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MULTI-OBJECTIVE GREEN DESIGN MODEL BASED ON COSTS, CO_2 EMISSIONS AND SERVICEABILITY FOR HIGH-RISE BUILDINGS WITH A MEGA-STRUCTURE SYSTEM

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Abstract. In light of growing environmental concerns, the reduction of CO_2 emissions is increasingly vital. Particularly in the construction industry, a major contributor to global carbon emissions, addressing this issue is critical for environmental sustainability and mitigating the accelerating impacts of climate change. This study proposes the Optimal Green Design Model for Mega Structures (OGDMM) to optimise CO_2 emissions, cost-effectiveness, and serviceability in high-rise buildings with mega structures. The OGDMM examines the impact of each material and structural design of main members on these three critical aspects. Analytical results for high-rise buildings (120–200 m, slenderness ratio: 2.0–8.0) demonstrate that OGDMM can reduce CO_2 emissions and costs by an average of 4.67% and 3.97%, respectively, without compromising serviceability. To ensure comprehensive evaluation, this study introduces five new evaluation indicators encompassing environmental, economic, and serviceability performances of high-rise buildings. Based on these criteria, optimised structural designs for high-rise buildings are classified into four categories according to slenderness ratio, leading to the formulation of corresponding design guidelines. The model's applicability is further validated through its application to a 270-m-tall high-rise building in Korea, showing reductions in CO_2 emissions and costs by 8.99% and 18.50%, respectively, while maintaining structural serviceability.

Keywords: structural optimisation, green design, high-rise building, mega-structure system, serviceability.

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1. Introduction

The world became aware of global warming in the 1950s; since then, this phenomenon has been established as a major issue in the global environment. The National Climatic Data Centre of the National Oceanic and Atmospheric Administration [NOAA] reported that the average global surface temperature has increased by an average of 0.07 °C every decade, and the global sea level has risen by ~21–24 cm since 1880 (NOAA, 2019, 2020). To combat these issues, efforts to reduce carbon dioxide (CO_2) emissions (which are the primary cause of global warming) are being pursued in various industries, including the construction sector. The United Nations Environment Program [UNEP] reported in 2018 that building usage and construction account for 36% of CO_2 emissions from all industries, with 30% emitted from buildings and 6% emitted during construction (UNEP, 2018). This is the largest contributor to CO_2 emissions of any industry, underscoring the importance of reducing emissions in the construction sector (Peng & Stewart, 2016; Du & Karoumi, 2014).

Studies on the reduction of CO_2 emissions from buildings and construction processes have been conducted in various fields of the construction industry (e.g., materials, construction, and maintenance). CO_2 emissions from the construction process account for 6% of those of all industries (as reported by UNEP), which includes environmental impact from building materials (e.g., rebars, cement, and glass) (UNEP, 2018). In addition, Zhang and Wang (2016) analysed CO_2 emissions across building life cycles (i.e., from the production and transport of building materials to the construction, operation, and demolition of the finished building) from 2005 to 2012. They found that CO_2 emissions from the building material production process accounted for 73% of the construction sector's CO_2 emissions. Thus, efforts to reduce CO_2 emissions in building construction have been made across various areas in the past years, including structural system and envelope design, eco-friendly materials, facilities, material manufacturing, and maintenance (Wang & Adeli, 2014; Koo et al., 2015; Migilinskas et al., 2016; De la Fuente et al., 2017; Yi et al., 2017; Ashrafi et al., 2013; Bae et al., 2020; Gschösser et al., 2014; Peñaloza et al., 2018; Kim et al., 2015; González & Navarro, 2006).

Meanwhile, the UNEP report (UNEP, 2018) and the study by Zhang and Wang (2016) showed that CO_2 emissions from building materials contributed ~4.38% of the emissions from all industries. Therefore, further studies into the reduction of CO_2 emissions via less wasteful building designs (i.e., studies into sustainable designs that consider CO_2 emissions) are critically important. Research on reducing CO_2 emissions through structural design initially began with attempts similar to optimising material quantities for cost-effectiveness. Paya-Zaforteza et al. (2009) proposed a methodology using simulated annealing (SA) to optimise frame design in reinforced concrete (RC) buildings. Applied to typical building frames of eight stories, the methodology showed a potential reduction of up to 3.8% in CO_2 emissions, although construction costs increased by 2.77%. Yeo and Gabbai (2011) illustrated the potential benefit of structural optimisation for embodied energy in RC structures. Their numerical analysis optimised an RC structure to decrease embodied energy by about 10% while increasing costs by 5%. These studies suggest that composite structural systems can minimise carbon emissions while maintain the same structural performance through a combination of different elements, even if construction costs increase.

While earlier studies made significant strides, they often overlooked the trade-off relationship between the cost of construction and CO_2 emissions. Minimising CO_2 emissions and reducing the construction time and cost simultaneously is challenging due to their trade-off relationship, where decreasing one tends to increase the other (Thu Bui & Alam, 2008). Consequently, various studies have aimed to balance both environmental impacts and costs. Park et al. (2014) provided design guidelines for reducing both CO_2 emissions and costs associated with structural materials during the structural design phase of RC columns. Their parametric study investigated the impact of design factors on CO_2 emissions and costs. Camp and Huq (2013) optimised CO_2 emissions and costs in RC frames and compared the performance of a hybrid big bang-big crunch algorithm with SA and genetic algorithm (GA). Choi et al. (2019) proposed a multi-objective green design model based on GA for mega columns in high-rise buildings, analyzing the impact of changes in required axial load and moment on each design parameter for green structural design, and proposed corresponding design guidelines. Lee et al. (2020) proposed a multi-objective sustainable design model integrating CO_2 emissions and costs for slabs in office buildings. An et al. (2019) proposed a sustainable design model for the core walls of office buildings with slenderness ratios ranging from 2.93–4.93, further analyzing the impact of changes in core wall structural design and building heights on CO_2 emissions and costs. As studies continue to report on green design analyses for various structural systems and the application of different optimisation techniques, research in structural optimisation considering environmental impacts remains an active area. Recently, there has been increased research interest on green structural design in approaches using heuristic techniques such as GA, SA, evolutionary computation, and differential evolution, as well as machine learning applications (Zhan et al., 2024; Chen et al., 2023; Farahzadi & Kioumarsi, 2023; Kaveh et al., 2020; Eleftheriadis et al., 2018; Kanyilmaz et al., 2022; Gan et al., 2019).

However, in terms of the target structures, the above-mentioned studies have primarily focused on optimising the design of specific structural elements (e.g., columns and beams), considering mostly the environmental impact of structures. A few studies have been reported on RC or steel frames; however, the combined effects of different structural systems in real structures have not been analysed in detail. When designing the structural system for a building, the structural system's load-bearing capacity (which considers the interaction between elements) and resistance to deformation are secured before designing each element individually. Hence, research into the reduction of both CO_2 emissions and cost for an entire building structure (wherein the interaction between elements is considered instead of the design of individual elements) is required.

Recently, various types of high-rise structural systems have been applied in the design and construction of high-rise buildings as the number of such buildings being built (e.g., high-rise towers with a height of more than 500 m) continues to increase. Research on the structural design of high-rise buildings has mostly focused on cost and structural safety (Mavrokapnidis et al., 2019). However, the construction cases of complex structural systems (e.g., tube structures, outrigger systems, and mega-structure system) have increased. Among these structural systems for high-rise buildings, the mega-structure system adopts large columns, core walls, and outriggers as major structural elements. In general, four or eight mega columns are placed at the outer periphery of the structure on a typical floor plan, and the core walls (located inside of the floor plan) are connected to the mega columns via outriggers. The system is a complex three-dimensional (3D) structural system wherein the load placed upon the small columns located at the outer periphery is transmitted to the mega columns via the belt truss. However, previous studies on the reduction of CO_2 emissions and costs for the major structural elements of the mega structure (e.g., mega columns and walls) focused on simple elements while neglecting the interactions between them. Moreover, studies on optimising structural systems for high-rise buildings have mostly focused on strength or stiffness design (Choi et al., 2017; Park et al., 2013; An et al., 2019; Oh et al., 2017).

However, most high-rise building structural designs are separated according to the slenderness ratio into strength (slenderness ratio: 2.0–5.0) and stiffness (slenderness ratio: 5.0–8.0) designs; hence, eco-friendliness and economic efficiency design indictors are neglected. CO_2 emissions and cost increase in proportion to the amount of materials used in the building; hence, optimisation designs that consider these metrics in the design of the entire structure for high-rise buildings (which requires large amounts of materials) are required.

For efficient and applicable green design optimisation of mega-structure systems, the entire system for buildings, including the interaction between individual members, should be considered, and not just the design of individual members. Moreover, the experimental results of the studies on multi-objective green design showed that the trend of the optimal designs can vary significantly for each member or system (Choi et al., 2023). However, to the best of the authors' knowledge, multi-objective optimisation techniques for the entire mega-structure systems in high-rise buildings have rarely been reported. Moreover, serviceability is one of the most critical issues in high-rise buildings (Li et al., 2004; Choi et al., 2022). Therefore, the design of high-rise buildings should not only consider the structural safety of each member, but also the serviceability of the entire system. In their study on the sustainable design model for core walls, An et al. (2019) considered only serviceability by limiting the displacement at the top floor of the building to 1/500 of the total building height. Thus, most studies on multi-objective optimisation of high-rise buildings limit the displacement of the top floor to 1/400 or 1/500 of the total building height. Although additional top floor displacement control can further mitigate serviceability issues, few studies have considered serviceability as well as CO_2 emissions and costs of the entire system for high-rise buildings.

In this study, an optimal green design model for mega structures (OGDMM) was proposed. The proposed OGDMM yields a multi-objective optimal design solution that increases the eco-friendliness and economic efficiency of a mega structure through efficient structural design, whilst minimising the structure's CO_2 emissions and cost by optimising the amount of material required for construction. In addition, the interaction of the entire structural system is considered and optimised to overcome the limitation of existing approaches where only each local member is optimised. The optimised structural designs of high-rise buildings with a mega-structural system having the slenderness ratios of 2.0–8.0 are obtained using the proposed model, and the effects of the strength and size of each material and the sectional design of each member on the CO_2 emissions and costs of the entire system are analysed. Furthermore, new evaluation indicators are proposed to consider the serviceability of high-rise buildings. Based on the proposed technique, four design areas are proposed in which environmental performance, economic performance, and serviceability are considered simultaneously. Mega-structure systems in high-rise buildings are classified into strength and stiffness designs via the slenderness ratio to propose new design guidelines sensitive to the slenderness ratio and consider building eco-friendliness and economic and serviceability efficiency. Finally, to verify the applicability of this technique, the OGDMM was applied to actual high-rise buildings, and the performance of the model is evaluated through the optimal green designs presented from this approach.

2. Configuration of the optimal green design model for mega structures (OGDMM)

In this study, the OGDMM was applied to derive optimal design solutions that minimise both the cost and CO_2 emissions of a high-rise building with a mega structure. This section describes the design variables, constraints, and objective functions required to configure the OGDMM, as well as the OGDMM algorithm (a multi-objective optimisation model) itself.

2.1. Design variables

A mega structure is a representative structure system used for high-rise buildings (Chung & Yoo, 2019). Figure 1 shows a typical mega-structure building form. The structural system is composed of eight mega columns (placed at the outer periphery), internal shear core walls, and connecting outriggers. In this study, only the mega columns,

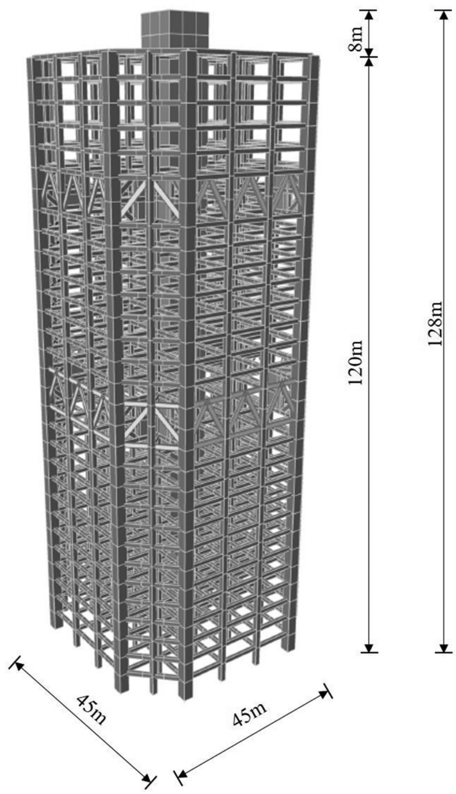

Figure 1. 3D example of mega-structure system in high-rise buildings

shear core walls, and outriggers marked in Figure 2 are considered as the design variables of the optimisation target; the remaining frames and non-structural materials (e.g., internal columns, beams, and slabs) are excluded. Here, H represents the total height of the building and B represents the width. Furthermore, B_w and S_c denote the width of a shear core wall and the distance between the centres of the outer columns, respectively.

Among the characteristics of a mega structure, the CO_2 emissions are most heavily influenced by the mega-column diameter of the columns, shear core wall thickness, number of outriggers, compressive strength of the concrete, and yield strength of the rebars. These were selected as shown in Figure 3.

In Figure 3a, D_c, D_{s1}, and D_{s2} denote the diameters of the rebars used in the columns and those placed horizontally and vertically in the shear core walls, respectively. The yield strength of D_c is F_{yr_c} and those of D_{s1} and D_{s2} are F_{yr_w}. Furthermore, the compressive strength of the concrete used in the column (shown in Figure 3a), shear core wall (shown in Figure 3b), and outrigger wall (shown in Figure 3c) is f_{ck}. In Figure 3b, p_1 and p_2 are the spacings between the rebars placed horizontally and vertically in the shear core wall. The dimensions of the H-beam in the column are ($H_c \times B_c \times t1_c \times t2_c$) (height, width, web thickness, and flange thickness, respectively) and its yield strength is F_{yr_c}. The dimensions and strength of the H-beams employed as outriggers are similarly expressed as ($H_o \times B_o \times t1_o \times t2_o$) and F_{yr_o}, respectively. Furthermore, T_w and L_c denote the thickness of the shear core wall and the width of the column, respectively. In this instance, the column was specified as a square. The number of floors upon which outriggers are installed is expressed as N (as shown in Figure 2a). Table 1 shows the detailed application ranges of each design variable. The number of floors with outriggers was set as either 1, 2, or 3. In each case, the location with a minimum lateral displacement at the top of a building was designated as the location of floors

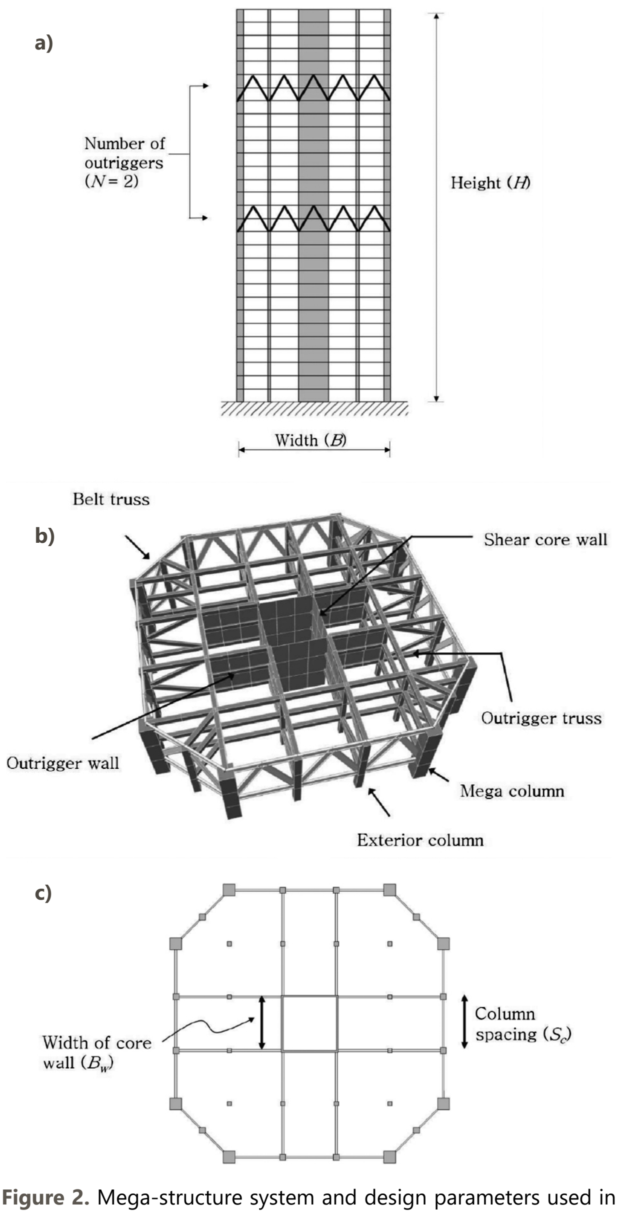

Figure 2. Mega-structure system and design parameters used in this study: illustration for a – sectional view of a mega structure; b – shear core wall, outrigger, mega columns, and c – floor plan of mega structure

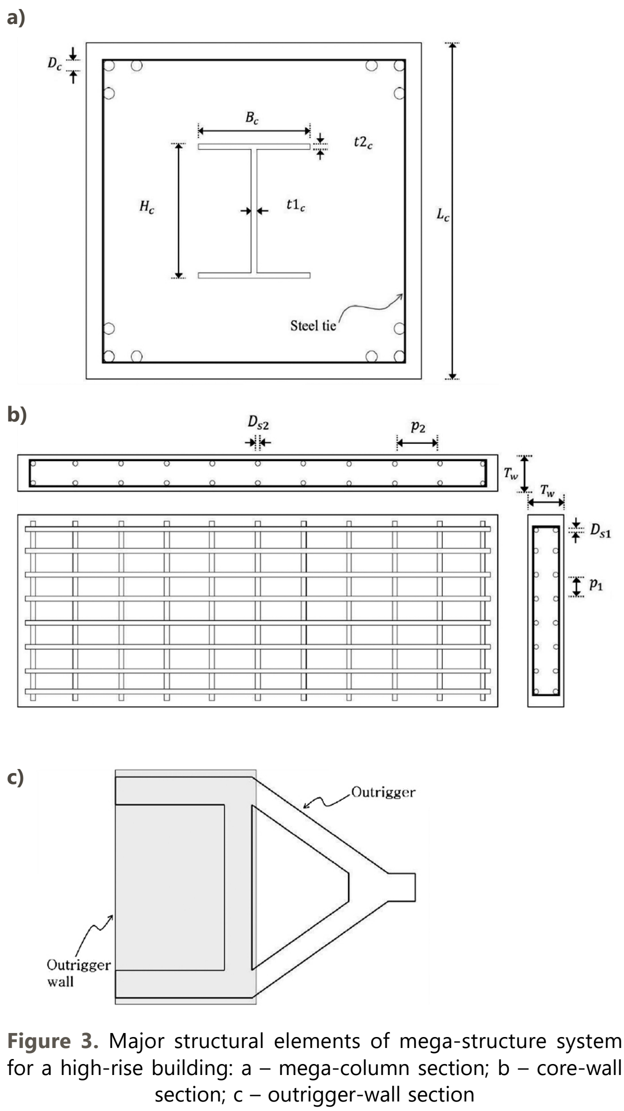

Figure 3. Major structural elements of mega-structure system for a high-rise building: a – mega-column section; b – core-wall section; c – outrigger-wall section

with outriggers, following previous studies (Park et al., 2016; Ministry of Construction and Transportation, 2016). In this study, 14 discrete design variables were used for the optimisation of high-rise buildings with mega structures. Although many studies have performed structural optimisation using NSGA-II with discrete design parameters (An et al., 2019; Bae et al., 2020; Camp & Huq, 2013; J. Choi et al., 2019, 2023; S. W. Choi et al., 2017; J. Lee et al., 2005; M. G. Lee et al., 2020; Oh et al., 2017; Park et al., 2006, 2013, 2014, 2016; Rajeev & Krishnamoorthy, 1992), having too many or highly discrete design parameters can hinder the efficiency of the optimisation model. Therefore, the number and specifications of design variables should be carefully selected.

2.2. Constraints

When designing a structure, each element or system should satisfy the corresponding design constraints. In this study, Korean Building Code [KBC] (Ministry of Construction and Transportation, 2016) and Concrete Design Guide (Korea Concrete Institute [KCI], 2012) were referred to examine whether the variables satisfied the safety constraints. The design loads applied in this study were limited to axial (dead and live) loads and wind loads. Axial loads are applied as a combination of a dead load, which is the total weight of the materials that constitute the high-rise buildings, and a live load of 5 kN/m^2, which is used in typical houses, offices, and shopping centres. In this case, the load factors for the combination of dead and live loads are 1.2 and 1.6, respectively. Wind loads are the most dominant lateral loads in high-rise buildings. To predict the structural response of high-rise buildings, we used a basic wind speed of 30 m/s and an importance coefficient of 1.0 based on KBC (Ministry of Construction and Transportation, 2016). Subsequently, these loads were applied in different ways depending on the building height. In addition, analysis was conducted using the existing approximate analysis model to reduce the computation time required for iterative analysis; furthermore, it was assumed that the displacement of the top floor of the building was produced by the bending deformation of the core walls and outriggers as well as the axial deformation of the mega columns under wind loads. Thus, rigid joints were assumed between the outriggers and core walls, and pin joints were considered between the outriggers and mega columns. In addition, it was assumed that only axial forces were applied to the mega columns.

The analysis model also included constraints on the cross-section of the mega columns, compressive and tensile strengths of the columns, shear force and bending moment design of the core walls, compressive strength stiffness against the flexural buckling of outriggers, and displacement of the top floor. These can be primarily classified into constraints upon the basic specifications, strength, stiffness, and horizontal top-floor displacement. The related equations are as follows.

First, the basic specification constraints are:

$$\frac{A_{s\_c}}{A_{g\_c}} > 0.01; \tag{1}$$

$$\frac{A_{sr\_c}}{A_{g\_c}} > 0.004; \tag{2}$$

$$T_w \geq \max\left\{\frac{\min(B_w, H_w)}{25}, 100\text{ mm}\right\}; \tag{3}$$

$$p_1 \text{ and } p_2 \leq 3T_w \text{ or } 450\text{ mm}; \tag{4}$$

$$\frac{A_{s1\_w}}{A_{g1\_w}} \geq \begin{cases} 0.0020 \\ 0.0025 \end{cases} \left(\text{for } (D_{s1} \leq D16) \text{ and } \left(F_{yr_w} \geq 400\text{ MPa}\right)\right); \tag{5}$$

$$\frac{A_{s2\_w}}{A_{g2\_w}} \geq \begin{cases} 0.0012 \\ 0.0015 \end{cases} \left(\text{for } (D_{s2} \leq D16) \text{ and } \left(F_{yr_w} \geq 400\text{ MPa}\right)\right). \tag{6}$$

Equations (1) and (2) constrain the reinforcement ratio of the column. A_{s_c}, A_{sr_c}, and A_{g_c} are the cross-sectional areas of the rebars and H-beam used in the column (shown in Figure 3a) and the cross-sectional area of the entire column, respectively. Equations (4)–(6) express the constraints on the core wall design (see Figure 3b); these include a constraint on the minimum thickness of the core wall (Eqn (3)) and constraints on the spacing (Eqn (4)) and

Table 1. OGDMM design variables

Design variables	Application range
Concrete compressive strength (f_{ck})	21, 24, 27, 30, 35, 40, 50, 60, 70, 80 (MPa)
Rebar yield strength (F_{yr_c}, F_{yr_w})	300, 400, 500 (MPa)
Rebar specifications (D_c, D_{s1}, D_{s2})	D10, D13, D16, ..., D35, D38, D41 (mm)
H-beam yield strength (F_{yr_c}, F_{yr_o})	490, 520, 570 (MPa)
H-beam dimensions (H_c×B_c×$t1_c$×$t2_c$), (H_o×B_o×$t1_o$×$t2_o$)	(244×252×11×11), (248×249×8×13), ..., (933×308×21×35), (943×309×22×40) (mm)
Core wall thickness (T_w)	35, 37, 39, ..., 85 (cm)
Core wall rebar spacing (P)	10, 12, 14, ..., 40 (cm)
Mega-column width (L_c)	70, 72, 74, ..., 130 (cm)
Number of floors with outriggers (N)	1, 2, 3

reinforcement ratios for the horizontal (Eqn (5)) and vertical (Eqn (6)) rebars. Here, A_{s1_w} and A_{s2_w} are the areas of the rebars placed horizontally and vertically in the core wall, respectively, and A_{g1_w} and A_{g2_w} are the cross-sectional areas of the core wall in the vertical and horizontal directions, respectively.

The strength constraints are:

$$P_n = \begin{cases} P_{no}\left[0.658^{\left(\frac{P_{no}}{P_e}\right)}\right] & \left(\text{for } \frac{P_{no}}{P_e} \le 2.25\right) \\ 0.877P_e & \left(\text{for } \frac{P_{no}}{P_e} > 2.25\right) \end{cases}; \quad (7)$$

$$\varnothing_c P_n > P_u. \quad (8)$$

The design compressive strength of a bi-axially symmetric embedded composite column under an axial load $\varnothing_c P_n$ is expressed as Eqn (7), and Eqn (8) stipulates that the compressive strength of the composite column must exceed its required strength P_u. Here, $\varnothing_c$ is the flexural buckling coefficient (dependent on the slenderness ratio), and P_{no} and P_e are the nominal axial strength and elastic buckling stress of the composite column, respectively; these are respectively expressed as:

$$P_{no} = A_{s\_c}F_{y\_c} + A_{sr\_c}F_{yr\_c} + 0.85A_{con\_c}f_{ck}; \quad (9)$$

$$P_e = \pi^2\left(EI_{eff}\right)/\left(KL_n\right)^2. \quad (10)$$

K is the effective length coefficient of the element, L_n is the lateral support length of the element, and A_{con_c} and EI_{eff} denote the concrete area of the composite column and effective stiffness of the composite section, respectively.

The strength conditions for the core wall are:

$$V_u \le \varnothing_v V_n \le \varnothing_v \frac{5}{6}\sqrt{f_{ck}}T_w d_w; \quad (11)$$

$$V_n = V_{con} + V_s\left(\text{for } V_{con} = \frac{1}{6}\sqrt{f_{ck}}T_w d_w,\ V_s = \frac{A_{vh}F_{yr\_w}d_w}{p_2}\right). \quad (12)$$

Equation (11) states that the design strength of the core wall $\varnothing_v V_n$ must exceed the ultimate shear force V_u but not exceed the upper limit V_n $\left(\frac{5}{6}\sqrt{f_{ck}}T_w d_w\right)$ of the nominal shear strength. The nominal shear strength of the core wall is expressed as the summed shear strengths of the concrete (V_{con}) and rebars (V_s), as shown in Eqn (12). Here, $\varnothing_v$ is the shear modulus, d_w is the effective depth of the core wall, and A_{vh} is the cross-sectional area of rebars included in the rebar spacing. Furthermore, we have that

$$M_u \le \varnothing_m M_n = \varnothing_m\left[0.5\left(A_{s2}F_{yr\_w} + N_u\right)\left(L_w - c\right)\right], \quad (13)$$

which states that the design strength of the core wall for moment $\varnothing_m M_n$ must exceed the required moment M_u. If it is lower than the required moment, additional rebars must be installed. Here, $\varnothing_m$ is the moment coefficient, N_u is the axial load, and c is the distance between the compressive zone of the wall and the neutral axis. Lastly, we have that

$$F_e = \frac{\pi^2 E_s}{\left(KL_n / r_o\right)^2}; \quad (14)$$

$$F_{cr} = \begin{cases} F_{cr}\left[0.658^{\left(\frac{F_{y_c}}{F_e}\right)}\right] & \left(\text{for } \frac{F_{y_c}}{F_e} \le 2.25\right) \\ 0.877F_e & \left(\text{for } \frac{F_{y_c}}{F_e} > 2.25\right) \end{cases}; \quad (15)$$

$$\varnothing_c F_{cr} > P_{br} = 0.02\frac{M_r C_d}{h_o}. \quad (16)$$

These constrain the strength of the outrigger to ensure it is robust against buckling. F_e (Eqn (14)) is the elastic buckling stress of the pure steel element and F_{cr} (Eqn (15)) is the strength of the outrigger against buckling; here, E_s and r_o are the elastic and section moduli of the H-beam. Furthermore, P_{br}, M_r, C_d, and h_o (Eqn (16)) are the required strength against buckling, required bending strength, coefficient of curvature, and distance between flange centres, respectively.

The stiffness of the outrigger is constrained by

$$S = \frac{1}{E_s I_o} + \frac{2}{A_{g\_o}{}^2\left(EA\right)_c}; \quad (17)$$

$$S > \beta_{br} = \frac{1}{\varnothing_c}\left(\frac{4M_r C_d}{L_n h_o}\right). \quad (18)$$

The stiffness S (Eqn (17)) of the outrigger must exceed the required stiffness β_{br} (as expressed in Eqn (18)). In these equations, I_o is the moment of inertia of the outrigger, and A_{g_o} and $(EA)_c$ are the total area of the outrigger and the cross-sectional performance of the mega column, respectively.

As mentioned in Introduction, when designing building structures, an individual examination of each element of the building (considering the entire structure of inter-element interactions) is necessary. We solve this by constraining the displacement of the top floor of the building, which arises through the mega columns, core walls, and outriggers. The detailed contents regarding the displacement of the top floor of the building are expressed using

$$\Delta_{t.o.p} = \int_0^H \frac{H}{E\left(I_t\left(H-x\right)+I_b x\right)}\left(\frac{w_t x^2}{2} + \frac{(w_b - w_t)x^3}{6H}\right)xdx - \sum_{i=1}^{n}\int_{x_i}^{H}\frac{HxM_k}{E\left(I_t\left(H-x\right)+I_b x\right)}dx; \quad (19)$$

$$\Delta_{t.o.p} \le \frac{H}{500}. \quad (20)$$

When uniformly varying horizontal loads are applied to a structure with a height of H and n outriggers, the horizontal displacement of the top floor of the building is expressed as $\Delta_{t.o.p}$ (Eqn (19)) and constrained via Eqn (20). Here, I_t and I_b are the moments of inertia of the core at the top and bottom of the structure, respectively. Similarly, w_t and e_b are the magnitudes of the horizontal load at the top and bottom of the structure, respectively. Furthermore, the restraining moment of the i-th outrigger is expressed as M_i.

2.3. Objective functions

This study aimed to derive a multi-objective optimisation method that minimises both the cost and CO_2 emissions of a mega structure. To achieve this objective, two objective functions are formulated as

$$\text{Minimize } f_{CO_2} = \Sigma\Big[\Big(W_{s_c}E_{s_c} + W_{sr_c}E_{sr_c} + W_{con_c}E_{con_C}\Big) + \Big(W_{sr_w}E_{sr_w} + W_{con_w}E_{con_w}\Big) + \Big(W_{s\_o}E_{s\_o} + W_{con\_o}E_{con\_o}\Big)\Big]; \tag{21}$$

$$\text{Minimize } f_{COST} = \Sigma\Big[\Big(W_{s\_c}C_{s\_c} + W_{sr\_c}C_{sr\_c} + W_{con\_c}C_{con\_C}\Big) + \Big(W_{sr\_w}C_{sr\_w} + W_{con\_w}C_{con\_w}\Big) + \Big(W_{s\_o}C_{s\_o} + W_{con\_o}C_{con\_o}\Big)\Big], \tag{22}$$

where

$W_{s\_c} = V_{s\_c}\rho_{s\_c}$, $W_{sr\_c} = V_{sr\_c}\rho_{sr\_c}$;
$W_{con\_c} = V_c - \left(V_{s_c} + V_{sr_c}\right)$, $W_{sr\_w} = V_{sr\_w}\rho_{sr\_w}$;
$W_{con\_w} = \left(V_w - V_{sr\_w}\right)\rho_{con\_w}$, $W_{s\_o} = V_{s\_o}\rho_{s\_o}$;
and $W_{con\_o} = \left(V_o - V_{s\_o}\right)\rho_{con\_o}$.

Subscripts *con*, *s*, and *sr* denote the concrete and steel (H-beam and rebars) materials, respectively; subscripts *c*, *w*, and *o* denote the mega column, core wall, and outrigger, respectively; *V* is the volume of each material; and ρ is the density. Herein, $\rho_c = 2300\ kg/m^3$ and $\rho_s = 7850\ kg/m^3$ were applied as densities for each material. Furthermore, *E* in Eqn (21) expresses the CO_2 emissions per unit weight of concrete and steel, and *C* in Eqn (22) expresses the cost per reference unit.

The CO_2 emissions and cost of the entire mega structure were derived by accurately calculating the quantity of each material, multiplying it by *E* and *C*, and then summing the results. We extracted data from previous studies to calculate the CO_2 emissions and cost per reference unit for steel and concrete; the values are listed in Table 2. The unit cost for each material was obtained from Korea Price Information [KPI] (2019). Unit CO_2 emissions for each material were derived from previous studies on the regression model for the emission factors of construction materials (Ji et al., 2014; Park et al., 2013; Hong et al., 2012). The rebar and H-beam are both made of steel; however, they have different unit costs and CO_2 emissions because of the different manufacturing processes. In the regression model, emission factors were validated for concrete with a compressive strength of up to 50 MPa. However, concrete with higher compressive strengths may be used in high-rise buildings. Therefore, in this study, emission factors for concrete up to 80 MPa were estimated based on the linear relationship of the regression model. The corresponding data were judged applicable because this study focused on analysing the CO_2 emission and cost trends with respect to the slenderness ratio for a high-rise building.

Table 2. Unit CO_2 emissions (Ji et al., 2014; Park et al., 2013; Hong et al., 2012) and unit cost (KPI, 2019) by material

Material	Strength (MPa)	Unit CO_2 emissions (kg/kg)	Unit costs (USD/kg)
Concrete	21	0.2055	0.0210
	24	0.2154	0.0220
	27	0.2253	0.0230
	30	0.2368	0.0242
	35	0.2452	0.0250
	40	0.2908	0.0297
	50	0.3451	0.0354
	60	0.4083	0.0421
	70	0.4804	0.0498
	80	0.5604	0.0585
Rebar	300	0.3857	0.577
	400	0.3963	0.581
	500	0.4242	0.604
H-beam	490	6.60	0.87
	520	6.66	0.88
	570	7.37	0.97

3. OGDMM application

To apply the proposed OGDMM, it must be capable of determining an appropriate structural design trade-off between the CO_2 emissions and cost for a mega-structure building. In mega structures, various elements are used in considerable quantities; hence, the time and cost required to find the optimal design solution increases if a conventional trial and error method is applied. These problems were overcome via a heuristic discovery method that finds the answer to a given topic by introducing a certain standard (if no clear or feasibly efficient method is available). For a complex problem involving multiple variables, the heuristic method can be used to approach the optimal solution closest to the correct answer (given the limited time and information available). In the field of construction, structural optimisation has been performed through the GA heuristic method (Rajeev & Krishnamoorthy, 1992; Hayalioglu & Degertekin, 2005; Lee et al., 2005; Deb et al., 2000, 2002; Park et al., 2006; Honda et al., 2013). The GA is a mathematical formulation of Darwin's principle of the survival of the fittest: entities with superior genetic factors ultimately survive. Expressed algorithmically, the genetic information corresponds to a combination of design variables, and the given environment and superior factors correspond to constraints and objective functions. Various combinations of design variables are applied to identify the best optimisation model. In this study, OGDMM was constructed by introducing non-dominated sorting genetic algorithm II (NSGA-II), which facilitates the application of two or more objective functions (here, CO_2 emissions and cost). The population size and maximum generation used in this case are 64 and 100, respectively.

The stop criteria of NSGA-II can be determined using the hypervolume indicator, which measures the volume of the objective space dominated by the non-dominated solutions. However, in this study, it was determined by trial and error. The crossover and mutation ratios used in the algorithm are 0.95 and 0.05, respectively; these values are commonly used in studies on structural optimisation (An et al., 2019; Choi et al., 2019, 2023; Lee et al., 2020; Park et al., 2013, 2014, 2016).

3.1. Application of OGDMM to a typical mega-structure building

To verify the optimisation algorithm, we applied it to a 30-story mega-structure building with a height of 120 m. The floor plan of the building and elements was as described in Section 2.

Figure 4 shows the CO_2 emissions and cost for the multi-objective optimisation solutions obtained from OGDMM. The 64 initial designs finally converged to nine optimal ones. The optimal solutions obtained from a heuristic algorithm such as NSGA-II do not always guarantee a global optimum. To avoid such issues, a mutation process was applied in this study. Furthermore, all optimal designs from OGDMM presented in this study were validated against all structural designs that can be combined with design variables. In the result graph, the three optimal solutions on the left (low CO_2 emissions) were classified as Group A, whilst the three solutions on the right (low cost) were classified as Group C. Finally, the three solutions offering both reduced CO_2 emissions and cost between the two groups were classified as Group B. The optimal solutions in Groups A, B, and C were assigned numbers 1–3. Table 3 summarises the CO_2 emissions and cost of each result.

We analysed the design variables of each optimal solution: all were found to have the same values (with the exception of the length of one side of the column, rebars and H-beam placed in the column, and number and sizes of outriggers). For Group A, the length of one side of the column was relatively short, and the amount of steel materials used was large. In contrast, for Group C, the size of the column was large compared to Group A but the amount of steel material used was small. Finally, Group B was intermediate between Groups A and B. In each group, solutions were classified according to the number and sizes of outriggers. Under an increasing number of outriggers, the outrigger size tended to become smaller. The quantity of concrete and steel used in the building varied according to the changes in design variables pertaining to the columns and outriggers; this difference in quantity appears to have affected the CO_2 emissions and cost. Table 4 summarises the design variables that lead to differences between each group.

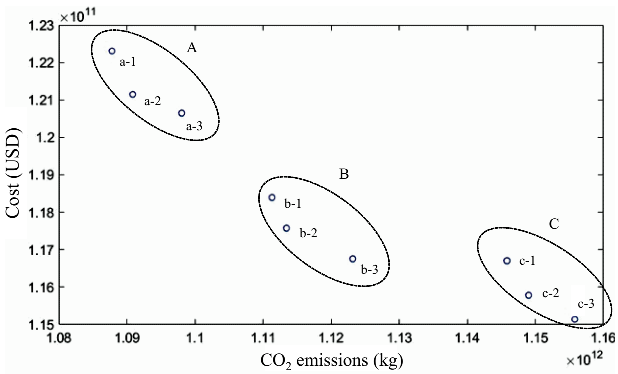

Figure 4. Optimal solutions for a 120-m-tall building with a mega-structure system

The average quantities of concrete and steel used in each group were found to be 4,171 and 72.03 m^3 for Group A; 4,321 and 67.56 m^3 for Group B; and 4,559 and 63.21 m^3 for Group C. The primary difference between the concrete and steel used in the three groups was attributable to the difference in the length of one side of the mega column and the sizes of the rebars and H-beam placed therein. As evident from Table 4, in Group A, the cross-sectional area of the mega column was small; however, the sizes of the rebars and H-beam were large. In contrast, for Group C, the cross-sectional area of the column was relatively large but the sizes of the steel materials were small. Finally, Group B showed an intermediate trend between Groups A and C. Concrete and steel (rebars and H-beam) are the two materials used in mega-structure high-rise buildings: concrete is inexpensive but releases a relatively large amount of CO_2 compared to steel, whereas steel emits a small amount of CO_2 but is more expensive. Consequently, the differences in the quantities of these two materials lead to differences in the CO_2 emissions and cost between Groups A, B, and C. The trade-off relationship attributed to these two materials is also consistent with that in previous studies where CO_2 emissions and cost were simultaneously optimised at the member level (An et al., 2019; Camp & Assadollahi, 2015; Honda et al., 2013; Kim et al., 2020; Lee et al., 2020).

Three solutions were obtained in each group because of the difference in the number of outriggers. When outriggers were installed on only one floor of the building, a relatively large (458×417× 30×50) H-beam was used. However, as the number of floors with outriggers increased, the size of outriggers became smaller ((414×405×18×28)

Table 3. CO_2 emissions and cost of optimal solution for a mega structure of height 120 m

Group	Solutions	CO_2 emissions (×10^{12} kg)	Costs (×10^{11} USD)
Group A	a-1	1.08781	1.22308
	a-2	1.09104	1.21224
	a-3	1.09782	1.20622
Group B	b-1	1.11136	1.18408
	b-2	1.11457	1.17327
	b-3	1.12335	1.16729
Group C	c-1	1.14607	1.16932
	c-2	1.14911	1.15748
	c-3	1.15580	1.15139

Table 4. Design variables of each solution for a mega structure of height 120 m

Design variables	Optimal solutions								
	Group A			Group B			Group C		
	a-1	a-2	a-3	b-1	b-2	b-3	c-1	c-2	c-3
D_c	D22	D22	D22	D19	D19	D19	D16	D16	D16
H_c (mm)	386	386	386	340	340	340	298	298	298
B_c (mm)	299	299	299	250	250	250	201	201	201
H_o (mm)	458	414	394	458	414	394	458	414	394
B_o (mm)	417	405	405	417	405	405	417	405	405
$t1_o$ (mm)	30	18	18	30	18	18	30	18	18
$t2_o$ (mm)	50	28	18	50	28	18	50	28	18
T_w (cm)	35	35	35	35	35	35	35	35	35
L_c (cm)	74	74	74	78	78	78	84	84	84
N (floors)	1	2	3	1	2	3	1	2	3

for N = 2 and (388×402×15×15) for N = 3); hence, the increase in the quantity of steel was insignificant. However, the quantity of concrete used in outrigger walls increased in proportion to N. Consequently, owing to the difference in the masses of materials used (with respect to the number of floors with outriggers), three optimal solutions were derived in each group. However, the quantities of concrete and steel used in outriggers had a minimal impact on the overall CO_2 emissions and cost (compared to the sizes of the mega columns) because they contributed only 11.7% and 16.9% of the total quantity, respectively.

In addition, the quantities of concrete and steel in the core walls did not significantly alter the CO_2 emissions and cost between the optimal solutions because all walls had a specified size; however, the quantities constituted 47% and 40% of the quantity of each material used in the entire building, respectively.

3.2. Application of OGDMM to mega structures of heights 120–200 m

When the OGDMM was applied to a 30-story mega-structure building of height 120 m, 9 optimal solutions were derived; consequently, among the design variables, those pertaining to the size of the column and outrigger had a major impact on the CO_2 emissions and cost. Given the heights of recent high-rise buildings, the height of the mega structure considered in Section 3.1 was increased to analyse optimal solutions for mega structures of 120 m (30 stories) or higher, as well as the subsequent trends in CO_2 emissions and cost.

The basic configuration of the building resembled that presented in Section 3.1, and the algorithm was applied as the number of floors was increased in increments of two (height: 8 m) up to a maximum of 50 (building height: 200 m). Figure 5 shows the CO_2 emissions and costs of the optimal designs when the proposed model was applied to each building height. Each optimised mega-structure design resulted in (as in Section 3.1) solution groups optimised for CO_2 emissions (CO2 Group), cost (COST Group), and both objectives (Multi Group). When the design variables for the optimal solutions were compared, the main elements that distinguished the CO2, Multi, and COST Groups from each other were those related to the sizes of the column (e.g., D_c, (H_c×B_c×$t1_c$×$t2_c$), and L_c). In each group, differences in CO_2 emissions and cost arose through the design variables pertaining to the outriggers (e.g., N and ((H_o×B_o×$t1_o$× $t2_o$)). Under an increase in building height, the differences between the solutions for each group decreased. This may be because the change in the quantity of outrigger elements was insignificant compared to the increase in the quantity of column and core wall elements as the building height increased. Although the quantity of outrigger elements constituted 17.09% of the total quantity of elements in the building (on average) when the building height was 30 stories, the ratio decreased to 5.87% (on average) (less than half that for 30 stories) when the building height was 50 stories. Table 5 shows the average CO_2 emissions and the cost of each section with respect to the building height.

For buildings adopting mega-structure systems of 11 different heights, the average CO_2 emissions and cost were found to be 1.454×10^{12} kg and 1.636×10^{11} USD, respectively, for the CO2 Group; 1.509×10^{12} kg and 1.571×10^{11} USD, respectively, for the Multi Group; and 1.583×10^{12} kg and 1.525×10^{11} USD, respectively, for the COST Group. Further, by comparing the CO_2 emissions and cost of each group, it was found that the CO2 Group reduced CO_2 emissions by 3.64% (5.5×10^{10} kg) and 8.14% (1.29×10^{11} kg) compared to that with the Multi and COST Groups, respectively; meanwhile, the COST Group reduced costs by 26.6% (4.19×10^{10} USD) and 29.55% (4.84×10^{10} USD) compared to that with the Multi and CO2 Groups, respectively.

3.3. Analysis of the OGDMM results

In Sections 3.1 and 3.2, it was found that the sizes of mega columns and the sizes and number of outriggers had the largest impact on the OGDMM results. The design variables related to the sizes of mega columns were the diameters of the placed rebars (D_c), dimensions of the H-Beam (H_c×B_c×$t1_c$×$t2_c$), and length of one side of the column (L_c).

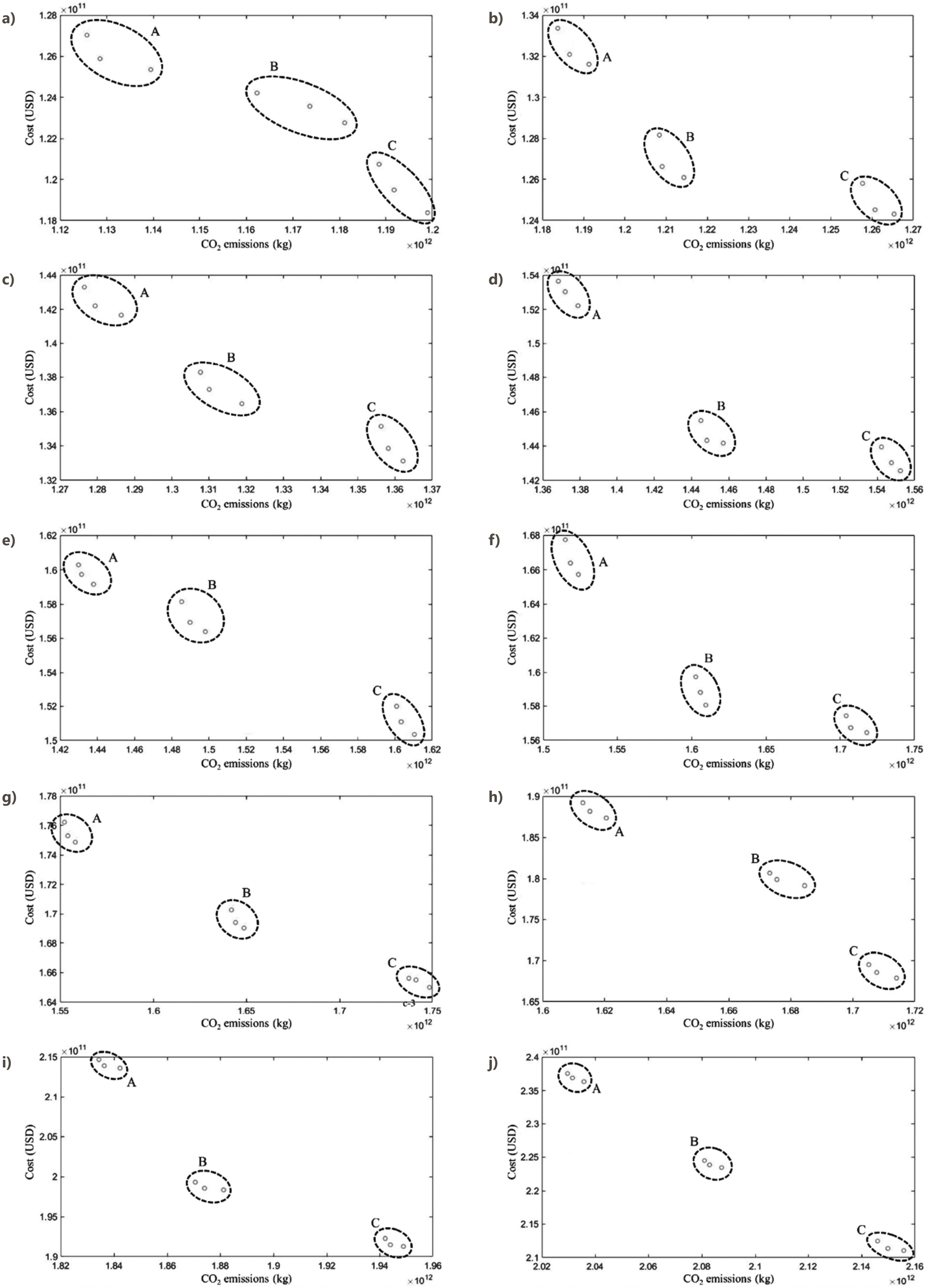

Figure 5. Optimal solutions for buildings with a mega-structure system classified into CO2, COST, and Multi Groups (building height: a – 128 m; b – 136 m; c – 144 m; d – 152 m; e – 160 m; f – 168 m; g – 176 m; h – 184 m; i – 192 m, j – 200 m)

Table 5. Variation of average CO_2 emissions and costs for mega structures of 120–200 m

Number of floors (height)	CO2 Group		Multi Group		COST Group	
	CO2 ($\times 10^{12}$ kg)	Costs ($\times 10^{11}$ USD)	CO2 ($\times 10^{12}$ kg)	Costs ($\times 10^{11}$ USD)	CO2 ($\times 10^{12}$ kg)	Costs ($\times 10^{11}$ USD)
30 (120 m)	1.09222	1.21385	1.11643	1.17488	1.15033	1.15940
32 (128 m)	1.13145	1.26076	1.17280	1.23490	1.19365	1.19665
34 (136 m)	1.18734	1.32307	1.20956	1.26976	1.26145	1.24767
36 (144 m)	1.28102	1.42370	1.31215	1.37425	1.35886	1.34081
38 (152 m)	1.37262	1.53002	1.45053	1.44579	1.544664	1.43147
40 (160 m)	1.43319	1.59739	1.49160	1.57218	1.60506	1.51072
42 (168 m)	1.51893	1.66466	1.60621	1.58886	1.70817	1.56644
44 (176 m)	1.55550	1.75440	1.64250	1.69465	1.74245	1.65371
46 (184 m)	1.61632	1.88495	1.67813	1.79796	1.71129	1.68650
48 (192 m)	1.77310	1.97093	1.83361	1.88948	1.98674	1.86587
50 (200 m)	2.03294	2.36948	2.08440	2.23864	2.15135	2.11882

In contrast, the design variables related to outriggers were the outrigger dimensions ($H_o \times B_o \times t1_o \times t2_o$) and number of floors featuring outriggers (N). In this section, the effect of each variable upon the OGDMM results is analysed to identify more efficient optimal solutions.

The main materials used in mega-structured high-rise buildings are steel (rebars and H-beam) and concrete. Although steel is more costly than concrete, it produces less CO_2. In contrast, concrete is inexpensive (compared to steel) and generates considerable CO_2 emissions. The cost and CO_2 emissions of a building are determined by the quantities of the two different materials. In this study, the sizes of the mega columns and outriggers play an important role in determining these quantities.

In the case of mega columns, the length of one side of the column and the dimensions of the H-beam are the primary variables. Under identical load conditions, all optimal solutions satisfy the required strengths for mega columns; however, the contributions of steel and concrete to the strength vary according to the length of one side of the column and the dimensions of the H-beam. For 30 stories and a column height of 4 m, the average quantities of steel and concrete used in mega columns for the CO2 Group were 43.41 and 1,270 m^3, respectively. For the COST Group, these were 3.46 and 1,659 m^3, respectively. For the CO2 Group, the contribution of steel to strength was higher than that of the other two groups, and the increase in the quantity of steel (i.e., a reduction in the quantity of concrete) increased the cost (but reduced the CO_2 emissions). In contrast, in the COST Group, the quantity of concrete used in columns was larger than that of the other two groups; thus, more CO_2 was emitted. The Multi Group showed an intermediate pattern between the other two groups.

Outriggers exhibited a pattern similar to that of mega columns. The sizes of outriggers varied according to the number of outriggers used in the system. These sizes were relatively large at N = 1 and decreased as N increased. However, in contrast to mega columns, the quantity of materials used for outriggers significantly varied according to the variable (N) as the number of structures varied. The quantity of concrete used in outrigger walls varied substantially.

Table 6 shows the quantities of outrigger elements and their increase rates with respect to N for the 30-story mega-structure building of floor height 4 m mentioned in Section 3.1. Although the quantity of steel increased by 0.7 m^3 (6.03%) and 1.82 m^3 (14.80%) compared to that in the previous step (attributable to the increase in N), that of the concrete used in the outrigger walls increased by 235.5 m^3 (83.66%) and 225.4 m^3 (43.60%). This may be because concrete occupying a certain volume (regardless of the outrigger size) is more significantly affected by N than by the quantity of steel, which is significantly affected by the dimensions of the H-beam used as an outrigger.

In addition, in contrast to mega columns (for which the quantity of materials increases according to the number of floors, separately from the quantity change dependent on column size), the change in the quantities of outrigger elements with respect to the number of floors is insignificant because the number of structures is fixed at a maximum of N = 3. Therefore, under an increasing building height, the ratio between the quantity of outrigger elements and the total quantity of elements in the building decreases. Moreover, whilst the quantity of outrigger elements accounted for 17.09% of the total quantity of elements in the building (on average) when the building height was 30 stories,

Table 6. Changes in the quantities of outrigger elements with respect to N in a 30-story building

Materials		Number of outriggers		
		N = 1	N = 2	N =3
Concrete	Quantity (m^3)	281.5	517.0	742.4
	Increased quantity (m^3)	–	235.5	225.4
	Increase rate	–	83.66%	43.60%
Steel	Quantity (m^3)	11.60	12.30	14.12
	Increased quantity (m^3)	–	0.7	1.82
	Increase rate	–	6.03%	14.80%

the ratio decreased to 5.87% (on average) (less than half that at 30 stories) when the building height was 50 stories. Consequently, this reduced the differences in CO_2 emissions and cost between the solutions in each group.

4. Application of OGDMM to actual mega-structure buildings

The results presented in Section 3 indicate that the sizes of columns and outriggers significantly influence the CO_2 emissions and cost. In particular, the design variables related to the column size (e.g., L_c, ($H_c \times B_c \times t1_c \times t2_c$), and D_c) significantly affect the solutions, and the effects of the sizes and numbers of outriggers on the results reduced with increasing building height. Each building condition is further subdivided, and the OGDMM is applied to analyse its behaviour under various conditions. Finally, based on the analysis data, design guidelines that consider the economic efficiency and eco-friendliness of mega-structure high-rise buildings are presented and subsequently applied to actual building cases to verify the efficacy of the proposed OGDMM.

4.1. Analysis of the OGDMM results

For high-rise buildings, the design method varies depending on the slenderness ratio. In general, a strength design (i.e., one that determines the load-bearing capacity of a structure or element) is applied when the slenderness ratio is 5.0 or less; meanwhile, a stiffness design (i.e., one that determines the deformation capacity of a structure) is applied when the slenderness ratio is 5.0–8.0 (Park et al., 2016). Furthermore, a strength design is applied according to the allowable strength of each element, whereas a stiffness design is adopted according to the maximum horizontal displacement at the top of the building. These are optimal designs that treat the behaviour of the building as varying with respect to height (slenderness ratio); they were proposed to satisfy the strength or stiffness conditions required for each slenderness ratio. However, these design methods (i.e., those based on strength or stiffness with respect to slenderness ratio) focus on safety, while neglecting its eco-friendliness and economic efficiency.

In this study, OGDMM was applied whilst the slenderness ratio of the mega-structure high-rise building was varied. Based on the results, we present an optimal design method that considers the economic efficiency and eco-friendliness of the building with respect to the slenderness ratio. For the section and design variables, the conditions described in Section 3 were applied.

OGDMM was applied and the slenderness ratio was increased from 2.0 to 8.0 in increments of 0.1; only the maximum and minimum values of the CO_2 emissions and cost for the optimal solution were extracted for each slenderness ratio, as shown in Figures 6a and 5b.

Given the width of the building, outrigger elements were not applied at a slenderness ratio of 4.0 or lower because the strength design was dominant. Consequently,

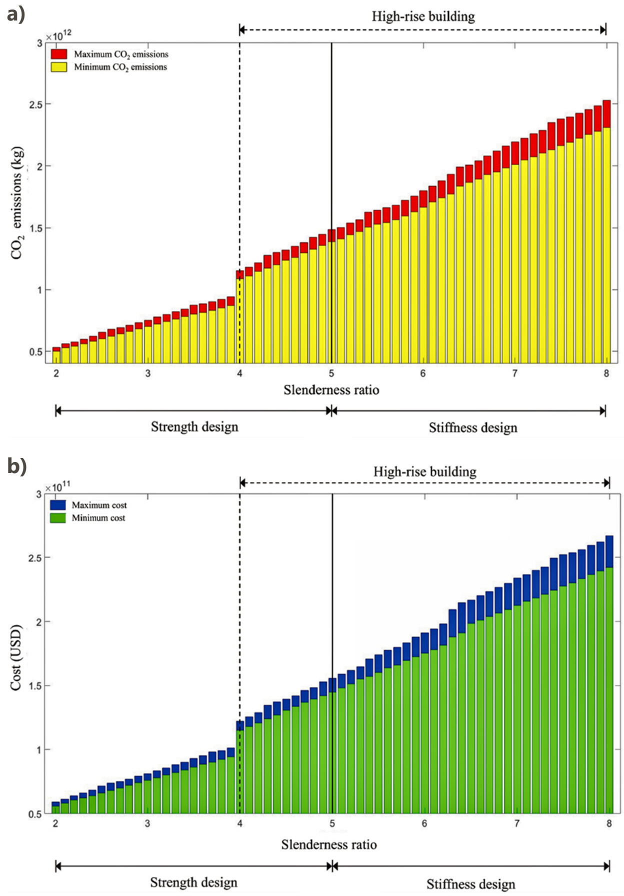

Figure 6. CO_2 emissions and cost with respect to slenderness ratio: maximum and minimum a – CO_2 emissions and b – costs

significant differences in the CO_2 emissions and cost of the building were observed around a slenderness ratio of 4.0. When the slenderness ratio (building height) was increased, the total quantity of materials increased, and hence, the maximum and minimum CO_2 emissions and cost values increased proportionally thereto, as shown in Figure 6. In addition, the difference between the maximum and minimum values also increased. This may be because the difference in the quantities of elements specified by the design variables per unit height increased as the building height increased. However, at certain points, the maximum and minimum values of CO_2 emissions and cost – or the difference between them – increased suddenly because the design variables of the OGDMM were not continuous; this occurred when design variables of higher strength (or larger size) were applied to satisfy constraints and the differences between variables were large.

4.2. Result analysis

Through the results in Section 4.1, the maximum or minimum CO_2 emissions and the cost of the building at each slenderness ratio were identified. These can serve as guidelines for the CO_2 emissions and cost of the building (with respect to the slenderness ratio). However, to apply the data as guidelines, the actual behaviour of the building must be considered.

As described above, at a slenderness ratio of 5.0–8.0, a stiffness design that takes the horizontal displacement of the top floor of the building as an evaluation criterion is generally applied. This becomes an important criterion in terms of actual serviceability (as well as simple structural stability) because the horizontal displacement attributable to the lateral load increases as the building height increases. The proposed OGDMM also includes a constraint on the horizontal displacement of the top floor (via Eqn (19)) but it only satisfies the minimum criterion (a top-floor horizontal displacement of or less than 1/500 of the building height) and does not evaluate the relevant performance. Therefore, in this section, applicable optimal solutions were derived by comparing the top-floor horizontal displacements of each optimal result; consequently, design guidelines for mega-structure high-rise buildings were presented.

The optimal results derived in Section 4.1 via the application of OGDMM exhibited patterns similar to the results in Section 3. Although certain case-based differences were found, nine optimal solutions were derived at most slenderness ratios; these were mainly classified into the CO2, Multi, and COST Groups, depending on the size of the column. Each group was then subdivided according to the size of the outriggers. In addition, when the height (slenderness ratio) increased, the difference in CO_2 emissions and cost between the solutions in the CO2, Multi, and COST Groups exhibited a tendency to decrease in the same manner. Table 7 shows the average differences in CO_2 emissions and cost among the CO2, Multi, and COST Groups at each slenderness ratio (5.0 or higher).

As shown in Table 7, when the slenderness ratio increases, the difference in the values of solutions belonging to the same optimisation group gradually decrease.

Table 7. Averaged differences in CO_2 emissions and costs of optimal solutions from CO2, Multi, and COST Groups

Slenderness ratio	Average differences	
	CO_2 emissions (%)	Costs (%)
5.0	0.417	0.511
5.2	0.383	0.478
5.4	0.358	0.439
5.6	0.327	0.406
5.8	0.299	0.368
6.0	0.270	0.333
6.2	0.241	0.292
6.4	0.212	0.260
6.6	0.188	0.228
6.8	0.159	0.193
7.0	0.133	0.161
7.2	0.112	0.129
7.4	0.090	0.099
7.6	0.063	0.059
7.8	0.036	0.024
8.0	0.009	0.001

In particular, at a slenderness ratio of 7.4 or higher, the difference becomes less than 0.1%. When the difference between the values of solutions in the same group is extremely small, reducing the lateral displacement of the building is more efficient in terms of improving building serviceability, despite the slight increase in CO_2 emissions and cost. Analysis of the optimal solutions shows that the top-floor horizontal displacements at N = 2 and 3 ($\Delta_{t.o.p}2$, $\Delta_{t.o.p}3$) were 95% and 94% of that at N = 1 ($\Delta_{t.o.p}1$), when the slenderness ratio was 5.0. However, $\Delta_{t.o.p}2$ and $\Delta_{t.o.p}3$ were 87 and 84% that of $\Delta_{t.o.p}1$ when the slenderness ratio was 8.0, indicating that the difference increases proportionally with the slenderness ratio. In other words, the difference in environmental/economic performance and the difference in serviceability between optimal solutions exhibit different trends according to the increase in the slenderness ratio.

Hence, the serviceability indicator expressed by the top-floor horizontal displacement was added to the previously presented environmental and economic design guidelines for mega-structure high-rise buildings. In this study, the difference in the values of the solutions within the same optimisation group (hereafter denoted "VMD") is defined as

$$VMD = \frac{\alpha D.C.A + \beta D.CO_2.A}{2} \left(\%\right), \quad (23)$$

where α and β, which are importance factors, satisfy α + β = 2 and α, β > 0. The difference in cost average (DCA, %) expresses the difference in the average costs of optimal solutions, and the difference in CO_2 emissions average (DCO2A, %) is the difference in the average CO_2 emissions of optimal solutions. A total of four areas were classified according to their VMD values, as shown in Table 8.

First, when VMD was equal to or higher than 0.5%, design was undertaken by prioritising eco-friendliness and economic efficiency rather than other indicators (e.g., strength and stiffness). Here, the constraint on the top-floor horizontal displacement was mitigated and $H/400$ was applied. We refer to this case as being "oriented towards eco-friendliness and economic efficiency". In the area where VMD was equal to or higher than 0.3% and less than 0.5%, design was undertaken based on the eco-friendliness and economic efficiency, but the constraint on the top-floor horizontal displacement was set to $H/500$; this is the original criterion for high-rise buildings.

Table 8. Classification of design areas with respect to eco-friendliness, economic efficiency, and serviceability of the optimal solution

VMD* (%)	Design area
VMD ≥ 0.5	Design oriented towards eco-friendliness and economic efficiency
0.3 ≤ VMD < 0.5	Design based on eco-friendliness and economic efficiency
0.1 ≤ VMD < 0.3	Design based on non-equivalent three objects
VMD < 0.1	Design based on equivalent three objects

We refer to this case as being "based on eco-friendliness and economic efficiency". Further, in the design area for eco-friendliness and economic efficiency, the existing OGDMM-based optimal design method presented in Section 4.1 was applied. Next, where VMD was less than 0.3%, the optimal design was derived via the application of stiffness as an objective function (in the same manner as eco-friendliness and economic efficiency). In the area where VMD was equal to or higher than 0.1% and less than 0.3%, the importance of stiffness was set lower compared to the other objective functions (referred to as "three non-equivalent objects"). Finally, where VMD was less than 0.1%, the optimal solution was derived by setting an equal importance for the three objective functions (referred to as "three equivalent objects"). In the design areas based on three non-equivalent or equivalent objects, the number of floors with outriggers was limited to two or three by considering the top-floor displacement tendency. Moreover, in this study, the importance of stiffness in the design area for three non-equivalent objects was set as half those of eco-friendliness and economic efficiency.

4.3. Design guidelines

In this section, the design areas specified via the VMD (presented in Section 4.2) are applied to the optimal design solution through the existing OGDMM. The new guidelines derived for the CO_2 emissions and cost at each slenderness ratio are shown in Figure 7.

Slenderness ratios of 2.0–4.7 marked out the design area oriented towards eco-friendliness and economic efficiency; ratios of 4.8–6.0 indicated the design area based on eco-friendliness and economic efficiency. Furthermore, slenderness ratios of 6.1–7.3 marked the design area for three non-equivalent objects and those of 7.4–8.0 denoted the design area for three equivalent objects.

A comparison of the results in Figures 6 and 7 reveals that both CO_2 emissions and cost decreased in the design area oriented towards eco-friendliness and economic efficiency. This can be attributed to the sizes of structures that resist lateral loads (e.g., core walls and outriggers), which decrease via the mitigation of the top-floor horizontal displacement constraint. The CO_2 emissions and cost decreased by 4% (on average) in the area where the slenderness ratio was 4.0 (building height: 120 m) or less and by 6 or 7% (on average) where the slenderness ratio was 4.0 or higher. Furthermore, in the design area based on eco-friendliness and economic efficiency, the results were consistent with the previously published ones. In the design areas for three non-equivalent and equivalent objects, the maximum–minimum value differences for CO_2 emissions and cost decreased similarly. More specifically, the minimum CO_2 emissions increased and the maximum cost decreased. In contrast, in the design area for three non-equivalent objects, the minimum CO_2 emissions increased by 0.17% on average and the maximum cost decreased by 0.21%. Finally, in the design area based on three equivalent objects, the minimum CO_2 emissions increased by 0.03% and the maximum cost decreased by 0.04%.

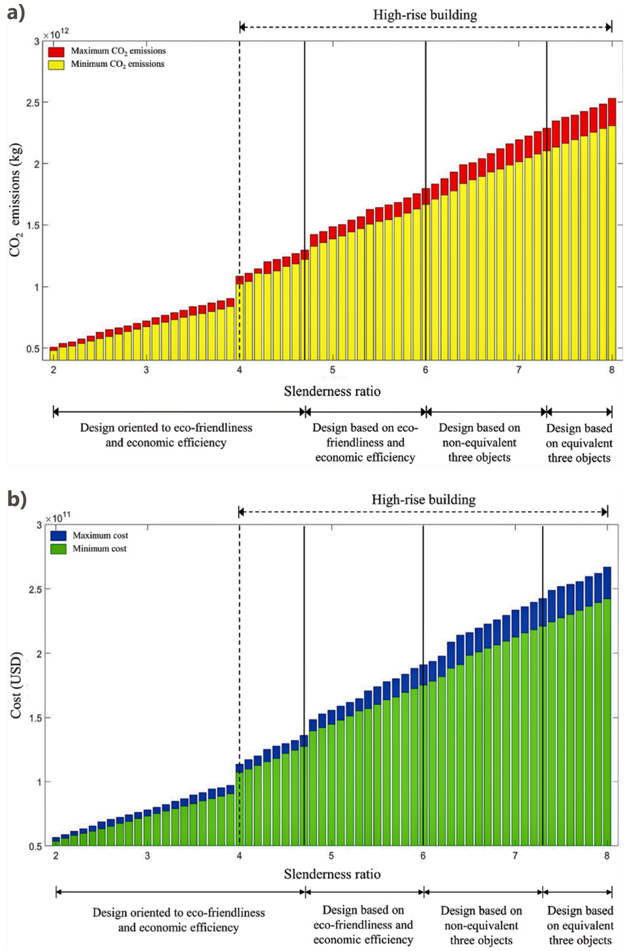

Figure 7. OGDMM-based mega-structure high-rise building design guidelines: a – CO_2 emission guidelines with respect to slenderness ratio and b – cost guidelines with respect to slenderness ratio

Although the minimum CO_2 emissions increased slightly in the design areas for three non-equivalent and equivalent objects, the reduction of the maximum cost was faster, and resistance to the lateral load was also higher compared to the existing optimal solutions. Therefore, the performance exceeded that of the previously presented optimal solutions in terms of eco-friendliness, economic efficiency, and serviceability.

4.4. Application to an actual building

To verify the effectiveness of the proposed OGDMM-based optimal design guidelines, the optimal design solutions were applied to an actual building and the resultant CO_2 emissions and costs were compared with their design values.

The actual building used in this study was a high-rise apartment building with a height of 270 m; it was composed of SRC mega columns, shear core walls, and outriggers (similar to the example solution presented in this study). Furthermore, elements besides the design variables presented in Section 2 were set as they were in the actual building and applied to the OGDMM-based optimal design guidelines according to the corresponding conditions.

Consequently, the performance of the optimal design solutions was compared with that of the actual building, as shown in Figures 8 and 9. Hereafter, the actual building is referred to as "T3".

OGDMM was applied whilst the slenderness ratio was increased according to the cross-section of T3, and the design area (according to VMD) was applied to the results. The width of the applied building was ~50 m; hence, it was classified as a high-rise building (height: 120 m) at a slenderness ratio of 2.4 or more. A slenderness ratio of 2.0–4.1 denotes the design area oriented towards eco-friendliness and economic efficiency; those in the range 4.2–5.1 denote the design area based on eco-friendliness and economic efficiency. Furthermore, slenderness ratios of 5.2–5.9 and 6.0–6.4 denote the design areas for three non-equivalent and equivalent objects, respectively. However, for slenderness ratios of 6.6 or higher, no optimal solution was derived because the constraint on the top-floor displacement was satisfied. Furthermore, the CO_2 emissions and cost of each optimal solution, depending on the slenderness ratio and design area, showed tendencies similar to those of the example building above.

When the CO_2 emissions and cost of the OGDMM-based structural solutions were compared with the values for T3, it was found that T3 exceeded the maximum value of the optimal solution for both CO_2 emissions and cost at a constant slenderness ratio (5.4), as shown in Figure 9. In particular, the difference in cost was significant. This may be because the shear core walls were reinforced with steel (which is more expensive than concrete) to reduce the top-floor displacement for T3. Moreover, contrary to the fact that higher CO_2 emissions and cost were observed (compared to the optimal solution), the top-floor displacement decreased. This is because the structure was reinforced using reinforcements such as braces, as mentioned above.

Figure 9 shows the CO_2 emissions (10^{12} kg) and cost (10^{11} USD) for each optimisation group; the average values were 8.54 and 9.84, respectively, for the CO2 Group; 8.75 and 9.37, respectively, for the Multi Group; and 9.23 and 9.05, respectively, for the COST Group. The average top-floor horizontal displacement (m) of the optimisation group solutions was 0.442 m for N = 2 and 0.429 m for N = 3. A slenderness ratio of 5.4 indicated the design area for three non-equivalent objects; hence, N was set as 2. The CO_2 emissions, cost, and top-floor horizontal displacement of T3 were 9.61, 11.15, and 0.388, respectively.

For T3, CO_2 emissions increased by 12.64%, 9.94%, and 4.22% compared to each optimisation group, and the costs required were 13.31%, 18.99%, and 23.20% higher, respectively. However, as mentioned, the top-floor horizontal displacement decreased by 12.21% (N = 2) and 9.55% (N = 3) compared to that for the optimisation groups. Considering the average and summarising the data indicated that the horizontal displacement of T3 was 10.88% smaller (on average) compared to the OGDMM-based optimal solutions; however, its CO_2 emissions and cost were ~8.99% and 18.5% higher. Thus, when the importance values of eco-friendliness, economic efficiency, and serviceability were set to 1:1:0.5 (as a slenderness ratio of 5.4 belongs to the design area for three non-equivalent objects), T3 was considered inefficient compared to the OGDMM-based optimal solution. In other words, it was confirmed that the optimal OGDMM solutions exhibited a higher performance than the actual building design. This verifies the efficacy of the OGDMM-based optimal design guidelines proposed here.

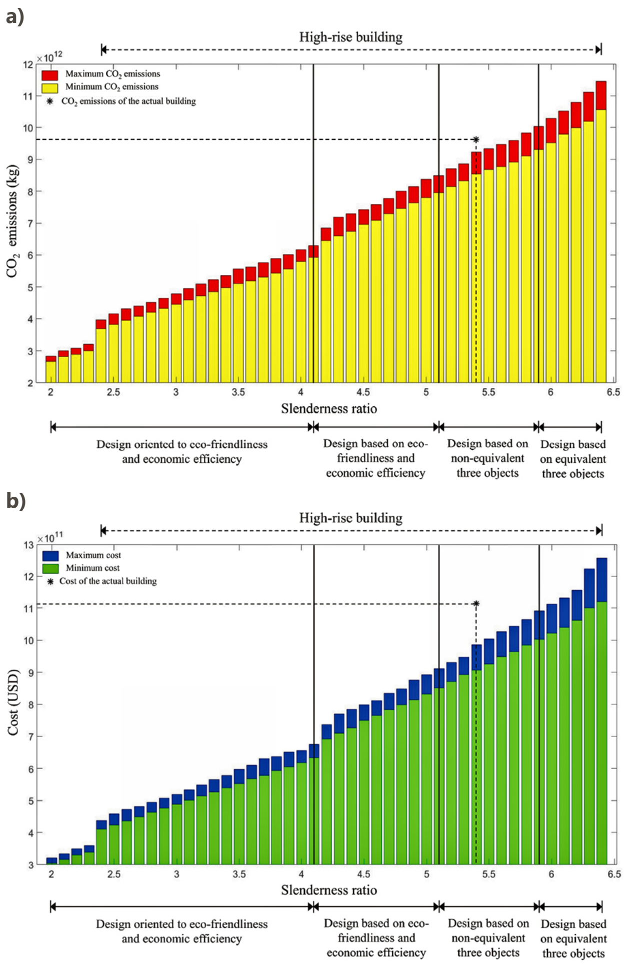

Figure 8. Performance comparison between optimal design solutions and actual design for an actual building: a – CO_2 emissions and b – costs with respect to slenderness ratio

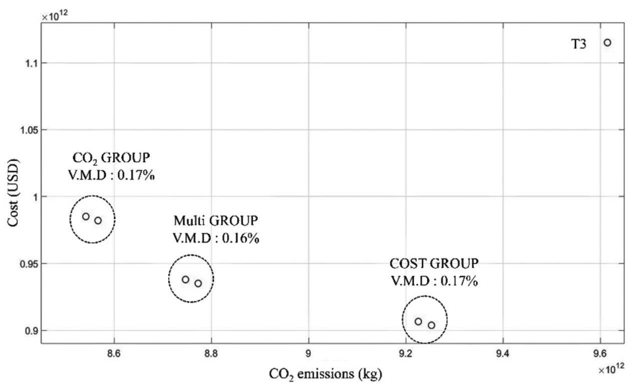

Figure 9. Performance comparison between optimal solutions and actual design for buildings with a slenderness ratio of 5.4

4.5. Optimal design based on user preferences

In this section, based on the optimal solutions presented in Section 4.4, the CO_2 emissions and cost of each solution are analysed to derive the final results according to user preferences. For the six optimal solutions marked in Figure 9 and labelled as Models A, B, C, D, E, and F (Model A: CO_2 emission optimisation solution; Models B–E: multi-objective optimisation solutions; and Model F: cost optimisation solution), the specific CO_2 emissions, costs, and top-floor horizontal displacements of each solution are as shown in Table 9.

Table 9. CO_2 emissions, cost, and top-floor horizontal displacement of each optimal solution

Optimal solution	CO_2 emissions ($\times 10^{12}$ kg)	Costs ($\times 10^{11}$ USD)	Top displacement (m)
Model A	8.542	9.850	0.442
Model B	8.557	9.837	0.429
Model C	8.747	9.379	0.442
Model D	8.762	9.367	0.429
Model E	9.226	9.065	0.443
Model F	9.242	9.053	0.430

The slenderness ratio of the building (5.4) belongs to the design area for three non-equivalent objects; hence, the ratio of OGDMM user preferences for eco-friendliness, economic efficiency, and serviceability was assumed to be 2:2:1, respectively.

In this study, the efficiencies of the optimal solutions applicable to the three non-equivalent and equivalent object design areas were quantitatively compared using

$$T-CEEA(\%) = \frac{CO_2 \text{ emission reduction rate}(\%)}{\text{Cost increase rate}(\%) + \text{Horizontal displacement increase rate}(\%)} \times 100; \quad (24)$$

$$T-CEA(\%) = \frac{\text{Cost reduction rate}(\%)}{CO_2 \text{ emission increase rate}(\%) + \text{Horizontal displacement increase rate}(\%)} \times 100; \quad (25)$$

$$T-HDEA(\%) = \frac{\text{Horizontal displacement increase rate}(\%)}{CO_2 \text{ emission reduction rate}(\%) + \text{Cost reduction rate}(\%)} \times 100; \quad (26)$$

$$CVA(\%) = \alpha(T-CEEA) + \beta(T-CEA) - \gamma(T-HDEA). \quad (27)$$

Equation (24) expresses the three-object-based CO_2 emission efficiency analysis (T-CEEA). Furthermore, Eqns (25) and (26) show the three-object-based cost efficiency analysis (T-CEA) and three-object-based horizontal displacement efficiency analysis (T-HDEA), respectively. Consequently, using each derived efficiency analysis value, a comprehensive value analysis (CVA) of the optimal solutions is obtained using Eqn (27). In this instance, α, β and γ represent the user preferences for eco-friendliness, economic efficiency, and serviceability. These are set to 2, 2, and 1, respectively.

The overall performances of Models B–E (multi-objective optimisation solutions) were evaluated by applying the data in Table 9 to Eqns (23)–(26). Consequently, Model B realised efficiencies of 38.53% (T-CEEA), 1.20% (T-CEA), 46.48% (T-HDEA), and 32.98% (CVA); furthermore, for Models C–E, performances of (30.59%, 29.29%, 55.99%, and 63.77%) for Model C, (36.97%, 37.26%, 42.60%, and 105.86%) for Model D, and (1.21%, 36.34%, 62.99%, and 12.11%) for Model E were recorded [where the formulation (T-CEEA, T-CEA, T-HDEA, CVA) is used). Thus, when user preferences for eco-friendliness, economic efficiency, and serviceability were 2:2:1, Model D was found to achieve the highest overall performance. Therefore, the user should select Model A (CO_2 emission optimisation solution) if they prioritise eco-friendliness, Model F (cost optimisation solution) if they prioritise economic efficiency, the existing T3 design plan if they prioritise the top-floor horizontal displacement, and Model D if they want to consider eco-friendliness, economic efficiency, and serviceability in a comprehensive manner (2:2:1).

5. Conclusions

An OGDMM for the multi-objective optimisation of high-rise buildings with a mega-structure system was proposed. The OGDMM explored the structural design with efficient top floor displacement to optimise CO_2 emissions and costs in the design phase of high-rise buildings with a mega structure and simultaneously improve serviceability. The proposed model considers various design loads, member buckling, and top floor displacement constraints to satisfy the safety and serviceability of the structure.

The analytic results based on OGDMM for a 120-m-height high-rise building with a mega structure show that optimised structural designs are most dominant in the dimensions of mega columns and the sizes of steel and rebar. The CO2 Group selects smaller mega column dimensions and larger steel or rebar sizes than that in the COST Group. The Multi Group selects variables that are intermediate between the CO2 and COST Groups. This is because steel materials incur a higher cost than concrete for the same performance, but they have relatively lower CO_2 emissions. These results are consistent with previous studies on multi-objective optimisation for specific members. The CO_2 emissions of the optimised models tend to increase and the costs decrease with an increase in the number of outriggers in high-rise buildings. The design of the shear wall did not significantly impact the optimisation although it required a large amount of concrete and steel (47% and 40%, respectively).

These behaviours of the optimised model remained consistent even with variations in the slenderness ratio (or building height, number of floors). When OGDMM was applied at a slenderness ratio of 2.0–8.0, the sizes of mega columns and outriggers most significantly affected the CO_2 emissions and cost, as in the previous step. The multi-objective optimised models reduced CO_2 emissions by an average of 4.67% compared to that with cost-optimised models and reduced costs by an average of 3.97% compared to that using CO_2-optimised models. As the height of the building increased, the volume ratio of the outrigger to the total structural system decreased. Thus, the impact of the outrigger on CO_2 emissions and costs also decreased.

A green structural design that simply considers reducing CO_2 emissions and costs can sometimes overlook serviceability issues that are common in high-rise buildings. For example, the optimised design for outriggers with a slenderness ratio of 8.0 can reduce the top floor displacement by 16% while only increasing CO_2 emissions and costs by less than 0.009% and 0.001%, respectively. Therefore, in this study, a new evaluation indicator, VMD, was proposed to consider not only the environmental and economic aspects of high-rise buildings but also the serviceability aspects. The performance of OGDMM was evaluated using this variable. Based on the performance analysis, the optimised design areas were classified into those oriented towards eco-friendliness and economic efficiency (VMD ≥ 0.5), those based on eco-friendliness and economic efficiency (0.3 ≤ VMD < 0.5), those based on three non-equivalent objects (0.1 ≤ VMD < 0.3), and those based on three equivalent objects (VMD < 0.1). Moreover, four indicators (T-CEEA, T-CEA, T-HDEA, and T-CVA) were presented and analysed to compare the efficiency of each optimised design. To verify the applicability, the proposed technique was applied to a 270-m-height high-rise building with a mega-structure system located in Seoul, Korea. The CO_2 emissions and costs of the structure were reduced by 8.99% and 18.5%, respectively. Thus, as indicated by the aforementioned results – obtained by applying the proposed OGDMM to an actual mega-structure high-rise building and evaluating the results (by classifying design areas according to VMD) –the proposed OGDMM is expected to help improve the eco-friendliness, economic, and serviceability efficiency of buildings.

In this study, the computational efficiency or sensitivity to change in control parameters for the proposed algorithm based on the NSGA-II was not considered. These can be considered in greater detail for a more efficient optimisation (e.g., computational costs). Furthermore, the analytical results in this study were presented based on a typical high-rise building with a mega-structure system with a slenderness ratio of 2.0–8.0. Different configurations of the structural system may lead to different results. However, even in the design of different mega structures, the multi-objective optimal design can be obtained based on the proposed OGDMM in the same way as described in Section 4.

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Author contributions

Conceptualization: S. H. L., H. S. P.; Methodology: J. C., H. S. P.; Software: S. H. L.; Validation: J. C., T. H.; Formal analysis: J. C., S. H. L.; Investigation: J. C., S. H. L.; Resource: T. H., D.-E. L., H. S. P.; Data curation: S. H. L., T. H., D.-E. L.; Writing – Original draft: J. C., S. H. L.; Writing – Review & Editing: J. C.; Visualization: S. H. L.; Supervision: H. S. P.; Project administration: D.-E. L., H. S. P.; Funding acquisition: D.-E. L., H. S. P.

Disclosure statement

The authors declare no conflict of interest.

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