Mansoura Engineering Journal

Volume 48 | Issue 2 Article 3

May 2023

Selecting the optimal formwork system for horizontal elements

Alaa Allam
Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt., engalaa.allam@mans.edu.eg

Emad Elbeltagi
Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt.

Mohamed Naguib Abouelsaad
Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt.

Mohamed E. El Madawy
Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt.

Recommended Citation

Allam, Alaa; Elbeltagi, Emad; Abouelsaad, Mohamed Naguib; and El Madawy, Mohamed E. (2023) "Selecting the optimal formwork system for horizontal elements," *Mansoura Engineering Journal*: Vol. 48 : Iss. 2 , Article 3.
Available at: https://doi.org/10.58491/2735-4202.3030

ORIGINAL STUDY

Selecting the Optimal Formwork System for Horizontal Elements

Alaa Allam*, Emad Elbeltagi, Mohamed Naguib Abouelsaad, Mohamed E. El Madawy

Department of Structural Engineering, Faculty of Engineering, Mansoura University, Mansoura, Egypt

Abstract

Various types of formworks are available in the market for construction of cast-in-place concrete structures. Formwork has a significant impact on both construction time and cost. As such, decision making on the optimal formwork system is difficult and time-consuming particularly for high-rise buildings, where any reduction in the cost of single-story formwork significantly decrease total construction cost. The aim of this article is to select the optimal formwork system using a Genetic Algorithm optimization model among Cuplock, Shore brace and Props systems that widely used in the market and getting the optimal design components for each system either. Market data on formwork components, systems, and pricing for many formwork manufacturers are gathered for this purpose. The proposed optimization model is applied on a case study project. Results show that the proposed optimization model significantly enhances the formwork design procedure and reduces formwork construction costs. The results indicate that the props system is the least expensive and easiest to construct, however it is limited to short story height up to 4.5 m. For higher heights, the Cuplock system is easier to construct and weighs less than shore brace but shore brace is resisting heavy loads and suitable for large spans.

Keywords: Formwork design, Formwork systems, Genetic algorithm, Optimization, Slab formwork

1. Introduction

The design of temporary structures for multi-story concrete buildings is vital and time consuming, as well as crucial. Any error in estimating the construction loads may result in the collapse of the formwork, resulting in worker deaths or injuries, as have occurred in several projects (Buitrago et al., 2018). Cost savings can be realized by reducing the cost of formwork systems during construction, especially for high-rise buildings. Although wood is still widely used due to its accessibility and simplicity of manufacturing, steel formwork has overtaken wooden formwork despite its higher initial cost but superior reusability (Peurifoy and Oberlender, 1996).

Typically, the design of the concrete structures and their formwork systems are carried out independently, with structural engineers designing the concrete structure and the contractor designing formwork for each part depending on its dimensions and geometry (Mansuri et al., 2017). Formwork failures result from faulty formwork design, inadequate shoring and reshoring, improper construction practices during construction, unstable support, and insufficient concrete strength to sustain the applied load after construction. The failure at one point in the formwork can become an extensive collapse through chain reaction (Chellappa and Ravindra Salve, 2021; Lee and Cho, 2020). Therefore, formwork should be designed by an engineer or by someone who has sufficient knowledge of forces and resistance of formwork materials. According to the literature, the construction sector witnesses more fatal injuries than any other industry, and worker illnesses and injuries cost the business billions of dollars annually (Huang and Hinze, 2006). Formwork failures caused by improper design or earlier removal of supports and inadequate lateral bracing have periodically occurred

Received 20 January 2023; revised 8 March 2023; accepted 11 March 2023.
Available online 19 May 2023

* Corresponding author at: Department of Structural Engineering, Faculty of Engineering, Mansoura University, Mansoura, 35516, Egypt.
E-mail address: engalaa.allam@mans.edu.eg (A. Allam).

https://doi.org/10.58491/2735-4202.3030

throughout the concrete construction (Melzner et al., 2013).

Formwork systems provide several concrete construction options to fit a structure's demands. Formwork construction is complicated, especially when its components are reused to establish different work zones. Biruk and Jaskowski (2017) suggested a mixed integer linear programming optimization methodology for vertical elements' formwork. The difficulty is selecting the quantity and size of panels according to the geometry of the concrete parts to reduce wall shuttering rental costs.

The choice of formwork system may be made according to a wide range of variables (Terzioglu et al., 2022). Consequently, the selection of the appropriate formwork system may depend on the perception of various construction professionals, such as formwork engineers (Basu and Jha, 2016). Most of the research that can be found in the relevant literature identified, ranked, and examined the criteria for selecting a given formwork system based on the opinion of construction experts (Shin et al., 2012). Moreover, analysis of formwork material is an important variable that affects the selection of formwork system (Terzioglu et al., 2021). Formwork system was also selected based on performance evaluation for high-rise buildings using regression analysis and their effect on project success (Rajeshkumar, Sreevidya).

Design of formwork for reinforced concrete structures requires effective management to reduce the duration and cost (Kim and Cho, 2015). Many studies have attempted to plan, design, and select the best formwork system to increase the speed of construction. For example, Elbeltagi et al. (2012) developed fuzzy logic-based model for selection of the appropriate horizontal and vertical formwork systems. Industry Foundation Classes schema was employed to optimize formwork design of concrete walls in building construction (Hyun et al., 2018). Moreover, a method was proposed to increase the proportion of the modular forms to increase formwork efficiency (Ham and Lee, 2018). Hyun et al. (2018) developed an optimization model using spatial analysis and building information modeling (BIM) for optimum wall formwork design. This model optimizes the formwork cost for only walls of concrete buildings.

There are several optimization tools, each suited to a particular context. Genetic algorithm (GA) is an effective metaheuristic optimization technique used for different optimization problems such as facility layout problem, supply network design, scheduling, forecasting, and inventory control (Katoch et al., 2021). GA is a well-known algorithm inspired from biological evolution (Michalewicz and Schoenauer, 1996). It searches a large spectrum of potential solutions for a problem, as opposed to limiting the search to the often-assumed small area (Hegazy, 1999; Pothen).

This paper presents a model for formwork design and optimization using GAs. The proposed model selects the best combination of formwork elements for the used formwork system from several available formwork systems. Then, the proposed model is automated to facilitate the formwork design and optimization process. This research starts by identifying the design steps of slab formwork elements and the code recommendations. Then, it studies the local and global market and prepares the different data for the different systems of formwork. For the purpose of design automation, an automated design tool is developed. Afterward, an optimization model using GAs is developed for optimal formwork design. Finally, the model is applied on a case study project to test its validity.

2. Materials and methods

2.1. Data collection

There are several formwork systems used in the market. Many companies and manufacturers are combatting for selling and growing in the market. Every manufacture produces a formwork system with all data for this system and its components, dimensions, and design capacities. Modular system (cuplock or ringlock system), load bearing tower system (frame or shore bracing systems), and Flex (props system) are the most formwork systems used to support horizontal elements. Formwork used to support horizontal elements like slabs or beams consists of decking and falsework. Decking consists of sheathing like plywood, secondary beams ‘joists,’ and main beams/bearer ‘stringers.’ Fresh concrete is poured on sheathing to take its shape. Secondary and main beams are used to support the sheathing and transfer loads to the falsework. Secondary and main beams could be timber boards like 2’ × 4′, timber h20, or steel, etc. Falsework is the shoring system that supports formwork decking. It consists of vertical and horizontal members, lateral bracing, and accessories to join them. Figs. 1 and 2 show the types of the most horizontal formwork widely used and their components.

Each formwork component has a unique cost depending on the cost of formwork materials, installation cost, and use cycle. Consequently, it is essential to determine the best components for a formwork system to reduce its cost. The improvement of the formwork system will result in a

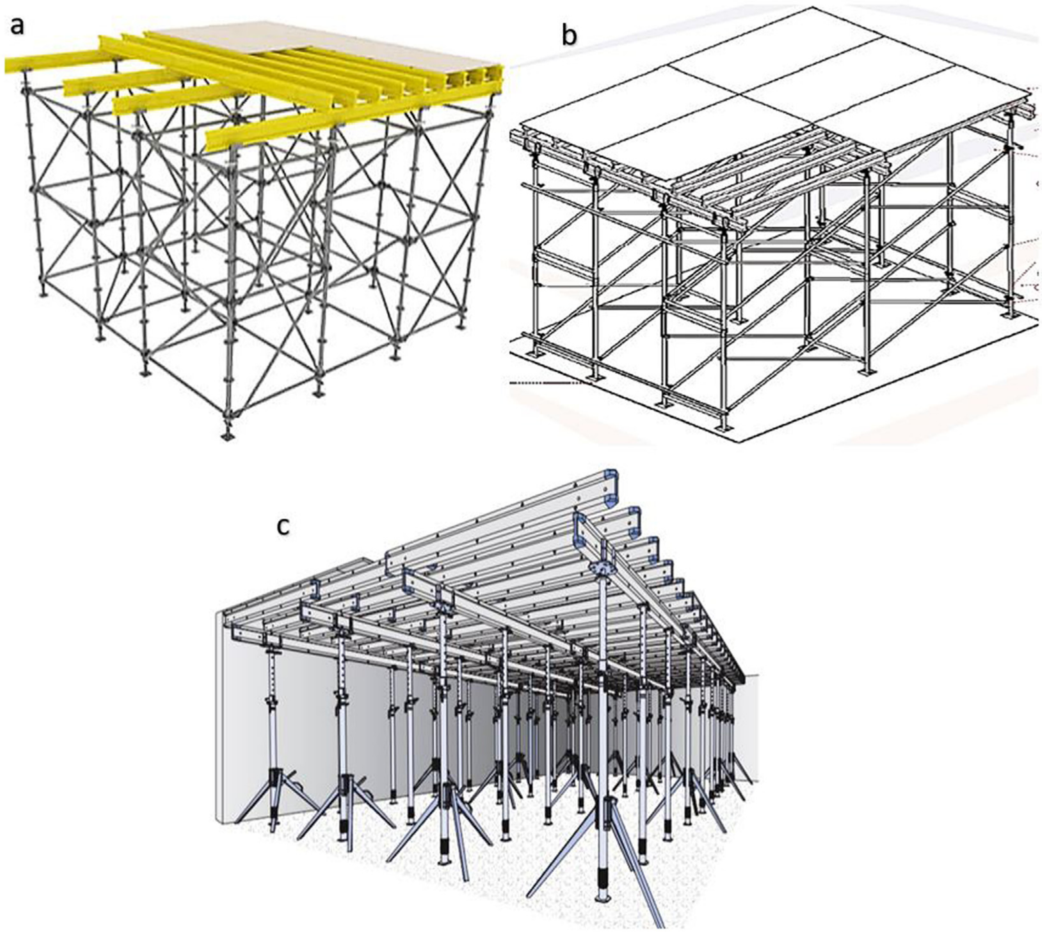

Fig. 1. Some slab formwork systems: (a) cuplock, (b) shore brace, and (c) props.

decrease in the construction cost of the concrete skeleton, particularly for high-rise structures.

2.2. Formwork design

Many professional institutions have published standards and specifications for formwork design and planning. In 2015, the American Society of Civil Engineers published 'Design loads on structures during construction' (Design loads on structures during, 2015). These specifications provide the lowest loads for formwork design. Subpart Q (concrete and masonry) outlines OSHA's regulations (OSHA 29 CFR, 1926). The book 'Guide to formwork for concrete (ACI 347R-14)' (American Concrete Institute, 2014) for the American Concrete Institute (ACI) provides detailed guidance for formwork design and construction and provides detailed step-by-step procedures to design different formwork components to enhance formwork efficiency. ACI 347R-14 (American Concrete Institute, 2014) reported that formworks can represent 60% or more of the overall cost of a concrete construction. Thus, demands careful consideration when designing and constructing the formwork. Moreover, the British Standards Institution provides the code of Practice for Temporary Structures Procedures and the Permissible Stress for Falsework (BSI, 2019).

To automate the design process, a database of all formwork elements is created along with their geometrical data, allowable bending, and shear stresses and deflection, which are obtained from manufacturers' catalogs. Load w for a square meter of floor is calculated for horizontal elements based on concrete self-weight, pouring and working as live load, and self-weight of decking. Statistical system for each element is established. Then, based on the given loads and statistical system, moment, shear,

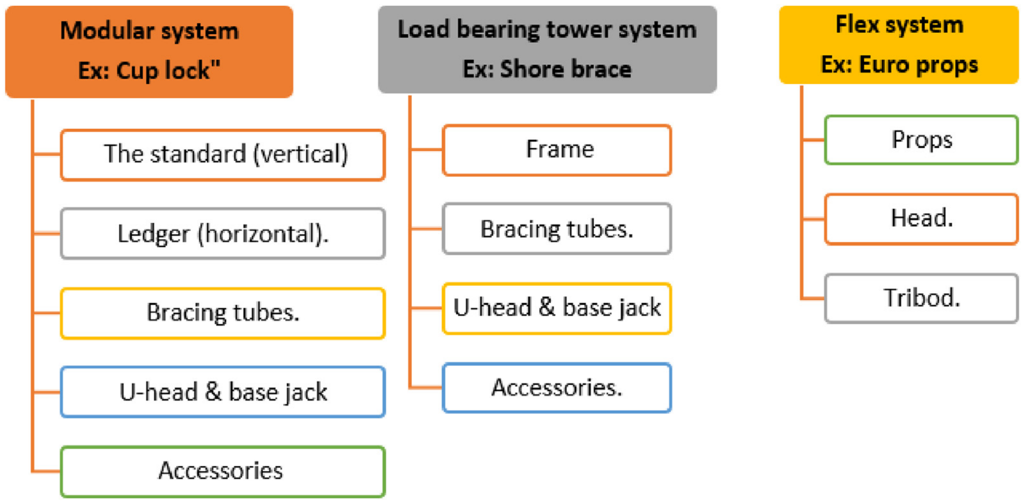

Fig. 2. False work systems' components.

and deflection are estimated automatically for all elements. Plywood is designed as a continuous beam for more than three spans with maximum moment $= \frac{w\times L^2}{10}$, max shear $= 0.6 \times w \times L$, and max deflection $= \frac{0.0065\times w\times L^4}{EI}$. Then, loads on secondary beams (W1), load on main beams (W2), and needed reactions are calculated. Secondary and main decking beams' maximum moment, shear, and deflection are calculated according to the number of spans (one, two, or three and more) with double cantilever as shown in Table 1. These design equations are stored as functions in the automated system and coded using C#, which decreases the time required for the design.

Vertical elements are designed to resist the main beam maximum reaction. Horizontal load resistance ensures safety against lateral loads like wind. As such, diagonal bracing provided in vertical and horizontal planes is used to resist lateral loads and to prevent instability of individual members according to 'Code of practice for temporary work procedures and the permissible stress design of falsework' (BSI, 2019).

2.3. *Formwork optimization*

Obtaining the optimal formwork system that reduces cost and saves time is an essential task. In this study, a GA-based formwork optimization model is presented. It was decided to select the formwork that just satisfies the design criteria constraints with the objective to maximize what is called 'the design ratio, I,' calculated as the maximum actual straining actions obtained from a given design over the allowable straining actions (Eq. (1)), as shown in Fig. 3. The design ratio should not exceed one. Then, the objective function is to maximize the sum of the design ratios (Eq. (2)).

$$\text{Design ratio } (I_i) = \frac{\text{Actual straining actions}}{\text{Allowable straining actions}} \qquad (1)$$

Table 1. Maximum straining actions on decking beams and reactions on supports.

	One span	Two spans	Three or more spans
Max moment	$\frac{w\times Lc^2}{2}$ *or* $\frac{w\times Lc^2}{2} - \frac{W\times L^2}{8}$	$\frac{w\times Lc^2}{2}$ *or* $\frac{W\times L^2}{9}$	$\frac{w\times Lc^2}{2}$ *or* $\frac{W\times L^2}{10}$
Max shear	$w \times Lc$ *or* $0.5 \times w \times L$	$w \times Lc$ *or* $0.6 \times w \times L$	$w \times Lc$ *or* $0.6 \times w \times L$
Max deflection	$\frac{5\times w\times L^4}{384\times E\times I}$	$0.8 \times \frac{5\times w\times L^4}{384\times E\times I}$	
Max reaction	$0.5 \times w \times L + wLc$	$1.2 \times 5w \times L$	$1.1 \times w \times L$

L, single beam span; Lc, a cantilever length.
$w = W_1$, load calculted on secondary beam, L, L1 span of secondary beam.
$w = W_2$, load calculted on main beam; L, L_2 span of main beam.

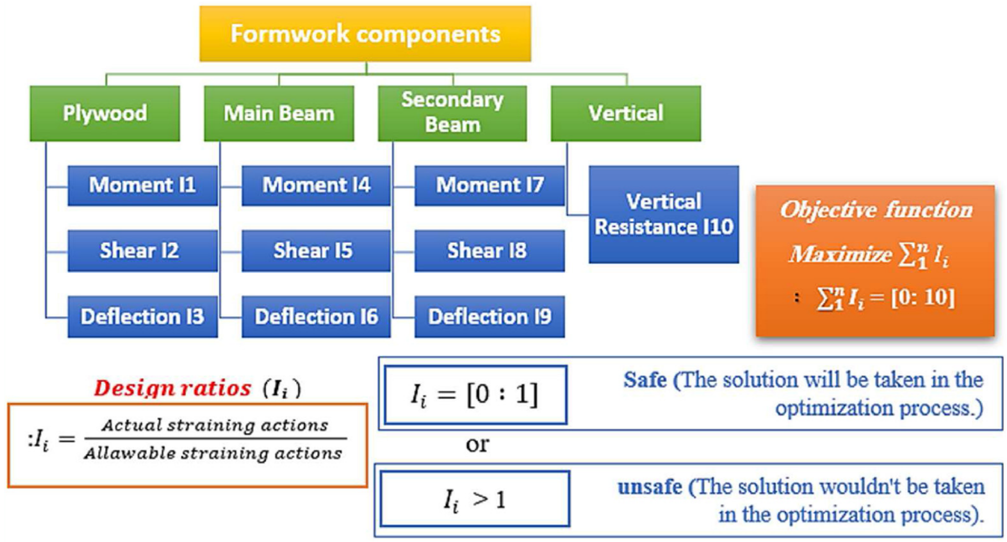

Fig. 3. Formwork design ratios.

$$\text{Objective function} = \text{Maximize} \sum_{1}^{n} I_i \qquad (2)$$

where $I_i = [0 : 1]$

n: is the number of calculated straining actions required for design = 10 (Fig. 3).

$$\sum_{1}^{n} I_i = [0 : 10]$$

The optimization process is shown in Fig. 4. The design variables are the types and lengths of formwork components: plywood types, secondary beam types, secondary beam length, main beam types, main beam length, vertical element height, horizontal element length, and bracing tube length. Data related to formwork element types and lengths are recorded based on those available in the market. Thickness of slab and story height are user inputs for the design process. Design constraints are imposed to ensure the safety of any design solution for maximum moment, shear, and deflection calculations. Geometrical constraints based on the structure geometry of the slab, as well as the placements of the openings, columns, column panels, and beams, also affect the elements' length variables.

3. Case study application

The developed model is applied for the design and optimization of a slab formwork system for a given building as shown in Fig. 5, with area of 828 m^2, floor height of 3.0 m, and a slab thickness of 20 cm. The developed application uses the slab boundary lines, openings, beams, columns' location, and story height to divide the slab into small rectangular areas with primary and secondary spacing in both directions. Then, the locations of the openings' borders, edges, beams, columns, and drop panels, if exist, are filtered to prevent formwork from being located in these filtered locations, as shown in Fig. 6.

The user enters the optimization parameters and then the optimization process starts by clicking on the 'optimization' button as shown in Fig. 7. Many trials are performed for obtaining the best GA parameters: crossover rate, mutation rate, population size, and number of generations. A variety of experiments were carried out using a wide range of values for these parameters on the case study application. Accordingly, 1000, 0.8, 0.05, and 1000 were used for population size, crossover rate, mutation rate, and generations, respectively. In this case study, three formwork systems (cuplock, Euro props, and shore brace) are experimented with to select the optimal one.

4. Results and discussion

Optimization is made for the three systems, cuplock, Euro props, shore brace (each system individually), and the cost is calculated (Eq. (3)) for the optimized solution for each system according to estimated quantities. The results of the optimization process include the identification of plywood type,

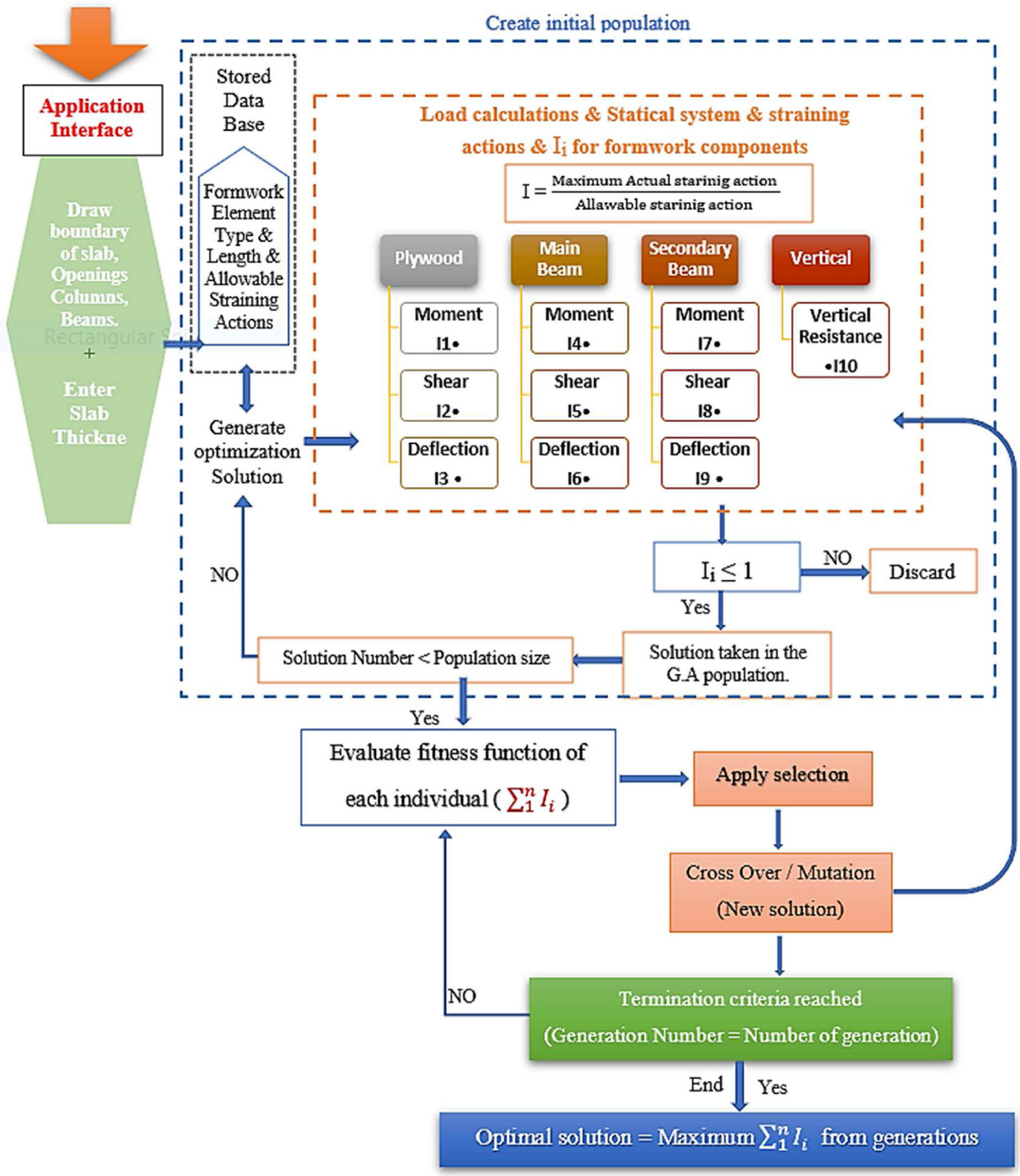

Fig. 4. Flow chart for the proposed GA approach for slab formwork design optimization. GA, genetic algorithm.

$$\text{Cost} = \sum_{1}^{n} \left\{ \left(quantity_i \times unit\ rent\ price_i \right) + \left(quantity_i \times unit\ purchace\ price\ /\ numberof\ uses \right) \right\} \tag{3}$$

spacing between secondary beams, secondary beams type and length, main beams type and length, and spacing between vertical element spacing in both directions. All findings may be exported to Excel Sheets for reporting and comparison purposes. Unit prices are stored in the cost database, and the user is allowed to change it if the element is rented or purchased, as shown in Fig. 8.

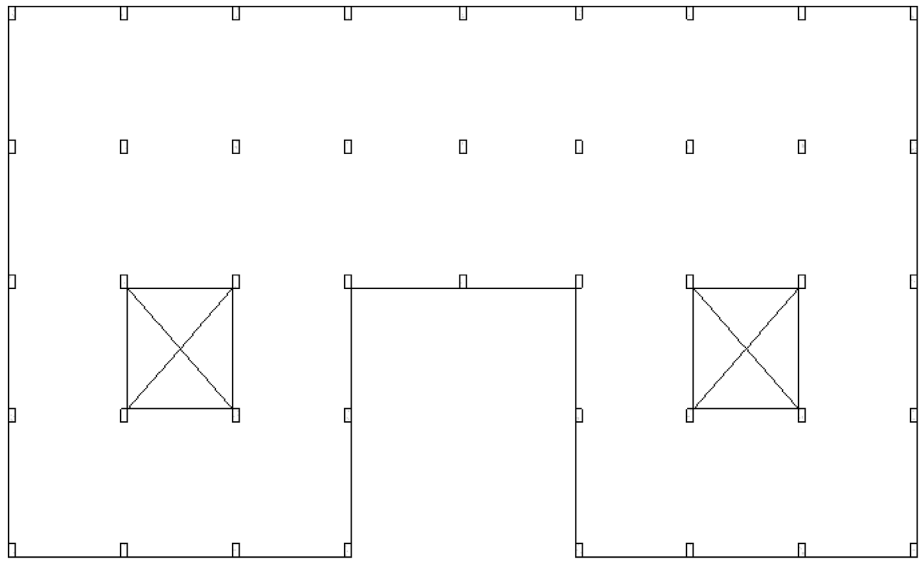

Fig. 5. Case study project modeled on the proposed application.

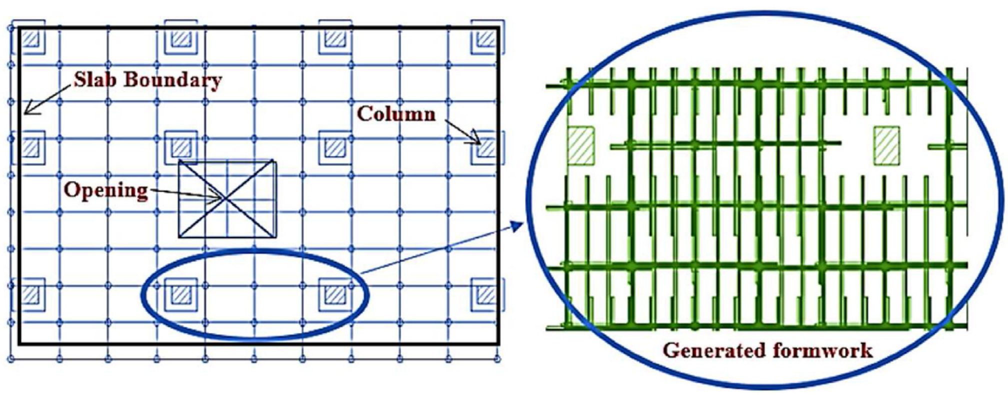

Fig. 6. Slab division concept.

Fig. 9 is an example of the results of the cuplock system. It demonstrates that the proposed algorithm met the design criteria with design ratios (Ii < 1) for all elements (this is also performed for all types of formworks used). The optimal solution is a combination of the formwork system elements representing the optimization variables (plywood type, secondary beam type, length, and spacing, main beam type, and length, and vertical element spacing in both directions). Moreover, required quantities are estimated as presented in Fig. 10. The cost is calculated based on those quantities, so that the least cost solution could be selected. Subsequently, once the optimal solution has been determined, its two-dimensional visualization is generated, as seen in Fig. 11. Consequently, the suggested method reduces the time necessary for two-dimensional drawings and quantification.

Fig. 12 illustrates the solution that had the least cost for the three systems with different slab thicknesses. It has been discovered that the Euro props system has the lowest cost. This is due to the fact that the system's vertical elements are supported by tripods, with no horizontal elements linking them.

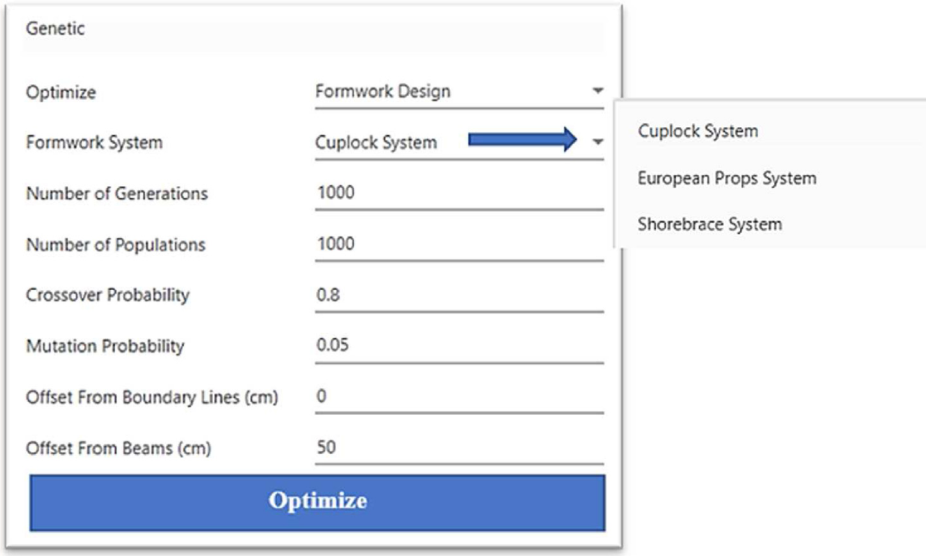

Fig. 7. User interface for optimization parameters for selected formwork system.

Additionally, the prop vertical element length can be lengthened to support heights up to 4.5 m without the need for additional elements or additional cost. However, if the story height exceeds 4.5 m, the props system would not be applicable; therefore, cuplock or shore brace systems are a good alternative as their costs are comparable and they can be used for any height.

Due to the stochastic nature of the GA, it is anticipated that each run would generate different

Formwork Elements Cost

Cost Database

Formwork Element Name	Monthly Rent | Purchase Cost (LE)	Unit Cost Measure	Cost Type	No. Uses
Betofilm 18mm	250	Area	Purchase	10
Cofiform Plus 17.5mm	300	Area	Purchase	10
Douglas Fir 19mm	350	Area	Purchase	10
Wisaform Birch 18mm	400	Area	Purchase	10
Acrow Beam S12	10	Length	Rent (Monthly)	
Double Acrow Beam S12	20	Length	Rent (Monthly)	
Aluminum Beam	7	Length	Rent (Monthly)	
Double Aluminum Beam	14	Length	Rent (Monthly)	
S Beam 12	10	Length	Rent (Monthly)	
Timber H20	7.5	Length	Rent (Monthly)	
Timber 2x4	42.5	Length	Purchase	10
Timber 2x5	53.13	Length	Purchase	10
Timber 2x6	63.75	Length	Purchase	10

Fig. 8. Sample of the cost database.

Plywood: (Section: Betofilm 18mm,Selected Span: 55 cm, Max Span: 55 cm)

Check Name	Allowable	Actual	Ratio	Status
Moment	0.044000	0.019039	0.433	SAFE
Shear	0.662000	0.167646	0.253	SAFE
Deflection	0.203704	0.192354	0.944	SAFE

Secondary Beam: (Section: Timber 2x4, Length: 420 cm)

Check Name	Allowable	Actual	Ratio	Status
Moment	0.070000	0.052470	0.750	SAFE
Shear	0.500000	0.262350	0.525	SAFE
Deflection	0.300000	0.222224	0.741	SAFE

Main Beam: (Section: Timber H20, Length: 450 cm)

Check Name	Allowable	Actual	Ratio	Status
Moment	0.500000	0.314820	0.630	SAFE
Shear	1.100000	0.944460	0.859	SAFE
Deflection	0.300000	0.242350	0.808	SAFE

Shoring System: (Cuplock System, M.B. Direction: 180 cm, S.B. Direction: 120 cm)

Check Name	Allowable	Actual	Ratio	Status
Normal	2.511000	1.967625	0.784	SAFE

Fig. 9. Formwork elements, design ratios, and corresponding cost for the optimal solution.

Formwork Elements Quantification Detail Result (Cuplock).

Element Name	Count	Cost Type	Optimize Unit Cost
CupLock Ledger 1.50 m, (Steel 37)	1458	Rent (Monthly)	3.68
CupLock Vertical 1.50 m, (Steel 37)	407	Rent (Monthly)	6.15
U-Head Jack Solid	407	Rent (Monthly)	5.3
Post Head Jack Solid	407	Rent (Monthly)	4.26
Scaffolding Tube 2.00 m	221	Rent (Monthly)	2.63
Pressed Prop Swivel Coupler	442	Rent (Monthly)	1.16
TIMBER_2X8 L=270 cm	365	Purchase	8.5
TIMBER_2X5 L=360 cm	501	Purchase	5.313
TIMBER_2X5 L=210 cm	31	Purchase	5.313

Fig. 10. Slab formwork elements' quantities for the optimal solution.

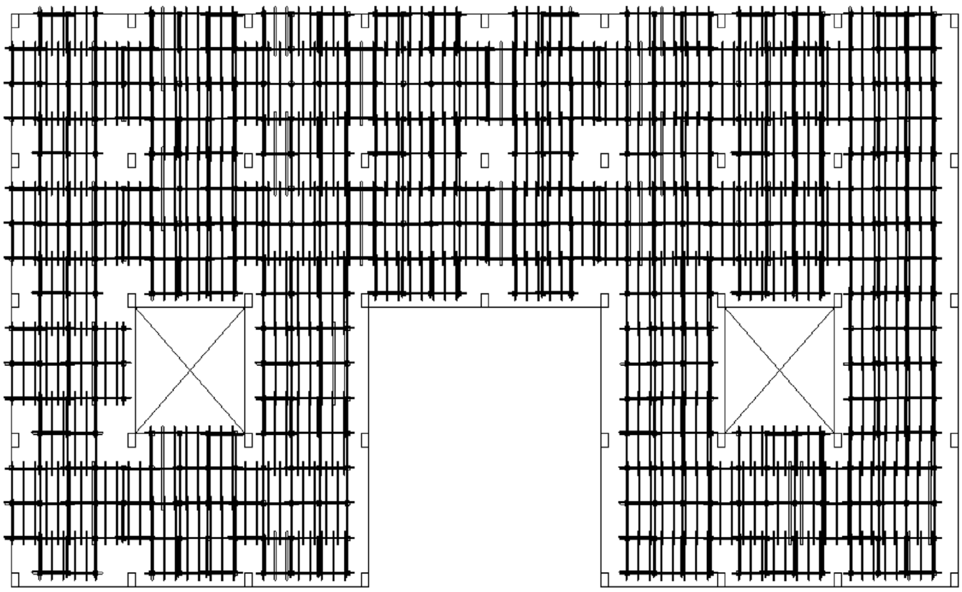

Fig. 11. Formwork visualization and the extracted two-dimensional drawing for the optimized solution.

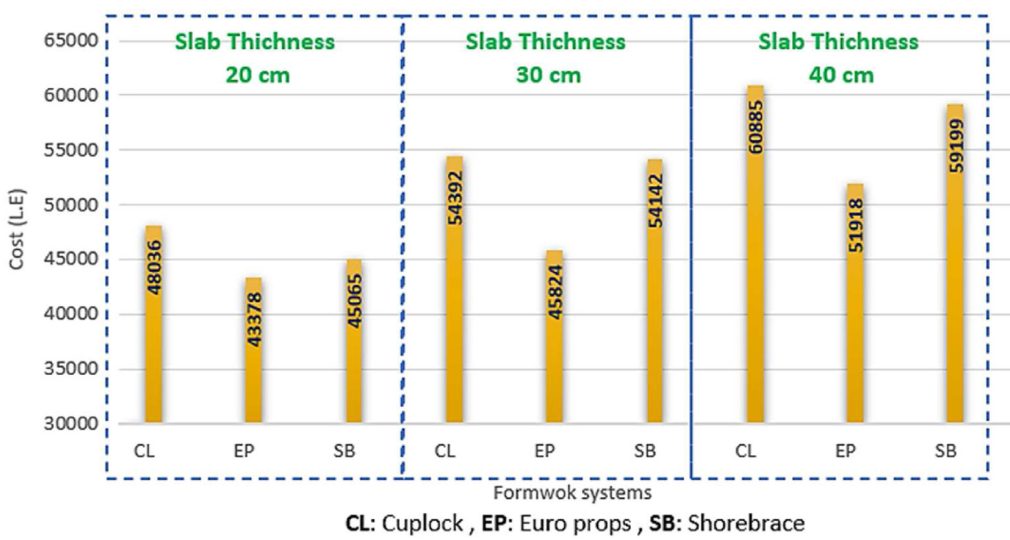

Fig. 12. Cost results for formwork systems with different slab thickness.

outcomes for the same set of parameters. As a result, 10 runs were conducted, and Table 2 offers the optimal option, which represents the highest design ratio at the lowest cost. Table 2 displays the findings for each formwork system combination for slabs of different thicknesses (secondary beam type and length, main beam type and length, shoring spacing direction 2, and shoring spacing direction 1). The same plywood type is used, 'Betofilm 18 mm,' for all systems; however, secondary beam spacing varied. Table 2 also displays the processing times for each solution. It ranges from 1.2 to 2.6 min. Consequently, the proposed method reduces the time required from formwork practitioners to design the formwork, increases efficiency by obtaining the minimum cost of formwork system, obtains the

Table 2. Results for secondary beams, main beams, and shoring vertical spacing.

Slab thickness (cm)	20			30			40		
Formwork system	CL	EP	SB	CL	EP	SB	CL	EP	SB
Processing time (min)	1.2	1.3	1.3	1.2	1.3	1.4	1.4	2	1.8
Cost (LE)	48 036	43 378	45 065	54 392	45 824	54 142	60 885	51 918	59 199
Plywood type	Betofilm 18 mm			Betofilm 18 mm			Betofilm 18 mm		
Secondary beam clear spacing (cm)	50	50	50	45	45	45	40	40	40
Secondary beam type/length (cm)	Timber 2’ × 4′ $L = 420$	Timber 2’ × 4′ $L = 300$	Timber 2’ × 4′ $L = 360$	Timber 2’ × 4′ $L = 420$	Timber 2’ × 4′ $L = 420$	Timber 2’ × 4′ $L = 450$	Timber 2’ × 5′ $L = 450$	Timber 2’ × 4′ $L = 210$	H20 $L = 330$
Main beam type/length (cm)	H20 $L = 450$	Timber 2’ × 6′ $L = 360$	Timber 2’ × 6′ $L = 300$	Timber 2’ × 8′ $L = 240$	Timber 3’ × 6′ $L = 360$	Timber 2’ × 6′ $L = 210$	Double timber 2’ × 6′ $L = 420$	Timber 2’ × 8′ $L = 450$	Double timber 2’ × 8′ $L = 450$
Shoring spacing Dir 1 (cm)	180	120	120	150	130	120	120	120	120
Shoring spacing Dir 2 (cm)	120	120	120	120	120	110	150	110	120

CL, cuplock; EP, Euro props; SB, shore brace.

optimal combination for multiple formwork systems, and estimates the quantities required for construction for all system components and accessories.

5. Conclusions

There are numerous formwork systems available for concrete structures, making it difficult to choose a given formwork system. Formwork design is a repeating effort for designers; therefore, manual formwork design for several systems to select the ideal one is time consuming and prune to design errors. Consequently, automating the design of formwork systems can enhance the design process by reducing design time and giving precise formwork quantities and costs. This study provided a GA-based optimization approach for slab formwork design for a variety of formwork systems to select the optimal system. The used optimization model was automated to maximize design ratios and compute the best solution's cost based on estimated quantities. The user draws the slab and inputs the thickness and height of the floor. The suggested model then estimates concrete pressure and stresses on formwork elements based on the acquired data, which is then used to optimize formwork design depending on the availability and cost of formwork components. After analyzing several optimization options and their cost, Euro props formwork system provides the lowest cost; however, this is limited to a height of 4.5 m maximum, based on the prop height, and no extension could be added to the prop for more height. Therefore, for heights more than 4.5 m, the Cuplock system or shore brace is more suitable based on their estimated cost. In conclusion, the suggested formwork design and optimization methodology would considerably improve the efficiency of the formwork design process, reduce construction costs, and reduce design time. In addition, the same data extraction and analysis might be used to develop automated solutions to comparable situations. Future study might concentrate on the analysis of forms with a higher degree of irregularity, including construction planning.

Credit authorship contribution statement

Study conception or design of the work: Alaa Allam, Emad Elbeltagi, Mohamed Naguib Abouelsaad, Mohamed E. El Madawy; Visualization: Alaa Allam, Emad Elbeltagi; Data collection and tools: Alaa Allam, Mohamed E. El Madawy; Data analysis and interpretation: Alaa Allam, Emad Elbeltagi; Investigation: Alaa Allam, Mohamed E. El Madawy; Methodology: Alaa Allam, Emad Elbeltagi,

Mohamed Naguib Abouelsaad; Project administration: Emad Elbeltagi, Mohamed Naguib Abouelsaad; Resources: Alaa Allam, Mohamed Naguib Abouelsaad, Mohamed E. El Madawy; Statistical analysis: Alaa Allam, Emad Elbeltagi; Software: Alaa Allam; Supervision: Emad Elbeltagi, Mohamed Naguib Abouelsaad, Mohamed E. El Madawy; Drafting the article: Alaa Allam; Critical revision of the article: Emad Elbeltagi; Final approval of the version to be published: Emad Elbeltagi, Mohamed Naguib Abouelsaad, Mohamed E. El Madawy.

Conflict of interest

There are no conflicts of interest.

References

American Concrete Institute, 2014. ACI 347R-14: Guide to Formwork for Concrete. American Concrete Institute, MI, USA.

Basu, R., Jha, K.N., 2016. An AHP based model for the selection of horizontal formwork systems in Indian residential construction. Int. J. Struct. Civil. Eng. Res. 5 (2), 80−86.

Biruk, S., Jaskowski, P., 2017. Optimization of vertical formwork layout plans using mixed integer linear programming. Int. J. Civil. Eng. 15, 125−133.

BSI, 2019. BS 5975: 2019. Code of Practice for Temporary Works Procedures and the Permissible Stress Design of Falsework.

Buitrago, M., Moragues, J.J., Calderón, P.A., Adam, J.M., 2018. Structural failures in cast-in-place reinforced concrete building structures under construction. In: Makhlouf, Abdel Salam Hamdy, Aliofkhazraei, Mahmood, Heinemann, Butterworth (Eds.), Handbook of Materials Failure Analysis. Mathew Deans. Elsevier, pp. 153−170, 1st Chapter.

Chellappa, V., Ravindra Salve, U., 2021. Understanding the fall-related safety issues in concrete formwork. E3S Web Conf. 263, 02007.

ASCE Committee of the Codes and Standards Activities, 2015. Design Loads on Structures during Construction. American Society of Civil Engineers, Reston, VA.

Elbeltagi, E.E., Hosny, O.A., Elhakeem, A., Abdelrazek, M.E., El-Abbasy, M.S., 2012. Fuzzy Logic Model for Selection of Vertical Formwork Systems. Const. Eng. Manag. 138, 832−840.

Ham, N., Lee, S.-H., 2018. Empirical study on structural safety diagnosis of large-scale civil infrastructure using laser scanning and BIM. Sustainability 10, 4024.

Hegazy, T., 1999. Optimization of resource allocation and leveling using genetic algorithms. J. Construct. Eng. Manag. 125, 167−175.

Huang, X., Hinze, J., 2006. Owner's role in construction safety. J. Construct. Eng. Manag. 132, 164−173.

Hyun, C., Jin, C., Shen, Z., Kim, H., 2018. Automated optimization of formwork design through spatial analysis in building information modeling. Autom. ConStruct. 95, 193−205.

Katoch, S., Chauhan, S.S., Kumar, V., 2021. A review on genetic algorithm: past, present, and future. Multimed. Tool. Appl. 80, 8091−8126.

Kim, K., Cho, Y., 2015. BIM-based planning of temporary structures for construction safety. Congr. Comput. Civil. Eng. Proc. 2015, 436−444.

Lee, J., Cho, J., 2020. An inference method of safety accidents of construction workers according to the risk factor reduction of the bayesian network model in linear scheduling. Int. J. Manag. 11, 11−18.

Mansuri, D., Chakraborty, D., Elzarka, H., Deshpande, A., Gronseth, T., 2017. Building information modeling enabled cascading formwork management tool. Autom. ConStruct. 83, 259−272.

Melzner, J., Zhang, S., Teizer, J., Bargstädt, H.-J., 2013. A case study on automated safety compliance checking to assist fall protection design and planning in building information models. Construct. Manag. Econ. 31, 661−674.

Michalewicz, Z., Schoenauer, M., 1996. Evolutionary algorithms for constrained parameter optimization problems. Evol. Comput. 4, 1−32.

Peurifoy, R.L., Oberlender, G.D., 1996. Formwork for Concrete Structures, 3rd ed. McGraw Hill Co., New York.

Pothen, A.S.. Artificial intelligence and its increasing importance. https://www.researchgate.net/publication/358058444 [Accessed 10 October 2022].

Rajeshkumar, V., Sreevidya, V., 2019. Performance evaluation on selection of formwork systems in high rise buildings using regression analysis and their impacts on project success. Arch. Civ. Eng. LXE (2), 209−222.

Shin, Y., Kim, T., Cho, H., Kang, K.-I., 2012. A formwork method selection model based on boosted decision trees in tall building construction. Autom. ConStruct. 23, 47−54.

Terzioglu, T., Polat, G., Turkoglu, H., 2021. Analysis of formwork system selection criteria for building construction projects: a comparative study. Buildings 11, 618.

Terzioglu, T., Turkoglu, H., Polat, G., 2022. Formwork systems selection criteria for building construction projects: a critical review of the literature. Can. J. Civ. Eng. 49, 617−626.