Heliyon 10 (2024) e26064

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Optimizing the superstructure configuration of highway bridges for cost-effective construction

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ARTICLE INFO

Keywords:
Construction projects
DSS
Highway bridges
Superstructure
Optimization

ABSTRACT

The structural progress of bridges in conjunction with efficiency has gained researchers' attention in the last few decades. Structures optimization applying mathematical analysis is utilized to achieve sustainability in the design and construction of bridges. Despite the extensive research in this area of knowledge, further structural optimization development needs to be developed.

The main goal of this research is to develop a decision support system (DSS) that selects the optimum superstructure configuration for highway bridges, considering financial and technical parameters. The most common structural systems in the longitudinal and transverse directions of bridges are considered in this research. Simple and continuous spans are included in the longitudinal direction, while open and closed sections for the transverse direction. Different construction materials are considered as well, like reinforced concrete, pre-stressed concrete, steel sections, and composite sections, to achieve a wide diversity of alternatives. The developed DSS was illustrated graphically as a map for the optimum superstructure configuration for certain span and span to depth ratio combinations. These different configurations obtained from the DSS were mapped three times. The first was based on direct cost only, the second on construction time only, and the third on the total cost of each alternative. Eventually, the DSS was verified using collected case studies and proposed a convenient selection of bridge superstructure configurations within the considered range of span dimensions.

1. Introduction and background

Bridges are a major and dynamic constituent of the high and roadways of any country, as they denote a significant percentage of country's economy. With rapid development all over the world, society has progressively advanced construction needs for transportation systems and infrastructure [1]. Consequently, super-span bridges, high-speed railway bridges, and ultra-long sea-crossing bridges are more often executed in many regions. At the same time, new materials, new technologies, new technical theories, and new structures have emerged, and the level of technical application of bridge construction has reached an extraordinary level [2].

Decision support systems have been extensively implemented in the last few decades in several industry fields to support decision makers [3]. DSS can provide remarkable assistance to asset managers and owners in major decisions with several constraints [4]. Therefore, it is clearly a very complicated task, as there are a tremendous number of viable alternatives due to the increasing structural

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https://doi.org/10.1016/j.heliyon.2024.e26064
Received 29 May 2023; Received in revised form 6 February 2024; Accepted 7 February 2024

and design complexity [5]. Most problems, in reality, do not have a definite best solution, although an optimum one can be extracted from a set of viable solutions [6]. DSS is computer-based software that aids in making decisions by using a model to identify the related data in making the decision. Recently, DSSs have been widely used all over the world, which highlights the fact that they are accepted as significant time-saving and cost-saving managerial tools [7].

Due to the rapid increase in city populations and urbanization, citizens' transportation is obligated to be more efficient. Bridges have a major role in the urban transportation network, so based on their development, infrastructure and transport systems are improved. Currently, the advancement of bridge industry technologies has caused the emergence of significant issues such as construction cost optimization, sustainable maintenance, construction efficiency, and optimization of the cost-to-performance ratio [8].

The superstructure of bridges was specified as a significant and critical aspect of increasing the efficiency of bridges. Bridge superstructure can be categorized as open and closed systems as plate girder bridges and box girder bridges, respectively [9]. Box girder bridges are more beneficial in terms of durability and torsion; on the other hand, they are less advantageous in terms of construction cost. Plate girder bridges are more beneficial in maintenance and construction costs but they are less advantageous in constructability and durability [10]. Consequently, plate girder systems are favored by bridge engineers due to their cost effectiveness and efficiency [11]. As stated by another research as well, in order to optimize the ratio of cost to performance in bridges, the efficiency of the superstructure should be maximized mentioning that it is the most effective approach. The authors also assured that designers and bridges' engineers lately prefer plate girder superstructures because of their cost advantages [12].

In China, according to government statistics, until 2016, there were more than 800 000 highway bridges; concrete bridges accounted for more than 95% [13]. Jiponov and Georgiev [14] assured that prefabricated prestressed beams are the most common system in Bulgaria for spans of 20, 40, and even 60 m. After only around thirty years of operation, serious deterioration was recorded, and partial or total replacement was obligated for the superstructure in many cases. In these cases, selecting a new feasible superstructure is vital. Low cost, fast construction, and high reliability are the key parameters for such processes. The authors mentioned that for 20–25 m spans, the typical cast-in-situ RC superstructure is the lowest in cost. However, the combined steel-RC superstructure can be considered as well due to its fast execution and the unnecessity of dense scaffolding.

As natural resources are finite, they must be used optimally. One step in this direction is utilizing optimization techniques in structural design. An extensive amount of research discussing structural optimization has been published since Schmit's pioneering work in the 1960s [15], but not many have focused on structural design optimization [16].

The researcher also assured that developing a DSS for selecting the optimum superstructure configuration will increase automation in the design process. Satisfactory design can be carried out in a shorter time, human errors can be decreased, costs will be at a minimum, and the whole design process will be less random. Therefore, performing cost optimization on large, realistic 3D structures is extremely significant.

According to Zaheer et al. [17] and Yu Li et al. [18], structural optimization can be classified into four categories: size optimization, shape optimization, topology optimization, and multi-objective optimization. The decision support system implemented for this purpose can utilize optimization to satisfy a user-specific objective.

Recently, several researchers have developed their multi-criteria decision support systems, such as Elhegazy et al. [19] for repairing techniques of concrete bridge girders, another study [20] for selecting the optimum structural system for multi-story steel buildings, El-Aghoury et al. [21] for obtaining the optimum cross-section dimensions of composite steel beams under static loads, Mahdi et al. [22] for identifying the optimum retaining wall type for restricted highway project sites, and El-Aghoury et al. [23] to select the optimum steel portal frame. Moreover, Özceylan [24] discussed choosing an optimal transportation mode by integrating an AHP-based model evaluated for logistics activities; additionally, Grażyna and Izabela utilized cycle development software models as conceivable alternatives [25].

2. Aim and originality of the study

As previously discussed, recent research should emphasis optimization of realistic and large structures to enhance use of optimization techniques in structural design practice. The purpose of this research is to contribute to minimizing the gap between practice and theory by implementing optimization in practice. A decision support system is developed to find the optimum superstructure configuration for highway bridges to attain cost-effective construction. A decision support system with an optimization model of bridges was established to make the optimization beneficial, as the developed DSS contributes to potential cost savings by selecting the optimum superstructure configuration of bridges. On the other hand, conventional preliminary design provides indeterminate information on the optimum material distribution for decks, where most of the structural mass is located.

The proposed DSS is developed to determine the optimum superstructure configuration for highway bridges, considering direct cost, construction time, and total cost. Simple and continuous spans are considered in the longitudinal direction, while open and closed sections in the transverse direction. Different construction materials are deliberated through the proposed DSS, such as reinforced concrete, pre-stressed concrete, steel sections, and composite sections, to achieve a wide diversity of alternatives. The developed DSS was illustrated graphically as a map for the optimum superstructure configuration for certain span and span to depth ratio combinations, considering the current market conditions in Egypt, and then verified using collected case studies.

3. The different considered superstructure configurations

In order to achieve full and comprehensive optimization plan, the superstructure of bridges is deliberated from several aspects as illustrated in this section:

3.1. *Girder type*

The superstructure carries loads from the deck across the span and to the bridge supports. The superstructure is the element that supports the deck and the loads applied to it. There are many types of superstructure girders considering transverse direction: single web beams/girders (I beams), box beams/girders (multi-web). And considering longitudinal direction: beams, trusses, arches, rigid frames, cable-supported bridges, and suspension bridges [26,27]. As mentioned previously and as per the literature, the most common


a) Cast in situ RC beams b) Pre-cast PT beams


c) Cast in situ RC box section d) Pre-cast PT box section


e) Continuous steel plate girder f) Simply support steel plate girder


g) Continuous steel truss h) Simply support steel truss

Fig. 1. Most common superstructure systems for highway bridges: a) Cast in situ RC beams, b) Pre-cast PT beams, c) Cast in situ RC box section, d) Pre-cast PT box section, e) Continuous steel plate girder, f) Simply support steel plate girder, g) Continuous steel truss, and h) Simply support steel truss.

types are considered in this paper [28,29].

3.2. Girder continuity

Bridge spans can be classified into simply supported and continuous spans. Creating continuity in the superstructure of bridges was embraced by engineering communities all over the world, as continuous superstructures develop redundancy for critical conditions like vehicular impacts, overload conditions, earthquakes, storms, and blasts. Moreover, it enhances the durability of the bridge by eliminating joints at the ends. Structural efficiency is improved as well by having greater spacing and longer spans [30]. There are specific cases for designing a simply supported bridge, like having spans that are unavoidably different in depth, length, and geometries. Simply supported bridges are also utilized when it is an interchange, or at short crossings, or at locations where uneven settlements are likely to occur [31]. Fig. 1 shows photos of the most common superstructure systems for highway bridges, as follows: 1a) Cast in situ RC beams, 1b) Pre-cast PT beams, 1c) Cast in situ RC box section, 1d) Pre-cast PT box section, 1e) Continuous steel plate girder, 1f) Simply support steel plate girder, 1g) Continuous steel truss, and 1h) Simply support steel truss.

3.3. Construction materials

Construction materials play an essential role in creating optimized DSS for any structure. They have a direct influence on the direct and total costs of projects and on the construction schedules as well. In pre-stressed concrete, improved material strengths, more efficient shapes, the pre-stress forces, and closely controlled manufacturing allow them to withstand heavier loads. They are also capable of spanning greater distances and supporting heavier live loads. Bridges using pre-stressed concrete have been widely used in the United States since World War II. Pre-stressed concrete is generally more economical than traditional reinforced concrete because the pre-stressing force lowers the neutral axis, putting more of the concrete section into compression. Also, the pre-stress steel has superior strength, so fewer pounds of steel are needed [32]. Steel sections are also able to carry heavier loads and better withstand the vibration and shock of ever-increasing live loads [33]. Eventually, to mention a few advantages of utilizing composite sections in bridges, they are decreasing the steel consumption, increasing rigidity in horizontal and vertical planes, and reducing the needed scaffolding, which aids in minimizing the total cost and construction time [34]. Reinforced concrete, pre-stressed concrete, steel sections, and composite sections are included in this paper. Fig. 2 presents the commonly used materials in superstructure systems for highway bridges, as follows: 2a) Cast in situ concrete, 2b) Pre-cast pre-stressed, 2c) Steel girder, and 2d) Composite girder.

4. Methodology

The research methodology was divided into four phases: collecting data from the literature, designing several configurations of the superstructure, developing the decision support system using the outputs of the previous stages, and mapping the optimum


a) Cast in situ concrete
b) Pre-cast pre-stressed
c) Steel girder
d) Composite girder

Fig. 2. Commonly used materials in superstructure systems for highway bridges: a) Cast in situ concrete, b) Pre-cast pre-stressed, c) Steel girder, and d) Composite girder.

superstructure configuration for each case. Eventually, verifying the developed maps using actual case studies. Each stage is discussed in detail in the following sections.

4.1. Phase 1

The methodology used began with determining the most common alternatives for the superstructure system of the highway bridge. This study considered four aspects of configuring the superstructure of bridges, as follows:

- Type (girders, box section, truss)
- Continuity (simple, continuous)
- Material (concrete, pre-stressed concrete, steel, composite)
- Construction method (cast in situ, precast)

The valid combinations of these four aspects are 24 alternatives as listed below:

1) Simple-RC-Beam-In situ
2) Continuous -RC-Beam-In situ
3) Simple-RC-Beam-Pre cast
4) Continuous -RC-Beam-Pre cast
5) Simple-PT-Beam-In situ
6) Continuous -PT-Beam-In situ
7) Simple-PT-Beam-Pre cast
8) Continuous -PT-Beam-Pre cast
9) Simple-RC-Box-In situ
10) Continuous -RC-Box-In situ
11) Simple-RC-Box-Pre cast
12) Continuous -RC-Box-Pre cast
13) Simple-PT-Box-In situ
14) Continuous -PT-Box-In situ
15) Simple-PT-Box-Pre cast
16) Continuous -PT-Box-Pre cast
17) Simple-Steel-Beam
18) Continuous -Steel-Beam
19) Simple-Composite-Beam
20) Continuous -Composite-Beam
21) Simple-Steel-Truss
22) Continuous -Steel-Truss
23) Simple-Composite-Truss
24) Continuous -Composite-Truss

The next step was to determine the boundaries of the study. The considered span range was 15–100 m. As per literature, below 15 m, slab-type bridges are dominating and above 100 m is the zone of cable-stayed bridges. On the other hand, the boundaries of the span/depth ratio were selected within the common range of 10–40. The considered (span-span/depth) space was divided into 18 values for (span) and 7 values for (span/depth). The combinations with a depth less than 0.6 m were neglected due to deflection limitations; hence, the considered (span-span/depth) space contains only 120 combinations.

4.2. Phase −2

The main riddle in the study was to design the 2880 cases (120 combinations x 24 alternatives = 2880 cases). It was conducted using the well-known CSI-BRIDGES software [35]. Its pre-defined parametric modelling module was extremely helpful and saved a lot of time and effort.

Certain design parameters were kept constant in all models, including material properties, loading values, and combinations, and deck dimensions were as follows:

- Material Proprieties:

Concrete compressive strength	(fcu)	= 35	MPa	(fc' = 28 MPa)
Reinforcement bars yield stress	(fy)	= 400	MPa	
Post tension cables yield stress	(fy)	= 1395	MPa	(0.75 fu)
Steel sections yield stress	(fy)	= 360	MPa	

- Load values and combinations:
  - o All dead, live (including impact, breaking forces), wind, seismic, temperature loads and corresponding load combinations were automatically generated and assigned by CSI-BRIDGES according to AASHTO design code [36].
- Deck dimensions
  - o Total width of bridge (W) = 20 m
  - o Spacing between longitudinal elements (S):
    - Girders = 2.5 m
    - Box webs = 5.0 m
    - Trusses = 10.0 m

o RC deck slab thickness (ts):

For girders	= 0.25	m	(S = 2.5 m)
For box section	= 0.35	m	(S = 5.0 m, top and bottom slabs)
For trusses	= 0.25	m	(Secondary beams @2.5 m)

Valid alternatives must satisfy the serviceability limits; accordingly, any alternative with deflection greater than span/600 under live load was eliminated, considering that any deflection due to dead loads will be compensated by pre-cambering.

4.3. Phase −3

The next step was to survey the quantities of each model and calculate their direct costs, construction durations, and hence their total costs. The calculations considered the average unit price and productivity of each item based on the current Egyptian market (Nov. 2022), as listed in Table 1. Extra time periods were considered for some activities such as concrete curing, P.T. duct grouting, and grouting below bearing pads. The indirect cost depends on the size of the contracting company and its overheads; in this study, an average value of 50 000 LE/day was considered.

4.4. Phase −4

Finally, three optimum choices were selected for each (span, span/depth) combination; the first considered only the direct cost, and the second considered only the construction time, while the third considered the total cost (cost and time impact). The selected choices for each case were arranged in the (span, span/depth) space to form a map for the optimum alternatives. The next section presents and discusses these outputs.

5. Results and discussions

The outputs of the three considered cases (direct cost, construction time, and total cost) are presented in Figs. 3–5, respectively. Each figure contains a mapping for the optimum structural system and its corresponding cost and construction time, as follows: a) Optimum System, b) Total Cost, c) Construction Time, and d) Total Cost/m^2.

As shown in Fig. 3a, b, 3c, and 3d, the optimum structural system considering only the direct cost is dominated by RC cast in situ beams for short and deep spans (Alt. 2, 4). With increasing the span and reducing the depth, the optimum choice is shifted to continuous PT beams (Alt. 6, 8). For shallower or longer spans, continuous PT box sections (Alt. 14, 16) became cheaper. Finally, continuous steel beams (Alt. 18, 20) are the right choice for very compacted spans ($L/D > 35$), while steel trusses (Alt. 22, 23) are the optimum choice for deep and medium spans longer than 50 m.

The values in the direct cost map are smoothly increased from 1.0 million LE at the upper left corner (deep short spans) to 64.0 million LE at the lower right corner (compacted long spans). Construction time also increased in the same direction, but with some roughness (scattered pattern) because it was not the considered factor in mapping the alternatives.

Fig. 4a, b, 4c, and 4d illustrate the optimum structural system, considering only the construction time. The optimum alternative map indicated a reduction in both the RC and PT systems (beams and box sections). Steel systems became dominant alternatives due to their fast manufacturing and erection processes, regardless of their cost. Also, it could be noted that the area of steel beams was enlarged while the area of the steel trusses was reduced because constructing the steel trusses is much slower than the steel plate girders, especially with the advances in automatic welding technology. On the opposite of the previous case, the smooth increase here is in construction time as it is the criterion considered, while the scattered pattern is shown in the cost.

Eventually, Fig. 5a, b, 5c, and 5d present the outputs, considering the total cost. It shows a mid-point choice between the two previous cases because it considered both cost and time impact. For deep short spans, concert beams (RC and PT) were selected to satisfy cost, and pre-cast was selected to satisfy construction time. Beyond this zone, the impact of construction time was insignificant, and hence, the choices almost matched the ones in Fig. 3 (considering direct cost).

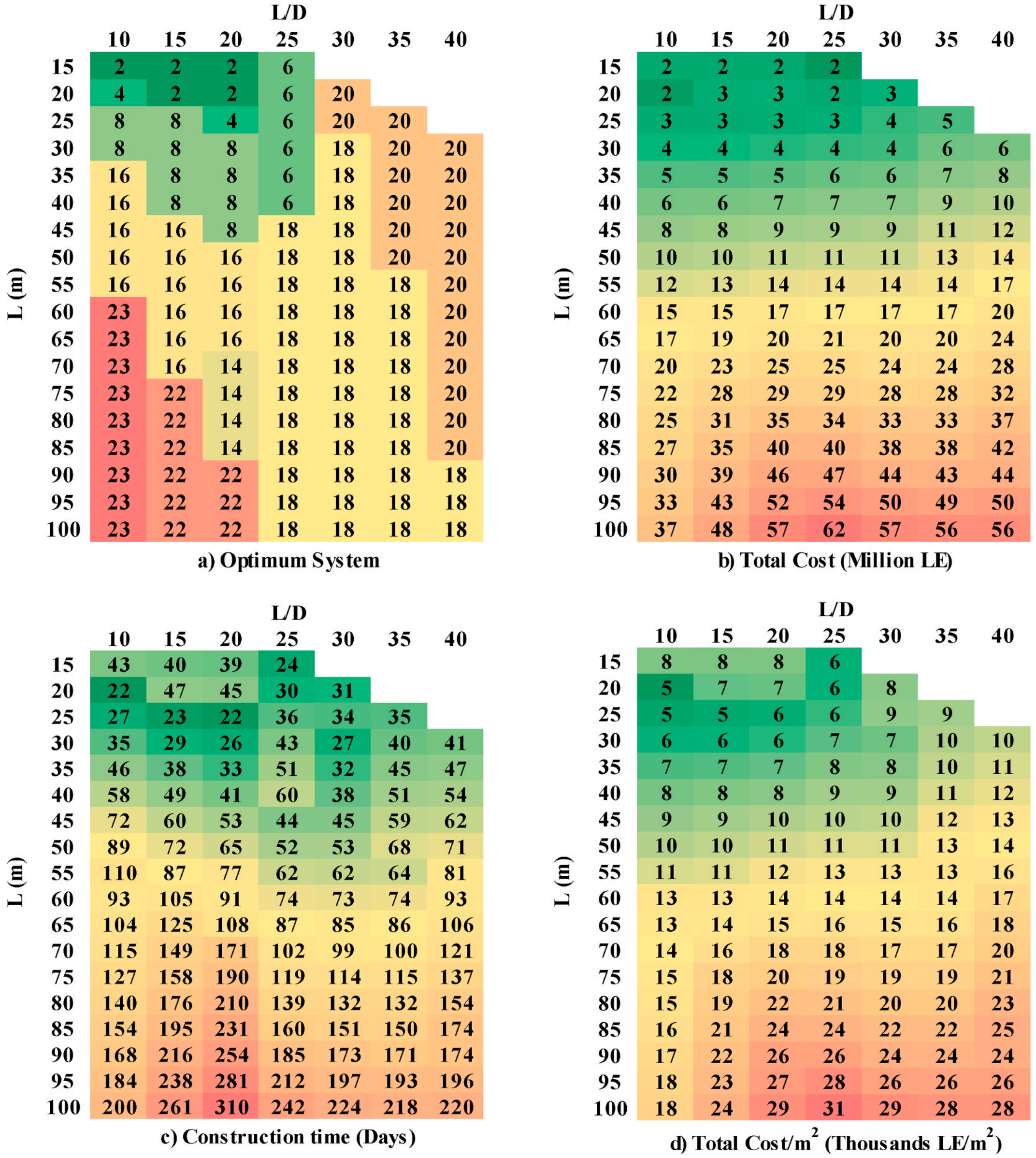
As expected, the cost smoothly increased from the deep short spans to the long-compacted spans, while the construction time suffered some scattering in the transition zone between steel trusses and steel beams because this zone was dominated by cost.

In previous research conducted by Bakhoum et al. [29], the authors collected data on 46 bridges over the Nile in Egypt. It was found

Table 1
Considered average unit prices and productivities.

Item	RC Vol.	RFT rebar weight	P.T. Cables weight	Steel sections weight[a]	Bearing Pads	Formwork area	Transport & Erection
Unit	m3	ton	ton	ton	Pad	m2	ton
Unit price (LE/Unit)	2000	20000	60000	30000	20000	500	1000
Productivity (Unit/day)	100	50	15	15	4	50	20

[a] Unit price of steel section in trusses was considered 1.5 times that for plate girders.



L (m) \ L/D	10	15	20	25	30	35	40
15	2	2	2	6			
20	4	2	2	6	20		
25	8	8	4	6	20	20	
30	8	8	8	6	18	20	20
35	16	8	8	6	18	20	20
40	16	8	8	6	18	20	20
45	16	16	8	18	18	20	20
50	16	16	16	18	18	20	20
55	16	16	16	18	18	18	20
60	23	16	16	18	18	18	20
65	23	16	16	18	18	18	20
70	23	16	14	18	18	18	20
75	23	22	14	18	18	18	20
80	23	22	14	18	18	18	20
85	23	22	14	18	18	18	20
90	23	22	22	18	18	18	18
95	23	22	22	18	18	18	18
100	23	22	22	18	18	18	18

a) Optimum System

L (m) \ L/D	10	15	20	25	30	35	40
15	2	2	2	2			
20	2	3	3	2	3		
25	3	3	3	3	4	5	
30	4	4	4	4	4	6	6
35	5	5	5	6	6	7	8
40	6	6	7	7	7	9	10
45	8	8	9	9	9	11	12
50	10	10	11	11	11	13	14
55	12	13	14	14	14	14	17
60	15	15	17	17	17	17	20
65	17	19	20	21	20	20	24
70	20	23	25	25	24	24	28
75	22	28	29	29	28	28	32
80	25	31	35	34	33	33	37
85	27	35	40	40	38	38	42
90	30	39	46	47	44	43	44
95	33	43	52	54	50	49	50
100	37	48	57	62	57	56	56

b) Total Cost (Million LE)

L (m) \ L/D	10	15	20	25	30	35	40
15	43	40	39	24			
20	22	47	45	30	31		
25	27	23	22	36	34	35	
30	35	29	26	43	27	40	41
35	46	38	33	51	32	45	47
40	58	49	41	60	38	51	54
45	72	60	53	44	45	59	62
50	89	72	65	52	53	68	71
55	110	87	77	62	62	64	81
60	93	105	91	74	73	74	93
65	104	125	108	87	85	86	106
70	115	149	171	102	99	100	121
75	127	158	190	119	114	115	137
80	140	176	210	139	132	132	154
85	154	195	231	160	151	150	174
90	168	216	254	185	173	171	174
95	184	238	281	212	197	193	196
100	200	261	310	242	224	218	220

c) Construction time (Days)

L (m) \ L/D	10	15	20	25	30	35	40
15	8	8	8	6			
20	5	7	7	6	8		
25	5	5	6	6	9	9	
30	6	6	6	7	7	10	10
35	7	7	7	8	8	10	11
40	8	8	8	9	9	11	12
45	9	9	10	10	10	12	13
50	10	10	11	11	11	13	14
55	11	11	12	13	13	13	16
60	13	13	14	14	14	14	17
65	13	14	15	16	15	16	18
70	14	16	18	18	17	17	20
75	15	18	20	19	19	19	21
80	15	19	22	21	20	20	23
85	16	21	24	24	22	22	25
90	17	22	26	26	24	24	24
95	18	23	27	28	26	26	26
100	18	24	29	31	29	28	28

d) Total Cost/m^2 (Thousands LE/m^2)

Fig. 3. Outputs considering only direct cost: a) Optimum System, b) Total Cost, c) Construction Time, and d) Total Cost/m.^{2}.

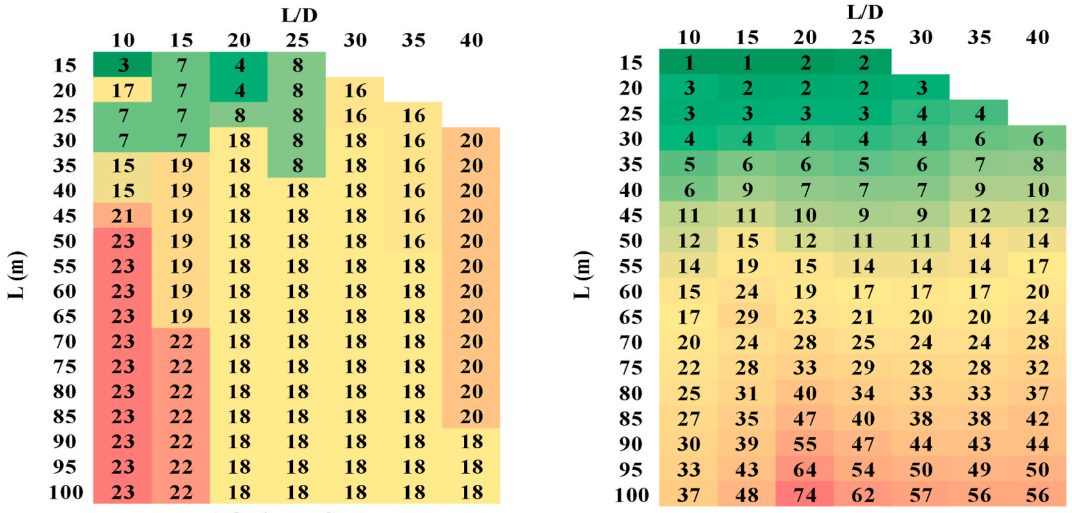
that steel trusses were constructed for spans ranging from 40 to 85 m, steel beam bridges for spans of about 20 m, prestressed concrete bridges from 52 to 100 m, and reinforced concrete bridges from 60 to 90 m. This is so close to the results obtained in Fig. 5.

In another study by Morcous et al. [37], the authors reported that box girder bridges with a fully pre-stressed superstructure were convenient for long spans, while I-shape fully pre-stressed girders were for medium spans. This was relatively reasonable, as the authors only considered fully pre-stressed superstructures. Fragkakis et al. [38] also assured that for bridges with long spans, precast box girder bridges were dominant.

Consequently, the optimum superstructures obtained in Fig. 5 utilizing the developed model are very reasonable, especially after comparing them with the previously mentioned articles, keeping in mind that the developed model specifies the optimum superstructure configuration for each span considering different construction aspects as mentioned before.

6. Validation

In order to validate the results of this study, 19 case studies were collected for the superstructure of highway bridges under construction in Egypt. The actually used structural systems of the superstructures of these bridges were compared with the optimum ones from Figs. 3–5. This comparison is summarized in Table 2. For each case study, (span), (span/depth), (the actual system), (the

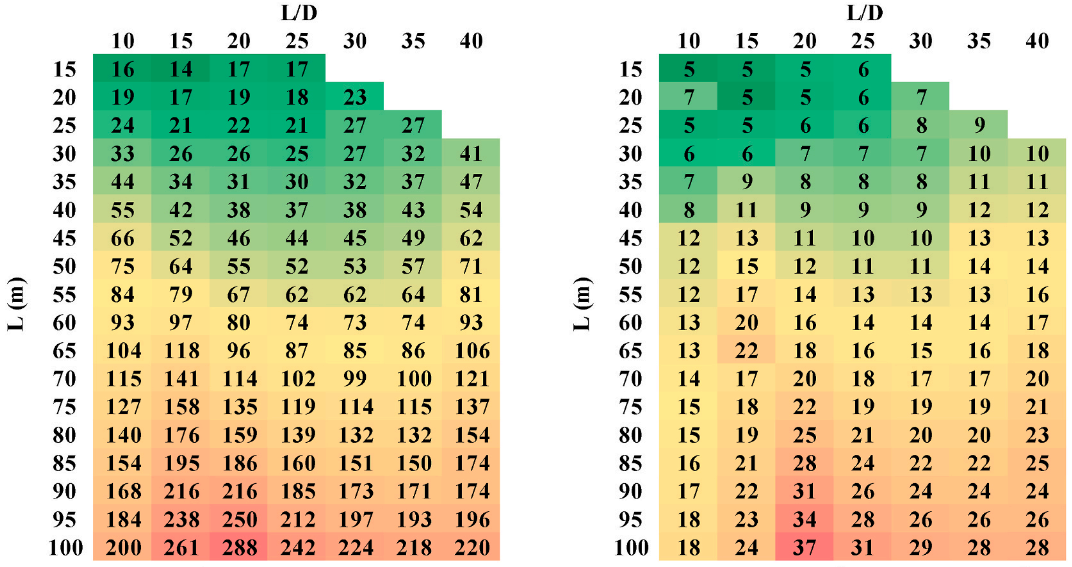


	L/D						
L (m)	10	15	20	25	30	35	40
15	3	7	4	8			
20	17	7	4	8	16		
25	7	7	8	8	16	16	
30	7	7	18	8	18	16	20
35	15	19	18	8	18	16	20
40	15	19	18	18	18	16	20
45	21	19	18	18	18	16	20
50	23	19	18	18	18	16	20
55	23	19	18	18	18	18	20
60	23	19	18	18	18	18	20
65	23	19	18	18	18	18	20
70	23	22	18	18	18	18	20
75	23	22	18	18	18	18	20
80	23	22	18	18	18	18	20
85	23	22	18	18	18	18	20
90	23	22	18	18	18	18	18
95	23	22	18	18	18	18	18
100	23	22	18	18	18	18	18

a) Optimum System

	L/D						
L (m)	10	15	20	25	30	35	40
15	1	1	2	2			
20	3	2	2	2	3		
25	3	3	3	3	4	4	
30	4	4	4	4	4	6	6
35	5	6	6	5	6	7	8
40	6	9	7	7	7	9	10
45	11	11	10	9	9	12	12
50	12	15	12	11	11	14	14
55	14	19	15	14	14	14	17
60	15	24	19	17	17	17	20
65	17	29	23	21	20	20	24
70	20	24	28	25	24	24	28
75	22	28	33	29	28	28	32
80	25	31	40	34	33	33	37
85	27	35	47	40	38	38	42
90	30	39	55	47	44	43	44
95	33	43	64	54	50	49	50
100	37	48	74	62	57	56	56

b) Total Cost (Million LE)



	L/D						
L (m)	10	15	20	25	30	35	40
15	16	14	17	17			
20	19	17	19	18	23		
25	24	21	22	21	27	27	
30	33	26	26	25	27	32	41
35	44	34	31	30	32	37	47
40	55	42	38	37	38	43	54
45	66	52	46	44	45	49	62
50	75	64	55	52	53	57	71
55	84	79	67	62	62	64	81
60	93	97	80	74	73	74	93
65	104	118	96	87	85	86	106
70	115	141	114	102	99	100	121
75	127	158	135	119	114	115	137
80	140	176	159	139	132	132	154
85	154	195	186	160	151	150	174
90	168	216	216	185	173	171	174
95	184	238	250	212	197	193	196
100	200	261	288	242	224	218	220

c) Construction time (Days)

	L/D						
L (m)	10	15	20	25	30	35	40
15	5	5	5	6			
20	7	5	5	6	7		
25	5	5	6	6	8	9	
30	6	6	7	7	7	10	10
35	7	9	8	8	8	11	11
40	8	11	9	9	9	12	12
45	12	13	11	10	10	13	13
50	12	15	12	11	11	14	14
55	12	17	14	13	13	13	16
60	13	20	16	14	14	14	17
65	13	22	18	16	15	16	18
70	14	17	20	18	17	17	20
75	15	18	22	19	19	19	21
80	15	19	25	21	20	20	23
85	16	21	28	24	22	22	25
90	17	22	31	26	24	24	24
95	18	23	34	28	26	26	26
100	18	24	37	31	29	28	28

d) Total Cost/m^2 (Thousands LE/m^2)

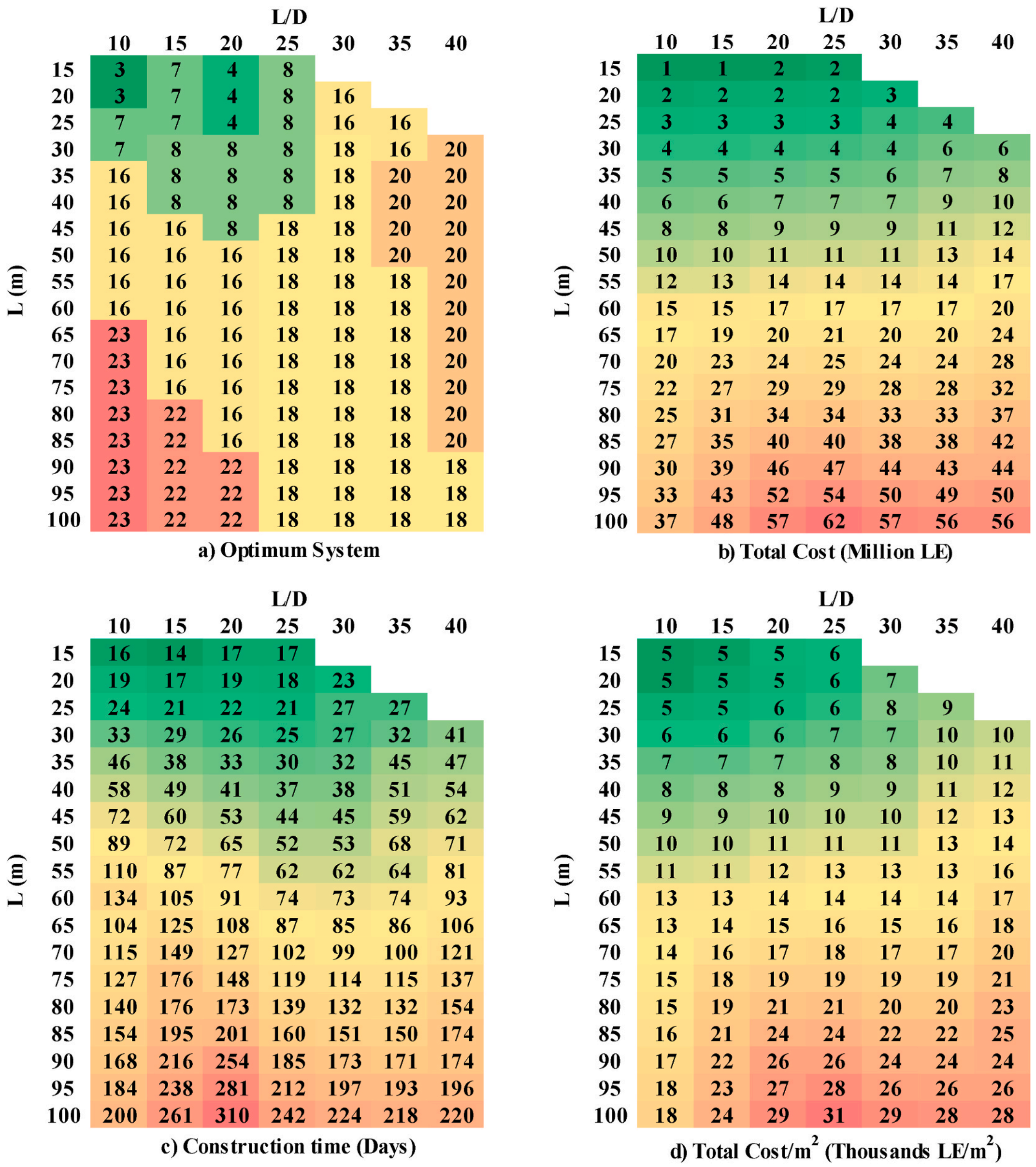
Fig. 4. Outputs considering only construction time: a) Optimum System, b) Total Cost, c) Construction Time, and d) Total Cost/m.^{2}.

optimum system considering only construction time), (the optimum system considering only direct cost), and (the optimum system considering total cost) are listed. The matched systems are shaded in the table. The distribution of these 19 case studies in the (span, span/depth) space is graphically presented in Fig. 7, while Fig. 6 presents the locations of these case studies.

After studying and evaluating the 19 case studies, 8 cases (42%) properly matched the first DSS (only direct cost), 17 cases (90%) properly matched the second DSS (only construction time), and 12 cases (62%) properly matched the third DSS (total cost). This obviously indicated that priority in current highway bridge projects in Egypt is for construction time, which matches the observed boom in fast-track highway projects and to serve the prompt construction schedules in the last decade in Egypt.

6. Conclusions

This study aimed to develop a decision support system to help developers and designers select the optimum structural system for the superstructure of highway bridges. 24 different superstructure configurations were considered in this study, including all different combinations of materials (RC, PT, steel, and composite), girder types (beams, box, and trusses), continuities (simply supported and continuous), and construction techniques (cast in situ and pre-cast). Three versions of the decision support system were developed, the first considering only the direct cost, the second considering only the construction time, and the third considering the impact of both cost and time presented by the total cost. The accuracy of the three decision support systems was verified using 19 collected case



	L/D						
L (m)	10	15	20	25	30	35	40
15	3	7	4	8			
20	3	7	4	8	16		
25	7	7	4	8	16	16	
30	7	8	8	8	18	16	20
35	16	8	8	8	18	20	20
40	16	8	8	8	18	20	20
45	16	16	8	18	18	20	20
50	16	16	16	18	18	20	20
55	16	16	16	18	18	18	20
60	16	16	16	18	18	18	20
65	23	16	16	18	18	18	20
70	23	16	16	18	18	18	20
75	23	16	16	18	18	18	20
80	23	22	16	18	18	18	20
85	23	22	16	18	18	18	20
90	23	22	22	18	18	18	18
95	23	22	22	18	18	18	18
100	23	22	22	18	18	18	18

a) Optimum System

	L/D						
L (m)	10	15	20	25	30	35	40
15	1	1	2	2			
20	2	2	2	2	3		
25	3	3	3	3	4	4	
30	4	4	4	4	4	6	6
35	5	5	5	5	6	7	8
40	6	6	7	7	7	9	10
45	8	8	9	9	9	11	12
50	10	10	11	11	11	13	14
55	12	13	14	14	14	14	17
60	15	15	17	17	17	17	20
65	17	19	20	21	20	20	24
70	20	23	24	25	24	24	28
75	22	27	29	29	28	28	32
80	25	31	34	34	33	33	37
85	27	35	40	40	38	38	42
90	30	39	46	47	44	43	44
95	33	43	52	54	50	49	50
100	37	48	57	62	57	56	56

b) Total Cost (Million LE)

	L/D						
L (m)	10	15	20	25	30	35	40
15	16	14	17	17			
20	19	17	19	18	23		
25	24	21	22	21	27	27	
30	33	29	26	25	27	32	41
35	46	38	33	30	32	45	47
40	58	49	41	37	38	51	54
45	72	60	53	44	45	59	62
50	89	72	65	52	53	68	71
55	110	87	77	62	62	64	81
60	134	105	91	74	73	74	93
65	104	125	108	87	85	86	106
70	115	149	127	102	99	100	121
75	127	176	148	119	114	115	137
80	140	176	173	139	132	132	154
85	154	195	201	160	151	150	174
90	168	216	254	185	173	171	174
95	184	238	281	212	197	193	196
100	200	261	310	242	224	218	220

c) Construction time (Days)

	L/D						
L (m)	10	15	20	25	30	35	40
15	5	5	5	6			
20	5	5	5	6	7		
25	5	5	6	6	8	9	
30	6	6	6	7	7	10	10
35	7	7	7	8	8	10	11
40	8	8	8	9	9	11	12
45	9	9	10	10	10	12	13
50	10	10	11	11	11	13	14
55	11	11	12	13	13	13	16
60	13	13	14	14	14	14	17
65	13	14	15	16	15	16	18
70	14	16	17	18	17	17	20
75	15	18	19	19	19	19	21
80	15	19	21	21	20	20	23
85	16	21	24	24	22	22	25
90	17	22	26	26	24	24	24
95	18	23	27	28	26	26	26
100	18	24	29	31	29	28	28

d) Total Cost/m^2 (Thousands LE/m^2)

Fig. 5. Outputs considering total cost: a) Optimum System, b) Total Cost, c) Construction Time, and d) Total Cost/m.^{2}.

studies. The outcomes of this research could be concluded from the following points:

- RC and PT beams dominate the short, deep spans (upper left corner of the (span, span/depth) space) up to a span of about 40 m and a span/depth of about 25. While the steel trusses dominate the long, deep spans (lower left corner of the (span, span/depth) space) for spans longer than 60 m and (span/depth) below 20. Concrete box sections (RC or PT) occupy the middle zone between concrete beams and steel trusses (medium-deep spans). Steel beams dominate the medium-depth spans, with span/depth between 25 and 30 for medium-length spans, and 25 to 35 for long spans. Finally, composite beams dominate the very compacted spans, with a span/depth of more than 35.
- Concrete zones (RC, PT, beams, and box) expanded at the expense of steel beams and trusses when only direct costs were considered. Conversely, the steel beam zone expanded at the expense of concrete and steel truss zones when only construction time was considered. A more balanced distribution occurs when the total cost is considered.
- Among the 19 case studies, 42% correctly matched the first DSS (only direct cost), 90% correctly matched the second DSS (only construction time), and 62% correctly matched the third DSS (total cost). This clearly indicated that priority in current highway

Table 2
Comparison between actual and optimized systems.

Location	Bridge	Span (m)	Span. Depth	Actual system	Optimized system		
					Direct cost	Time	Total cost
Regional Ring Road	Bahr Shaben	25	14	**7**	8	**7**	**7**
	El-Atf	10	10	**3**	2	**3**	**3**
		30	15	**8**	**8**	7	**8**
	Bagoria	13	22	**4**	2	**4**	**4**
	26th July	80	9	**23**	**23**	**23**	**23**
	El-Marg	71	25	**18**	**18**	**18**	**18**
Samlout	Bridge 3	40	16	**16**	8	19	**16**
	Bridge 4	33	15	**8**	**8**	19	**8**
	Bay (A4-A5)	37	22	**18**	6	**18**	8
Quos	Bridge 4	45	16	**19**	16	**19**	16
	Bridge 5	35	18	**18**	8	**18**	8
	Bridge 6	38	19	**18**	8	**18**	8
Shenwan	Bay (1–2)	37	28	**18**	**18**	**18**	**18**
Hawaber	Bay (A1 - P1)	50	20	**18**	16	**18**	16
Malawi	Bridge 2	45	18	**18**	8	**18**	8
	Bridge 10	31	20	**18**	8	**18**	8
Moise	Bay (A4-A5)	45	28	**18**	**18**	**18**	**18**
	Bay (A6-A7)	60	25	**18**	**18**	**18**	**18**
Berty	Bay (P04–P05)	55	35	**18**	**18**	**18**	**18**

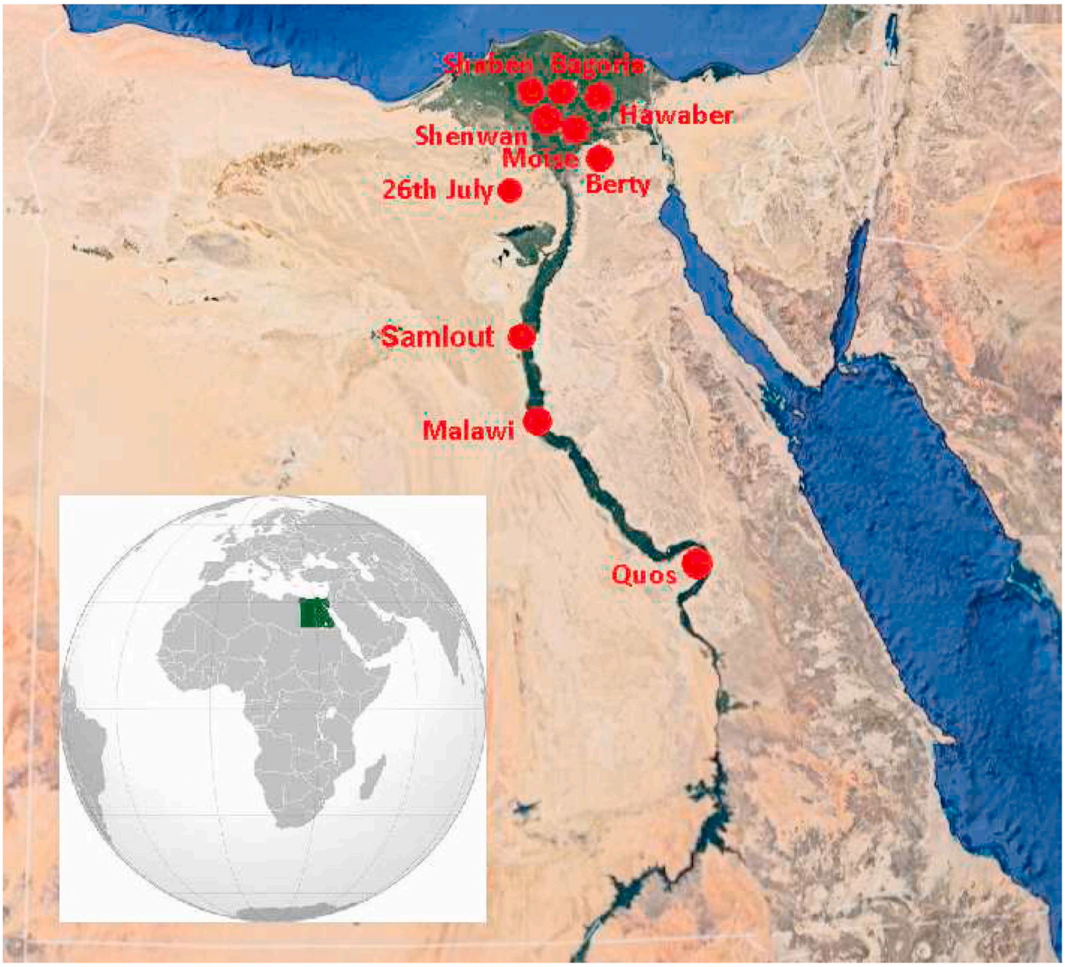
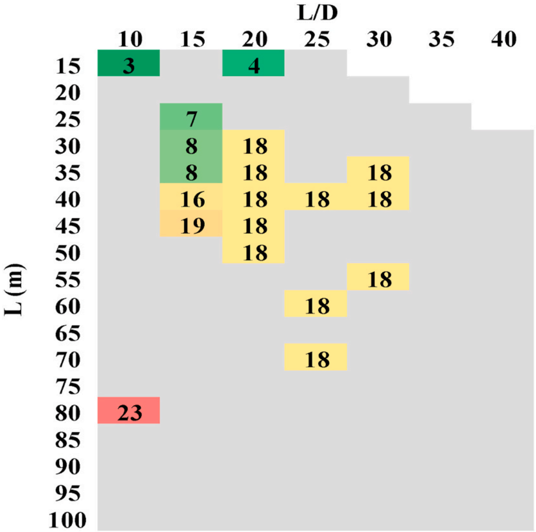


Fig. 6. Locations of the collected case studies.



L (m) \ L/D	10	15	20	25	30	35	40
15	3		4				
20							
25		7					
30		8	18				
35		8	18		18		
40		16	18	18	18		
45		19	18				
50			18				
55					18		
60				18			
65							
70				18			
75							
80	23						
85							
90							
95							
100							

Fig. 7. The actually used systems in the collected case studies.

bridge projects in Egypt is for construction time, which matches the observed boom in fast-track highway projects in the last decade in Egypt.

Based on these conclusions, the following recommendations are proposed:

- Extending the scope of the proposed DSS to include an assessment of the environmental impact of the selected superstructure configurations. Considering parameters such as energy consumption and lifecycle analysis to promote sustainable bridge design practices and contribute to environmental conservation efforts.
- Expanding the case studies beyond the Egyptian context and considering bridge projects from different regions with varying environmental, economic, and social conditions. This broader analysis will help validate the applicability and effectiveness of the DSS in diverse settings and facilitate its adoption in international bridge design practices.
- Upgrading the developed DSS to incorporate multi-criteria decision-making techniques, considering not only cost and time but also other important parameters such as sustainability, aesthetics, constructability, and community impact. This will enable a more comprehensive evaluation of superstructure configurations and support decision-making processes that align with broader project objectives.
- Integration of the developed DSS with BIM technology to enable more efficient and accurate data exchange, visualization, and collaboration among project stakeholders. This integration can enhance the overall efficiency and effectiveness of bridge design processes.

Data availability statement

Data associated with this study is not deposited into a publicly available repository as all data, models, and code generated or used during the study is proposed in the submitted article.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Dina M. Mansour: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Ahmed M. Ebid:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ibrahim M. Mahdi:** Writing – review & editing, Writing – original draft, Conceptualization. **Hisham A. Mahdi:** Writing – review & editing, Writing – original draft, Validation, Resources, Conceptualization. **Anwar F. Elkadi:** Writing – review & editing, Validation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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