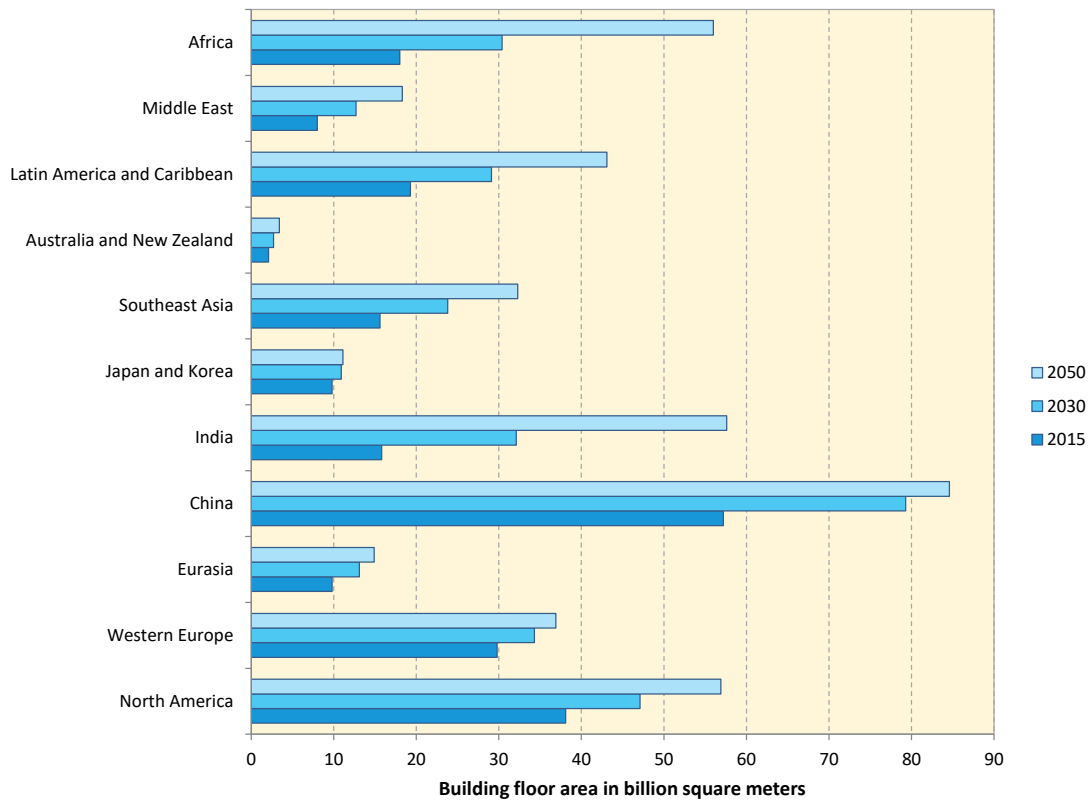
Figure 5. Estimates of the building floor area growth for years 2015, 2030 and 2050 by region according to United Nations Environment Programme (UNEP).
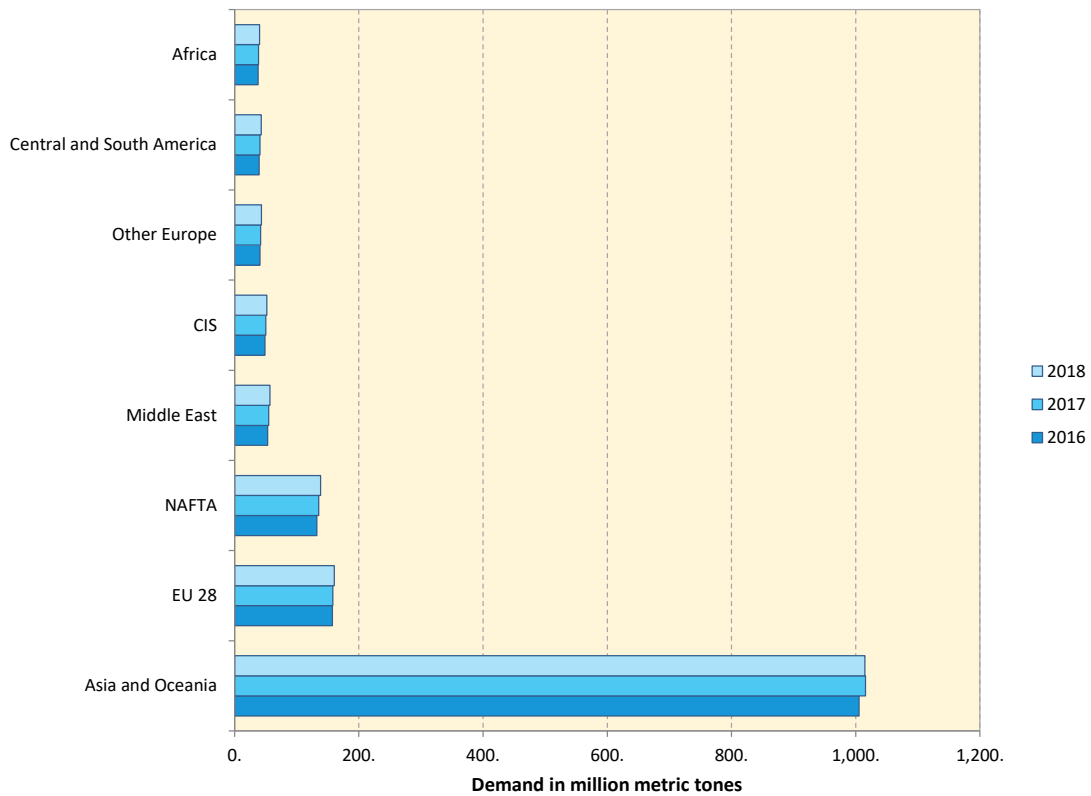
Figure 6. Estimated demand for steel worldwide between 2016 and 2018, by region. The values refer to finished steel products, and the quantities for 2017 and 2018 are projections.
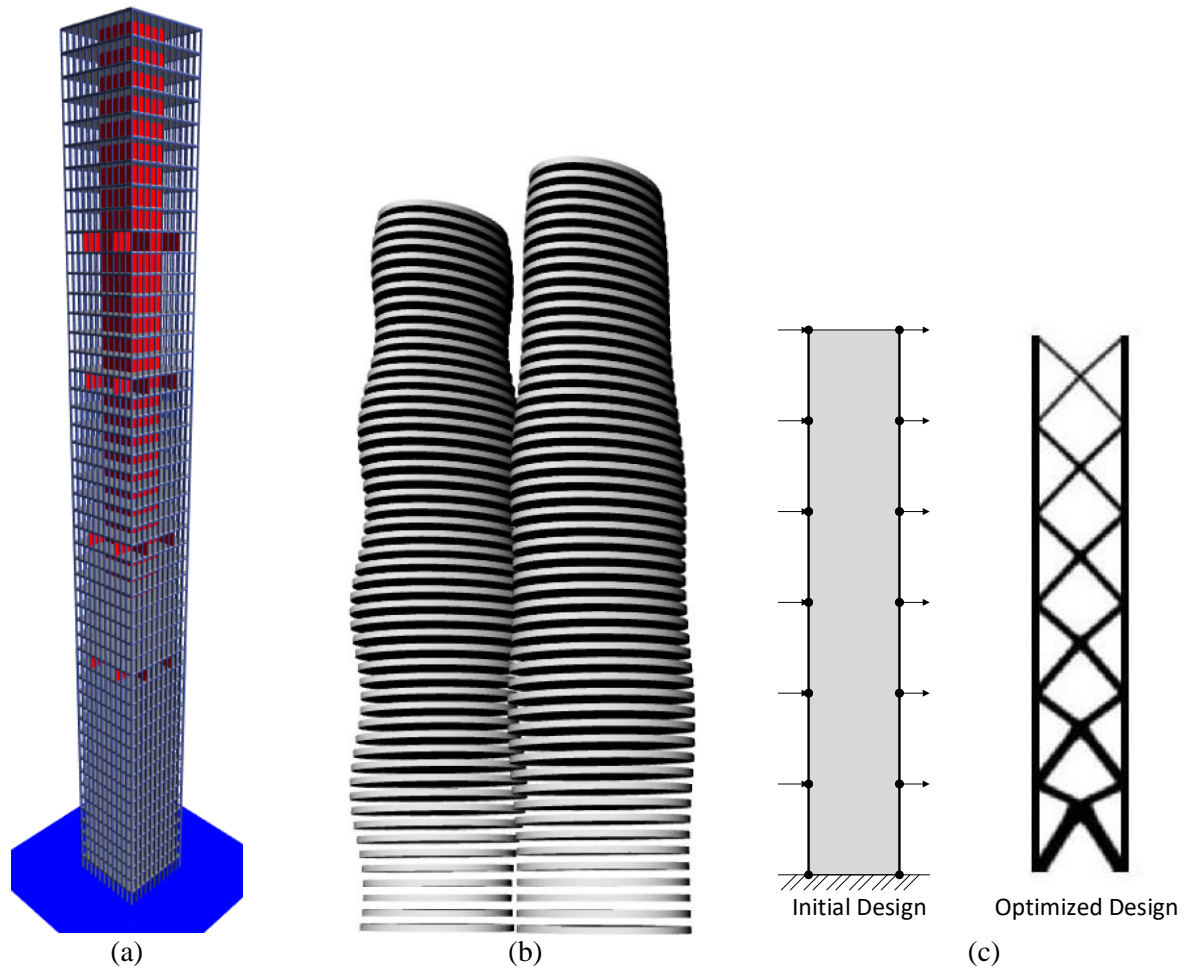
Figure 7. The three classes of structural optimization: (a) sizing (structural elements of the skyscraper structural system), (b) shape (parametric design of a tower) and (c) topology (initial vs optimized design).
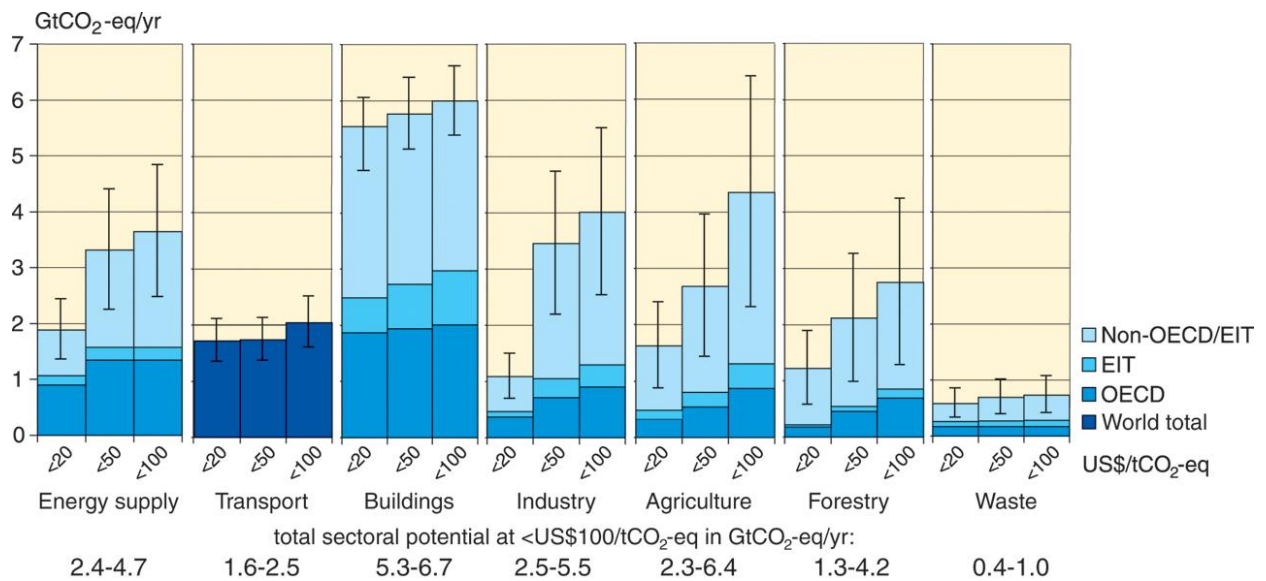
Figure 8. Estimated economic mitigation potential by sector and region using technologies and practices expected to be available in 2030. The potentials do not include non-technical options such as lifestyle changes [34].
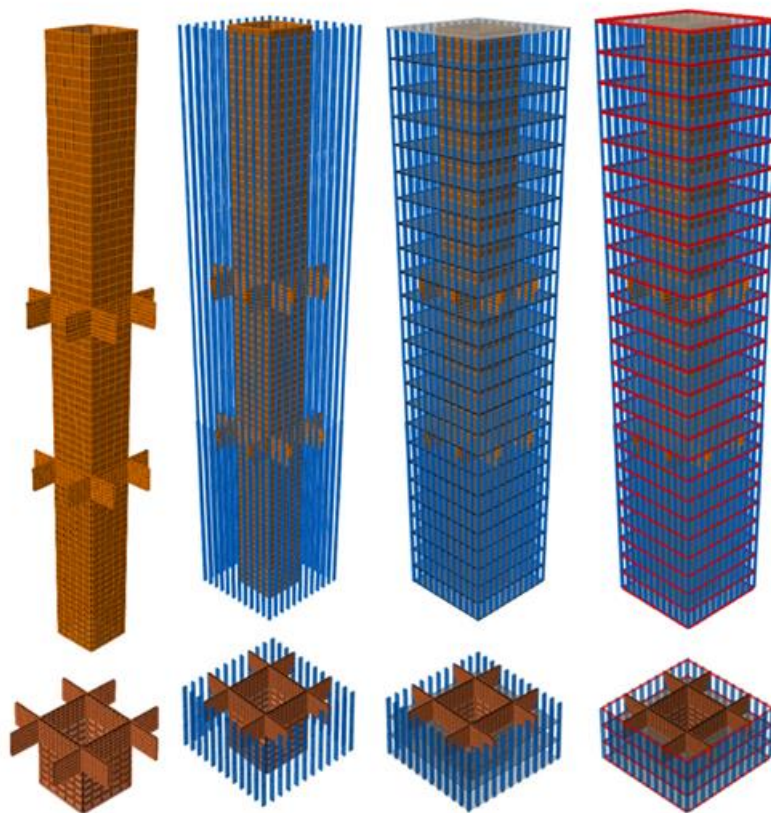
Figure 9. High-rise building structural system.

(a)

(b)
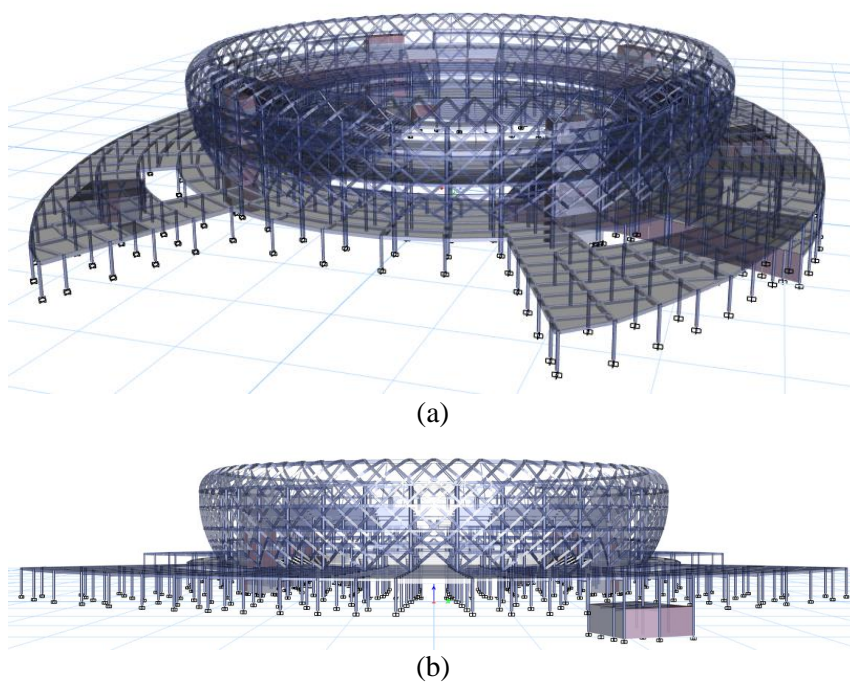
Figure 10. Jinan stadium structural system: (a) panoramic and (b) side view.

TABLES

Year	Floor Area (billion m²)	Production (million tons)		Usage in buildings (million tons)	
		Cement	Steel	Concrete	Steel
2015	223.50	4100.0	1620.0	24600.0	340.2
2016	232.36	4200.0	1630.0	25200.0	342.3
2030	315.50	5787.7	2286.8	34726.2	480.2
2050	415.10	7614.8	2911.9	45688.9	611.5

Table 1. The building floor area (in billion m²), annual material production and use for building construction (in million tons).

| Year	Usage reduction	Material	CI market (%)		
			0.10%	0.50%	5.00%
2016	5.00%	Concrete (million m³)	0.53	2.63	26.25
		Steel (million kgr)	17.12	85.58	855.75
	10.00%	Concrete (million m³)	1.05	5.25	52.50
		Steel (million kgr)	34.23	171.15	1711.50
2030	5.00%	Concrete (million m³)	0.72	3.62	36.17
		Steel (million kgr)	24.01	120.06	1200.59
	10.00%	Concrete (million m³)	1.45	7.23	72.35
		Steel (million kgr)	48.02	240.12	2401.19
2050	5.00%	Concrete (million m³)	0.95	4.76	47.59
		Steel (million kgr)	30.57	152.87	1528.75
	10.00%	Concrete (million m³)	1.90	9.52	95.19
		Steel (million kgr)	61.15	305.75	3057.49

Table 2. The reduction on the annual material demand for building construction in million m³ of concrete and million kgr of steel; for different scenarios on average material use reduction achieved and percentage of optimization-based design technology by CI.

Year	Usage reduction	CI market (%)		
		0.10%	0.50%	5.00%
2016	5.00%	0.57	2.83	28.25
	10.00%	1.13	5.65	56.50
2030	5.00%	0.79	3.94	39.42
	10.00%	1.58	7.88	78.85
2050	5.00%	1.01	5.07	50.69
	10.00%	2.03	10.14	101.39

Table 3. The annual environmental benefit achieved in terms of energy consumption due to the material use reduction (in trillion BTU); for different scenarios on average material use reduction achieved and percentage of optimization-based design technology by CI.

Year	Usage reduction	CI market (%)		
		0.10%	0.50%	5.00%
2016	5.00%	0.06	0.30	3.02
	10.00%	0.12	0.60	6.04
2030	5.00%	0.08	0.42	4.20
	10.00%	0.17	0.84	8.41
2050	5.00%	0.11	0.54	5.43
	10.00%	0.22	1.09	10.86

Table 4. The annual environmental benefit achieved in terms of GHG emissions due to the material use reduction (in million metric tons of CO_2e); for different scenarios on average material use reduction achieved and percentage of optimization-based design technology by CI.

City	Million metric tons CO_2e	City	Million metric tons CO_2e	City	Million metric tons CO_2e
Adelaide	0.49	Madrid	10.26	Rotterdam	31.51
Athens	4.71	Milan	5.98	Tokyo	70.13
Boulder	1.72	New York City	49.39	Toronto	18.32
Chicago	33.50	Paris	5.20	Udine	0.61
Lausanne	0.50	Pittsburgh	4.80	Venetia	1.42
Lisbon	1.93	Porto	1.02	Wellington	1.08
London	40.19	Reykjavík	0.35	Zaragoza	1.79
Los Angeles	29.02	Rome	10.01	Zurich	1.82

Table 5. The annual GHG emissions per city (in million metric tons of CO_2e).

Year	Usage reduction	CI market (%)		
		0.10%	0.50%	5.00%
2016	5.00%	0.15	0.74	7.39
	10.00%	0.30	1.48	14.78
2030	5.00%	0.23	1.13	11.28
	10.00%	0.45	2.26	22.56
2050	5.00%	0.34	1.71	17.07
	10.00%	0.68	3.41	34.14

Table 6. The annual economic profit achieved due to the material use reduction (in billion USD); for different scenarios on average material use reduction achieved and percentage of optimization-based design technology by CI.

Structural elements	Concrete type	Storey	Box Constraints / Step	Reference Design	Optimized Design
Columns	C90/105	1 to 17	$800\ mm \leq DV_i \leq 2100\ mm$ ($i = 1,2,3$), $step = 50$mm	**1800** (DV1) $\times$ 800	**2000** $\times$ 800
		18 to 34		**1400** (DV2) $\times$ 800	**1800** $\times$ 800
		35 to 50		**800** (DV3) $\times$ 800	**1100** $\times$ 800
Perimeter Beams	C60/75	1 to 17	$150\ mm \leq DV_i \leq 800\ mm$ ($i = 7,8,9$), $step = 50$mm	900 $\times$ **700** (DV7)	900 $\times$ **300**
		18 to 34		900 $\times$ **700** (DV8)	900 $\times$ **300**
		35 to 50		900 $\times$ **700** (DV9)	900 $\times$ **300**
Core Shear Walls	C90/105	1 to 17	$800\ mm \leq DV_i$ ($i = 4,5,6$), $step = 100$mm	**1600** (DV4)	**1500**
		18 to 34		**1400** (DV5)	**900**
		35 to 50		**1000** (DV6)	**800**
Slabs	C60/75	1 to 17	-	400	400
		18 to 34			
		35 to 50			
Outriggers	C90/105	17	-	1200	1200
		25			
		34			
		41			
GHG emissions (million metric tons of CO_2e)				93.3	81.4
Energy consumption (trillion BTU)				0.747	0.664
Cost (million USD)				83.3	76.5

Table 7. High-rise building test example: reference and optimized designs (dimensions of cross-sections in mm).

Structural elements	Material type	Storey	Reference Design	Optimized Design
Columns	C40/50	COL1	600 (DV1) × 400 (DV2)	750 × 300
		COL2	500 (DV3) × 500 (DV4)	500 × 600
		COL3	600 (DV5)	600
		COL4	1000 (DV6)	700
		COL5	1100 (DV7)	1300
		COL6	700 (DV8)	500
		COL7	800 (DV9)	900
Beams	C28/35	BM1	500 (DV10) × 600 (DV11)	650 × 700
		BM2	800 (DV12) × 1200 (DV13)	650 × 1100
		BM3	600 (DV14) × 600 (DV15)	400 × 400
		BM4	600 (DV16) × 500 (DV17)	450 × 600
		BM5	700 (DV18) × 400 (DV19)	500 × 300
		BM6	600 (DV20) × 400 (DV21)	600 × 400
		BM7	600 (DV22) × 200 (DV23)	600 × 300
		BM8	700 (DV24) × 1000 (DV25)	870 × 900
		BM9	700 (DV26) × 600 (DV27)	800 × 700
		BM10	800 (DV28) × 1000 (DV29)	800 × 700
		BM11	700 (DV30) × 500 (DV31)	800 × 600
		BM12	1000 (DV32) × 1000 (DV33)	800 × 800
		BM13	700 (DV34) × 800 (DV35)	700 × 800
		BM14	900 (DV36) × 600 (DV37)	800 × 700
		BM15	800 (DV38) × 500 (DV39)	900 × 600
		BM16	500 (DV40) × 500 (DV41)	400 × 600
		BM17	1000 (DV42) × 600 (DV43)	1100 × 400
		BM18	600 (DV44) × 300 (DV45)	600 × 200
		BM19	700 (DV46) × 300 (DV47)	600 × 200
		BM20	700 (DV48) × 200 (DV49)	700 × 200
		BM21	500 (DV50) × 350 (DV51)	550 × 350
		BM22	500 (DV52) × 300 (DV53)	600 × 400
		BM23	300 (DV54) × 300 (DV55)	250 × 200
Shear Walls	C28/35	SW1	120 (DV56)	100
		SW2	300 (DV57)	200
Slabs	C28/35	SL1	120 (DV58)	80
		SL2	150 (DV59)	150
		SL3	200 (DV60)	180
Truss Elements	S250	TR1	100	120
GHG emissions (million metric tons of CO_2e)			5.8	4.7
Energy consumption (trillion BTU)			3.78E-02	3.05E-02
Cost (million USD)			7.3	5.9

Table 8. Jinan stadium test example: reference and optimized designs (dimensions of cross-sections in mm).

Cross Section	Lower (mm)	Upper (mm)	Step (mm)	Lower (mm)	Upper (mm)	Step (mm)
Columns						
DV1 × DV2	500	750	50	300	500	50
DV3 × DV4	300	650	50	300	650	50
DV5	400	750	50			
DV6	650	1300	50			
DV7	750	1400	50			
DV8	450	900	50			
DV9	250	500	50			
Beams						
DV10 × DV11	300	650	50	400	750	50
DV12 × DV13	500	1050	50	800	1550	50
DV14 × DV15	400	750	50	400	750	50
DV16 × DV17	400	750	50	300	650	50
DV18 × DV19	450	900	50	250	500	50
DV20 × DV21	400	750	50	250	500	50
DV22 × DV23	400	750	50	200	250	50
DV24 × DV25	450	900	50	650	1300	50
DV26 × DV27	450	900	50	400	750	50
DV28 × DV29	500	1050	50	650	1300	50
DV30 × DV31	450	900	50	300	650	50
DV32 × DV33	650	1300	50	650	1300	50
DV34 × DV35	450	900	50	500	1050	50
DV36 × DV37	600	1150	50	400	750	50
DV38 × DV39	500	1050	50	300	650	50
DV40 × DV41	300	650	50	300	650	50
DV42 × DV43	650	1300	50	400	750	50
DV44 × DV45	400	750	50	200	400	50
DV46 × DV47	450	900	50	200	400	50
DV48 × DV49	450	900	50	200	250	50
DV50 × DV51	300	650	50	200	450	50
DV52 × DV53	300	650	50	250	400	50
DV54 × DV55	200	400	50	200	400	50
Shear Walls						
DV56	70	160	10			
DV57	200	400	10			
Slabs						
DV58	70	160	10			
DV59	90	200	10			
DV60	120	270	10			
Truss Elements						
DV61	50	140	10			

Table 9. Jinan stadium test example: box constraints (dimensions in mm).