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Integrated FEM, CFD, and BIM Approaches for Optimizing Pre-Stressed Concrete Wind Turbine Tower Design

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Abstract

Today, all over the world, people are looking for sustainable energy with modern systems for the coming generations. Wind energy plays a crucial role in supplying electricity to modern systems worldwide. Onshore turbines are necessary to ensure efficient and economical operation of taller wind towers, which can reach up to 100 m. However, building taller turbine towers faces many challenges, such as complex cross-sectional design, multiple stresses, and high construction costs due to different variables. To combat these challenges, this article proposes an optimization design aimed at enhancing the cost-effectiveness of the pre-stressed concrete wind turbine industry, making it accessible to the wind turbine market and design engineers. The main idea of the research is an integration of design criteria and cost conditions by creating a C# plugin to determine the optimal design with minimum cost as an add-in to a 3D software simulating program. This integration helps to calculate computational fluid dynamics (CFD) using the finite element method (FEM) and minimizes costs in building information modeling (BIM), which covers some gaps from the previous works. The study presents a methodology for designing concrete wind towers and facilitating data exchange between finite element software (Ansys) and BIM software by IFC files. The optimization problem in this article is a multi-objective problem, with an optimal design that minimizes costs by reducing the vibrational wear satisfied by suitable structural stiffness. Results showed an optimal design for the concrete wind tower, resulting in a 24% reduction in material costs for the same height compared to conventional alternatives.

Keywords: Optimization; Multi Objectives; P.S Concrete Structures; Horizontal Axis Wind Generators; Ansys; Finite Element Analysis.

1. Introduction

The global shift towards sustainable energy sources has significantly increased research focused on renewable energy alternatives. Among these, wind power has emerged as a key contender due to its clean, renewable, and efficient electricity generation capabilities. Numerous studies emphasize wind energy's economic and environmental advantages, especially with the steady decline in the Levelized Cost of Electricity (LCOE). For instance, in 2010, over 95% of onshore wind projects had a global weighted average LCOE higher than the lowest fossil fuel-fired alternatives. However, by 2022, advancements in technology and optimization reduced the LCOE of onshore wind projects by 52%, making wind energy a cost-effective solution compared to fossil fuels [1]. Despite these advancements, there remain substantial gaps in optimizing the structural and economic aspects of wind turbine towers, particularly from a construction and design perspective.

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Wind turbine towers are pivotal to ensuring the reliability, efficiency, and cost-effectiveness of wind energy systems. They bear critical structural loads and support key components such as the rotor, power transmission systems, and control mechanisms. Tower design significantly impacts the overall performance, with approximately 17% of the total capital costs of a wind turbine attributed to the tower structure [2, 3]. Given the economic importance of tower optimization, current research has increasingly focused on improving design parameters such as cross-sectional dimensions and height-to-width ratios, which directly influence both structural stability and cost efficiency. However, most existing studies have not adequately addressed the integration of advanced computational tools in tower design, leaving a gap in exploiting multi-disciplinary optimization techniques. Lotfy [4] proposed a novel system featuring a triangular cross-section composed of three columns positioned at each corner of the triangle, a design commonly employed in precast concrete wall panels. The tower's tapered profile minimizes the area exposed to wind forces, thereby reducing the total weight and applied moment. Hub heights of 75 and 100 meters for a 3.6 MW wind turbine were designed using this system, and its performance was compared with that of a conventional conical steel tower of similar hub height. The results demonstrated that the proposed design offers several advantages, including lower initial costs, minimal maintenance requirements, and the ability to be erected quickly and efficiently. Eissa et al. [2] conducted a comprehensive study on a prestressed concrete structural system for wind turbine towers, focusing on an innovative design aimed at addressing the challenges of traditional systems. Their proposed tower features an octagonal cross-section with internal ribs at the base, gradually reducing in dimensions along the height to optimize weight and cost. A 100-meter-high tower designed for a 3.6 MW turbine was analyzed using finite element software (Ansys), with a particular focus on aerodynamic principles to improve structural efficiency. The findings revealed that the prestressed concrete design achieved a significant reduction in material costs and maintenance requirements compared to conventional steel towers. Furthermore, the study emphasized the advantages of the proposed system, including reduced construction time, enhanced dynamic performance, and improved sustainability through optimized material use and aerodynamic design. Eissa & Hasan [5] presented a comprehensive study on a new octagonal pre-stressed concrete wind turbine tower design, addressing the critical challenges of stress concentration, construction complexity, and material usage.

The integration of advanced computational tools has become a cornerstone in modern wind turbine tower design, addressing the increasing demands for efficiency, sustainability, and cost-effectiveness. Tools such as Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and Building Information Modeling (BIM) have revolutionized how engineers approach design challenges. While these tools provide valuable insights individually, their combined application has demonstrated even greater potential in tackling complex, multi-faceted problems in wind turbine tower systems [6, 7]. FEA enables precise structural analysis to ensure the tower's reliability under both static and dynamic loads such as wind gusts and seismic forces, while CFD aids in optimizing aerodynamic performance by designing tower geometries that minimize wind resistance. BIM complements these tools by facilitating data sharing and automating responses to design changes, creating a unified framework for seamless collaboration across disciplines. A recent study on advances in wind turbine tower design emphasized the integration of Building Information Modeling (BIM) with Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). This approach addressed challenges in design accuracy and construction efficiency by streamlining collaboration and enabling precise simulations. The study demonstrated a 15% reduction in design errors and construction costs, highlighting the potential of combining these advanced tools to optimize wind turbine tower performance and cost-effectiveness [8]. The importance of integration lies in leveraging the strengths of these tools collectively, addressing limitations inherent in their standalone use. For instance, FEA evaluates structural performance but cannot account for detailed aerodynamic forces, which CFD provides. Similarly, BIM ties these analyses together by enabling real-time decision-making, reducing manual errors, and streamlining construction workflows. Studies have shown that combining BIM with FEA and CFD enhances the accuracy of simulations, supports modular construction methods, and ensures compliance with critical design requirements, such as deflection limits, cross-section optimization, and material efficiency [9-11]. Currently, advancements in this integrated approach have also emphasized its role in promoting sustainability. For example, the use of recyclable materials and circular design principles in wind turbine tower construction reduces environmental impact and aligns with global sustainability goals. By addressing material costs, natural frequencies, structural deflections, and all other structural behaviors within a unified framework, the integration of FEA, CFD, and BIM offers significant benefits for designing wind turbine towers that are structurally robust, economically viable, and environmentally sustainable [12, 13].

The proposed system incorporates internal ribs at the corners of the octagonal cross-section, enhancing the rigidity and uniformity of the structure while reducing stress concentrations in critical areas. The design, evaluated for a 100-meter tower supporting a 3.6 MW turbine, demonstrated significant reductions in deformation and stress by approximately 50% and 30%, respectively, compared to traditional designs. The study employs Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) using ANSYS to simulate wind pressure effects, analyze structural stresses, and ensure compliance with design codes. The results revealed that the octagonal design with internal ribs achieved better performance than traditional circular and plain octagonal cross-sections. The proposed system not only met safety and performance requirements but also offered advantages in cost-effectiveness, ease of transportation, and reduced environmental impact. When compared with the previous study by Eissa & Hasan [5], which focused on an octagonal cross-section with internal ribs, the current study extends the analysis by incorporating CFD to simulate wind flow patterns and validate aerodynamic efficiency. Both studies align in emphasizing the superiority of octagonal pre-stressed concrete designs over traditional steel towers, particularly for hub heights exceeding 100 meters. The integration of advanced design principles and numerical simulations in both works underscores the evolution of wind turbine tower designs toward more efficient and sustainable solutions. So, this study aims to build upon these advancements by developing an optimization framework that leverages the interoperability of FEA, CFD, and BIM. The proposed framework focuses on minimizing construction material costs and improving structural performance while ensuring compliance with design requirements such as cross-section thickness, deflection limits, and natural frequency constraints. Moreover, it seeks to address the existing gaps in previous research, including issues such as stress concentrations in critical structural areas, the impact of aerodynamic forces on tower performance, and the lack of integration between structural optimization and practical construction methodologies. By automating and streamlining the design process, this study aims to bridge the gap between theoretical advancements and real-world applications, thereby enhancing the efficiency, durability, and cost-effectiveness of wind turbine tower systems.

2. Research Methodology

To satisfy the aims of the study, Figure 1 shows a workflow that expresses step-by-step the process of the research to create a plugin multi-objective for optimization of the design criteria and components with minimum cost at the same time. The plugin created by C# is available for sharing, using, and transferring data and information within multi-software (ANSYS & Revit as a simulation tool) at the same time.

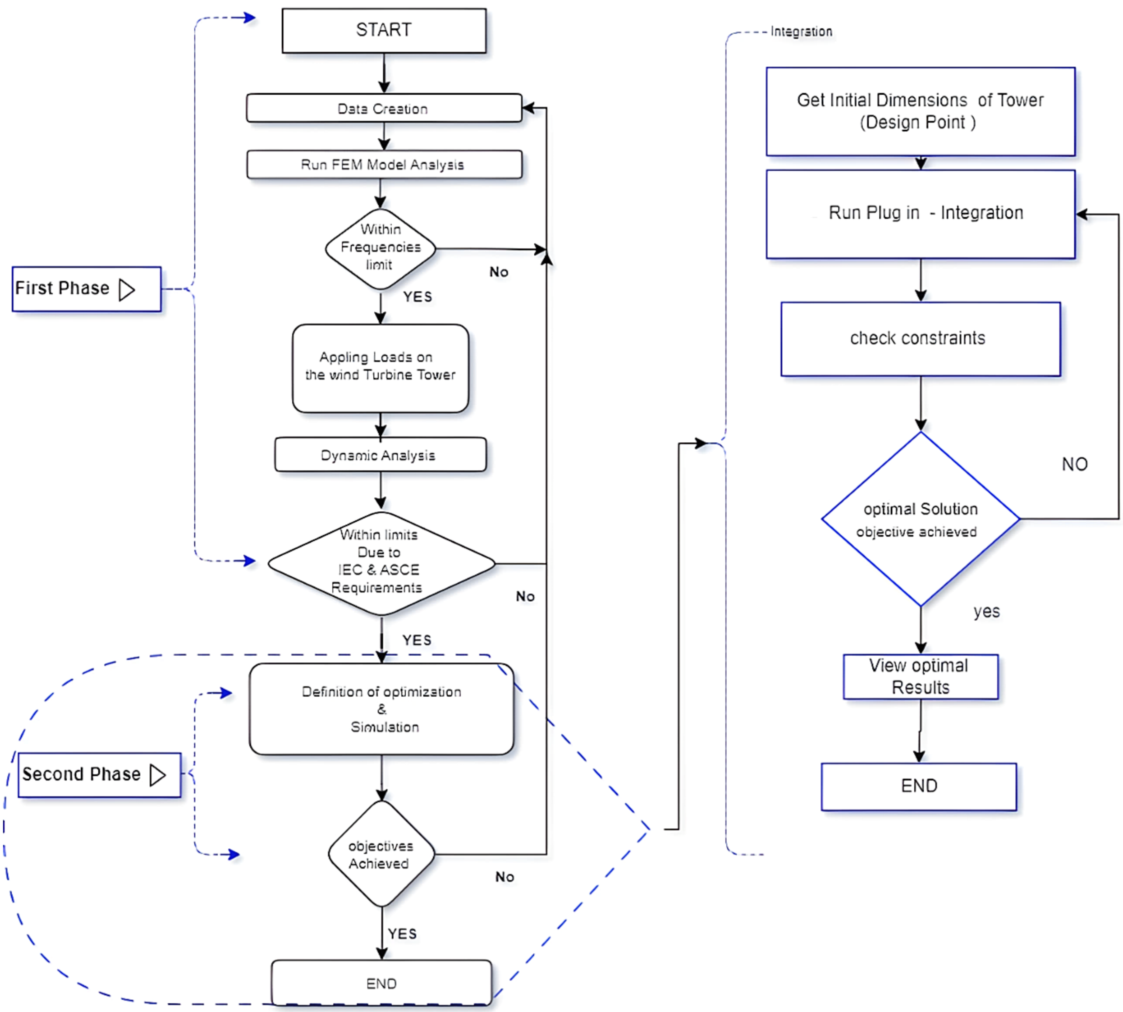


Figure 1. The Main Workflow for the research

The first step involves using ANSYS software to conduct structural analysis, design, and optimization focused on construction parameters rather than cost. The optimization process addresses constraints such as natural frequency, deformation, normal stress, and fatigue under various load cases. This step includes creating an initial design in ANSYS, undergoing iterative optimization to ensure that each design update meets the specified constraints, and performing three-dimensional modeling to evaluate the physical effects on the structure.

The second phase focuses on integrating ANSYS with Building Information Modeling (BIM) technology using the IFC files. The current study integrates the information data obtained by sharing the data from computational fluid dynamics (CFD) and the data of the finite element method (FEM) within IFC files to building information modeling (BIM) and optimization algorithms using a new proposed plugin with Revit. A custom plugin is developed to facilitate data exchange between these tools, involving exporting analysis results from CFD and FEM software to the BIM 3D model and then back to the BIM environment. The sharing data in this study and the workflow of the plugin are shown in Figure 2. The sharing data and the proposed plugin are designed within two stages. The first stage is divided into four steps, which are:

- Create a finite element model (FEM) with IFC file.
- Sharing the analysis of CFD as an IFC file.
- Establish a protocol for collecting these IFC files.
- Integrate the IFC files above with the Revit model.
- The second stage is divided into two steps, which are:
- At this step the plugin runs using a code designed by C#
- The optimization check is running at this step, then decide if arrive to at the optimal solution or make another iteration to arrive at the optimal solution.

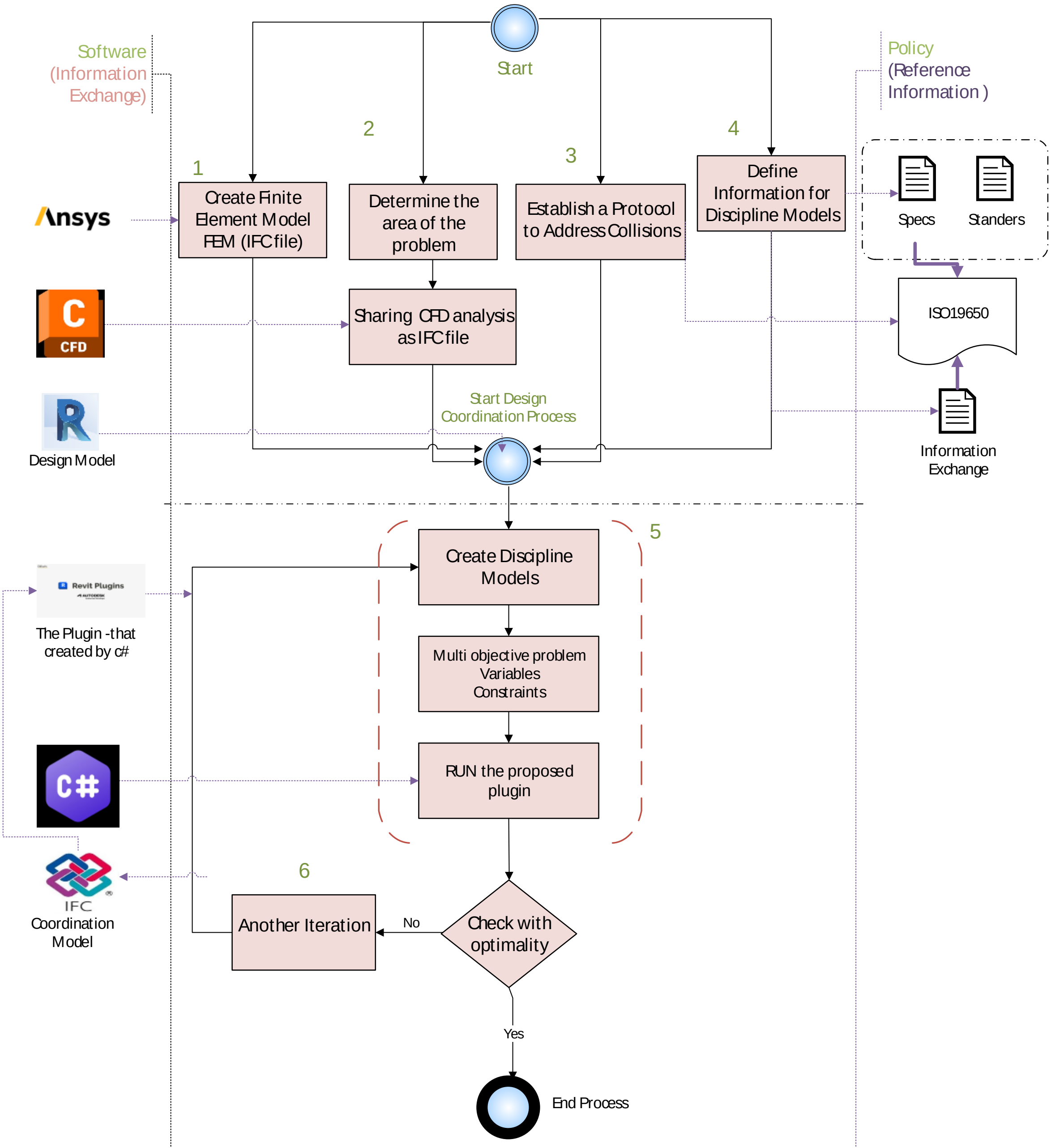


Figure 2. The Workflow of Sharing Data of the Proposed Integration Optimization Plugin

So, the summary of the process is exporting structural analysis data from Ansys and CFD to BIM software, using the IFC files. Then, updating the BIM model based on the optimized design from ANSYS, validating the integrated model, and visualizing the final optimized design within the BIM software. The main benefit of this plug-in is interoperability with a suitable type and creating a dynamic environment for sharing data with multi-tools with optimum performance without any interruption using IFC files. This integration ensures an efficient, cost-effective structural optimization process that accurately reflects the physical and economic considerations in the BIM environment, enhancing the overall design and analysis workflow for the wind turbine tower. In this phase, the cost optimization depends on materials, and construction costs are calculated also by the same plugin. The plugin considered the design methodology of a pre-stressed concrete tower adheres to the standards and limits set by codes such as IEC 61400-12 [13], ASCE 7-10 [14], ACI 318 [15], and IEC 61400–1 (2005) [16], as well as guidelines from NREL. The design parameters are linked to these specifications and codes. The height of the tower is influenced by several primary factors, including location, wind speed, and humidity, which can vary. Therefore, it is essential to consider the wind profile and turbulence when determining the tower's height. Additionally, the design must meet the conditions outlined in IEC classes 1, 2, and 3 to ensure adequate insulation and protection from environmental elements. These limitations are considered within the methodology to ensure the structural design and optimization processes align with the required standards and environmental conditions.

3. Modeling

3.1. Fluid-Structure Interaction

Fluid-structure interaction (FSI) involves the interplay between fluid and solid structures, where the fluid influences the deformation of the solid geometry, and the deformed geometry, in turn, affects the fluid variables. FSI is a multiphasic problem that combines fluid and solid mechanics. There are two main types of FSI interactions: one-way and two-way. In one-way FSI, computational fluid dynamics (CFD) and finite element analysis (FEA) solvers operate independently, with the CFD results applied as a load to the mechanical analysis. In two-way FSI, both solvers run simultaneously, transferring results between CFD and FEA until overall equilibrium is achieved [17]. For this research, we are using a one-way FSI approach for the simulation process.

3.2. Mechanical Model of the Pre-Stressed Concrete Wind Turbine Tower

The pre-stressed concrete wind turbine tower exhibits a tapered profile, with varying cross-sections along its height. This tapering geometry contributes to the tower's structural efficiency and helps optimize material usage. The internal structure of the tower comprises pre-stressing tendons arranged vertically along the tower's height (Figure 3). These tendons tend to introduce compressive stresses in concrete, thereby increasing the tower's resistance to bending moments and tensile stresses arising from wind loads and the weight of the turbine components.

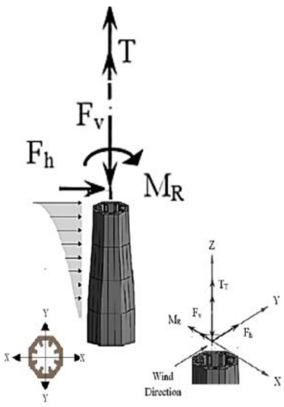


Figure 3. Mechanical model of the pre-stressed concrete wind turbine tower [5]

The mechanical model of the pre-stressed concrete tower considers the tapered geometry, the arrangement of pre-stressing tendons, and the material properties of the concrete and steel. The model considers the interaction between the concrete and the pre-stressing tendons, as well as the transfer of forces between them. The pre-stressing forces are applied to the tendons, which in turn compress the concrete, creating a favorable stress state that enhances the tower's structural performance.

3.3. Structure Modeling

The structural model includes the full geometry of a wind turbine, including the tower, nacelle, and rotor. We created a 3D model using ANSYS/Design Modeler, following the specifications outlined in our published article on wind turbines with more than 3.6 MW of power and standing above 100 meters tall, in the subsequent step, the tower model was integrated into an appropriate enclosure frame recommended by the manufacturer, as illustrated in Figure 4. Regarding CFD modeling for wind turbine towers, selecting optimal computational domain dimensions is paramount for achieving a precise balance while managing computational expenses. As per widely recommended criteria, upstream distances of 5-10 times the tower diameter, downstream distances of 10-20 times the diameter, lateral distances of 5-10 times the diameter, and enclosure heights of 2-3 times the tower height are typically proposed [11]. For this study, we've confidently established the domain dimensions at 6 times the tower diameter upstream, 1.5 times downstream, and 4 times laterally. This strategic arrangement enables us to capture flow phenomena while preserving computational efficiency adeptly.

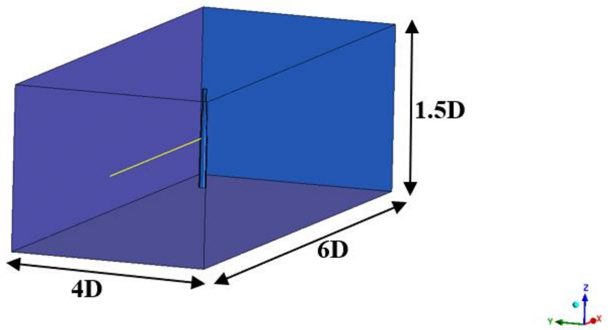


Figure 4. Enclosure of Wind Turbine Tower Model

The computational domain dimensions in this study deviated from common guidelines, employing a more compact configuration with lateral distances of 4D and a height of 1.5D. Such spatial constraints could influence the simulation outcomes in several ways. The restricted lateral space might induce artificial flow confinement, potentially leading to enhanced flow velocities and elevated pressure coefficients near the tower.

The limited vertical extent could affect the natural development of flow patterns, particularly in the upper regions where flow separation and reattachment occur. These spatial limitations may impact the accuracy of wake predictions and vortex formation processes, especially in regions close to the domain boundaries. While these constraints warrant consideration during result interpretation, the data remains meaningful, particularly for analyzing flow characteristics in the lower tower sections where boundary influences are minimized. Future studies might benefit from exploring the sensitivity of results to domain size variations.

3.4. Meshing

CFX-mesh technology specializes in generating meshes that excel at capturing boundary layer dynamics while meeting stringent quality standards. The system supports multiple element types in its meshing capabilities. For three-dimensional applications, it can generate tetrahedral, prismatic, and pyramidal elements, while two-dimensional modeling allows for hexahedral element integration. Given the geometric complexity encountered in this investigation, we implemented a tetrahedral mesh configuration utilizing ANSYS's advanced size function. This approach proved particularly valuable in generating precise mesh elements near wall boundaries. To enhance mesh uniformity, we applied mapped face meshing techniques specifically to the nacelle, rotor, and tower surfaces [11].

The mesh generation methodology for this investigation employs CFX-Mesh technology within ANSYS to achieve high-quality discretization that effectively captures boundary layer phenomena. The simulation domain utilizes a hybrid meshing approach, combining tetrahedral elements for complex geometries with strategic mesh refinement near critical surfaces. For the tower structure, the tetrahedral mesh was selected due to its adaptability to complex geometries, while the advanced size function in ANSYS was implemented to ensure high-quality mesh generation, particularly around solid boundaries. To enhance solution accuracy, mapped face meshing was applied specifically to the tower surfaces, ensuring uniform element distribution across critical sections. The tower geometry required special consideration, implementing a dual-element strategy that utilizes hexahedral elements in high-stress regions (particularly at the base) and tetrahedral elements in areas with complex geometrical features across the transverse sections.

The mesh quality was continuously monitored during generation through key metrics including element skewness, aspect ratio, and orthogonality. Particular attention was paid to regions near wall boundaries where structural loads are expected to be significant. The mesh resolution was progressively refined in these areas to ensure adequate capture of stress distributions. For the transverse sections, special consideration was given to maintaining mesh uniformity, where finer mesh elements were implemented to accurately resolve the structural response characteristics. The transition between different mesh densities was carefully controlled to maintain smooth element size gradients, thereby enhancing solution stability, as shown in Figures 5 to 7, respectively.

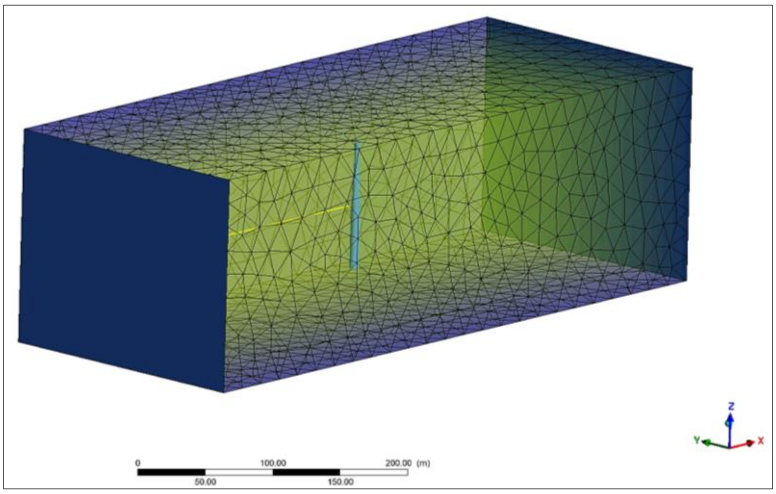


Figure 5. Enclosure meshing of wind Tower

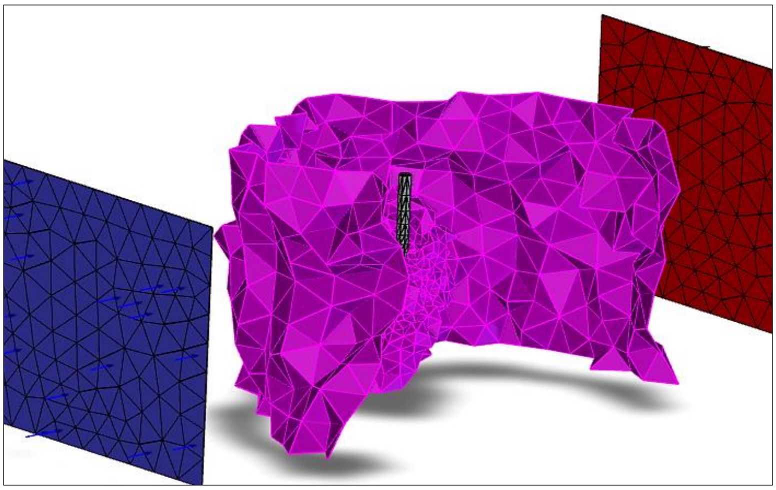


Figure 6. Enclosure meshing of wind Tower (Partitions)

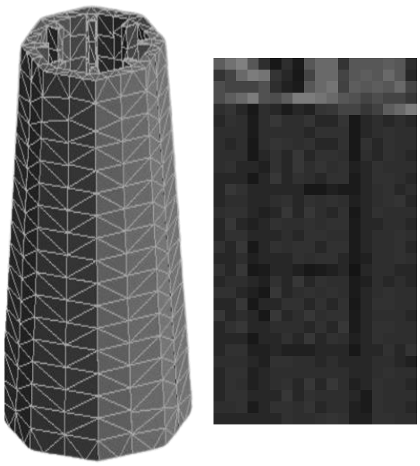


Figure 7. Different types of meshes

3.5. k-ω Modeling

The k-ω model is well-suited for predicting turbulence near walls. This model is based on transport equations for turbulence kinetic energy, k, and the specific dissipation rate, ω. One of the key advantages of the k-ω model is its ability to accurately account for low-Reynolds-number effects near walls, allowing for more precise and robust modeling of these areas. However, a notable drawback of the model is its high sensitivity to free-stream conditions, which can impact accuracy in specific flow scenarios. This study uses the k-ω turbulence model to assess near-wall turbulence effects, employing two transport equations: one for turbulent kinetic energy (k) and another for the specific dissipation rate (ω). Although this model is a focus of the current study, its effects were previously discussed in our last publication [12].

This study has selected the Shear Stress Transport (SST) model for both stationary and rotating domains due to its advantages over the k-ε model. The SST model combines the strengths of the k-ω model near walls with the robustness of the k-ε model in free-stream regions, offering a balanced approach that improves overall accuracy and turbulence model stability [12].

3.6. Set up of the Wind Turbine Model

After creating appropriate meshes for all components, the next step is to define domains, boundary conditions, analysis types, and interfaces. This article focuses on modeling the wind turbine tower, placing it within the stationary domain.

To accurately simulate the flow around the tower in ANSYS, transient analysis is utilized instead of steady-state analysis. This method accounts for the changing flow variables over time, requiring the definition of total time and time step in the analysis section. It's crucial to ensure that the time step size is sufficiently small to capture dynamic behavior and accurately resolve the transient simulations effectively. Consequently, the optimization model in this study includes the strategies and methodologies used in the analysis and design, optimization problem formulation, and implementation portions of this research. In addition, it includes a case study, a discussion of numerical results, and conclusions. Ansys and BIM ware were used to solve case study optimization problems [9, 18].

On the other hand, the advanced computational techniques enable the exploration of various design alternatives, leading to the development of innovative tower configurations that maximize energy output while ensuring the long-term structural integrity of the tower. The integration of FEM and CFD analysis ultimately contributes to the advancement of sustainable wind energy technologies, fostering the development of cost-effective and reliable solutions for the future of renewable energy generation [3, 10, 19]. Transient loads such as wind gusts and dynamic wind loads can exert significant forces on wind towers. By optimizing the design, the structural performance of the tower can be enhanced, ensuring that it can withstand these dynamic loads without excessive deformation or failure. This leads to increased safety and reliability of the structure. Also, transient loads can induce fatigue stress on wind towers, which can lead to cumulative damage over time.

Therefore, this study involves integrating computational fluid dynamics (CFD) and finite element method (FEM) into building information modeling (BIM) with the help of an optimization proposed plugin. A custom workflow is developed to coordinate the exchange of data between the different tools. This may involve exporting the results obtained from performing the analysis in the CFD and FEM software to the BIM 3D model and then exporting the results back to the BIM environment. The optimization problem in this article is multi-objective, with an ideal design being one that both minimizes costs and maximizes structural stiffness to reduce vibrational wear on turbine components.

3.7. Theoretical Model and Evaluation of Wind Turbine Tower

In our previous studies, such as those referenced in Hasan & Khalil [3] and Eissa & Hasan [5], we investigated the effects of wind resistance, generator gravity, and tower self-weight on the natural frequency, stress, and strain of pre-stressed concrete wind turbine towers theoretically and compared to FEM model, both research studies are followed various design codes, Including IEC 61400-1 [16], the dynamic behavior can be modeled using the Euler-Bernoulli beam equation. The equation is defined as:

$$E_I \frac{d^4 w(x,t)}{dx^4} + m\frac{\vartheta^2 w(x,t)}{\vartheta t^2} = F_{wind}(x,t) + F_{gravity}(x) \tag{1}$$

where E is the modulus of elasticity of the pre-stressed concrete, and I represent the moment of inertia of the octagonal cross-section, which varies with height. The term $w(x,t)$ indicates the transverse deflection at a given position x and time t, while m is the mass per unit length, influenced by both the generator's weight and the self-weight of the tower. The equation includes three primary forces: F_{wind} (x,t) $F_{wind}\ (x,t)$, which is the dynamic wind load distributed along the height and varying over time, a point load due to the gravitational force of the generator at the top of the tower, and $F_{Self}(x)$ which represents the distributed self-weight of the structure.

The natural frequency $w_n$is derived from this equation using the expression:

$$w_n = \sqrt{\frac{k_{eff}}{k_{meff}}} \tag{2}$$

where k_{eff} is the effective stiffness that accounts for the pre-stressed design and geometry, and k_{meff} is the effective mass, including the combined weight of the generator and tower. Additionally, stress (σ) and strain (ϵ) are evaluated under combined loading conditions using the relationships:

$$\sigma(x) = \frac{M(x)}{I}.y + \frac{N_{prestress}}{A}, \in(x) = \frac{\sigma(x)}{E} \tag{3}$$

where $M(x)$ represents the bending moment influenced by external loads, y is the distance from the neutral axis to the extreme fiber, $N_{prestress}$ is the pre-stressing force enhancing the tensile capacity, and A is the cross-sectional area of the concrete. This analytical framework provides a comprehensive understanding of structural behavior, aiding in the optimization of wind turbine tower designs for enhanced stability and efficiency.

4. Optimization

Many points must be considered in the multi-objectives optimization that can be summarized in the following.

4.1. Optimal Dimensions of Cross-Section

The initial dimensions were considered according to Guo et al. [11]. Then, Optimization concepts were implemented to reach the best cross-section dimension at the lowest cost. During the optimization process, design requirements of relevant specifications and industry standards are used as the constraints. The Optimization variables used in this estimation are design variables, independent parameters, dependent variables, and constant variables. There are specific principles that are used for control to find the optimal solution considered in this study, which can be summarized as the following principles:

- The performance of the structure and stability conditions.
- Wind load and Aerodynamics behavior;
- Integration data between multi-tools;
- Multi-Objective Optimization and Trade-Off Management;
- Regulations with standards and design codes;
- Cost minimization with different materials.

4.2. Design Variables

The variables tabulated in Table 1 show the main design variables related to the dimensions of the tower cross-section.

Table 1. The main design variables related to the dimensions of the tower cross-section

<table>
<tr><th colspan="4">Variables</th></tr>
<tr><th colspan="2">Design Variables</th><th colspan="2">Independent variables</th></tr>
<tr><th>Symbol</th><th>Meaning</th><th>Symbol</th><th>Meaning</th></tr>
<tr><td>Ts</td><td>thickness of cross-sections</td><td>$V\ ref$</td><td>wind speed reference</td></tr>
<tr><td>Tr</td><td>the thickness of the rib</td><td>Fht</td><td>horizontal force at the tip of the tower</td></tr>
<tr><td colspan="2">Dependent Variables</td><td rowspan="2">Mtt</td><td rowspan="2">torsional moment at the tip of the tower</td></tr>
<tr><td>Symbol</td><td>Meaning</td></tr>
<tr><td>ve50</td><td>expected wind speed after 50 years</td><td>Mot</td><td>overturning moment at the tip of the tower</td></tr>
<tr><td>Do b</td><td>the outer diameter of the tower at the base</td><td>σat</td><td>allowable stresses of the tower</td></tr>
<tr><td>DoT</td><td>the outer diameter of the tower at the top</td><td>δat</td><td>allowable deflection of tower</td></tr>
<tr><td>Z</td><td>tower height above the ground</td><td>E</td><td>concrete modulus elasticity</td></tr>
</table>

4.3. Objective Function

The primary objective of this study is to minimize the total cost of the wind turbine tower by optimizing two critical components: the amount of concrete used and the quantity of pre-stressed tendons. Initially, the cost function focuses on combining the quantities of these materials with their respective unit costs. However, to enhance the optimization process and consider multiple important factors, the study incorporates additional objectives beyond just cost. These include minimizing the top deflection of the tower to ensure structural stability and reducing the environmental impact associated with material usage, such as the carbon footprint from concrete and steel tendons. To satisfy this First and Derivative Tests are used in this research for multi-variable calculations for the difference between the first and second derivate that identify the maximum and the local minimum with Hessian matrices. The optimization problem is expressed through the following objective function:

$$\text{Mc}=\mu c \times qc + \mu p \times qp \tag{4}$$

where: Mc is Material Cost, μc is the unit cost of concrete, μp is unite cost of pre-stressed tendon, qc is quantity of concrete and qp is quantity of pre-stressed tendons.

To achieve this, the optimization process involves developing a multi-objective function that balances these key factors. We assign specific weights to each objective to reflect their relative importance: the objectives below are determined after calculating their weight and relative importance: Cost minimization, structural integrity (in terms of top deflection), and environmental sustainability. In addition, constraints are applied to ensure that the optimized design meets all necessary safety and performance standards. These constraints include limitations on maximum allowable deflection to prevent structural failure, ensuring sufficient strength to avoid buckling, and maintaining the overall cost within a specified budget. By incorporating these multiple objectives into the optimization framework, the study aims to find the most efficient design for the wind turbine tower, considering cost, performance, and sustainability. The function aims to balance the quantities of these materials with their respective costs, ensuring the structure remains both economically viable and structurally sound. By minimizing, we directly reduce the overall material expenses of the tower, focusing on efficient material usage without compromising performance or safety. In practice, optimizing this function involves adjusting the design parameters to reduce material quantities while maintaining the required mechanical properties, such as stiffness, strength, and durability. The interdependency between concrete volume and tendon tensioning is carefully considered to ensure cost-effectiveness at every stage of the design.

4.4. Constraints

The optimization process is subject to a set of constraints that ensure the structural integrity and functional performance of the wind turbine tower. These constraints are derived from essential design requirements and govern the behavior of the design variables. They ensure that the optimized solution meets the necessary safety, performance, and durability standards. The primary constraints include:

- ***Natural Frequency***: The tower's natural frequency must remain within specified limits to avoid resonance with the turbine's operating frequency range. This ensures the structure's dynamic stability and prevents detrimental vibrations.
- ***Local Buckling Limits***: The design must prevent local buckling in any part of the tower. This constraint ensures that the structural elements can withstand the applied loads without experiencing localized failure or deformation.
- ***Top Deflection Limits***: The tower's maximum top deflection is restricted to prevent excessive sway or tilt under wind loads and operational conditions. This constraint guarantees the operational reliability of the turbine and maintains the required alignment for power generation.
- ***Allowable Compression Stresses***: The compressive stresses in the concrete must remain within the allowable limits to avoid material crushing or failure. This constraint ensures that concrete can support the applied loads without exceeding its capacity.
- ***Allowable Tension Stresses***: The tensile stresses in the pre-stressed tendons are limited to prevent overstretching or failure. This constraint ensures that the tendons provide the necessary reinforcement while maintaining the required safety margin.

Each of these constraints plays a critical role in guiding the optimization process, ensuring that the reduction in material quantities does not compromise the tower’s structural performance. By carefully balancing these constraints with the objective function, we achieve a cost-effective yet robust tower design.

5. Validation

This section validates the proposed wind turbine tower design by comparing it with the Muskulus & Schafhirt [20] 2004 LWST Phase I Project Conceptual Design Study by LaNier [21]. The 2004 study serves as a benchmark for hybrid steel/concrete towers, assessing different design strategies for improving performance and reducing costs. By evaluating the proposed pre-stressed concrete tower against the findings from LaNier’s study [21], this comparison aims to verify the new design’s structural performance, stability, and cost-effectiveness. The analysis emphasizes the proposed system’s innovative features and practical benefits, demonstrating its suitability for real-world implementation in wind turbine tower engineering. Table 2 shows a comparison between results from the benchmark problem and the results from the proposed integration system with a percentage between the differences of the results.

Table 2. Comparison between results from the LaNier section and the results from the proposed integration system with a percentage between the differences of the results

Behavior	Optimal Proposed Section	LaNier section	% Difference
Natural Frequencies	0.45	0.489	8.67%
Top Deflection Cm	41	45	9.76%
Max. compression MPa	14.8	15	1.35%
Max. Tension MPa	0.24	0.26	8.33%
Top Deflection Cm According to Earthquake	0.72	0.80	11.11%
Total Material Cost (R)	1573880	1962066	24%

The proposed section was validated against LaNier's section, with key behavioral parameters compared. The natural frequencies showed a slight increase of 8.67%, indicating improved vibrational stability. The top deflection under regular conditions increased by 9.76%, remaining within acceptable limits. The maximum compression stress saw a minimal rise of 1.35%, while the maximum tension increased by 8.33%, demonstrating enhanced load-bearing capacity. Under seismic conditions, the top deflection increased by 11.11%, suggesting that the proposed section offers improved resistance to earthquake-induced forces while maintaining structural integrity. The proposed section demonstrated a significant 24% reduction in total material costs when compared to LaNier's section, highlighting a more efficient utilization of resources. This reduction in material expenditure emphasizes the economic advantages associated with the proposed design in comparison to LaNier's and MSC's [3, 21].

6. Case Study

To validate the optimization method's effectiveness, a case study was performed using real-world parameters from the Eastern Sea Bridge Wind Farm in Shanghai, China, focusing on a 100-meter prestressed concrete tower designed for a 3.6 MW XD wind turbine. The study involved comprehensive load analyses, including Extreme Operating Gust (EOG), Extreme Wind Speed (EWM), seismic loading evaluated through multimode linear analysis, and second-order moments. Site-specific conditions, such as a design basic wind speed of 42.5 m/s and terrain roughness classified as category D as shown in the next table, were considered. The geometry utilized for this analysis was based on the proposed system presented in Eissa et al. [2] as shown in Figure 7.

The case study was carried out to apply the proposed add-in with the BIM model for the design of a 3.6 MW wind turbine tower, utilizing load information and an operational manual provided by the turbine's manufacturer, by the IEC 61400-1 standard [16]. This standard specifies several wind models that must be evaluated in wind turbine design. For this analysis, two critical models were selected Extreme Operating Gust EOG and Extreme Wind Speed EWS as detailed in the next Table. As per IEC 61400-1 [16], a load factor of 1.35 was applied to account for wind turbine loads under extreme conditions. Both extreme wind speeds during non-operational periods and extreme gusts during operational periods were evaluated to form the basis for the ultimate and service load combinations.

These combinations ensure that the tower is robust enough to endure extreme wind conditions, both while the turbine is operating and while it is idle. Table 3 presents all the load combinations considered in this study, highlighting the key conditions the tower must be designed to withstand.

Table 3. Technical parameters for the wind turbine

Rated power	3.5 MW
Rotor Diameter	115 m
Cut in wind speed	2.5 m/s
Cut out wind speed	25.0 m/s
Rotor speed	13.2 rpm
Upper component	314912 kg
Tower height	100 m
Wind class IEC	I
Average wind speed	10 m/s
Extreme wind speed (E W M)	59.5 m/s
Gust wind speed (EOG)	35.1 m/s

The specifications of the geometry have been thoroughly described in the previous studies [2, 5], where the proposed octagonal cross-section with internal ribs was detailed in terms of dimensions, tapering profiles, and stress concentration mitigation strategies, furthermore, our proposed system a wind turbine tower with an octagonal pre-stressed concrete cross-section—is used as a case study. The design includes internal ribs at the corners to improve structural integrity and reduce stress concentrations. The modular structure allows for disassembly into eight larger sections at the base and four smaller sections at the top, facilitating transportation and assembly. BIM (Revit) and Ansys were utilized to create a full-scale 3D model of the tower, optimizing its performance under different load conditions, as shown in the following figures (Figures 8 and 9) [2, 5]. This case study demonstrates how the design achieves an efficient balance between material usage and structural strength, providing a practical and cost-effective solution for wind turbine support.

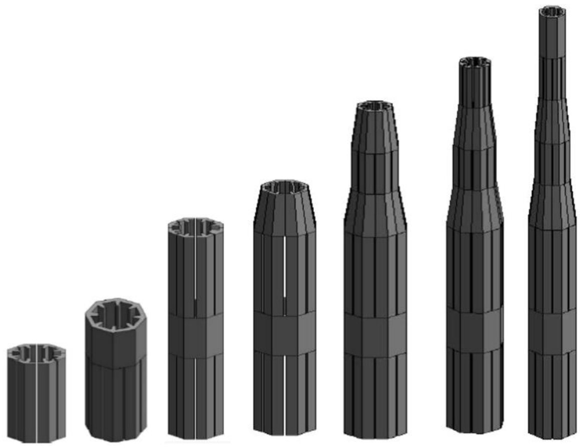


Figure 8. A wind turbine tower with an octagonal pre-stressed concrete cross-section (case study)

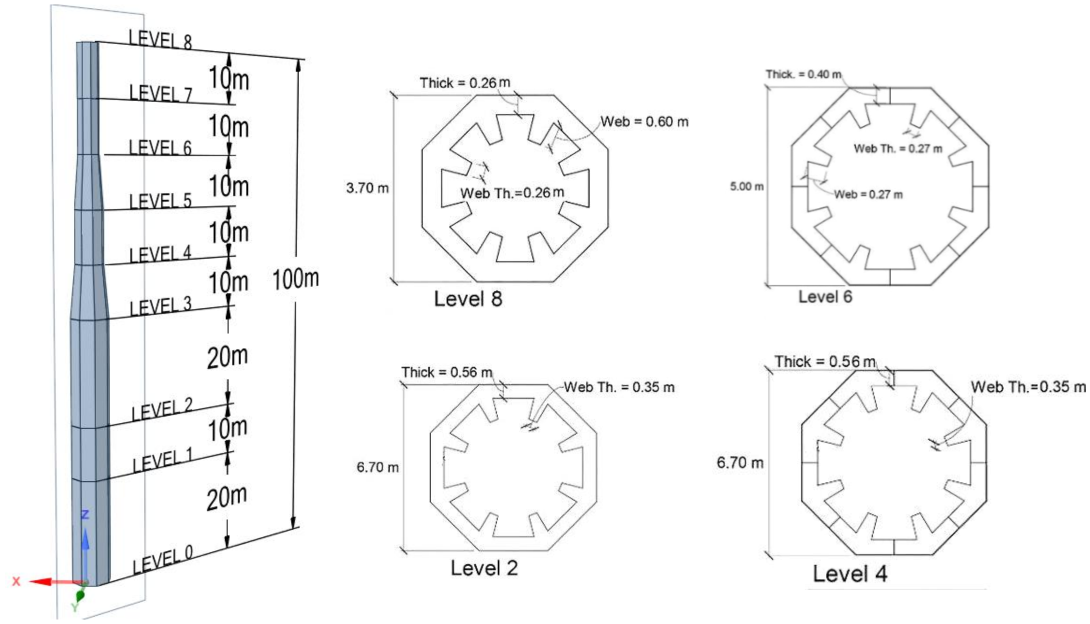


Figure 9. Cross-section details for octagonal pre-stressed concrete (case study)

This step is very important as it is the basis of all the following steps. In this step, a 3D model is created with a high level of detail (LOD 400) as shown in Figure 10.

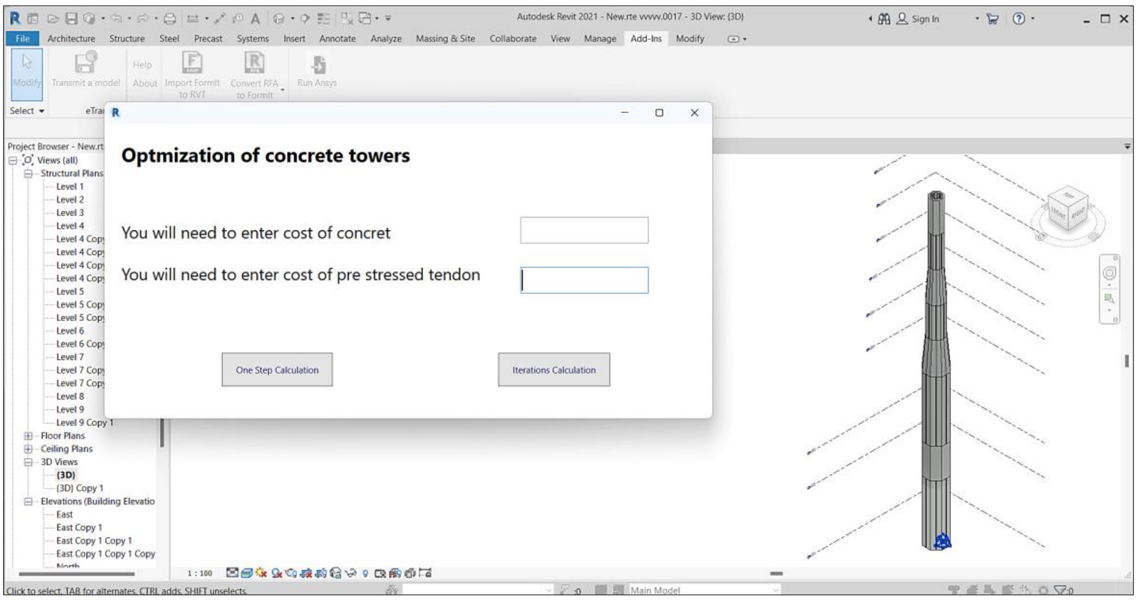


Figure 10. 3D Model of the Building

After adding the plugin to Revit, the screen of Revit changes as shown in Figure 9 with the main three buttons.

- ***Data Entry*:** This step is the main idea of the add-in, at this stage, the user must fill in the remaining cells for the exported Excel sheet from the previous step, as was described in section 4 – methodology.
- ***Import Excel Data*:** At this step, the user imports the previous Excel sheet to the 3D model that was created in Revit in step number one. Once the Excel sheet is imported into the model, all the data is linked together with a compatible model and ready for the next and final step.

7. Discussion and Calculate a Sheet

At this step, the add-in asks the user for the total available budget for maintenance at this round, and then the user presses the calculation button. Then, the add-in is running and finds the optimum solution within this budget and the most important objects with their components as shown in Figure 11. Finally, Table 4 shows the final output of the integrated proposed system for all iterations done to arrive at the optimal solution of analysis with the corresponding material cost for the optimal one as shown in Figure 12. The results mention multiple points that optimize the different iterations of the design, such as material optimization performance, dynamic response characteristics, deformation analysis, and stress distribution evaluation. Each point of these points will be discussed briefly and respectively at the next words. At first, quantitative analysis of the tower optimization process demonstrated significant material reduction efficiency across 14 iterative cycles. The concrete volume exhibited a systematic decrease from an initial quantity of 1117.5 m³ to a final optimized volume of 767.5 m³, representing a 31.3% reduction in material usage. The thickness reduction was implemented in consistent 100 mm increments, allowing for controlled evaluation of structural response at each optimization stage. This methodical approach to material reduction maintained critical geometric ratios while achieving substantial improvements in material efficiency. Secondly, the fundamental frequency response exhibited remarkable stability throughout the optimization sequence, maintaining values between 0.45 to 0.452 Hz, well within the specified design parameters of 0.22-0.66 Hz as shown in Figure 13-a. Statistical analysis of frequency variation across iterations showed a maximum deviation of less than 0.5%, indicating negligible impact on dynamic response characteristics despite significant material reduction. This stability in frequency response suggests effective preservation of the structure's dynamic properties throughout the optimization process. For the deformation analysis, structural deformation metrics demonstrate predictable and controlled increases correlating with material reduction. Under standard loading conditions, maximum deflection increased from 362.6 to 417.6 mm (15.2% increase), while combined wind and seismic loading resulted in deflection progression from 711.9 to 720.9 mm (1.3% increase), as shown in Figure 13-b. Both parameters-maintained compliance with the 1% height limitation criterion across all iterations. The differential between standard and combined loading deflection responses suggests effective load distribution mechanisms were maintained throughout the optimization process. Finally, for the stress distribution evaluation, the analysis of stress distribution patterns revealed systematic progression in both compression and tension domains. Compressive stress magnitude increased from -8.07 MPa to -14.8 MPa (83.4% increase), while tensile stress exhibited progression from 0.144 MPa to 0.246 MPa (70.8% increase). Both parameters demonstrated asymptotic behavior approaching but not exceeding their respective design limits of 15 MPa and 0.25 MPa as shown in Figure 13-c. The stress evolution patterns indicate optimal material utilization while maintaining structural integrity within prescribed safety margins.

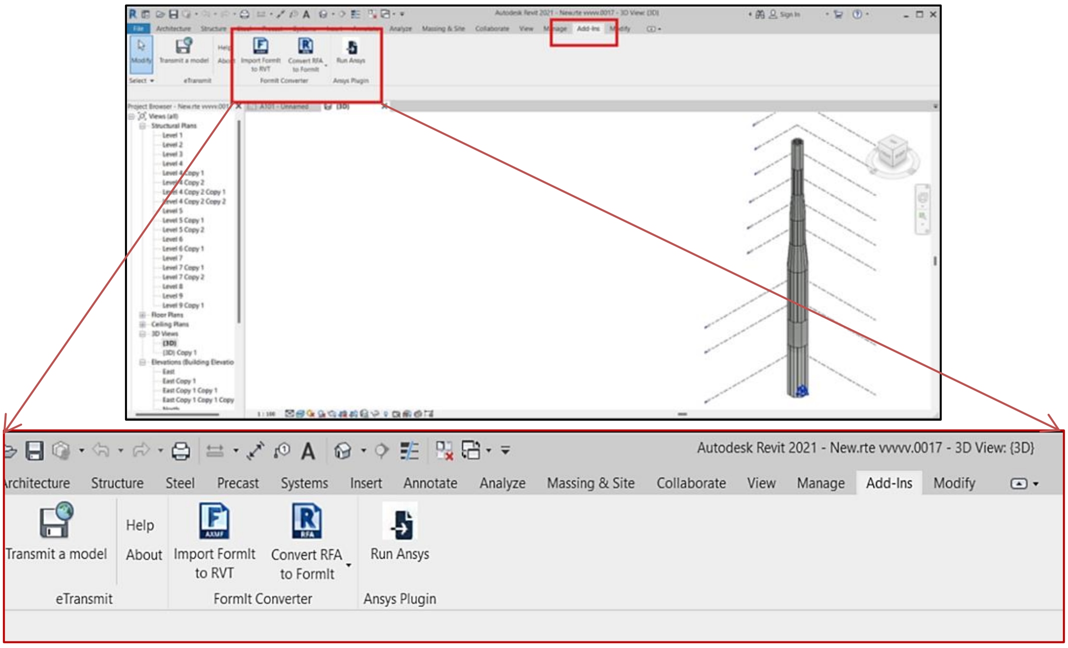


Figure 11. Revit-Screen after Integrating the Proposed Add-in

Table 4. The output results of the case study for all iterations done by the proposed integration system

Iteration No.	Tower Thickness	Concrete Quantity Before (m^3)	Reduced Value (mm)	Concrete Quantity After (m^3)	Fundamental Frequency	Tower Deflection (mm)	Tower Deflection Load Case Wind + Earthquake	Tower Stress	
					0.22 to 0.66 HZ	1% of total height	1% of total height	15 MPa	0.25 MPa
								Compression	Tension
1	Top of Tower / Med of Tower / Bottom of tower	1117.5	100	1092.5	0.4512	362.6	711.9	-8.07	0.144
2		1092.5	200	1067.5	0.4512	366.1	712.3	-8.71	0.149
3		1067.5	300	1042.5	0.4513	369.6	712.8	-9.73	0.151
4		1042.5	400	1017.5	0.4513	373.4	713.2	-10.59	0.158
5		1017.5	500	992.5	0.4513	377.2	713.9	-12.46	0.167
6		992.5	600	967.5	0.4515	381.2	714.6	-12.55	0.175
7		967.5	700	942.5	0.4516	385.3	714.9	-12.9	0.18
8		942.5	800	917.5	0.4516	389.41	715.5	-13.01	0.195
9		917.5	900	892.5	0.4517	393.7	716.5	-13.4	0.2
10		892.5	1000	867.5	0.4518	398.4	716.8	-13.9	0.21
11		867.5	1100	842.5	0.4519	402.1	717.5	-14.1	0.23
12		842.5	1200	817.5	0.4520	407.6	718.4	-14.48	0.235
13		817.5	1300	792.5	0.4521	412.5	719.2	-14.7	0.241
14		792.5	1400	767.5	0.4522	417.6	720.9	-14.8	0.246

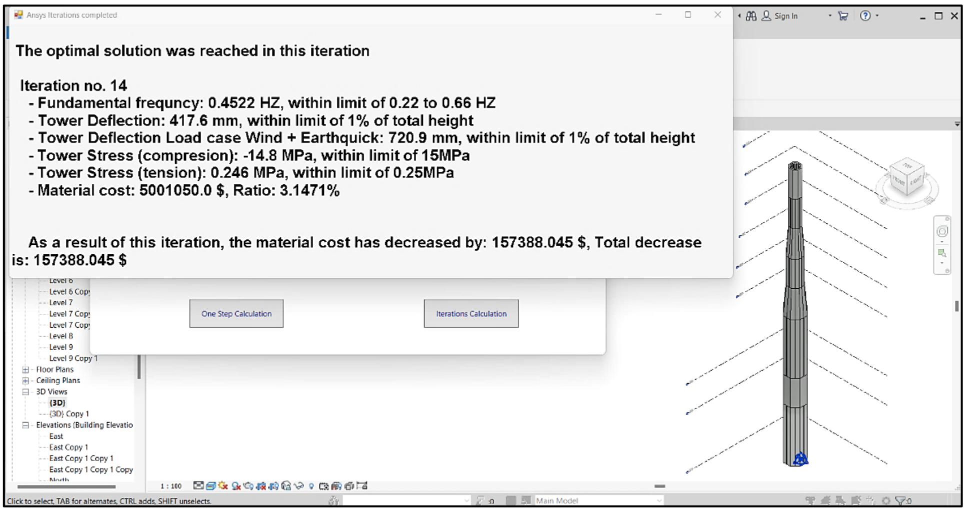
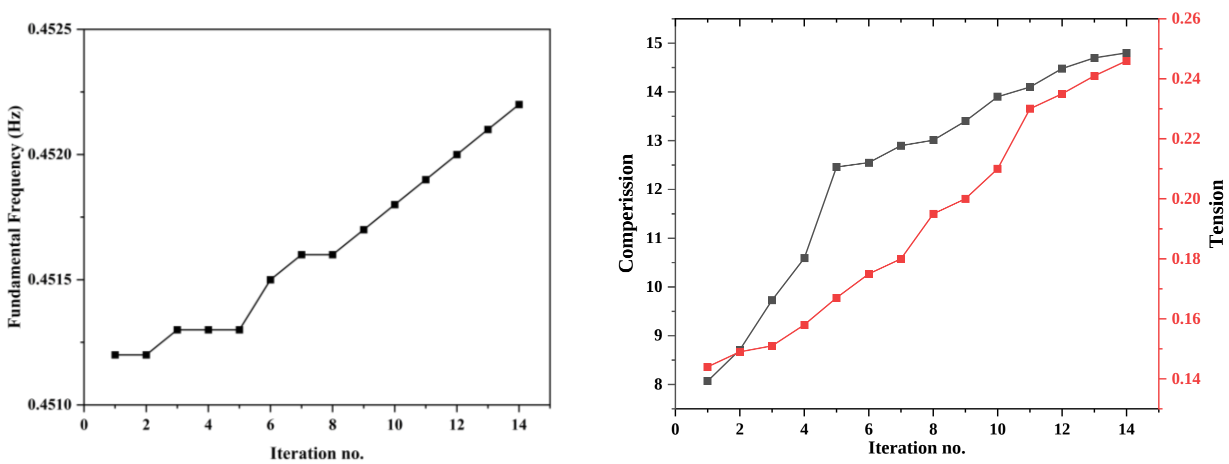
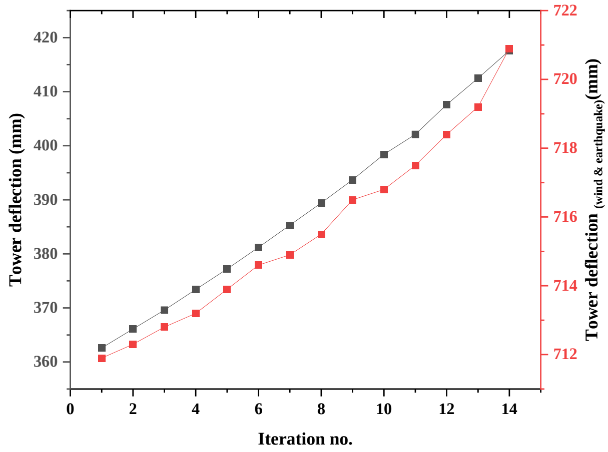


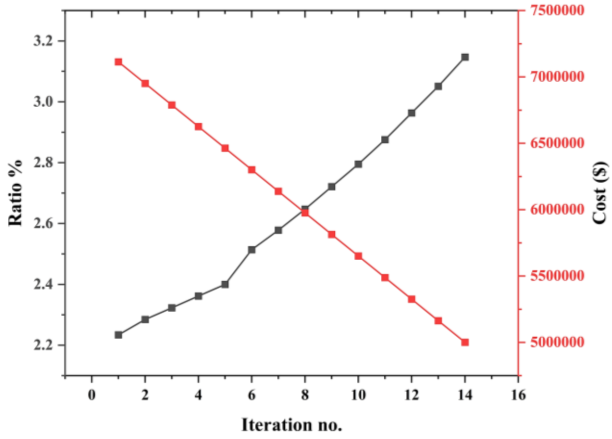
Figure 12. List of Maintenance Items with Allowable Budget



(a) (b)



(c)



(d)

Figure 13. a) List of Maintenance Items with Allowable Budget, b) List of Maintenance Items with Allowable, c) List of Maintenance Items with Allowable Budget, d) List of Maintenance Items with Allowable Budget

8. Conclusions

A very strong tool has been created in this paper mainly for the designers of Pre-Stressed Concrete Wind Turbine Towers to optimize their design to satisfy the actual stresses facing the body of the turbine with minimum cost. This integration helps to calculate computational fluid dynamics (CFD), finite element method (FEM), and minimize cost in building information modeling (BIM). The main idea of the research depended on facilitating data exchange between finite element software (Ansys) and BIM software. A plugin created by C# has been created to solve a multi-objective optimization problem to satisfy and minimize costs with suitable structural stiffness to reduce vibrational wear on turbine components. This plugin is easy to use as an add-in to the BIM software, which is very popular now in the design and construction sector. Also, a validation of the proposed plugin has been illustrated with a common benchmark problem to examine the plugin's performance and determine its accuracy. The results showed that the proposed integration plugin is effective and applicable to use in the industry. A case study has been created and optimized in this paper, which introduced multiple iterations of solutions and determined the optimum design that satisfies the different stresses with a minimum budget. Finally, there are some main points summarized below as the conclusions of the research:

- Optimization of wind turbine towers is necessary today to be an alternative source to the traditional sources.
- Data sharing is the best tool to find the optimal solution to many different problems.
- The accuracy of the proposed framework is acceptable to introduce it to the industry.
- The proposed plugin helps the decision-makers find the optimal design with the minimum cost within a suitable time related to the traditional method of design.
- The IFC file is the perfect tool for sharing data within the integration of multi-software and disciplines.
- Optimal design for the concrete wind tower, resulting in a 25% reduction in material costs for sections of the same height compared to conventional alternatives.
- Quantitative analysis of the framework's performance indicates substantial improvements in design optimization efficiency, with marked reductions in computational processing time compared to traditional methodologies.
- The demonstrated capability to simultaneously optimize structural performance and material utilization while maintaining compliance with engineering standards represents a significant advancement in wind turbine tower design.
- These results establish a robust foundation for future research in sustainable energy infrastructure optimization, while the validated computational framework provides practitioners with an empirically verified tool for implementing cost-effective designs in industrial applications.
- The successful integration of multiple analytical methodologies within a unified optimization framework represents a significant contribution to the field of sustainable energy infrastructure design.

Finally, more benefits can be achieved by the proposed integration system as good collaboration and coordination by depending on IFC files to facilitate the sharing of data between all software, which reflects on different goals of all stakeholders. Improved the efficiency and accuracy in the design phase mainly by using this integration at structural analysis and the environmental impacts at the same time which leads to minimizing the 'probability of errors and rework. Also, optimizing the performance of different turbines is considered. Finally, this integration targets the design phase mainly to avoid the multi-change orders with their cost overrun and to avoid other crises from these changes.

9. Declarations

9.1. Author Contributions

Conceptualization, A.E. and A.A.; methodology, A.E.; formal analysis, A.A.; investigation, A.A.; resources, A.E. and A.A.; data curation, A.E.; writing—original draft preparation, A.E.H.; writing—review.; visualization, A.A.; supervision, A.E.H.; funding acquisition, A.E., A.A., and A.E.H. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

9.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

9.4. Conflicts of Interest

The authors declare no conflict of interest.

10. References

[1] Wiser, R., Bolinger, M., & Hoen, B. (2022). Land-Based Wind Market Report: 2022 Edition. Office of Energy Efficiency and Renewable Energy, U. S. Department of Energy, Washington, United States.

[2] Eissa, A., El-Helloty, A., & Ehab, A. (2024). Structural Analysis of New Octagonal Pre-Stressed Concrete for on Shore Wind Turbine Tower using Computational Fluid Dynamics (CFD). Zhongguo Kuangye Daxue Xuebao, 29(2), 139-151.

[3] Hasan, A.M.A.S. & Khalil, E.A.B.E. (2020). Analysis and Design of Optimum Pre-Stressed Concrete Wind Turbine Towers. Master Thesis, Arab Academy for Science, Technology & Maritime Transport, Smart Village Campus, Alexandria, Egypt.

[4] Lotfy, I. (2012). Prestressed concrete wind turbine supporting system. Master Thesis, University of Nebraska, Lincoln, United States.

[5] Eissa, A. E., & Hasan, M. A. (2020). Modal analysis of prestressed concrete structural system for wind turbine tower. International Journal of Sciences: Basic Applied Research, 49(2), 108-118.

[6] Lee, S. L., & Shin, S. J. (2022). Structural design optimization of a wind turbine blade using the genetic algorithm. Engineering optimization, 54(12), 2053-2070. doi:10.1080/0305215X.2021.1973450.

[7] Wu, E., Chen, H., Qu, W., Huo, C., Liang, Z., Huang, X., Li, Z., Li, H., He, B., Yang, T., & Shen, Z. (2020). Wind Load Evaluation of Wind Turbine Tower Design. Journal of Physics: Conference Series, 1622(1), 012071. doi:10.1088/1742-6596/1622/1/012071.

[8] Alzoubi, Y., Muciaccia, G., & Ferrara, L. (2025). Advances in Wind Turbine Tower Design and Optimization. Proceedings of the RILEM Spring Convention and Conference 2024. RSCC 2024. RILEM Book series, 56, Springer, Cham, Switzerland. doi:10.1007/978-3-031-70281-5_23.

[9] Nicholson, J. C., Arora, J. S., Goyal, D., & Tinjum, J. M. (2013). Multi-objective structural optimization of wind turbine tower and foundation systems using insight: A process automation and design exploration software. 10th World Congress on Structural and Multidisciplinary Optimization, 19-24 May, 2023, Orlando, United States.

[10] Li, Y., Paik, K. J., Xing, T., & Carrica, P. M. (2012). Dynamic overset CFD simulations of wind turbine aerodynamics. Renewable Energy, 37(1), 285-298. doi:10.1016/j.renene.2011.06.029.

[11] Guo, J., Liu, C., Cao, J., & Jiang, D. (2021). Damage identification of wind turbine blades with deep convolutional neural networks. Renewable Energy, 174, 122–133. doi:10.1016/j.renene.2021.04.040.

[12] Miyake, S., Teske, S., Rispler, J., & Feenstra, M. (2024). Solar and wind energy potential under land-resource constrained conditions in the Group of Twenty (G20). Renewable and Sustainable Energy Reviews, 202, 114622. doi:10.1016/j.rser.2024.114622.

[13] IEC 61400-12 (2017). Wind Turbines Part1:Design Requirements. International Electrotechnical Commission, Geneva, Switzerland.

[14] ASCE/SEI 7-16. (2016). Minimum Design Loads and Associated Criteria for Buildings and Other Structures. American Society of Civil Engineers (ASCE), Reston, United States. doi:10.1061/9780784414248.

[15] ACI 318-14. (2014). Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14). American Concrete Institute (ACI), Michigan, United States.

[16] IEC 61400–1 (2005). Wind Turbines – Part 1: Design Requirements. International Electrotechnical Commission, Geneva, Switzerland.

[17] Li, Y., Zhang, Y., Timofte, R., Van Gool, L., Yu, L., Li, Y., ... & Wang, X. (2023). NTIRE 2023 challenge on efficient super-resolution: Methods and results. Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, 17-24 June, 2023, Vancouver, Canada.

[18] Cortés, J. A., Díez, L., Cañete, F. J., Sánchez-Martínez, J. J., & Entrambasaguas, J. T. (2011). Performance analysis of OFDM modulation on indoor broadband PLC channels. Eurasip Journal on Advances in Signal Processing, 2011. doi:10.1186/1687-6180-2011-78.

[19] Kenna, A., & Basu, B. (2015). A finite element model for pre-stressed or post-tensioned concrete wind turbine towers. Wind Energy, 18(9), 1593-1610. doi:10.1002/we.1778.

[20] Muskulus, M., & Schafhirt, S. (2014). Design optimization of wind turbine support structures-a review. Journal of Ocean and Wind Energy, 1(1), 12-22.

[21] LaNier, M. W. (2005). LWST Phase I project conceptual design study: Evaluation of design and construction approaches for economical hybrid steel/concrete wind turbine towers.. National Renewable Energy Lab (No. NREL/SR-500-36777), Golden, United States.

Appendix I

Steps of using the proposed Add-In

1. As a user I want to get the optimized iteration through Revit with the help of Ansys software
    A. First you need to open Revit.
    B. Choose your file or structure.
    C. Click on the “Add-In” tab.
    D. Click on the “Run Ansys” button.
    E. You will need to choose the cost of concrete that you want to calculate with
    F. You will need to choose the pre-stressed tendon that you want to calculate with
    G. Click on “One-step calculation”
    H. The page will open for the optimized iteration
    I. You can click on the “Run Ansys” button to run Ansys on your machine

2. As a user I want to walk through the iterations to get the optimized iteration through Revit with the help of Ansys software
    A. First you need to open Revit.
    B. Choose your file or structure.
    C. Click on the “Add-In” tab.
    D. Click on the “Run Ansys” button.
    E. You will need to choose the cost of concrete that you want to calculate with
    F. You will need to choose the pre-stressed tendon that you want to calculate with
    G. Click on “Iterations calculation”
    H. Page will open for the current iteration with data
    I. Click the “Next Iteration” button to get the next iteration
    J. On the optimized iteration you can click the “Run Ansys” button to run Ansys on your machine.

The design code of Plugin

````
NAMESPACE Revit
    DEFINE class ReadDataCommand implementing IExternalCommand
        METHOD Execute (parameters: command data, message, elements)
            // Initialize Revit application objects
            GET UIApplication from command data
            GET UIDocument from command data
            GET Document from ActiveUIDocument

            TRY
                // Show custom window for file interaction
                CREATE WindowView instance with UIDocument
                DISPLAY the window (ShowDialog)
            CATCH Exception ex
                SHOW error dialog with the message

            RETURN Result.Succeeded
---

### ** `App` Class**
```plaintext
NAMESPACE Revit

    DEFINE class App implementing IExternalApplication
        METHOD OnStartup (parameter: application)
            TRY
````
````

```
                // Create ribbon panel and buttons for Revit add-in interface
                CREATE RibbonPanel named "Ansys Plugin" on a new Revit tab
                DEFINE button data "Upload Button" with properties: name, path, command
type
                ADD button to ribbon panel with a specified image

            CATCH Exception ex
                SHOW error dialog with message

            RETURN Result.Succeeded

        METHOD OnShutdown (parameter: application)
            RETURN Result.Succeeded

        PRIVATE METHOD GetImage (parameter: name)
            LOAD assembly resources
            GET image from Resources using the specified name
            CONFIGURE and RETURN BitmapSource image
—

### **`CustomMessageBox` Class**
NAMESPACE Revit

    DEFINE class CustomMessageBox inheriting Form
        PRIVATE attributes: message label, okButton

        CONSTRUCTOR CustomMessageBox (parameters: message, title, buttonName)
            SET form properties (title, size based on screen, manual position)
            INITIALIZE messageLabel with message text and style, ADD to form

            IF buttonName is "Next"
                INITIALIZE okButton with "Next", set style, and ADD to form
                SET OkButton_Click as click event handler
            ELSE
                INITIALIZE okButton with "Run Ansys", set style, and ADD to form
                SET AnsysButton_Click as click event handler

        PRIVATE METHOD OkButton_Click (parameters: sender, event)
            SET dialog result to OK
            CLOSE the form

        PRIVATE METHOD AnsysButton_Click (parameters: sender, event)
            DEFINE ANSYS executable and project file paths
            SET arguments for ANSYS executable to open project file

            TRY
                START ANSYS process with arguments
            CATCH Exception ex
                SHOW message box with error details

        PUBLIC STATIC METHOD Show (parameters: message, title, buttonName)
            INSTANTIATE CustomMessageBox with parameters
            RETURN dialog result

—

### **`WindowView` Class**

NAMESPACE Revit

    DEFINE class WindowView inheriting Window
        PUBLIC attributes: uidoc, doc, visted
        PRIVATE attributes: parameter_dependancy, element_dependancy_string,
parameter_cost, parameter_id_mapping

        CONSTRUCTOR WindowView (parameter: UIDocument)
            INITIALIZE uidoc with UIDocument
            INITIALIZE doc with Document
            CALL InitializeComponent to set up UI
```

```
METHOD GetAllSteps (parameters: sender, event)
    TRY
        RUN script to generate output data
        PARSE output data into iterations array
        INITIALIZE headers array, totalMcDecrease, finalIteration

        FOR each iteration in iterations
            IF iteration is first, SET headers
            ELSE
                PARSE iteration data and format output string
                COMPUTE mcDecrease and update totalMcDecrease
                DISPLAY iteration data with CustomMessageBox
                UPDATE finalIteration with latest iteration output

        APPEND final statement to finalIteration
        DISPLAY final iteration summary with CustomMessageBox

    CATCH Exception exc
        SHOW error dialog with message

METHOD GetWithoutSteps (parameters: sender, event)
    TRY
        RUN script to generate output data
        PARSE output data into iterations array
        INITIALIZE headers array, totalMcDecrease, finalIteration

        FOR each iteration in iterations
            IF iteration is first, SET headers
            IF iteration is the 14th iteration, process and format final iteration
data
                COMPUTE mcDecrease and update totalMcDecrease
                STORE output in finalIteration

        APPEND final statement to finalIteration
        DISPLAY final iteration summary with CustomMessageBox

    CATCH Exception exc
        SHOW error dialog with message

METHOD NumberValidationTextBox (parameters: sender, event)
    VALIDATE that input text is a number

PRIVATE METHOD runScript
    PARSE input values from UI text boxes
    DEFINE script path and interpreter path
    CONFIGURE process to run Python script with arguments

    TRY
        START process and capture output
        RETURN output
```

For the python script:

```
FUNCTION calculation (parameters: country_value, quantity_conc, last_Mc, MupCost)
    TRY
        CONVERT country_value to float and assign to Muc
        CONVERT quantity_conc to float and assign to Qc
        CONVERT MupCost to float and assign to Mup
        SET constant Qp = 41.0

        CALCULATE current_Mc as (Muc * Qc) + (Mup * Qp)
        CALCULATE ratio as 1 - (current_Mc / last_Mc)
        ROUND ratio to 4 decimal places and multiply by 100

        RETURN current_Mc and ratio
    CATCH ValueError exception
```

```
        PRINT error message with invalid input values
        RETURN None, None


FUNCTION main (parameters: concreteCost, MupCost)
    DEFINE results_file_path with Excel file location

    TRY
        LOAD Excel data from results_file_path into sys_results_df DataFrame
    CATCH FileNotFoundError exception
        PRINT error message with missing file path
        RETURN

    SET init_Cost = 1
    INITIALIZE outputString as an empty string

    For each row (sys_row_loop) and index in sys_results_df
        IF index is 1
            EXTRACT values from row at columns 5 to 9 and assign to ffLimit, tdLimit,
tdlLimit, tscLimit, test limit
            APPEND values to outputString formatted as a single string

        IF index is 3
            CALL calculation with concreteCost, sys_row_loop at column 2, initial cost (1),
and MupCost
            ASSIGN result to init_Cost, discarding the second output

        IF index is 3 or higher
            EXTRACT values from row at columns 5 to 9 into variables ff, td, dl, tsc, tst
            CALL calculation with concreteCost, sys_row_loop at column 4, init_Cost, and
MupCost
            ASSIGN first result to init_Cost, second to ratio

            APPEND formatted string of init_Cost, ratio, ff, td, tdl, tsc, tst to
outputString

    PRINT outputString, removing the last "@" character


IF __name__ equals "__main__"
    ASSIGN command line arguments to concreteCost and MupCost
    CALL main with concreteCost and MupCost
```