Automated Mathematical-Based Design Framework for The Selection of Rigging Configuration

S.M.A.M Hashemi[a], S. Han[a], J. Olearczyk[b], A. Bouferguene[b], M. Al-Hussein[b], J. Kosa[c]

[a]Department of Building, Civil and Environmental Engineering, Concordia University, Canada
[b]Department of Civil and Environmental Engineering, University of Alberta, Canada
[c]NCSG Engineering Ltd., Canada
E-mail: seyedmohammadamin.minayhashemi@mail.concordia.ca, sanghyeok.han@concordia.ca, jaceko@ualberta.ca, ahmed.bouferguene@ualberta.ca, malhussein@ualberta.ca, joe.kosa@ncsg.com

Abstract –

Modularization in construction involves erection of large and heavy prefabricated modules at the job site. Modules, especially in industrial plants, are required to be lifted without any tilted angles vertically and horizontally to prevent applying bending moments to the lifting lugs and structural components. Configuration of rigging elements, which are the link between the crane hook and the module, plays a vital role in the load distribution to the rigging components. In practice, designing a rigging assembly to ensure safe and successful lifts is a time-consuming and tedious process relying heavily on guesswork, especially when the module's center of gravity is offset. In addition, the pitch angle of the module remains unknown until it is lifted, thus raising safety issues regarding the failure of rigging components. To overcome these limitations, this paper proposes a mathematical-based design framework which consists of: (1) collecting the module information; (2) designing a preliminary configuration by selecting the rigging components from the database; (3) Optimizing the number, size and capacity of the rigging components selected for the preliminary configuration in order to ensure that positions of module and spreader bars are set on parallel lines without tilted angles; and (4) reporting the list of used rigging components and visualizing their configuration as the output. To validate this framework, this paper uses a case study which designs the optimal rigging configuration for a 4-point pick module based on the inventory availability.

Keywords –

Crane rigging; Automation; Center of gravity offset

1 Introduction

Modularization is a growing trend in construction thanks to its efficiency in terms of time and cost. In industrial plants, the off-site constructed modules can typically be classified as pipe racks, cable trays and building modules [1]. These modules may have up to 16 lifting points. Once transported to the job site, the modules are lifted from the pick points to their set points. In order to prevent applying bending moments to the lifting lugs and structural components of the module, the modules are required to be lifted vertically and maintained in a horizontal position during the lift. Slinging arrangement of the rigging assembly determines how the load is distributed from the lifting lugs of the module to the crane's hook.

Anderson [2] enumerated three possible slinging arrangements of 4-point pick modules as they are shown in Figure 1.

In Figure 1-a, 4 shackles and 4 slings are used to transfer the load directly from the lifting lugs to the crane's hook. The alignment of the lifting lugs is important in this configuration. Each of them must be in plane towards the COG. Otherwise, according to the supplier's manual, a reduction in the capacity of the shackles might be needed based on the angle the shackles make with the slings to which they are attached [3]. It is recommended to design the lifting lugs, shackles, and slings in a way that two of them are able to carry the entire load due to possible differences in the angles between the slings and horizon when the COG is offset [2]. Sam [4], presented a spreadsheet to analyze and calculate the sling loads for this slinging arrangement with consideration of the variations in the COG location. Similar rigging configuration is used when the object is lifted from the bottom with vertical slings used to transfer the lifting points above the object. However, lifting from the bottom has the risk of instability especially when the object's COG is too high. Longman and Freudenstein [5] suggested an analytical necessary and sufficient criterion for Liapunov stability or asymptotic stability for the 4-point pick lift from below the load's COG. They defined an expression for the margin of stability in which the disturbance forces caused by crane hook motion during the lift can be tolerated.

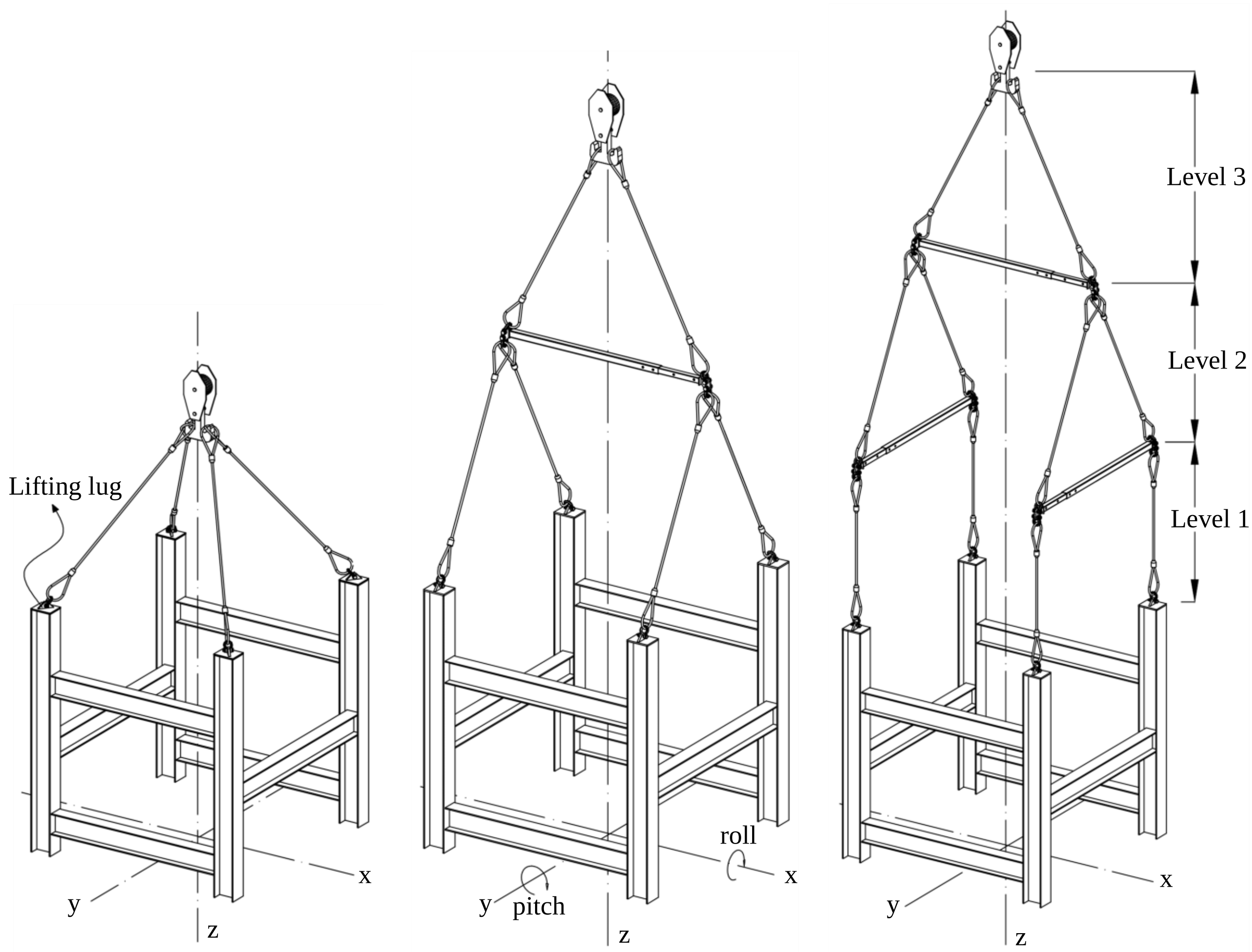

Figure 1-a Figure 1-b Figure 1-c

Figure 1. Three different slinging arrangements for a 4-poit pick module

In Figure 1-b, 8 shackles, 6 slings, and a spreader bar are used to first transfer the load from the lifting lugs to the spreader bar and from there to the crane's hook. The lifting lugs orientation needs to be along the y-axis of the module. In order to level up the module, the length of slings needs to be adjusted when the COG is offset. Regardless of the length of slings below the spreader bar, all of the slings will take the load [2].

In Figure 1-c, 16 shackles, 10 slings and 3 spreader bars are rigged in three levels. At the first level, the load is transferred vertically from the lifting lugs to two spreader bars along the y-axis of the module. From the second level to the crane's hook is virtually the same as Figure 1-b. When the COG is offset, in order to prevent the module from rolling and pitching (rotating around the x and y-axis of the object) the length of slings needs to be adjusted at the second and third level respectively. Needless to say, among the aforementioned slinging arrangement the latter is the only one that can ensure a vertical lift.

Operating two cranes and manipulating the length of their hoist lines could also be proposed as a way to control the pitch angle of the lifted module. However, operating a single crane is associated with a lower risk in comparison with operating two cranes or more. Thus, the lifting process is commonly accomplished by a single-crane operation unless the module, like vessels, necessitates vertical orientation at the set point [6]. In other words, it is not justifiable to add another crane only to have better control of the angle of lifted object considering the higher cost and risk of using more than one crane. In this regard, Chen et al [7] suggested a numerical model for manipulating the pitch angle of twin-hoisted objects with one crane. In their model, they adjust the length of the hoist lines of the boom and auxiliary jib to reach to the required pitch angle for the object during the lift. However, this model cannot be used to prevent the lifted object from rolling. In addition, the available capacity of the crane becomes more limited when crane's auxiliary jib is used which is necessary for their model.

Designing the rigging assembly is a time-consuming and tedious process relying heavily on guesswork, especially when the COG is offset and sling length adjustment is required. When a module is not level after being lifted due to a wrong guess about the required sling length, the assembled rigging components need to be unrigged and adjusted again which leading to waste of time and decrease in productivity. In this respect, this paper presents a mathematical-based design framework which automates the design of the rigging assembly for 4-point pick modules. To ensure a vertical lift the third mentioned slinging arrangement is considered

2 Methodology

2.1 Overview

As it was mentioned earlier, if the Module's COG is offset in order to level up the module and spreader bars the length of slings needs to be adjusted at different levels of the rigging assembly. To compensate the offset toward y-axis of the module the two slings at the second level and on the opposite side of the COG are lengthened. Similarly, to compensate the offset toward x-axis of the module the sling at the third level and on the opposite side of the COG is lengthened. Lengthening the sling at the first level of rigging assembly is not desired since the spreader bars remain inclined.

As there are no slings with exact required lengths, the specified required length is made up using a standard sling and a number of shackles in chain. Each shackle has a specific inside length published in the supplier's manual. The question is: How many and what size of shackles should be used to reach the required amount of increase to the length of the slings. Added shackles have to meet the capacity requirement based on the sling they are attached to.

The research implements an automated design framework, written in C# language within Microsoft.Net framework. To find the angle of the forces acting upon the rigging components and also to find the required amount of increase to the length of slings, Wolfram Mathematica kernel is called within the code to solve a system of 12 nonlinear equations. Having the forces calculated, the framework selects the appropriate rigging elements from the Microsoft Excel database to which it is bound. The calculations are done in two perpendicular 2D planes of the rigging assembly (i.e. xz and yz).

As shown in Figure 2, the algorithm starts off by collecting the module information. In the next step, a preliminary rigging assembly is designed in which the module's COG is assumed to be at its center. Then by considering the COG offset and based on the calculations at the second and third level, the number, size, and capacity of the rigging components selected for the preliminary design are optimized to ensure that the module and spreader bars are maintained in a horizontal position during the lift. Finally, as the output, a list of used rigging components and the used percentage capacity of them, total height and weight of rigging assembly and the configuration figure in two 2D views is reported.

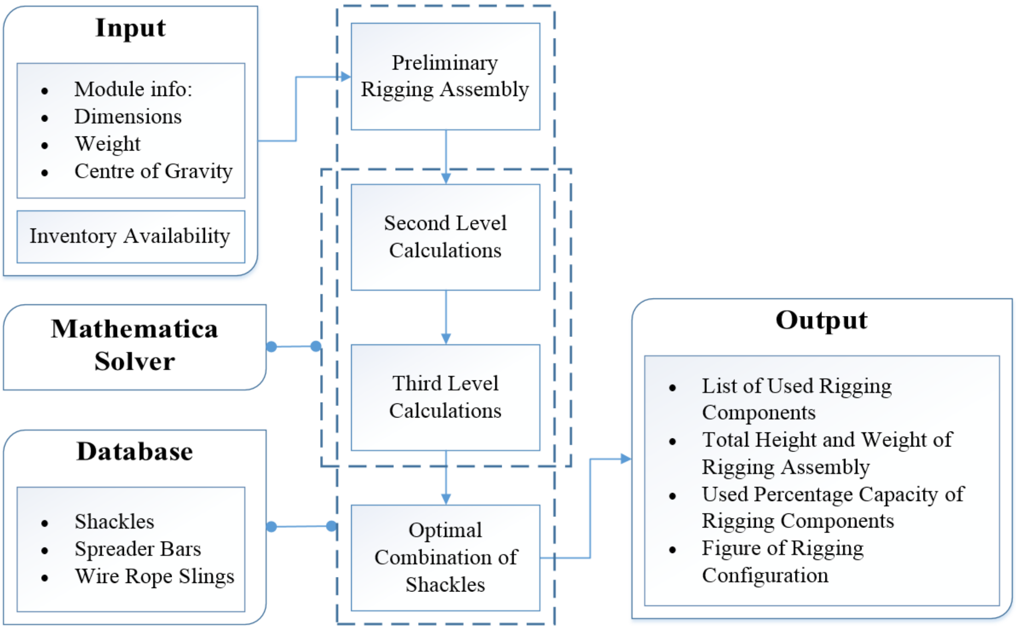

Figure 2. The framework algorithm

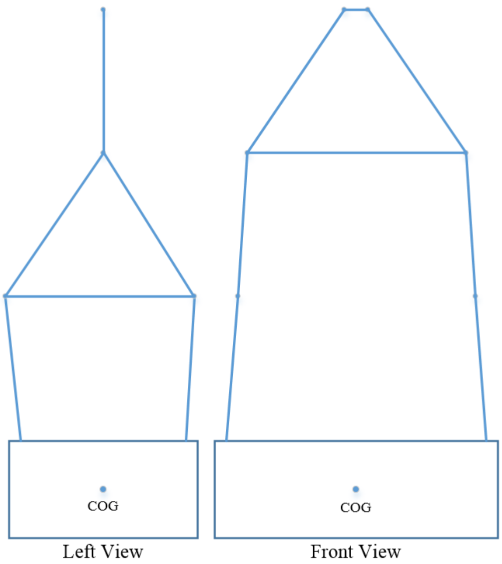

Figure 3. Left and front view of the rigging assembly for a 4-point pick module

2.2 Preliminary design

To design the preliminary rigging assembly, it is assumed that the module's COG is at its center. This will result in a symmetrical design in two perpendicular planes of the rigging configuration (Figure 3). The inclined lines in the figure represent the slings and the shackles they are attached to. The horizontal lines stand for the spreader bars except the top one in the front view which is the hook. Calculating the angles and in consequence, the forces acting upon the rigging components is straightforward due to the symmetrical configuration. Typically, the span of adjustable spreader bars has the intervals of one foot. Compared to the span of lifting lugs a shorter or longer spreader bar could be selected. This deviation in span will result in a non-vertical lift. In this case, the first four slings above the module, that are called drop slings, are lengthened to decrease their offset angle to the vertical line. The minimum acceptable offset angle is used as an input of the framework.

Based on the required capacity the minimum acceptable rated capacity is selected for each of the rigging components.

2.3 Second level calculations

The second level calculations are aimed at finding the angles between the slings and spreader bars and also calculating the required amount of increase to the slings when the COG offset is taken into consideration.

In either case shown in Figure 4, in order that the equilibrium conditions are satisfied the common point of inclined dashed red lines have to land on the vertical one. That is because the module's weight and the reaction force of the crane hoist lines to the hook is acting upon the vertical line; so the extensions of the inclined slings

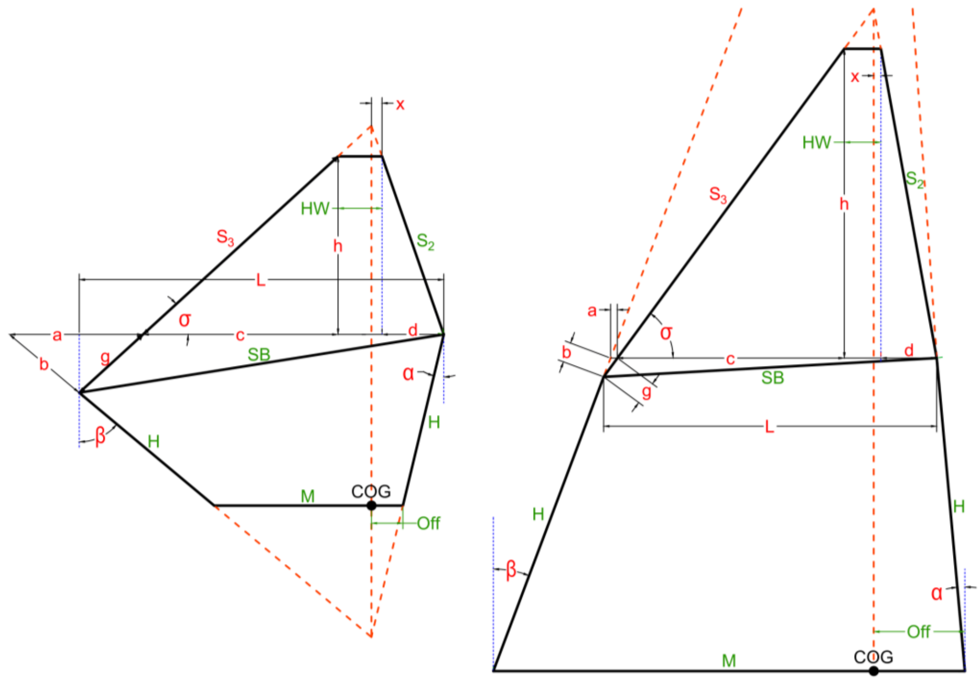

Figure 4. Schematic figure of rigging assembly when the spreader bar is longer (left figure) or shorter (right figure) than the distance between the lifting lugs

need to meet each other on the vertical line. To have a horizontal module, the spreader bar has a slight inevitable slope when the spreader bar and the module are unequal in length.

In Figure 4 (left) when the spreader bar is longer than the width of the module, there are 12 unknown variables, shown in red, which can be determined by solving a system of 12 nonlinear equations. The known and unknown variables are as follows:

Known variables: $\mathrm{HW}, M, \mathrm{Off}, \mathrm{SB}, \mathrm{S}_2, H$

HW: Width of the hook which is zero for the second level calculations.

M: Module width.

Off: The distance from the COG to the closer lifting lug in yz plane.

SB: Spreader bar length.

S_2: The total length of the sling and the shackles to which it is connected at the second level.

H: The total length of the drop sling and the shackles to which it is connected.

"HW", "ML" and "Off" are inputs of the framework. "SB", "S_2" and "H" are collected from the preliminary design.

Unknown variables: $x, \mathrm{S}_3, g, a, b, c, d, h, \alpha, \beta, \sigma, L$ as shown in Figure 4.

Where the equations are:

$$\mathrm{S_2}^2 = h^2 + d^2 \tag{1}$$
$$\mathrm{S_3}^2 = h^2 + c^2 \tag{2}$$
$$x/d = (\mathrm{HW} - x)/c \tag{3}$$
$$\mathrm{Off}/(H \operatorname{Sin} \alpha) = (\mathrm{M} - \mathrm{Off})/((H + b) \operatorname{Sin} \beta) \tag{4}$$
$$\mathrm{Off}/(x + d) = (\mathrm{M} - \mathrm{Off})/(a + c + \mathrm{HW} - x) \tag{5}$$
$$H \operatorname{Cos} \alpha = (H + b) \operatorname{Cos} \beta \tag{6}$$
$$b \operatorname{Cos} \beta = g \operatorname{Sin} \sigma \tag{7}$$
$$\mathrm{S}_3 \operatorname{Cos} \sigma = c \tag{8}$$
$$a = b \operatorname{Sin} \beta + g \operatorname{Cos} \sigma \tag{9}$$
$$L^2 + (g \operatorname{Sin} \sigma)^2 = \mathrm{SB}^2 \tag{10}$$
$$L = g \operatorname{Cos} \sigma + c + \mathrm{HW} + d \tag{11}$$
$$x + d = \mathrm{Off} + H \operatorname{Sin} \alpha \tag{12}$$

In Figure 4 (right), when the spreader bar is shorter than the width of the module equations 9 and 12 need to be replaced by the following two equations:

$$a + b \operatorname{Sin} \beta = g \operatorname{Cos} \sigma \tag{13}$$
$$x + d + H \operatorname{Sin} \alpha = \mathrm{Off} \tag{14}$$

And finally, when the length of spreader bar and the width of the module are the same, the value of a, b, g, α, β are equal to zero and S_3 is found using the following formula:

$$S_3 = \sqrt{\frac{(\mathrm{HW} - \mathrm{SB})^2(\mathrm{SB} - 2\mathrm{off}) + \mathrm{SB} \times S_2^2}{\mathrm{SB}}} \tag{15}$$

In any case, the required amount of increase (RAI) to the sling at the second level and on the opposite of the COG is equal to:

$$\mathrm{RAI} = \mathrm{S}_3 + g - \mathrm{S}_2 \tag{16}$$

That is, in fact, the difference between the length of two slings used above the spreader bar. In order to maintain the consistency at each level of the rigging configuration, identical slings are used and the required difference is made up by a chain of shackles.

After finding the unknown variables, the angles between the slings and spreader bars are calculated accordingly. Having the required capacity for each rigging component, the minimum acceptable rated capacity is selected from the database. If the COG is extremely offset, the angle of slings above the spreader bar will be very acute which increases the compression forces and bending moments applied to the spreader bar. In that case, there might not be any available spreader bar for the required capacity. So the next available longer sling will be selected for the slings above the spreader bar to increase the angle and decrease the required capacity.

2.4 Third level calculations

Similar to the second level calculations, the aforementioned system of equations is solved to find the RAI. However, some of the parameters have a different definition from their counterparts in the second level calculations.

M: Module length

Off: the distance from the COG to the closer lifting lug in xz plane.

S_2: The total length of the sling and the shackles to which it is connected at the third level.

H: the total height of the rigging assembly below the third level.

The rest of the parameters and equations are defined exactly the same as those in the second level calculations.

2.5 Optimal combination of shackles

In order to make up the optimal length with a chain of shackles, the goal function is defined as follows:

$$\mathrm{RAI} - \sum_{i=1}^{N} n_i d_i \leq 0 \tag{17}$$

Where:

RAI: The required amount of increase which calculated in the second and third level calculations.

N: The total number of shackles available with different size. Only those shackles which meet the capacity requirement based on the sling they are attached to.

n_i: The number of shackles i used in the chain.

d_i: The inside distance of shackle i.

This classic linear optimization problem is solved with a customized function using the Microsoft Solver

Table 1. The designed and used rigging components of rigging assembly on each level

	As Designed				As Used			
	Description	Required Capacity	Rated Capacity	Used Capacity	Description	Required Capacity	Rated Capacity	Used Capacity
Shackles attached to the lifting lugs	1-3/8 in (35 mm)	12.27 ton	13.5 ton	90.89%	1-3/4 in (44 mm)	12.27 ton	25 ton	49.08%
Drop slings	Ø1-1/4 in x 20 ft (Ø32 mm x 6.10 m)	27,052 lbs (12.27 ton)	30,000 lbs (13.61 ton)	90.17%	Ø2 in x 20 ft (Ø51 mm x 6.10 m)	27,051 lbs (12.27 ton)	74,000 lbs (33.57 ton)	36.56%
Spreader bars at level 2	NC-6L 14-24 @18 ft (5.49 m)	48,764 lbs (22.12 ton)	52,600 lbs (23.86 ton)	92.71%	NC-6L 14-24 @19 ft (5.79 m)	48,764 lbs (22.12 ton)	63,000 lbs (28.58 ton)	77.40%
Slings at level 2	Ø1-3/8 in x 15 ft (Ø35 mm x 4.57 m)	30,841 lbs (13.99 ton)	36,000 lbs (16.33 ton)	85.67%	Ø1-3/4 in x 20 ft (Ø44 mm x 6.10 m)	29,370 lbs (13.32 ton)	56,000 lbs (25.40 ton)	52.45%
Spreader bar at level 3	NC-8 18-31 @25 ft (7.62 m)	87,140 lbs (39.53 ton)	112,600 lbs (51.07 ton)	77.39%	NC-8 18-31 @25 ft (7.62 m)	87,140 lbs (39.53 ton)	112,600 lbs (51.07 ton)	77.39%
Slings at level 3	Ø2 in x 20 ft (Ø51 mm x 6.10 m)	56,100 lbs (25.45 ton)	74,000 lbs (33.57 ton)	75.81%	Ø2 in x 30 ft (Ø51 mm x 9.14 m)	51,755 lbs (23.48 ton)	74,000 lbs (33.57 ton)	69.94%
RAI at level 2	12.42 in (32.5 cm)				10.66 in (27.08 cm)			
RAI at level 3	18.38 in (46.69 cm)				12.62 in (32.05 cm)			
Total height	54 ft (16.46 m)				70 ft 6 in (21.49 m)			
total weight	4,414 lbs (2.00 ton)				5,591 lbs (2.54 ton)			

Foundation library.

3 Case study

In order to validate the framework, the rigging assembly design of a 4-point pick module is taken into consideration as a case study. The following described module has been successfully lifted and erected in one of the NCSG Crane & Heavy Haul Corporation's projects. The module has 45 ft. (13.72 m) length, 17 ft. 7 in (5.36 m) width and 15 ft. 1 in (4.59 m) height. The lifting lugs of the module which are located at its bottom make a 25 ft. 2 in (7.67 m) by 17 ft. 7 in (5.36 m) rectangle. The module's COG is offset by 1 ft. 6 in (0.46 m) and 1 ft. (0.29 m) from the center of the rectangle towards x and y-axis of the module respectively. Thus, sling length adjustment is needed at the second and third levels of the rigging configuration. As the lifting lugs are at the bottom of the module, the length of the drop slings is needed to be greater than the module height. This is added to the design framework as a constraint. The rigging assembly is designed by the proposed framework and is compared to what was actually used on the job site. Table 1 represents the designed and used rigging components of rigging assembly on each level. As it is clear in the table, the design with the proposed framework is more efficient as the total height and weight of the automatically designed rigging assembly are 23.31% and 21.05% less than manually designed one respectively. In order to increase the length of slings at level 2 of the rigging configuration, a combination of one 25-ton and one 13.5-ton shackle is added to make up a chain with 12.25 in (31.12 cm) length. Similarly, a combination of one 55-ton and one 35-ton shackle is added to the slings at level 3 to increase the length of the sling by 18.25 in (46.36 cm). In the manually designed rigging assembly, one 55-ton shackle has been added to both second and third level to increase the length of slings by 10.5 in (26.67 cm). The designed shackles for the lifting lugs might not be suited in term of size. In that case, larger shackles could be replaced after completion of the design to match the size of lifting lugs.

4 Summary and future research

In this paper, a mathematical based design framework is presented which automates the selection of rigging assembly for 4-point pick modules. The framework collects the module information and calculates the required capacity for each rigging component using a mathematical-based solver and selects the most suitable rigging components from the database. The final designed assembly ensures a vertical lift while the module and spreader bars are maintained horizontal during the lift. This results in a safe and time efficient lift in contrast to the current practice which is time-consuming and relies heavily on guesswork especially when the COG is offset.

This paper uses a case study in order to validate the practicality of the proposed framework. The case study proves that the automatically designed lift study is more efficient in terms of: total height and weight of the rigging assembly, inventory list of rigging components and detailed position of them.

The presented methodology is applicable to modules with 4 lifting points. In future research, the framework should be developed in order to automate the rigging assembly design for modules with more lifting points. As an instance, the rigging assembly for a module with 16 lifting points consists of 5 levels of rigging configuration which includes at least 270 rigging components [1]. This increases the complexity of the rigging system exponentially. In that respect, automation in rigging assembly design could be highly beneficial for large modules with more than 4 lifting points.

5 Acknowledgments

The authors would like to show their gratitude to the Natural Sciences and Engineering Research Council of Canada (NSERC) and NCSG Crane & Heavy Haul Corporation who supported this research.

References

[1] Westover L., Olearczyk J., Hermann U., Adeeb S., and Mohamed Y. Analysis of rigging assembly for lifting heavy industrial modules. *Canadian Journal of Civil Engineering*, 41(6), 512-522, 2014.

[2] Anderson J. K. *Rigging Engineering Basics*, 1(1), ITI Bookstore, Woodland, Washington 98674, 2013.

[3] The Crosby Group LLC. *Crosby General Catalogue*. 2801 Dawson Rd., Tulsa, OK 74110, 2017.

[4] Sam M. T. Offshore Heavy Lift Rigging Analysis Using Spreadsheet. *Practice Periodical on Structural Design and Construction*, 14(2), 63-69, 2009.

[5] Longman R.W. and Freudenstein, F. Stability Analysis of Lifting Rigs—Part 1: Necessary and Sufficient Conditions. *Journal of Engineering for Industry*, 97(2), 532-536, 1975.

[6] Han S., Hasan S., Bouferguene A., Al-Hussein M., and Kosa J. An integrated decision support model for selecting the most feasible crane at heavy construction sites. *Automation in Construction*, *87*, 188-200, 2018.

[7] Chen P., Zhuang Z., Chang C. and Kang S. A Numerical Model for the Attitude Manipulation of Twin-Hoisted Object. In *Proceedings of the 35th ISARC*, pages 211-215, Berlin, Germany, 2018.