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# COST OPTIMIZATION IN STRUCTURAL DESIGN FOR REINFORCED CONCRETE FRAMES USING JAYA ALGORITHM

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**Abstract**

This study analyzes and optimizes the structural design of three-dimensional (3D) reinforced concrete frame structures to minimize the amount of two main materials, including concrete and steel reinforcement, used in reinforced concrete frames. Jaya algorithm was developed based on evolutionary algorithms to build the structural optimization model. The objective function (minimum material cost) with variables being column and beam cross-sections was set up. In which, the constraints related to the maximum internal force and displacement being in the structural members satisfy limited strength and serviceability requirements. A subroutine written in Python was used to connect the optimization process to the structural analysis software, ETABS. The 3D reinforced concrete frame of a three-story building was selected for cost and design optimization analysis. In which, the optimization problem was solved in cases of three different maximum numbers of iterations, including 20, 35, and 50. In each iteration level, a setting of five independent runs was performed. The subroutine proved to be fast, robust, and convenient manner for solving optimization problems in designing 3D reinforced concrete frames. In which, the best optimal cost might be obtained after twenty iterations and the better convergence behavior occurred at higher numbers of iterations. The study results showed that, for this reinforced concrete frame, applying optimal design led to a materials cost reduction (success rate) by 33.67% compared to that of the conventional design. This success rate would fluctuate according to different nations' design codes.

*Keywords:* Cost optimization; Jaya algorithm; Python and ETABS; Number of iterations; Convergence behavior; Design code.

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## 1. Introduction

Currently, in the difficult economic situation worldwide, financial factors in construction projects are increasingly concerned. How to reduce construction costs is always desired by contractors and investors inspite and afford to find out the appropriate solution for this issue. In the total cost of building construction, the cost of construction materials accounts for a relatively large proportion. Therefore, some studies on applying optimal design of structures with the aim of reducing the weight of the structure are increasingly interested and developed. This is one of the effective solutions to reduce the construction costs. Nowadays, in the world, reinforced concrete (RC) structures are used popularly in building construction due to some advantages such as high bearing capacity, large fire resistance, and easy fabrication. In addition, this structural type is reasonable for using local materials and it is suitable for Vietnam's environment and climate conditions, etc. However, the optimization studies applied to RC structures are relatively few and have to face many difficulties, when considering the material distribution of the structure under external loads. For that reason, structures containing a single material type are often considered under optimization. In addition, the environmental protection and sustainable development are put under much attention. Hence, reducing negative impact on

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the environment from construction processes has become another important goal of optimization by reducing carbon dioxide ($CO_2$) emissions due to the use of less material. To achieve the goals mentioned above, many optimization methods are proposed to be developed and applied in the structural design of the building.

After several decades, there were many studies related to the field of optimization published in the world [1]. In which, the top three continents including Asia, Europe and North America account for 92% of the total number of research papers collected. However, at present, in Vietnam, studies on the optimization field especially optimizing structural design in construction are limited. These studies mainly were conducted on planar (two-dimensional, 2D) models for planar frame and truss structures, or other structural members such as columns, beams, panels, etc. [2–7]. In which, a planar steel truss was optimized in the consideration of different loading combination [2]. Another research [4] carried out to optimize steel roof trusses using machine learning-assisted differential evolution. Meanwhile, some planar steel frames were designed using different optimization algorithms [3, 5]. The optimization of steel frames using nonlinear inelastic analysis was done with performance comparison of metaheuristic algorithms. Other steel moment frames with panel-zone design were optimized using an adaptive differential evolution. In addition, the global optimization of laminated composite beams using an improved differential evolution algorithm [6] and predicting missile impact damages based on k-nearest neighbors and Bayesian optimization [7] were studied in detail. Only a few studies [8, 9] have been conducted on spatial models for steel frame and steel truss structures using different optimization algorithms, such as hybrid arithmetic optimization algorithm and differential evolution. Around the world, studies on optimizing structural design have received more attention and been increasingly implemented in recent years. These studies were carried out for both steel and RC structures, with some focusing on 2D planar models [10–12] and others on three-dimensional (3D) spatial models [13–16]. They were conducted to solve optimization problems applied to buildings. In the studies mentioned above, the optimization procedures were performed automatically with the support of structural analysis software integrated with programming languages (SAP2000-OAPI-MATLAB, etc.), utilizing naturally inspired algorithms such as the Artificial Bee Colony Algorithm, Firefly Algorithm, Genetic Algorithm, TLBO, IPGO Algorithm [17–21]. These algorithms have been applied to optimization problems in the field of construction and have produced relatively satisfactory results.

The optimization of structures has brought many economic benefits and contributed to reducing environmental pollution. However, traditional design calculations, mainly performed on 2D frames, often yield low optimization accuracy and are difficult to apply to actual constructions. Especially in Vietnam, no studies have been conducted on optimal cost design for 3D RC building frames. The results of this research trend could lead to reduced construction costs.

Hence, in this paper, the authors propose an automatic optimization design calculation process using a 3D spatial model. This process involves constructing integrated software that connects the structural analysis software ETABS with the Python programing language. A metaheuristic algorithm called the Jaya Algorithm was applied for optimal data resolution. The results of the optimization process with the integrated software, evaluated through the analysis of a three-story RC frame during calculation and design, meet the constraint conditions according to the current Vietnam design standards.

## 2. Methodology

### *2.1. Optimization problem in structural engineering*

The problem of structural design of construction buildings needs to ensure related safety conditions such as strength, stiffness and stability of the structure under the effect of external loads and other actions. Besides, further requirements also need to be considered including construction cost, buildability, aesthetics and sustainability for buildings. That is a significant issue for the engineers have to face when designing the building so that satisfying both technical and economical requirements as mentioned above. Traditional design methods mainly depend on the engineer's intuition, experience and skills (Fig. 1), so the design results of a construction building may not be really satisfactory.

Recently, in a competitive environment with scarce resources of labors and materials, engineers have to pay more attention to the construction cost. Hence, it is really necessary to design the building structures considering the optimization factor. Most optimization problems for building structures are quite complex, highly nonlinear and require discrete variables. Normally, traditional optimization methods do not meet the calculation capacity and time for large-scale construction buildings where the decisive variables are usually the cross-sectional area of the structural members. Up to day, different metaheuristic optimization algorithms have been used in several approaches, such as the Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Artificial Bee Colony (ABC) algorithm. Moreover, modern algorithms, for instance Evolutionary Algorithms (EAs), have been applied to the process of automating and streamlining the optimization design process with many advantages including simplicity, use of real numbers, easy evaluation of the objective function and fast convergence. However, depending on the characteristics of each type of optimization problem, the efficiency of the algorithms is also different.

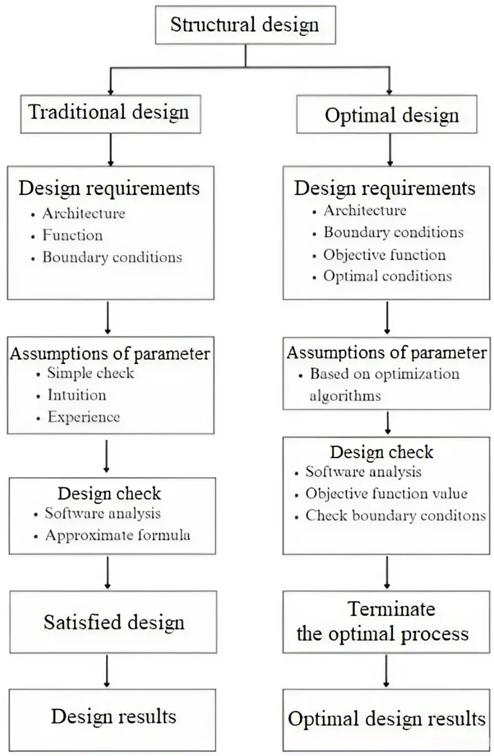



Figure 1. Structural design principles using traditional and optimal methods

EA is a term used to refer to a search and optimization algorithm based on the principle of natural evolution. EA is generally based on the notion that natural evolution is the most perfect, most logical, and optimal in itself. Throughout the natural evolution, new generations are always born to supplement and replace the old generation. The individual that is more developed, more adapted to the environment will survive. Individuals that do not adapt to the environment will be eliminated. Some typical EAs are commonly applied in structural optimization design such as an innovative algorithm combining multi-criterion decision-making (DM) and Particle Swarm Optimization (PSO) [14, 22] which models the flocks of birds and fish in search of food, Genetic Algorithm (GA) [11] simulating the evolutionary adaptation of biological populations based on Darwin's theory, Artificial Bee Colony (ABC) algorithm [23], Harymony Search (HS) algorithm [2], etc.

Due to the variety of structural problems, structural design optimization can be classified into section optimization, shape optimization and structure optimization. In this paper, the cross-section optimization problem is applied in the optimal design of the RC frame system on the 3D spatial model in order to reduce the amount of concrete and reinforcement used for the frame system, thereby reducing the cost of construction materials in buildings. The objective function, as can be seen in Eq. (1), is a material cost function, whose variables are the cross-sectional areas of columns and beams. Constraint conditions (2) include conditions related to strength, stiffness and geometrical dimensions of structural elements such as columns and beams in RC frames according to [24, 25].

Minimize the objective function:

$$F_{\text{cost}} = \sum_{i=1}^{n} C_{s,i} A_{s,i} L_{s,i} \gamma_s + C_{c,i} A_i L_i \tag{1}$$

with the following constraint conditions:

$$\begin{cases} 1 - S_i \leq 0 \\ f_i \leq f_{u,i} \\ \left| \dfrac{\Delta_{ds}}{\Delta_{ds}^u} \right| - 1 \leq 0; \left| \dfrac{\Delta_s}{\Delta_s^u} \right| - 1 \leq 0 \\ A_L \leq A_i \leq A_U \end{cases} \tag{2}$$

where, $i$ is the ordinal number of structural elements or members including columns and beams; $C_s$ and $C_c$ are the unit prices of reinforcement (million VND/ton) and concrete (million VND/m$^3$), respectively; $A_{s,i}$ and $A_i$ are the steel reinforcement area (m$^2$) and the cross-section area (m$^2$) in the $i$th (column or beam) member, respectively; $L_{s,i}$ and $L_i$ are the length of steel reinforcement in the $i$th member and the length of the $i$th member (m), respectively; $\gamma_s$ is the steel reinforcement density (ton/m$^3$); $n$ is total column and beam members; $S_i = R/U$ - the maximum load-bearing factor of the structure, which is the ratio between the load-carrying capacity of the structural element $i$th ($R$) and the effect caused by the external load ($U$); $f_i$ and $f_{u,i}$ are the maximum deflection and allowable deflection of the $i$th beam, respectively; $\Delta_s$ and $\Delta_{ds}$ are the maximum building's top displacement and story drift displacement, respectively; $\Delta_s^u$ and $\Delta_{ds}^u$ are the allowable building's top displacement and story drift displacement, respectively; $A_L$ and $A_U$ are available lower and upper limits of the column and beam cross-section areas used for optimal design. In which, $A_L$ is defined as 200 × 200 (mm) for both columns and beams; $A_U$ is defined as 1000 × 950 (mm) or 400 × 1200 (mm) for columns or beams, respectively. In this study, $C_s$ were applied as 11 million and 11.2 million VND/ton for longitudinal and stirrup rebars, respectively. Meanwhile, $C_c$ was applied as 0.95 million VND/m$^3$ for fresh concrete. These values might be fluctuated depending on various construction periods.

### *2.2. Jaya optimization algorithm*

Jaya algorithm has been developed based on evolution and swarm intelligence. The criterion of this algorithm is based on the concept that the solution obtained for a given problem should be directed towards the best solution and away from the worst solution. The advantage of Jaya's algorithm is its simplicity but powerful in solving optimization problems with both constrained and unconstrained conditions [26].

The optimization algorithms based on evolution and swarm intelligence are probabilistic algorithms and require common control parameters such as population size, number of generations, etc. In addition, different algorithms require separate control parameters for each particular algorithm. For example, GA used mutation probability, PSO algorithm used inertial weight (w) and so on. Proper adjusting of algorithm-specific parameters is an important factor affecting the performance of algorithms. Meanwhile, the Jaya algorithm does not require specific control parameters, except for the general control parameters that are individuals in the population and the maximum number of evolution rounds for the optimal model [27].

Based on Jaya algorithm, the structural optimization model for 3D RC frame is built with the following main steps:

- Step 1: Set up the objective function presented by Eq. (1) and the constraint conditions according to formula (2). Determine two basic parameters, including the number of individuals in the population (*NP*), namely the number of solutions for the dimensions and cross-sectional area of columns and beams, and the number of evolutionary rounds or called iterations for the optimal model (Iter.).

- Step 2: Determine the initial population randomly consisting of *NP* individuals (herein, individuals would be understood as values for the variables of the objective function).

- Step 3: Evaluate the best and worst individuals through the initial interaction between the individuals, by using the value of the objective function according to Eq. (1).

- Step 4: Build a new population based on mutation technique. In turn, each individual in the existing population is selected as the target individual to build a corresponding new individual. The individuals in the new population are built based on Eq. (3) as follows:

$$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i}\left(X_{J,best,i} - \left|X_{j,k,i}\right|\right) - r_{2,j,i}\left(X_{j,worst,i} - \left|X_{j,k,i}\right|\right) \quad (3)$$

where $X_{j,k,i}$ is the value of the $j$th design variable in the $k$th solution in the $i$th loop; $X'_{j,k,i}$ is the value of the $j$th design variable in the $k$th solution in the $i$th loop in the new population; $X_{J,best,i}$ is the best value of the design variable $j$ in the loop $i$ in the whole population; $X_{j,worst,i}$ is the worst value of the design variable $j$ in the loop $i$ in the whole population; $r_{1,j,i}$, $r_{2,j,i}$ are randomly generated values in the range from zero to one.

- Step 5: Evaluate new individuals in the new population. If this new individual has a better objective function value than that of the target individual, then it is selected as a substitute for the target individual in the new population. In the opposite case, the target individual continues to be kept.

- Step 6: Finish the optimization process. Step 2 is performed until the number of evolution rounds reaches the Iteration value then the optimization will stop. At this point, the optimal result obtained is the best individual in the final population.

To solve the proposed optimal model, in this study, a subroutine for optimization process has been built for connecting to the structural analysis software ETABS. The process of exchanging necessary data for optimal analysis such as structural element's parameters, geometrical features, internal forces, stresses, displacements, etc. was performed automatically. The subroutine, written by the Python programming language, describing the pseudo-code of Jaya algorithm, was shown as below. In addition, the flowchart for the optimization process using Jaya algorithm was presented as can be seen in Fig. 2.

The pseudo-code of JAYA algorithm

Initialize the parameters of JAYA algorithm ($NP, T, D$).
$NP$ – Population size or number of candidates
$T$ – Maximum number of iterations
$D$ – Number of design variables
Initialize a population of N solutions randomly
Calculate objective function $f(X_i)$ $\forall i = 1, 2, 3, \ldots, NP$
Evaluate the objective function: ($X_{best}$ and $X_{worst}$ are the best and the worst solution respectively)

*Set* $k = 1$
**while** $(k \leq T)$ **do**
  **for** $i = 1, \ldots, NP$ **do**
    **for** $j = 1, \ldots, D$ **do**
      Set $r_{1,j,i}$ = a random number from [0, 1]
      Set $r_{2,j,i}$ = a random number from [0, 1]
      Update Equation $X'_{j,k,i} = X_{j,k,i} + r_{1,j,i}\left(X_{J,best,i} - \left|X_{j,k,i}\right|\right) - r_{2,j,i}\left(X_{j,worst,i} - \left|X_{j,k,i}\right|\right)$
    **end for**
    **if** $f\left(X'_{j,k,i}\right)$ better than $f\left(X_{j,k,i}\right)$ **then**
      Set $X_{j,k+1,i} = X_{j,k,i}$
    **else**
      Set $X_{j,k+1,i} = X'_{j,k,i}$
    **end if**
  **end for**
  $k = k + 1$
  Update $X_{best}$ and $X_{worst}$
**end while**

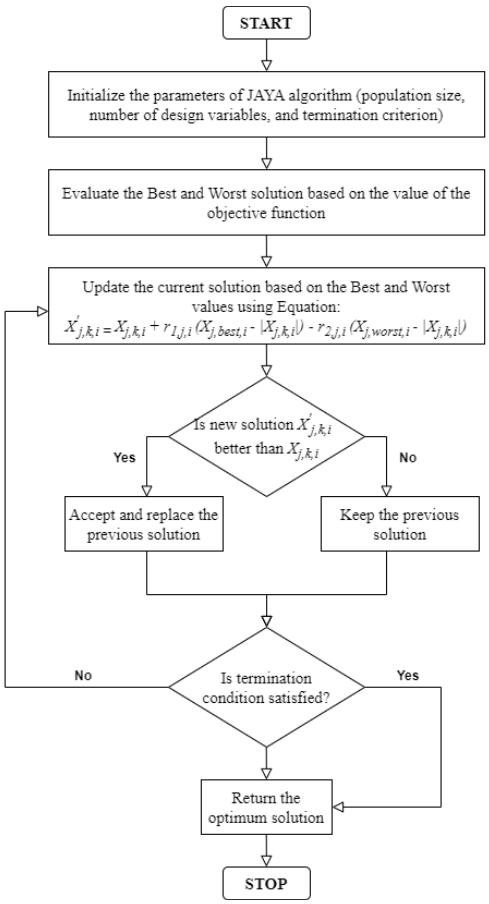



Figure 2. Flowchart of the optimization process using Jaya algorithm

### *2.3. Automated optimization process*

In the current 4.0 technology era, smart technologies are widely applied in technical fields, helping to quickly solve many problems. In the field of construction, the use of structural analysis and calculation software with the support of integrated programs is a trend and is also a typical example for the application of smart technology in the design and execussion of buildings. Some software packages for structural analysis are very well developed and familiar to civil engineers such as SAP2000, ETABS, Robot Structural, STAAD.Pro, etc. Specifically, besides sharing the results of structural analysis, these software also support the calculation to give the amount of concrete and reinforcement according to the design standards of some countries. With the amount of concrete and reinforcement received, the user could determine the constructional material cost by multiplying the resulting mass by the unit price of the respective material. However, with that process, users mainly analyze manually and have many questions as to whether that design model is the cheapest, most optimal model or not.

Previously, for considering optimization models in structural design, the processes of receiving, processing and exchanging optimized data (cross-sections, internal forces, stresses, etc.) were performed manually. Hence, this process is completely inappropriate and difficult to apply in practice. Currently, optimization models are built integrated with structural analysis software (SAP2000, ETABS, etc.) by using programming languages to perform the optimization process automatically. In which, the optimization data is automatically received from the structural analysis software, these data are processed through the optimization algorithm and then sent to the structural analysis program. The whole analysis process would iterate and find out the most appropriate solution.

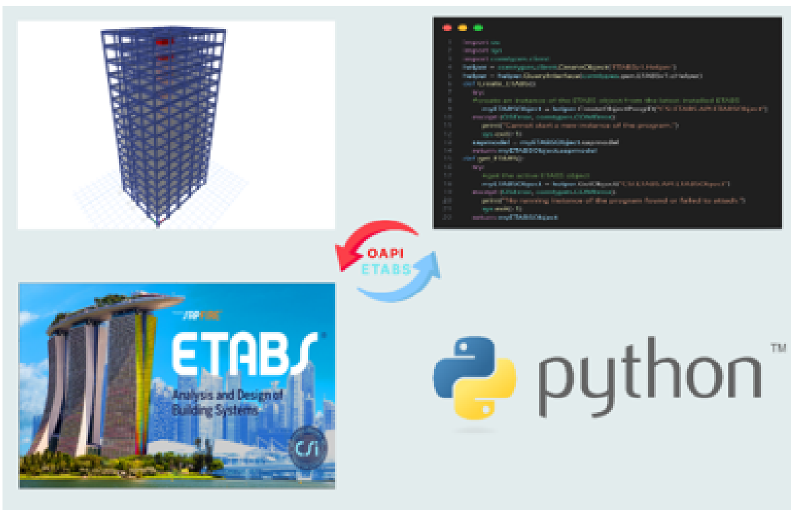



Figure 3. The optimization process with the connection between Python programming language and ETABS

In this study, the most suitable and lowest cost design solution was built on the 3D spatial model with the support of integrated software to solve the optimization problem. The built-in software was written for the structural analysis program ETABS version 19 with publisher-supported OAPI and was programmed in Python 3.10. The Jaya algorithm was used for the cost optimization process by exchanging data back and forth between Python and ETABS (Fig. 3).

## 3. Case study

### *3.1. Cost optimization for a 3D RC frame*

Design and cost optimization for a 3D RC frame would be conducted in this section. The process of analyzing and optimizing the problem is performed in the sequence as summarized in Fig. 4.

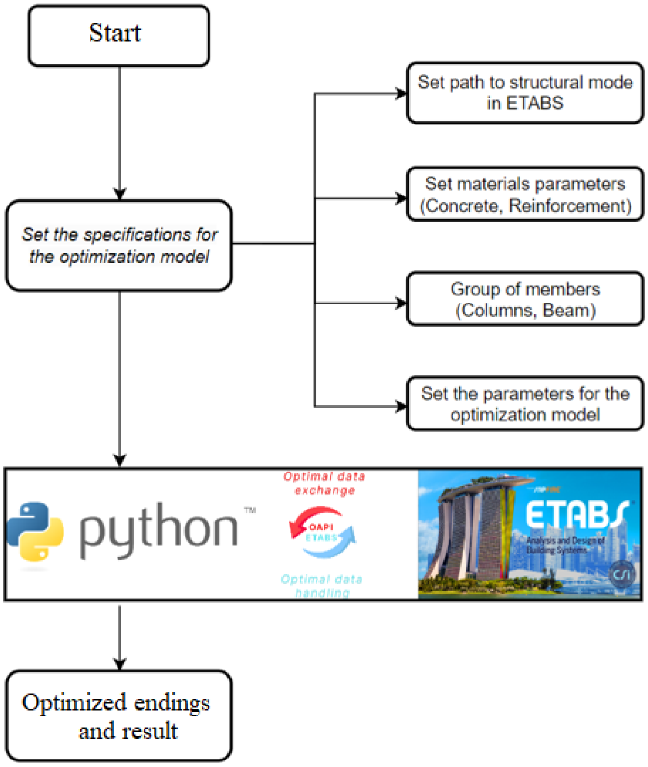


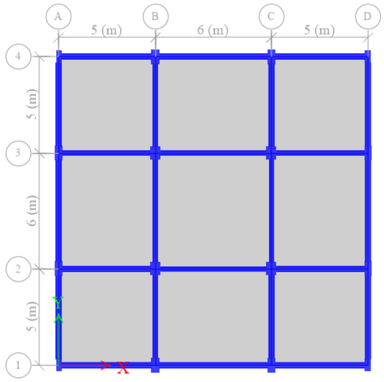

Figure 4. Summary of the cost-optimized design analysis process for RC frame structures

a. Parameters for structural model

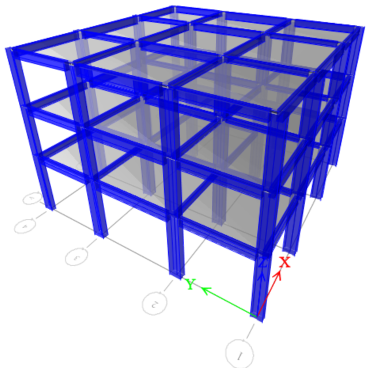
The RC frame structure was applied to a three-story building with the floor's area of 256 m$^2$, the height of the story from the first up to third floor is 4.5 m, 3.6 m, and 3.6 m, respectively. The structural model was built using ETABS including 48 columns and 72 beams, in which the cross-section shapes of the columns and beams are all rectangular (Fig. 5). In ETABS software, the column and beam elements were modeled using Timoshenko type and consistent mass with the consideration of shear deformation effect. Additionally, the slabs were modeled using shell element type in this structural analysis.

External loads and load combinations are determined according to the current load and action design standard of Vietnam, TCVN 2737:1995 [28]. The detailed data on loading cases applied on the building structure and load combinations are presented in Tables 1 and 2, respectively. Fig. 6 shows the case of wind load acting on the structural model (by ETABS).

The cross-sections of beams and columns for the initial solution of the analysis model are automatically selected through the built-in software. In this analytical model, columns and beams that are symmetrically positioned or have similar bearing characteristics were grouped in the same cross-section (e.g. corner column, boundary column, center column, middle beam, boundary beam, etc.). The grouping of these cross-sections helps to facilitate the construction process (Fig. 7).




(a) Plan of structural analysis model in ETABS




(b) 3D Structural analysis model in ETABS

Figure 5. RC frame structure model built in ETABS software

Table 1. Loading cases applied on the building structure

| DEAD LOADS OF SLABS | | | | |
|---|---|---|---|---|
| No. | Load | $P_{sls}$ (kN/m$^2$) | Factor | $P_{uls}$ (kN/m$^2$) |
| 1 | Self-weight | ETABS | 1.10 | ETABS |
| 2 | Additional load | 1.10 | 1.26 | 1.39 |
| DEAD LOADS OF WALLS | | | | |
| No. | Height wall (m) | $P_{sls}$ (kN/m) | Factor | $P_{uls}$ (kN/m) |
| 1 | 4.2 | 12.960 | 1.25 | 16.20 |
| 2 | 3.3 | 10.368 | 1.25 | 12.96 |
| 3 | 3.3 | 10.368 | 1.25 | 12.96 |
| LIVE LOADS | | | | |
| No. | Utilities | $P_{sls}$ (kN/m$^2$) | Factor | $P_{uls}$ (kN/m$^2$) |
| 1 | Roof | 0.5 | 1.30 | 0.65 |
| 2 | Office | 2.0 | 1.20 | 2.40 |
| WIND LOADS | | | | |
| No. | Story | Level (m) | $W_+$ (kN/m) | $W_-$ (kN/m) |
| 1 | 1 | 4.5 | 2.665 | 1.999 |
| 2 | 2 | 8.1 | 2.633 | 1.975 |
| 3 | 3 | 11.7 | 1.407 | 1.055 |

Table 2. Load combinations applied to the building structure

| Ultimate Limit State | | |
|---|---|---|
| No. | Combo | Load cases |
| 1 | Comb1 | DL + LL |
| 2 | Comb2 | DL + WLX |

| Ultimate Limit State | | |
|---|---|---|
| No. | Combo | Load cases |
| 3 | Comb3 | DL + WLXX |
| 4 | Comb4 | DL + WLY |
| 5 | Comb5 | DL + WLYY |
| 6 | Comb6 | DL + 0.9*(LL+WLX) |
| 7 | Comb7 | DL + 0.9*(LL+WLXX) |
| 8 | Comb8 | DL + 0.9*(LL+WLY) |
| 9 | Comb9 | DL + 0.9*(LL+WLY) |
| Serviceability Limit State | | |
| No. | Combo | Load case |
| 1 | Comb10 | DL + WL |
| 2 | Comb11 | DL + LL |

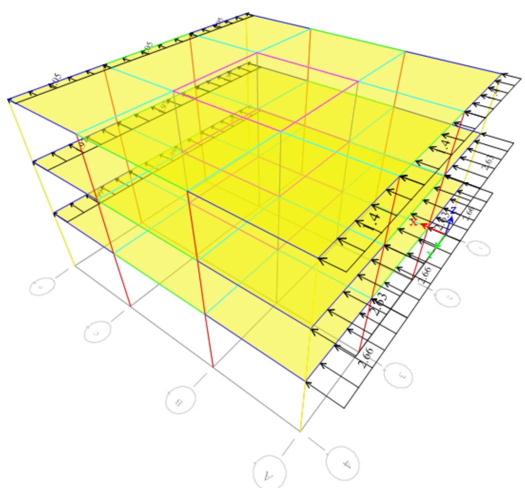


Figure 6. Wind loads applied to the optimized analysis model

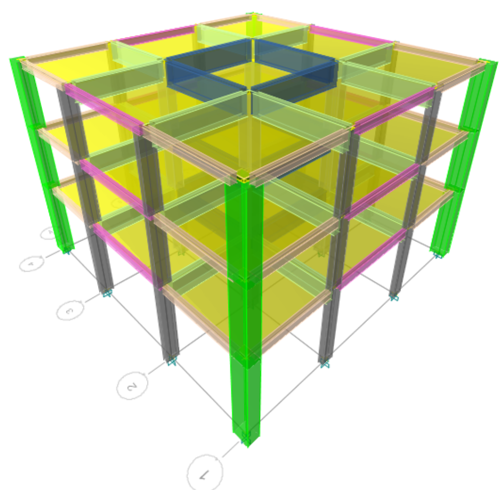


Figure 7. Structural element groups in RC frame structure

Table 3. Limiting parameters of constraint conditions

| No. | Type | Combo check | Limit |
|---|---|---|---|
| 1 | Building's top displacement | Comb10 | $h_b/500$ |
| 2 | Story's drift | Comb10 | $h_{si}/500$ |
| 3 | Beam's deflection | Comb11 | $L_j/200$ |

Abbreviation:
- $h_b$ is the height of the building;
- $h_{si}$ is the height of the $i^{th}$ floor;
- $L_j$ is the length of the $j^{th}$ beam.

In this study, reinforcement amount was calculated automatically by structural analysis software ETABS according to the RC design standard of Vietnam, TCVN 5574-2012 [24]. The steel reinforcing configuration for the column and beam members is based on the required reinforcing steel cross-area calculated for satisfying the consistent load-bearing capacity of structures. To determine the amount of steel reinforcement in the structural components, the 'Detailing' function in ETABS was used to select steel reinforcement bars after the Concrete Frame Design process has been completed. Meanwhile, the limiting parameters of the constraint conditions are complied with the RC design standard of Vietnam, TCVN 5574-2018 [25], as can be seen in Table 3.

b. Parameters for optimization model

According to the analysis process to optimize the cost of designing the RC frame structures (Fig. 4), the material parameters, the population size, the number of iterations, etc. was set up in the subroutine, with the interface shown in Figs. 8 and 9, to serve the analysis process. The main design variables were column and beam cross-section areas, and then leading to the appropriate steel reinforcement amount as mentioned in the sub-section above. The cross-sections of columns and beams have been divided into seven groups (Fig. 8), including three groups for columns and four groups for beams, depending on the locations of these structural members in the building.

In this section, the cost optimization analysis for an RC frame structure of a three-story building would be carried out. To investigate the convergence of the optimal cost during the optimization process, different number of maximum iterations, namely 20, 35 and 50, were set up for running the optimization problem for materials cost. In each level of iterations, five independent runs were selected to compare the optimal cost results and evaluate the robustness of the built optimization model. The average computational time of the optimization procedure with five independent runs for the maximum iteration number of 20, 35, and 50 was 117, 198, and 263 minutes, respectively.

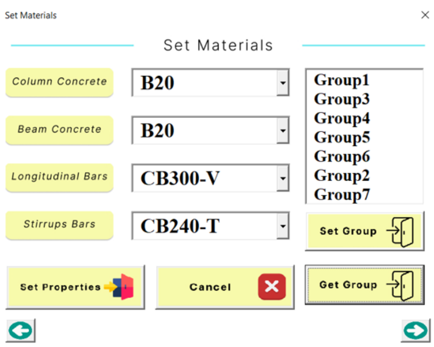



Figure 8. Material specifications for the analysis model

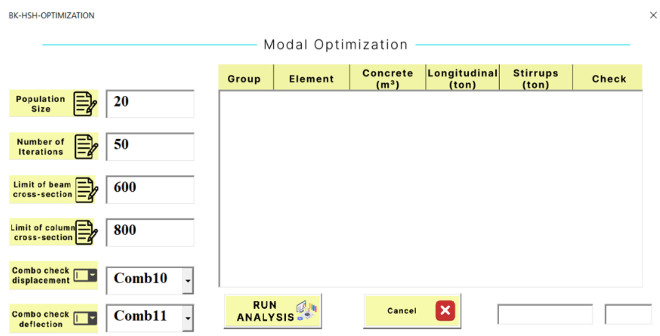
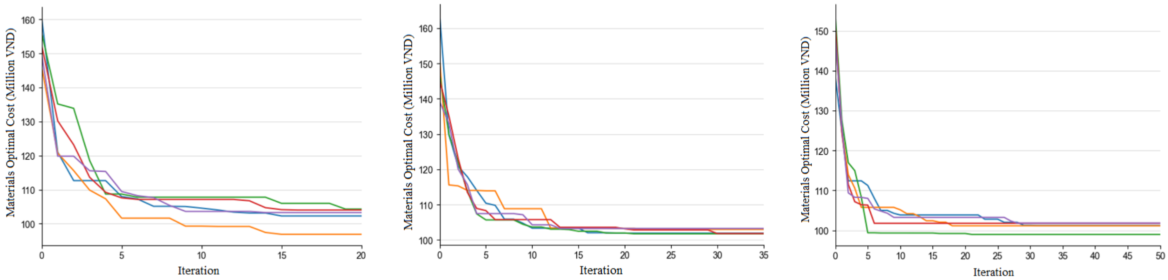



Figure 9. Optimized parameters for the analysis model

## *3.2. Results and discussions*

a. Results

Fig. 10 presented the relationship between the materials optimal cost and number of iterations in three cases of the maximum number of iterations applied, including 20, 35, and 50. In which, for each case, the results were shown by five independent runs. Meanwhile, Table 4 revealed the best solution of optimized cross-sectional areas of structural elements types (columns and beams) corresponding to three cases of maximum iterations as mentioned above. Table 5 presented the results of material details and optimum cost for the best solution from five independent runs in different maximum iterations.




(a) Maximum number of iterations: 20 (b) Maximum number of iterations: 35 (c) Maximum number of iterations: 50

Figure 10. The relationship between materials optimal cost and number of iterations

Table 4. The best optimized cross-sections of structural elements (Units: cm)

| Group of Elements | Symbol | Cross section | | | | | |
|---|---|---|---|---|---|---|---|
| | | Iter. = 20 | | Iter. = 35 | | Iter. = 50 | |
| | | Initial | Optimum | Initial | Optimum | Initial | Optimum |
| Group1 | | 65 × 85 | 20 × 20 | 30 × 65 | 20 × 35 | 70 × 50 | 20 × 20 |
| Group2 | | 35 × 35 | 25 × 30 | 20 × 60 | 20 × 35 | 90 × 20 | 25 × 30 |
| Group3 | | 25 × 95 | 35 × 30 | 75 × 75 | 50 × 20 | 70 × 35 | 40 × 20 |
| Group4 | | 35 × 35 | 20 × 50 | 20 × 35 | 20 × 20 | 25 × 50 | 20 × 60 |
| Group5 | | 35 × 70 | 20 × 55 | 25 × 45 | 20 × 20 | 25 × 50 | 20 × 60 |
| Group6 | | 20 × 30 | 20 × 20 | 30 × 70 | 20 × 60 | 30 × 45 | 20 × 20 |
| Group7 | | 20 × 20 | 20 × 20 | 20 × 35 | 20 × 20 | 30 × 50 | 20 × 20 |

Table 5. The material details and best optimum cost in different maximum iterations

| Group of elements | Element type | Concrete ($m^3$) | Longitudinal bars (ton) | Stirrups (ton) | Constraints satisfied |
|---|---|---|---|---|---|
| Iter. = 20 | | | | | |
| Group1 | Column | 1.871 | 0.400 | 0.083 | OK |
| Group2 | Column | 7.020 | 0.607 | 0.330 | OK |
| Group3 | Column | 4.914 | 0.312 | 0.204 | OK |
| Group4 | Beam | 11.43 | 0.870 | 0.217 | OK |
| Group5 | Beam | 7.556 | 0.595 | 0.127 | OK |
| Group6 | Beam | 4.512 | 0.788 | 0.120 | OK |
| Group7 | Beam | 2.724 | 0.629 | 0.065 | OK |
| Optimum cost: 96.868 (million VND) | | | | | |
| Iter. = 35 | | | | | |
| Group1 | Column | 4.212 | 0.386 | 0.138 | OK |
| Group2 | Column | 9.828 | 0.525 | 0.336 | OK |
| Group3 | Column | 4.914 | 0.263 | 0.180 | OK |
| Group4 | Beam | 11.25 | 0.805 | 0.218 | OK |

| Group of elements | Element type | Concrete ($m^3$) | Longitudinal bars (ton) | Stirrups (ton) | Constraints satisfied |
|---|---|---|---|---|---|
| Group5 | Beam | 4.767 | 0.691 | 0.092 | OK |
| Group6 | Beam | 6.732 | 0.876 | 0.153 | OK |
| Group7 | Beam | 4.086 | 0.682 | 0.083 | OK |
| Optimum cost: 101.737 (million VND) | | | | | |
| Iter. = 50 | | | | | |
| Group1 | Column | 1.872 | 0.322 | 0.07 | OK |
| Group2 | Column | 7.02 | 0.902 | 0.330 | OK |
| Group3 | Column | 3.744 | 0.312 | 0.219 | OK |
| Group4 | Beam | 13.716 | 0.812 | 0.250 | OK |
| Group5 | Beam | 8.244 | 0.556 | 0.136 | OK |
| Group6 | Beam | 4.524 | 0.769 | 0.120 | OK |
| Group7 | Beam | 2.736 | 0.618 | 0.065 | OK |
| Optimum cost: 98.979 (million VND) | | | | | |

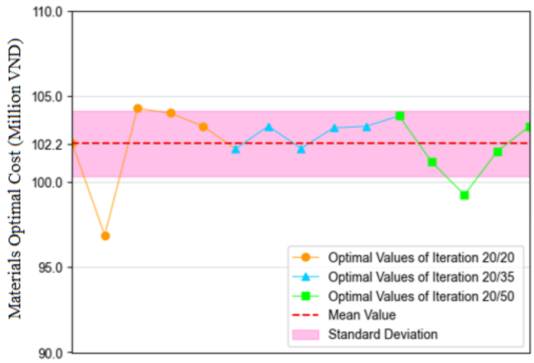
b. Discussions

With the study results (as Fig. 10, Tables 4 and 5) obtained from the optimization model after implementation for the three-story RC frame building as presented in the sub-section above, the following comments and evaluations would be discussed in this sub-section.

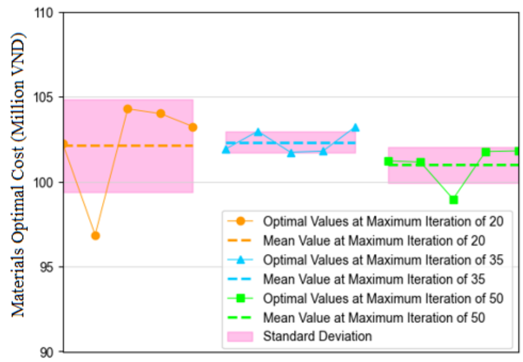
As can be seen in Fig. 10, the optimal result convergence speed of the Jaya algorithm was relatively fast at some initial iterations. The analysis data, collected from all fifteen independent runs in three cases of the maximum number of iterations, demonstrated that the optimal cost reduced 30.69% in average in the first ten iterations. And then, the optimal cost disclined 1.82% in average in the next ten iterations from the 10$^{th}$ to the 20$^{th}$ iteration. Lastly, for the cases of maximum number of iterations of 35 and 50, the results (Fig. 10(b), (c)) showed that the optimal cost has changed insignificantly beyond the 20$^{th}$ iteration.

The study results showed that the best optimized cross-sectional areas for structural elements, including columns and beams, and the best optimal cost accompany with details of material amount obtained from three cases of the maximum number of iterations have been found. The data on Table 4 revealed that there were different solutions of optimum cross-section areas in three cases of the maximum number of iterations used. This means that the designer can select the appropriate solution from them based on the architectural requirements. The optimum cost in three cases of the maximum number of iterations (20, 35, and 50) was 96.868, 101.737, and 98.979 millions VND, respectively (Table 5). Hence, the best optimum cost for concrete and reinforcement materials in the 3D frame of the three-story building in this study was 96.868 millions VND. Comparing to the initial design, the optimization design led to a reduction of materials cost (concrete and steel reinforcement) about 33.67%.

As discussed in the literature, the optimization process based on metaheuristic algorithms has a random characteristics. In this study, Jaya algorithm, an advanced modification of evolutionary algorithms, has been successfully used for the material cost optimization in an RC building. This algorithm demonstrates it's both advantages and drawbacks in application through the optimization process and the obtained optimal cost. The analysis data shown in Fig. 11(a) revealed that the convergence of the optimal cost was relatively good at the 20th iteration for all fifteen independent runs. In which, the standard deviation was 1.904 millions VND (mean value of 102.231 millions VND) and there was 80% optimal values standing in the standard deviation region, better than a normal probability distribution with 68% [29]. It means that, for the RC building in this study, the number of iterations for running needs to be equal or more than twenty. In addition, increase of the maximum number of iterations led to a better convergence behavior. Namely, the analysis data shown in Fig. 11(b) revealed that, for three cases of the maximum number of iterations, 20, 35, and 50, the mean value of the optimal cost was 102.137, 102.335, and 100.990 millions VND, respectively, and the standard deviation was 2.727, 0.640, and 1.042 million VND, respectively. It shows that, the best mean optimal value occurred in the case of the maximum number of iterations of 50. Meanwhile, the best standard deviation occurred in the case of the maximum number of iterations of 35.




(a) At the 20th iteration




(b) At the different maximum iterations

Figure 11. Evaluation of convergence behavior of the optimization process

## 4. Conclusions

Based on the results of the optimization analysis applied to the 3D RC frame of a three-story building in this study, some conclusions are drawn as follows:

An optimization model using Jaya algorithm has been successfully built and developed into a subroutine. Jaya algorithm is simple and free from algorithm-specific parameters with a fast, robust, and convenient manner for solving optimization problems in designing 3D RC frames. Especially, material cost optimization for the three-story building was good in efficiency. Namely, fleeting time for running and high convergence of optimization process were significant advantages of this algorithm. The optimization in this study showed that, the best optimal cost could be gained after running twenty iterations. However, a better convergence behavior has occurred at the higher number of iterations, thirty five and fifty.

The best optimized cross-sectional areas for structural elements (columns and beams) accompany with details of material amount and the best optimal cost has been gained for a medium RC building with three stories. It revealed that the best optimal cost for materials (concrete and reinforcement) in the 3D frame of this building was 96.868 million VND, leading to a reduction of materials cost (success rate) about 33.67% compared to that of the initial solution. This means that the optimal design helps to significantly cut off the construction spenditure.

Percentage of material cost reduction obtained from the optimization process not only depends on the building scale but also the specific design code applied. According to results conducted in other 3D RC buildings from the research project of the authors, the success rate of materials cost in the building frames dropped in a range from 30.7 to 33.7%. The success rates were also dependent on the Vietnam Design Codes [24, 25, 28], so these values could be changed when applying according to other nations' design codes.

The optimization model in this study could be applied to optimal design process for some medium RC building types such as private resident houses and shop houses. These buildings are designing and erecting widely not only in some Asian countries but also in other nations in the world. This will bring us both economic and environmental benefits in the construction activities in the future.

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**References**

[1] Mei, L., Wang, Q. (2021). Structural optimization in civil engineering: A literature review. *Buildings*, 11 (2):66.

[2] Hung, H. M., Hung, T. V. (2020). Optimization of planar trusses using direct design considering frequency constraints. *Vietnam Journal of Science and Technology*, 62(6).

[3] Ha, M. H. (2021). Performance comparison of metaheuristic algorithms for optimisation of steel framesusing nonlinear inelastic analysis. *Ministry of Science and Technology, Vietnam*, 63(6):28–32.

[4] Hieu, N. T., Cuong, N. Q., Tuan, V. A. (2021). Optimization of steel roof trusses using machine learning-assisted differential evolution. *Journal of Science and Technology in Civil Engineering (STCE) - HUCE*, 15(4):99–110.

[5] Truong, V.-H., Hung, H. M., Anh, P. H., Hoc, T. D. (2020). Optimization of steel moment frames with panel-zone design using an adaptive differential evolution. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 14(2):65–75.

[6] Phat, L. T., Long, N. N. P., Son, N. H., Vinh, H. H., Thang, L. A. (2020). Global optimization of laminated composite beams using an improved differential evolution algorithm. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 14(1):54–64.

[7] Doan, Q. H., Thai, D.-K., Tran, N. L. (2020). A hybrid model for predicting missile impact damages based on k-nearest neighbors and Bayesian optimization. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 14(3):1–14.

[8] X.Lieu, Q., Dang, K. D., Luong, V. H., Thai, S. (2022). Topology and size optimization for X-bracing system of nonlinear inelastic space steel frames. *Journal of Science and Technology in Civil Engineering (STCE) - HUCE*, 16(3):71–83.

[9] Do, D. T. T., Nguyen, T.-T., Nguyen, Q.-H., Bui, T. Q. (2022). A hybrid arithmetic optimization algorithm and differential evolution for optimization of truss structures subjected to frequency constraints. *Journal of Science and Technology in Civil Engineering (STCE) - HUCE*, 16(2):22–37.

[10] Tejani, G. G., Pholdee, N., Bureerat, S., Prayogo, D., Gandomi, A. H. (2019). Structural optimization using multi-objective modified adaptive symbiotic organisms search. *Expert Systems with Applications*, 125:425–441.

[11] Niaki, M. I., Maheri, M. R., Bagheri, M. (2016). Optimum design of 2-D reinforced concrete frames using a genetic algorithm. *THE TURKISH ONLINE JOURNAL OF DESIGN, ART AND COMMUNICATION*, 6(AGSE):1909–1919.

[12] Kaveh, A., Sabzi, O. (2012). Optimal design of reinforced concrete frames using big bang-big crunch algorithm. *International journal of civil engineering*, 10(3):189–200.

[13] Mangal, M., Cheng, J. C. P. (2018). Automated optimization of steel reinforcement in RC building frames using building information modeling and hybrid genetic algorithm. *Automation in Construction*, 90:39–57.

[14] Esfandiari, M. J., Urgessa, G. S., Sheikholarefin, S., Manshadi, S. H. D. (2018). Optimum design of 3D reinforced concrete frames using DMPSO algorithm. *Advances in Engineering Software*, 115:149–160.

[15] Kaveh, A., Behnam, A. F. (2013). Design optimization of reinforced concrete 3D structures considering frequency constraints via a charged system search. *Scientia Iranica*, 20(3):387–396.

[16] Bekdaş, G., Yucel, M., Nigdeli, S. M. (2021). Evaluation of metaheuristic-based methods for optimization of truss structures via various algorithms and Lèvy flight modification. *Buildings*, 11(2):49.

[17] Kaveh, A., Rezazadeh Ardebili, S. (2023). Optimum design of 3D reinforced concrete frames using IPGO algorithm. *Structures*, 48:1848–1855.

[18] Miguel, L. F. F., Lopez, R. H., Miguel, L. F. F. (2013). Multimodal size, shape, and topology optimisation of truss structures using the Firefly algorithm. *Advances in Engineering Software*, 56:23–37.

[19] Hussein, G., Taysi, N. (2013). Genetic algorithm optimization of space frame. In *2nd International Balkans Conference on Challenges of Civil Engineering, BCCCE, Epoka University*, Tirana, Albania, International Balkans Conferance on Challenges of Civil Engineering.

[20] Tahsin Öztürk, H., Dede, T., Türker, E. (2020). Optimum design of reinforced concrete counterfort retaining walls using TLBO, Jaya algorithm. *Structures*, 25:285–296.

[21] Baldissera dos Santos, R., Palomino Tamayo, J. L. (2020). Coupling SAP 2000 with ABC algorithm for truss optimization. *Dyna*, 87(212):102–111.

[22] Esfandiary, M. J., Sheikholarefin, S., Bondarabadi, H. A. R. (2016). A combination of particle swarm optimization and multi-criterion decision-making for optimum design of reinforced concrete frames. *International journal of optimization in civil engineering*, 6(2):245–268.

[23] Sonmez, M. (2011). Artificial Bee Colony algorithm for optimization of truss structures. *Applied Soft Computing*, 11(2):2406–2418.

[24] TCVN 5574:2012. *Vietnam design code for concrete and reinforced concrete structures*. Hanoi, Vietnam.

[25] TCVN 5574:2018. *Vietnam design code for concrete and reinforced concrete structures*. Hanoi, Vietnam.

[26] Venkata Rao, R. (2016). Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems. *International Journal of Industrial Engineering Computations*, 7 (1):19–34.

[27] Zitar, R. A., Al-Betar, M. A., Awadallah, M. A., Doush, I. A., Assaleh, K. (2021). An intensive and comprehensive overview of JAYA algorithm, its versions and applications. *Archives of Computational Methods in Engineering*, 29(2):763–792.

[28] TCVN 2737:1995. *Vietnam design code for loads and actions*. Hanoi, Vietnam.

[29] Krithikadatta, J. (2014). Normal distribution. *Journal of Conservative Dentistry*, 17(1):96.