Estimation of Mobile Crane Cycle Time to Improve the Accuracy of Modular-Based Heavy Construction Project Schedules

Ali Nikeghbali

A Thesis

In the Department

of

Building, Civil, and Environmental Engineering

Presented in Partial Fulfillment of the Requirements

For the Degree of

Master of Applied Science in (Building Engineering) at

Concordia University

Montreal, Quebec, Canada

August 2021

Concordia University

School of Graduate Studies

This is to certify that the thesis prepared.

By: Ali Nikeghbali

Entitled: Estimation of Mobile Crane Cycle Time to Improve the Accuracy of Modular-Based Heavy Construction Project Schedules

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Building Engineering)

Signed by the final Examining Committee:

_________________________________ Chair
Dr. R. Dziedzic

______________________________ Examiner
Dr. J. Lee

______________________________ Examiner
Dr. S. H. Han

______________________________ Supervisor
Dr. S. H. Han

Approved by____
Dr. Michelle Nokken, Graduate Program Director

Summer _______________________________________
Dr. Amir Asif, Dean, Gina Cody School of Engineering and Computer Science

Abstract

Estimation of Mobile Crane Cycle Time to Improve the Accuracy of Modular-Based Heavy Construction Project Schedules

Ali Nikeghbali

Modular-based construction projects rely heavily on mobile cranes for lifting large quantities of materials. In recent years, these materials have become heavier and larger, and construction site layouts have become more and more congested; these factors significantly impact efficiency and productivity. In practice, on these large sites today, lift planning takes place using an intuitive approach which increases project cost and decreases productivity. A lack of comprehensive methods to identify influential factors on crane motion speeds and motion types leads to difficulties in evaluating the accurate work cycle of cranes. Therefore, addressing mobile crane cycle times during operations is critical to enhancing productivity and rapid reaction in projects. In order to improve mobile cranes' cycle time project, the ability to accurately estimate the work cycle of mobile cranes is necessary. To address this need, this thesis proposes a methodology that involves five procedures: *(i)* model initiation to build up safety factor (SFs) and clearance functions; *(ii)* a lift analysis to study wind parameters and its effect on module shape, weight, and dimension; *(iii)* development of wind function; *(iv)* a model expansion to build up crane motion speeds function, and implementation of fuzzy if-then and inference system ; *(v)* time computation to estimate the crane cycle time. The proposed framework is proven effective by six case studies conducted on a large, congested industrial site. Accuracy in the case study's project for mobile crane estimation of cycle time were increased.

To my family; Sara, Iren and Emil

Acknowledgements

Firstly, I would like to express my most profound appreciation to my supervisor Dr. Sang Hyeok Han, in order to his endless support and help, persistent guidance, and inspiration. I am grateful for his significant effort and guidance during the past three years.

Especially, my most profound appreciation is given to my father, Mr. Faramarz Nikeghbali, and my mother, Aghdas Safaei, for their absolute love, and support during my whole life.

I would also like to thank my wife, Sara Darvish, for her patience and adoration. I could not overcome big problems and accomplish my goals without her infinite encouragement, and support.

Finally, I must also acknowledge my dear friends Eng. Ahmed Zaalouk, and Dr. Saeed Rokooei, for their great help and motivation.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

SF	Safety Factor
CFPs	Crane fixed position
CPWs	Crane Pick and Walk
3D	3 Dimensional
FIS	Fuzzy Inference System
DOM	Degree of membership
FEM	European Material Handling Federation
MF	Membership function
OSHA	The occupational Safety and Health Administration
MT	Metric tons
3D-CES	A three dimensional-based crane evaluation system
GC	Crane gross capacity
W_{Total}	Total weight
L_{Angle}	Lift angle for a provided movement
L_{Height}	Lift height
$T_{Penalty}$	Penalty time
DBMS	Relational database management system
SL	Super lift
T_{Total}	Total cycle time of operation
V_Z	Gust wind speed

Chapter 1: Introduction

1.1 Background and Motivation

Over the past few years, modular heavy construction has become increasingly popular. It is a cost-effective method in which reduction of material waste, site disorder, and construction time (i.e., weather-related delay minimization) is highly considered. [[1], [2]]. Modular construction is helpful for large-scale heavy-construction industries. In the period of modular construction projects in large-scale, heavy crawler cranes are commonly utilized for lifting loads tasks [[3], [4]], [2]. After module preparation at the factory side, they must be shipped to the job site where they need to be lifted and installed safely and efficiently in their final position by utilizing commonly mobile cranes that are increasingly used because of their higher capacity compared to the tower cranes [5]. In contrast, cranes are considered almost expensive (i.e., a few thousand dollars an hour) in terms of rental prices, but the installation of prefabricated modules off-site and transporting them on-site made heavy cranes efficient and practical concerning the projects' necessities [[6], [3]]. Modularization enables off-site fabrication, which enhances efficiency. Heavy-module operation-related activities are essential in off-site prefabrication since module shipment opens space available for other module preparations. In addition, on the jobsite, it enables another work front as heavy lift operation is almost on the critical paths of the projects [[3], [7]].

Moreover, cranes location in the projects is deterministic so that other equipment can be arranged after locating and considering cranes as the top importance of the equipment list [4]. In this respect, site productivity is highly dependent on the crane operation efficiency, which is highly related to the duration of the work cycle [[8], [2]]. Crane's efficient work with minimum crane operation cycle time in industrial projects is almost the production's bottleneck. Hence, shortening the cycle time of operation is the critical element in construction projects to achieve productivity and efficiency [[4], [2], [8]].

Tens of large and heavy modules need to be lifted and safely installed in the heavy construction to be placed in their designated point by utilizing cranes [[2], [3], [6]]. Inappropriately, lift planning on-site, in practice, is often based on the experience of experts and highly relies on trial and error, which is time-demanding, costly, and error-prone [[9], [3]], especially in heavy-industrial projects with a large number of modules. In this respect, practical application of lifting objects is vital to ensuring approaching the project's economic aims. Mobile cranes' high capacity has convinced project decision-makers to put them into high demand to apply them to construction projects.

For advancing to more industrialization and promoting productivity, the efficient work cycle time of the crane is significant [10]. Traditionally, factors that affect the duration of crane operation cycle are considered essential factors regardless of the working floor height at high-rise buildings. So, the time achieved is estimated. The accurate time needs to be applied to reach detailed time schedules [11].

The duration of the work cycle is affected by numerous factors, which are generally categorized into two groups of factors, including hard factors and soft factors, which both directly impact the cranes' work productivity [[8], [2]]. These two groups are classified as follows:

i. Hard factors (i.e., geometric relation between building, site, and crane and with crane technical features such as slewing and hoist velocity)
ii. Soft factors (i.e., cab ergonomic, weather, the field of vision, operator experience) [8].

Both directly impact construction productivity and safety, which are addressed by the construction research community. Hard factors govern the duration of the lifting cycle: the speeds generated by crane's motors and the relative location of pick-up and drop-off points in the time-distance-velocity equation [8]. To accurately predict the cycle time mode, the weather needs to be considered [[11], [8]]. Crane cycle times are almost divided into different segments due to the purpose of the study. Scholars have divided the cycle time into two two-part phases as following [8]:

i. Hook transfer toward load location
ii. Load gripping
iii. Transferring the load: that is started by hoisting up and finished at hoisting down moment.
iv. Installing of the load and releasing the rigging system

The research also shows that since cranes almost start a new cycle when they complete a half cycle, every half cycle is broken down into two segments: motion time of the hook (i.e., lift, travel vertical-horizontal-vertical and approach to the pickup/ drop off point and or rigging/ loading, and unrigging/unloading time).

1.2 Problem Statement

Mobile crane cycle time, including all motions involved in an operation, and factors that influence the speed of crane motions from lift to load positioning, has not yet been fully established in the current construction industry literature. In particular, for heavy modular construction, a method is needed to consider the following cycle time evaluation requirements. Scholars' efforts in this area lack:

i. The consideration of multiple influential factors in crane motion speeds

ii. The estimation or optimization of crane cycle time, studies mainly focus on shortest or optimization of paths

iii. Detailed motion speeds and time ranges for mobile crane operation remains untouched, although some research try to find the optimum operation paths

iv. The consideration of dynamic factors which effects (e.g., wind) mobile crane operations although, their effects are considerable

v. Research inaccurate project scheduling.

1.3 Objectives and Scope

The main objective of this research is to propose a method to improve the accuracy and efficiency of estimation of the cycle time of mobile crane operation in construction projects. This research also focuses on several sub-objectives as follows:

i. Develop a fuzzy logic-based method to estimate speeds of mobile crane motions, which integrates with three-dimensional (3D) visualization of operation to calculate cycle time

ii. Provide a numeric information platform to react rapidly to project schedule changes and allow efficient communication among project participants

iii. Validate the fuzzy logic-based cycle time estimation in modular-based construction projects

iv. Develop a platform to evaluate influential factors on crane cycle time by applying experts' opinions since the only available resources to estimate mobile crane cycle time in construction is expert's views.

The scope of this study is limited to the following aspects:

i. The evaluation of the work cycle is based on the mobile crane cycle time after the pre-lifting procedure until the time of positioning a load in which six different motions are involved (i.e., slewing, hoisting up/down, boom up/down, and load rotation by the hook)

ii. The lifting method is supposed to be a crane from fixed positions (CFPs) operation

iii. Among several factors which impact the care motion speeds, three are evaluated based on their importance and efficacies (i.e., Safety factor (SF), clearance, and wind).

Accordingly, to accomplish the research objectives, this study satisfies work cycle requirements by using a survey investigated by Han (2017) which identify the main influential factors on mobile crane motion speeds and classifies the factors based on their importance. Moreover, the survey indicates crane motions and acceptable motions' speeds during operation. To analyse the influential factors on motions speed, a fuzzy logic approach is implemented. This approach determines several motion speeds to calculate the time of operation in order to improve accuracy of crane cycle time. It also supports better-informed decision-making for project participants and accelerates the reaction to project changes. In this respect, the proposed framework consists of manly five core components:

i. Model initiation

ii. Lift analysis

iii. Development of wind function

iv. Model expansion

v. Time computation

To implement the planned framework and validate its effectiveness, a case study of six module operations in an industrial site in Alberta, Canada, is selected.

Chapter 2: Literature Review

2.1 Introduction

In order to understand the research surrounding mobile crane cycle time in modular-based large-scale industrial projects, a literature review that considers the tools and algorithms of such research is necessary. Although numerous attempts have been made to address efficient crane cycle time, the current efforts have weaknesses. This chapter provides a summary of mobile crane cycle time-related research.

2.2 State-of-the-Art Research in Crane Location

Improve production efficiency depends on the on-site layout and material management system which is highly affected by optimal equipment location on jobsites. In this regard, cranes transporting heavy materials that are the most utilized heavy equipment in construction sites have received attention. Hence, efficient selection of crane locations can improve project productivity and safety. However, in practice, experience engineers determine crane location via a trial-and-error process which is time-demanding and costly. Engineers and researchers have followed attempts to facilitate this process. Initial focuses have been on developing crane location optimization to better handling material supply [12]. In constructing of a public housing project in a high-rise building, Tam et al. [13] have proposed a genetic algorithm (GA) approach to optimize material supply and tower crane location. Research in crane and material supply location have been investigated due to the 2D implication of work sites. The 2D approach lacks the ability to recognize the potential conflict among existing obstacles and crane configuration, which creates complexity in practice. This complexity caused wasting more time to relocate cranes in the projects since part of collisions remains undetected in 2D planning. To address this problem, Tantisevi and

Akinci [14] have provided a 3-dimensional (3D) simulation of a project to recognize spatial collision-free to identify the optimal location due to dynamic crane behaviours. despite these efforts, schedule delays, spatial conflict, and inaccuracy of crane capacity limitations cause the relocation of crane, increasing the cost of operation. To overcome these issues, Sofouhi et al. [15] proposed a GA algorithm to determine the feasible mobile crane location by computing crane configuration in a given distance. Their work had been adopted to the heavy industrial projects in which numerous objects need to be lifted according to lifting sequences. Continuing the efforts of this study, Lie et al. [9]have proposed a binary (yes/no) methodology in lifting operation in which by calculating the minimum and maximum lift radii and controlling crane location inside mobile crane position area in configuration space (C-space). This method tried to control the creation of a path that connects pick-up points to drop-off points of the object lifting. If the designed method is not successful in finding a feasible path that happens on various crane fixed positions, the system proposes a walking path to complete the lifting process. Then, Lie et al. [16] have proposed a GA approach to cover walking with load operations in heavy industrial projects since crane walking operations make more complexity compared to operation from a fixed position. This method considers crane geometry, typical site constraints, and module geometry to calculate collision-free area in which mobile crane needs to locate within the collision-free area to pick-up the load. Then possible crane location is presented as an area in which load picks up is started. In this method, the designed path shows the start and finish point of the crane position for any lifted object. However, these efforts have two significant limitations.

i. 15% to 20% failure rate to find feasible crane location due to complexity and congestion level in the projects.

ii. Uncertainty in pick area of material supply where objects need to lift due to feasible crane locations.

To overcome the challenges above, Han [12] has proposed a method for motion planning in a 3D-based approach to consider feasible crane locations with associated material supply spots in heavy construction projects with numerous objects for lift. In the proposed methodology, to ensure the most efficient crane operation, it is needed to assess the crane operation's performance in selecting the crane location. In addition, Since studies have not considered multistage construction (i.e., disintegrating a complex project into a number of work zones) that can lead to suboptimal crane utilization costs until then, Justin et al. [17] have proposed a four-dimensional set cover problem (4D-SCP) model to overcome the issue. The provided model prepares better solutions in selecting and locating cranes for the project in multistage construction. Moreover, By applying A-star algorithm, Bagheri et al. [18] have attempted to optimize crane location by considering cost reduction of operation and reduce the possibility of crane accidents and failures due to predetermined lifting sequences.

2.3 State-of-the-Art Research in Crane Selection

Crane selection is an essential and time-consuming activity in projects since it contributes to productivity and effectiveness. For large-scale projects, crane selection is costly since hiring a crane cost a few thousand dollars an hour; researchers and engineers have attempted to facilitate crane selection in crane lift planning. Various algorithms have been utilized to develop applications and methodologies [[12], [19]]. In this regard, Han et al. [12] have categorized crane selection-based algorithms into two major groups: *(i)* factor-based algorithms and *(ii)* scenario-based algorithms. Hanna and Lotfallah [20] have categorized three general crane types (i.e., tower, mobile, and derrick cranes) to investigate optimal crane selection for different construction projects. They have utilized fuzzy logic to convert important project factors (i.e., building design, crane capability, safety, site conditions, and crane cost) into fuzzy sets to select the proper crane type. Sawhney and Mund [21] have investigated crane type and model selections by indicating sets of inputs (i.e., type of use, crane presence duration on site, height of construction, site spaciousness, crane relocation, foundation, site accessibility, and terrain topography) in IntelliCrane. This artificial neural network-based approach that includes historical data. Some researchers have developed scenario-based factors in type and model selection of cranes as crane type selection is impacted by considering the heaviest and/or largest lift radius. Engineers use valuable time to adjust crane charts and capacity tables for a project's conditions to avoid costly errors. In response to this problem, Al-Hussein et al. [19] have developed D-CRANE, a relational database management system (DBMS) that is designed to support effective crane selection. In addition, based on data collected from projects and rigging equipment, these researchers [22] have introduced a lift setting algorithm that determines the feasibility of crane selection and position. Furthermore, Al-Hussein et al. [23] have presented an optimization algorithm, Algorithm 2, to select and locate mobile cranes on construction job sites according to the minimum boom and/or jib length and higher crane capacity. Algorithm 2 considers the minimum working radius in the projects. Furthermore, Wu et al.'s [24] algorithm for mobile crane selection addresses the tedious procedure of reviewing crane capacity charts in order to consider a crane's geometrical characteristics, bearing pressure, and the dimensions of riggings and equipment. This algorithm has been combined with a three-dimensional (3D) system in order to integrate crane modelling, modelling 3D computer-aided design and simulation, rigging calculation, data management, and crane selection. Some lifts may need two cranes to operate. In a two-crane lifting operation, the selection of the cranes is based on their capacities and individual analysis of the cranes' lifts. As this is a time-consuming method for crane selection, Herman et al. [25] have proposed a methodology to carry out long lifted vessels using a single crane by developing a mechanism and a methodology. However, none of the above studies concerning crane selection tools and frameworks have validated of the crane type and model. Han et al. [12] have presented a method to monitor crane capacity and working radius to assess safety factors during an operation to prevent exceeding lifting capacity. This method enables crane engineers and project managers to guarantee a safe operation and validate the crane type and model selection. At this junction, it should be noted that this study does not encompass crane location and selection.

2.4 State-of-the-Art Research in Crane Support Design System

Fig. 1. Crane support system. (Photograph by Ali Nikeghbali)

Construction projects can be very hazardous. Behm [26] has described construction in North America as one of the most perilous industries for work-related fatalities. From 2009 to 2017, the Occupational Safety and Health Administration (OSHA) registered 175 deaths related to crane failure [3]. The US Bureau of Labour and Statistics [27] has reported the following reasons as the most common types of failures in cranes: outrigger failure, missing gravity centre control, overload, high wind, and side pull. This is due to reasons such as mobile crane design errors, lack of a proper support system, exceeding the crane's lift capacity caused by decision-making mistakes [28]. Crane support systems are vital elements that help avoid outrigger failure where the outriggers penetrate the ground during operation [29]. In practice, since a crane's body and its payload are moving elements, the crane support systems are not designed to consider maximum reactions, leading to improper crane support systems and outrigger failures. As a result, the dynamic force of slewing cranes is a critical factor in calculating any single outrigger's precise reaction. Sochacki [30] has investigated geometrical factors to analyse the stability of a laboratory model of truck cranes according to the load conditions and rope length in order to analyse dynamic stability. In addition, Hasan et al. [28] have introduced the calculation of outrigger reaction values of crawler and truck cranes in order to design an automated support system. This system provides a chart detailing the reaction of elements in a cranes' support system. This chart helps engineers to use steel plates or timbers to design the support system.

Moreover, in order to design a crane support system, Han et al. [12] have proposed a 3D visualization of crane operations. Proposed motion planning provides load and lifts angles efficiently and automatically to design the crane support system. This alternative facilitates the precise design of crane support systems. It should be noted that the present study does not consider crane support system design.

2.5 State-of-the-Art Research in Crane Operation Motion Planning

Recently, industrial construction projects have progressively involved heavier, larger, and longer objects such as modules and vessels utilizing single or cooperative crane operations [31]. Although cooperative lifts carry higher risk because of interaction among cranes, the practice of adopting two or more cranes in order to manage larger loads is becoming more popular. Therefore, a safe and reliable design of crane operation is essential. In this regard, motion planning has garnered attention in the design of crane operations. Kang and Miranda [32] have proposed an incremental coordination method to utilize two tower cranes in a relatively narrow project site. Due to their consideration of geometric and kinematic constraints of cranes, their methodology prevents collisions between cranes or between cranes and existing obstacles during operations. Despite the research efforts, the methods only consider 2D-based systems in which collision errors may not be precisely detected due to a lack of frequent reflex changes caused by the complexity of the project. It should be noted that effective motion plans search for the shortest operation paths. Therefore, prepared paths are drawn according to the identification and exclusion of possible special conflicts [[33], [34]]. In this regard, researchers have tried to unite the 2D-based path optimization algorithms with 3D evaluation to validate and support precise lifting paths [35]. Tantisevi and Akinci [36] have believed that to diagnose and eliminate possible crashes among crane configuration and existing structures, having detailed 3D of site layouts is essential. Change et al. [37] have introduced a method to automate the design of fast path planning in dual and single crane operations by applying two steps:

i. Building the crane operation into a 3D (C-space) considers the obstacles and crane's load capacity.
ii. Utilizing road map method to identify the collision-free paths taking into account C-space.

In addition, Albahnassi and Hammad [38] have proposed a framework that visualizes and simulates crane's operation due to dynamic changes of the job site. The idea of the framework is to operator by re-planning the operation close to real-time safely. According to two types of operations, including crane lift operation from fixed positions (CFPs) and crane pick and walk operations (CPWs), Lei et al. [16] have introduced 3D visualization by implying 3D Studio (3ds) Max to design mobile crane's motions in operation. However, in practice, the development of 3D visualization is time-consuming due to changes in site layouts and operational schedules. Hence, Han et al. [39] have presented a 3D visualization what-if-based method to evaluate motion planning in heavy industrial. A couple of limitations are involved in the research mentioned above as follows:

i. Most of the research has focused on collision-free paths, while in congested sites, the collision-free motion of crane body shapes is critical either
ii. This research has utilized 3D visualization as a validation tool but not as a design tool.
iii. The research has used applications as stand-alone tools to design error- prone motion planning. These errors decrease the preciseness during frequent design changes.

To overcome the limitations, Han. [12] has proposed 3D visualization-based motion planning, which is featured as following:

i. Integration of 3D visualization and mathematical algorithm to design CFP and CPW operations.
ii. Automated visualization and simulation for numerous lifts in crane operation.
iii. Satisfying collision-free paths of crane motions.

Thereafter, Han et al. [2] have proposed a three-dimensional-based crane evaluation system (3D-CES). This system design, verify and simulate 3D visualization of crane operation to support the most efficient selection of crane operation and planning the crane lift schedule according to the identification of safety and productivity aspects. Since crane efficient operation promotes site productivity which is directly related to the crane work cycle. Therefore, to increase productivity and support the efficient crane lifting cycle time, the research has provided a linear correlation function to identify allowable ranges of some motions of mobile cranes (i.e., slewing, boom up/down, hoist up/ down) due to safety identification of SF ranges of the lifts.

The similarity between designing mobile robots and mobile cranes has resulted in the shared application of path planning for mobile cranes in which the application of configuration space (C-space) has been introduced. Both are trying to optimize collision-free paths. Scholars have utilized numerous algorithms to design path planning. However, due to their computational costs, these algorithms may not manage complex environments. In order to increase functionality, Cai et al. [40] have proposed a parallel genetic algorithm (GA) that produces a hybrid C-space in a complex environment for a terrain crane lift. However, the GA-based method assumes a fixed number of configurations for given paths. To reduce the complexity of the computations for topological structure, mainly for a crane's large dimensions, C-space dimensions have been reduced to a lifted load 3D C-space which has been proposed in a study by Keyhani et al. [3]. In addition, sampling-based algorithms (e.g., rapidly exploring random tree (RRT), probabilistic road map method (PRM)) have been utilized by some researchers [3]. Due to repetitive steps in sample-based methods resulted from an initial guess, paths provided by these methods are limited in quantity. Then, these methods are not proper since they encounter difficulties where there are no feasible lift paths.

2.6 Fuzzy Logic Tool for Estimation of Mobile Crane Motion Speeds

In crisp logic, a proposition can be right or wrong, while a proposition can be both true and false at the same time. A fuzzy system is able to convert linguistic preferences to numerical equivalents, which is applied in many scientific contexts [41]. Moreover, expert opinions to solve a problem are usually expressed in the form of linguistic variables (e. g., Very Low or Moderate) in modelling and solving some issues. The single mathematical approach cannot cover these matters [[41] [42]].

Fuzzy logic is a patterning method that empowers dealing with the calculation that is imprecise rather than accurate [[43], [20]]. To transit between gradual sets in a specific variable, fuzzy logic uses membership functions besides if-then rules to make a model that can exchange inaccurate and uncertain information to certain and precise values. A fuzzy set includes elements that have membership degrees (DOMs) so that a membership function specifies the membership degrees of each element of set between 0 and 1 [44]. The most well-known fuzzy functions are triangular and trapezoidal forms [45]. Fuzzy rule-based systems have four steps [46]:

- Step1: fuzzification of input variables,
- Step2: determining the fuzzy functions of input and output variables,
- Step3: identifying and applying fuzzy inference system (FIS)
- Step 4: defuzzification

Mamdani and Sugeno are the most well-known inference systems due to fuzzy rule implications. Mamdani inference system is a theory-based system. To apply linguistic inference, Mamdani FIS is the best choice. However, Sogeno is utilized for mathematical analysis and linear systems. [47]. The implication of fuzzy logic to convert the linguistic criteria into algebraic measurements facilitate optimize a goal. Awad et al. [20] have proposed fuzzy logic approach to select proper crane type, as a highly acceptable method, in construction projects. since some parameters in crane cycle time and influential factors are qualitative, a subjective implicit cannot be directly combined into the classical decision-making process. In this regard, Fuzzy logic has key factors that make it well-suited to estimate crane cycle time as following:

i. Manipulating several input factors to identify their impact on outputs as motions
ii. Inferencing data due to expert's opinion
iii. Convert linguistic data (i.e., experts' opinion and influential variables ranges of efficacy) into numeric data to use perceptible mathematical calculation.

Due to these benefits, since motions' times are essential for calculating crane cycle time, estimating a proper cycle time needs calculation of crane motions time. However, the aforementioned literature does not support enough information to calculate the crane cycle time, especially from pick-up to the drop-off point in heavy construction projects, due to the following challenges:

i. None of the reviewed research has investigated the integrated and classified influential factors on mobile crane motions.
ii. Some researchers have studied to find correlation among influential factors and crane motions; however, not only are the influential factors are not fully recognized to be classified but all crane motions are not investigated (e.g., rotation of hook time).
iii. Previous research has investigated the influential factors as single fixed values, not range of efficacy.

In order to overcome the limitations related to previous studies, cycle time estimation of the mobile crane in modular-based heavy-industrial construction projects necessitates a well-matched method satisfying the following features:

i. Recognize all motions that influence the crane cycle time between pick-up and drop-off point
ii. Enable to classify influential factors on crane cycle time separately, then inference their weight impact on crane motions
iii. Making influential factors function so that measurement of factors efficacy is possible
iv. Calculate every single motion time and speed, taking into account the influential factors
v. An efficient method compatible with different crane types in heavy industrial projects facilitates project participants' decision-making.

Chapter 3: Proposed Methodology

The proposed methodology illustrated in Fig. 2 depicts the process flow to mobile crane operation cycle time on modular-based heavy industrial projects.

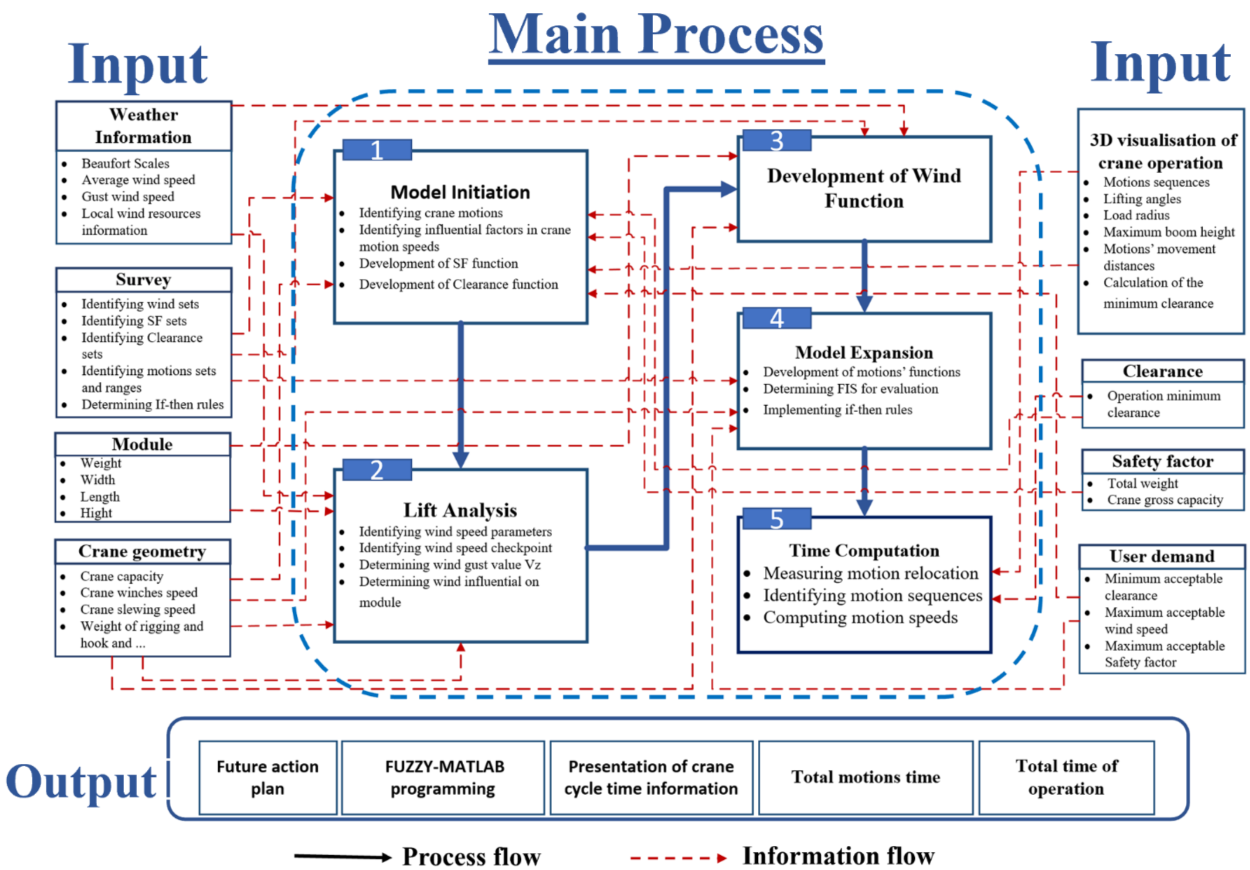


Fig. 2. The proposed methodology of mobile crane cycle-time estimation,

Core information – data collection

The required input data includes eight principal categories, which consist of:

i. Module information, including weight, width, length, the height of the module, and set location of the module on the jobsite

ii. Crane information, such as the maximum speeds of each of the various crane motions, including slewing speed, hoist up/down winch speed, boom up/down winch speed, boom length, lifting capacity chart, crane wind capacity, and crane geometry information

iii. Specific user demands such as allowable safety factors (SFs), wind speed, and clearance

iv. Three-dimensional (3D) visualization data (i.e., working radius, lifting angles, motion sequences) in accordance with the 3D visualization of crane lifts. Data extracted from 3D visualization shows motions sequences in operation, and the measurement of the load changing position in every motion horizontally and/or vertically

v. SFs information (i.e., crane's gross capacity (GC) and total weight (W_{Total})) of the lifted load according to the study that has been conducted by Han et al., 2017

vi. Clearance information (i.e., the distances of crane configuration and lifted a load from obstacles during an operation) due to the data collection from 3D visualization of operation for a minimum distance of lifted with existing obstacle

vii. Weather information, which for this study principally refers to wind-related factors: (i.e., average wind speed ($V_{Current}$), wind gust speed (V_Z), and calculation a couple of wind parameters by considering module and crane specifications, and standards (i.e., V_{Max}, $V_{Max-TAB}$, V_{Final})

viii. Survey information (i.e., identification of mobile crane motions and motions gradual sets with district boundaries, the influential factors in mobile crane motions speeds with factors gradual sets and their ranges, and if-then rules identifications).

Engineers and practitioners try to plane a lift in congested sites so that the crane does not need to process the operation by picking and walking with load (CPW). This helps mitigate the risk and complexity associated with the CPW operations and prevents avoidable mat costs during operations [6]. In addition, studies show that the absolute majority of crane lift operations in modular projects are planned to be done with crane fixed position (CFP). For example, records from major projects in Alberta, Canada, constructed by PCL Inc., 51 lifts out of 1561 lifts need the CPW method of operation, which accounts for 3.3% of all lifts. Thus, CFPs are dominant operations in congested sites [3]. Therefore, this research focuses on CFP operations. As a result, factors associated with CPW operations are not considered. Therefore, any preparation time, including installing the rigging system and the time required to disconnect the rigging system after positioning the load, is not included in data analysis due to the study scope.

Mobile cranes are equipped with specific features that enable them to perform their movements along different directional planes: horizontally, vertically, and rotationally [48]. Researchers have indicated that cranes complete their manoeuvres by utilizing different motions, much like as robots function [3]. Any action made by a mobile crane affects the crane's cycle time. To improve the accuracy of an estimation of mobile crane cycle time and the rapid reaction of schedule changes, it is essential to determine the duration for each motion. Finally, by adding the time for each motion (actual time (T_{Actual})) with the penalty time (time used between switching motions ($T_{Penalty}$)), the total time (T_{Total}) of each crane operation can be determined.

Notably, several factors can impact the speeds of mobile crane motions during a lifting process. This study uses results from Han (2017), which evaluates path planning of mobile cranes by considering a 3D visualization simulation to achieve optimum crane set location and reaching acceptable SF and clearance in lifting operation. This study also uses Han's survey as input data to recognize the influential factors on mobile crane motion speeds and identify mobile crane motions. The survey determines numerous factors which affect mobile crane motions. These factors are listed as follows:

i. SF, which pertains to identifying various ranges of SFs based on W_{Total} compared GC

ii. Weather, which for this study, only refers to the impact of wind on crane motions

iii. Clearance, which identifies the minimum distance between existing obstacles and crane configuration during crane operation

iv. Crane configuration, for instance; super-lift (SL) counterweight time which ensures floating of the SL tray, and setup time to change SL counterweight between lifts

v. Weight of the load: the heavier the load, the more hoist line is required, which affects the hoist speed

vi. Site condition: for instance, crane operating in live unit vs green-field/brown-field environment

vii. Rigging changes between lifts: rigging system may need adjustments to connect to the module

viii. Rigging detachment after installation if the load is set at the high elevation

ix. Crane re-configuration between lifts

x. Ground allowable pressure: crane boom orientation or crane working radius may cause high pressure below crawler, crane relocation may need crane complete or partial dis-assembly depending on the ground bearing pressure (GBP)

xi. Project sites safety policies such as lifting plan review and approval procedure

xii. Incorrect engineering data such as an error in centre of gravity (COG) location

xiii. Number of cranes involved in a lift

xiv. Crane manufacturer restrictions: for instance, slewing and walking at the same time may be forbidden if SL counterweight is mounted

xv. Boom de-icing and pre-work inspection during winter when cranes are winterized.

Finally, due to the limited scope of this study and factor's direct impact on the crane motion times, three are selected (i.e., SF, wind, clearance) to be studied. The survey results also show the numerous engaged motions in mobile crane operation, which are listed as follows:

i. Slewing movement (i.e., angular movement of crane boom in a horizontal plane in revolutions per minute (RPM))

ii. Hoist up movement (i.e., load vertical upward movement in a straight line in meter)

iii. Hoist down movements (i.e., load vertical downward movement in a straight line in meter)

iv. Boom up (i.e., the angular movement of boom by decreasing the working radius)

v. Boom down (i.e., the angular movement of boom by increasing the working radius)

vi. Rotation of load by crane hook around Z-axis

vii. Number of motion changes

viii. Walking.

Except walking, which is not included due to the limited scope of this study, all other factors are considered in estimating of the total time of mobile crane operation. In this junction, it should be noted that this study is a continuation the study conducted in 2017 by Han et al.[2] regarding the 3D evaluation of mobile crane operations. Therefore, in terms of SF and clearance, Han et al. (2017) results are used.

For this study, all data are entered, saved, compiled, and updated into Microsoft Excel, and for data processing, MATLAB programming is used. To do so, a program is written in MATLAB that receipts information from Excel and processes them due to designed functions and Inferencing system in MATLAB-Fuzzy to provide motions speed estimation and, in case of hook rotation, its time estimation. Various outcome information from this phase—including motions' relocations distances, motions' speeds, $T_{Penalty}$, and the cycle time of operations (T_{Total})—are added to the database, updated, and presented into Microsoft Excel. To achieve the methodological objective for estimating mobile crane's cycle time, the first step is to identify and develop influential variables on the crane's motions and then measure their degree of efficacy.

To calculate T_{Actual} of the mobile crane motions, factors that can affect the motions' speeds must be considered. In order to do so and to reiterate, the results of a survey by Han (2017) are used in which the participants are asked to define the crane motions and acceptable ranges of motion speeds of mobile cranes working on congested sites. They are also asked to identify the factors affecting mobile crane motions and their speed ranges. For this research, all information to determine safe and responsive lift operations in terms of SFs, mobile crane capacity, and path clearance concerning being collision-free is obtained from prior literature reports, according to Lei et al.[9] and Han et al. [2]. For accurate wind analysis that demonstrates the allowable wind speeds on the payload, factors pertaining to the mass and dimensions of the load, and the wind impact changes regarding the height of the load, are assessed.

Moreover, each factor's degree of efficacy needs to be assessed to evaluate the influence of SFs, wind, and clearance on crane motion speeds. It should be noted that the survey parameters are linguistic. For instance, SF describes five sets: Very Heavy, Heavy, Moderate, Light, Very Light. Any linguistic set is assigned gradual classes based on numeric category (e.g., (40% - 55%] for Light set in SF). Since the factors' ranges are the input of this assessment, subjectiveness can affect the preciseness and reliability of the results. This study uses fuzzy logic's linguistic descriptors to process the information and achieve numerical values To overcome this problem and decrease subjectivity. In addition, Fuzzy logic is the only algorithm available to interpret linguistic data into numeric values.

"Fuzzy logic enables dealing with inaccurate and uncertain information by providing a method for a gradual transition between different classes of continuous variables using unsharp boundaries" [31]. Thus, by applying this approach, input variables of an influential factor (e.g., SF) are not pertaining to one set (e.g., Heavy). However, pertaining to different sets with different membership degrees. This characteristic of the fuzzy logic algorithm makes it a proper method to evaluate influential of input factors by designing functions. The use of fuzzy logic guarantees a stable transaction among gradual sets of input factors. In other words, due to the subjectiveness of input variables and their impact on the precision and consistency of output data, fuzzy logic implements distinct factors classifications for the input data [43].

Moreover, the Fuzzy logic tool helps overcome the impact of data inaccuracy on motion speeds by empowering gradual transitions among adjacent sets of continuous variables [31]. A heuristic method is utilized to expand the (membership function) MF of outputs; additionally, applying "if-then" rules helps clarify the relationships among input and output variables. Adjacent sets of variables meet where their MF value is 0.50. The point of intersection shows a border angel where changes among sets occur [43]. Additionally, the total value of set memberships at the highest value cannot exceed 1 [49].

Two main features of the fuzzy logic-based approach are used to evaluate crane motions' speeds:

i. Classifying the influential input as variables (i.e., SF, clearance, and wind speed) in separate configurations, indicating each variables' different level of efficacy

ii. Applying fuzzy inferencing system (FIS), which interprets the relation of outputs and inputs variables using an expert opinion system.

Assess the cycle time of mobile crane operations in modular-based industrial construction settings based on the input information. This central process of cycle time estimation includes five procedures described sequentially:

i. ***Model initiation*** to build SF (i.e., ratio of W_{Total} to GC) and clearance functions in fuzzy logic supported by survey sets and previous studies.

ii. ***Lift analysis*** is conducted to identify the impact of wind parameters on the lifted load. Notably, wind velocity impacts objects according to their weight, dimensions, and shape.

iii. ***Development of wind function,*** which among six elements associated with the weather (i.e., temperature, atmospheric pressure, humidity, precipitation, cloud cover, and wind), this study targets the influence of wind for its direct impact on the crane motion speed as an essential variable to estimate the mobile cranes' cycle time [[2],

[3]]. In this respect, the Beaufort standard of wind scale along with survey sets are used to construct wind function in a fuzzy logic algorithm.

iv. ***Model expansion*** is conducted to build up crane motion speeds function as the output of fuzzy logic model by considering if-then rules and selecting proper fuzzy inference system (FIS)

v. ***Time computation*** is used to obtain results from data processing developed by fuzzy logic (e. g., motions' speeds) coupled with 3Ds max data (e. g., motions' relocation, and motions' sequences) to achieve the motions' times.

This framework results in the following output:

i. Cycle time estimation of mobile crane operation in modular-based construction projects, in CFP operations from lifting moment to positioning the load

ii. A motions' speeds datasheet that is used creates a motions' speeds table to determine precise crane speeds during operations.

iii. Presentation of the information numerically to communicate faster and with greater precision among stakeholders and project participants; this output data is vital for operational decision-making.

iv. Develop a flexible platform that can cover adding future influential factors in crane operating cycle time calculation through expanding designed fuzzy system.

3.1 Model Initiation

Studies often describe crane motions by considering a limited or single number of affective variables such as safety factors or collision-free paths [[2], [3], [29], [30], [32], [33]]. However, in practice, numerous variables (e.g., weather conditions, cab ergonomics, operator experience, field of vision, and ground conditions) influence a crane's motion speed and consequently its cycle time. To evaluate numerous variables, this study investigates essential factors and their impact on a crane's motion speeds by utilizing a survey. To reiterate, this study is limited in scope as it only includes CFP operations. According to the survey, SF is one of the concrete variables affecting a cranes' motions. Therefore, for any defined load to be lifted during the crane operation, one must consider the influence of SF, which is defined as the percentage of total weight (W_{Total}) over the gross capacity of the crane as presented in Eq. (1) and Eq. (2) [2].

$$GC \geq W_{total} = W_{Lifted} + W_{Hook} + W_{Sling} + W_{Spreadbar} + W_{Hoist} \quad (1)$$

Where:

- $\boldsymbol{W}_{Lifted}$ is lifted or object weight.
- $\boldsymbol{W}_{Hook}$ is hook weight.
- $\boldsymbol{W}_{Sling}$ is weight of sling.
- $\boldsymbol{W}_{Spreadbar}$ is weight of spreader bar.
- $\boldsymbol{W}_{Hoist}$ is weight of hoist ropes.

$$Safety\ factor\ (\%) = \frac{W_{Totla}}{GC} \times 100 \quad (2)$$

Where:

- $\boldsymbol{GC}$ is crane gross capacity.

Han et al. (2017) documented the linear correlation between SFs ranges and motion speeds (i.e., slewing, hoisting up/down, and boom up/down) in mobile cranes [2].

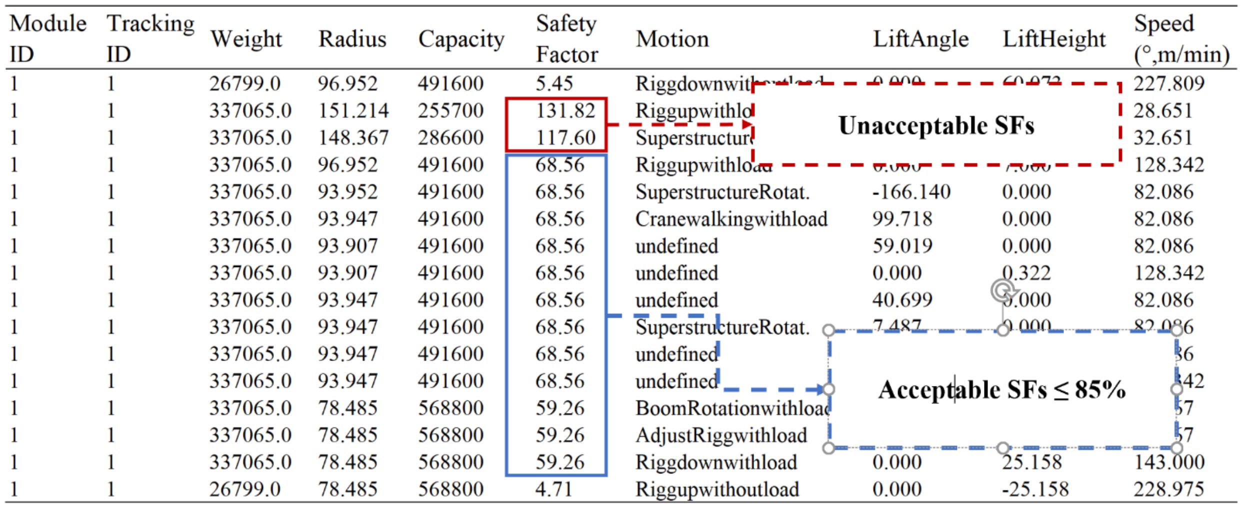
The resulting findings confirm that the SFs may change during the lifting process [2]. This change happens for different reasons, including the following three:

i. A change in the boom angle leads to a change in the load radius, altering a crane's gross capacity [2]

ii. A change in wind direction or wind intensity during load movement; as research shows, wind direction and velocity influence to change the boom angles [50]

iii. Slewing motion changes the quadrant of operation (e.g., side, front, or back operation), defined in the crane capacity chart provided by the manufacturer; consequently, it alters a crane's load capacity.

Among mentioned factors that changes SF values during operation, load radius changes are the only factor considered in this study because of information limitation for two other factors. For this research, the results achieved by Han et al. (2017)[2] are used for evaluating SF., SF changes due to adjustments in working radius during an operation, which alter a crane's gross capacity (GC). Acceptable SFs are selected from among the SFs created in the module lifting operation, as shown in Fig. 3. Higher SFs contribute to lower motion speeds. In addition, applying multiple SFs complicates the use of motion speed values in the calculation such that during an operation, numerous speeds are created. Therefore, in practice, there is a possible increase in errors. Therefore, the maximum SF is selected and applied to the fuzzy function to generate the safest operation.



Module ID	Tracking ID	Weight	Radius	Capacity	Safety Factor	Motion	LiftAngle	LiftHeight	Speed (°,m/min)
1	1	26799.0	96.952	491600	5.45	Riggdownwit[illegible]	[illegible]	[illegible]	227.809
1	1	337065.0	151.214	255700	131.82	Riggupwithlo[illegible]	[illegible]	[illegible]	28.651
1	1	337065.0	148.367	286600	117.60	Superstructur[illegible]	[illegible]	[illegible]	32.651
1	1	337065.0	96.952	491600	68.56	Riggupwithload	[illegible]	[illegible]	128.342
1	1	337065.0	93.952	491600	68.56	SuperstructureRotat.	-166.140	0.000	82.086
1	1	337065.0	93.947	491600	68.56	Cranewalkingwithload	99.718	0.000	82.086
1	1	337065.0	93.907	491600	68.56	undefined	59.019	0.000	82.086
1	1	337065.0	93.907	491600	68.56	undefined	0.000	0.322	128.342
1	1	337065.0	93.947	491600	68.56	undefined	40.699	0.000	82.086
1	1	337065.0	93.947	491600	68.56	SuperstructureRotat.	7.487	0.000	82.086
1	1	337065.0	93.947	491600	68.56	undefined	[illegible]	[illegible]	[illegible]
1	1	337065.0	93.947	491600	68.56	undefined	[illegible]	[illegible]	[illegible]
1	1	337065.0	78.485	568800	59.26	BoomRotationwithloa[illegible]	[illegible]	[illegible]	[illegible]
1	1	337065.0	78.485	568800	59.26	AdjustRiggwithload	[illegible]	[illegible]	[illegible]
1	1	337065.0	78.485	568800	59.26	Riggdownwithload	0.000	25.158	143.000
1	1	26799.0	78.485	568800	4.71	Riggupwithoutload	0.000	-25.158	228.975

Fig. 3. SFs calculation of a module operation [2]

According to the survey, linguistic sets of safety factors adjusted to the ranges of the sets in percentage are listed in Table 1.

Table 1. Safety factor sets and ranges in percent, taken from the survey

	Very Light	Light	Moderate	Heavy	Very Heavy
SF (Percentage)	X ≤ 40	40 < X ≤ 55	55 < X ≤ 70	70 < X ≤ 85	85 < X

Five SF sets beginning with less than 40% for "Very Light" to more than 85% for "Very Heavy" indicates due to the survey. In making the function of SFs in the fuzzy logic, the fuzzy logic regulations are implemented. In fuzzifying SF, building a fuzzy function is needed. Among different shapes of fuzzy functions (e.g., triangular, trapezoidal, and gaussian) triangular form of function is selected. By running a verification process, it is found that changes in input variables (i.e., effective factor in crane motions) values in triangular function contribute more sensitivity results in output variables (i.e., crane motions) leading to more accurate results. To build-up the function calculating the survey ranges mean values (i.e., the most probable value in a set) and assigning the maximum degree of membership function (DOM) (i.e. 1) is done. This calculated value is located as the vertex of the triangular form of the supposed function. To continue building the function, results from prior studies help determine another deterministic point in the function, which is “Very Heavy” set’s switching point, recalling that SFs are mainly set to be less than 85-90% [2]. The research also recommends that job managers or crane engineers should be present on the jobsite for any lifting operation in which the SF values are greater than 90%. Therefore, requiring the crane engineer to monitor operations at this plus-90% level guarantees that all participants accept 90% and higher values as absolute values for “Very Heavy” lifting. Therefore, in making membership function (MF), “Very Heavy” turns to membership degree of 1 reaching 90% as shown in Fig. 4. Knowing that “Very Heavy” set starts its MF of one when SF is 90% means that precede set is getting zero value at this point (i.e., 90 %) according to the fuzzy logic rules [49]. This point (90) is the upper limit of the “Heavy” set, which its DOM is zero. To determine the slope of the “Heavy” set, the average value of the set due to survey range (i.e., (70, 85]) is calculated (i.e., 77.5). This point (77.5) also shows where the “Very Heavy” set lower limit reaches DOM of zero [49].

Moreover, to build a fuzzy linear model, every two neighbouring fuzzy sets need to intersect at the point that the border angle has a (DOM) of 0.5. This represents an equal membership function in both sets [31]. By following this logic, all sets’ function is determined.

Safety factor				
Set ID	**Range**	**Mean Value**	**Lower limit**	**Upper limit**
Very Light	X ≤ 40%	20	0	47.5
Light	40 < X ≤ 55	47.5	20	62.5
Moderate	55 < X ≤ 70	62.5	47.5	77.5
Heavy	70 < X ≤ 85	77.5	62.5	90
Very Heavy	85 < X	90*	77.5	100

*According to the research

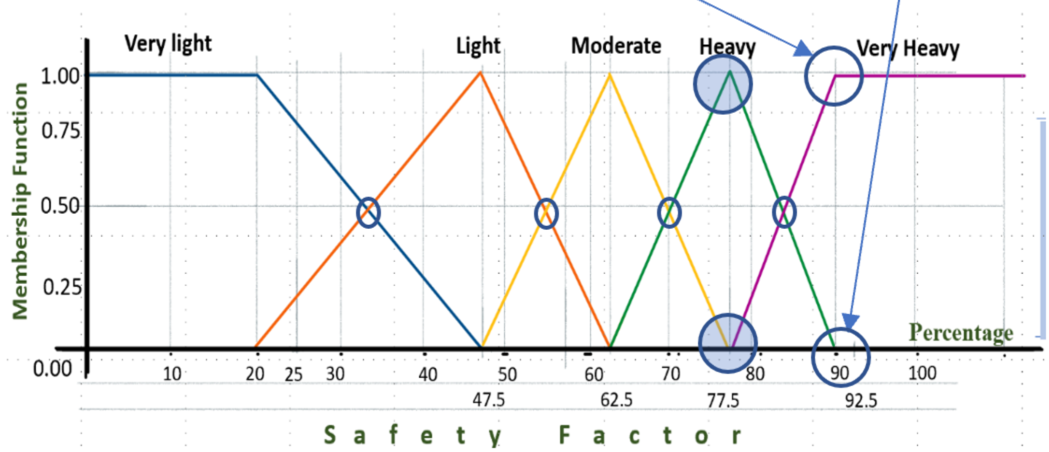


Fig. 4. MF of safety factor

3.1.1 Clearance Function

Having a clear path devoid of any potential obstacles is essential for accomplishing crane operations. Clearance, which refers to the minimum distance of the crane's configuration and its lifted load from obstacles during an operation, is critical in assessing motions' speeds [5]. The greater the clearance value, the faster the movement. In the planning stages of the projects, clearance can be recognized by 3D visualization of operation [2]. Clearance is a crisp value. However, to evaluate the input factors, building their function in the fuzzy logic algorithm is needed. To do so, by using the survey sets and ranges, upper and lower limits of all sets and all values in between getting DOM of 1 as presented in Fig. 5. Table 2. provides clearance sets and ranges from "Very Congested" to "Very Clear".

Table 2. Clearance sets and ranges, taken from survey

Linguistic range	Very Congested	Congested	Moderate	Clear	Very Clear
Unit	Meter	Meter	Meter	Meter	Meter
Clearance	$X \leq 0.15$	$0.15 < X \leq 0.3$	$0.3 < X \leq 0.9$	$0.9 < X \leq 3.05$	$3.05 < X$

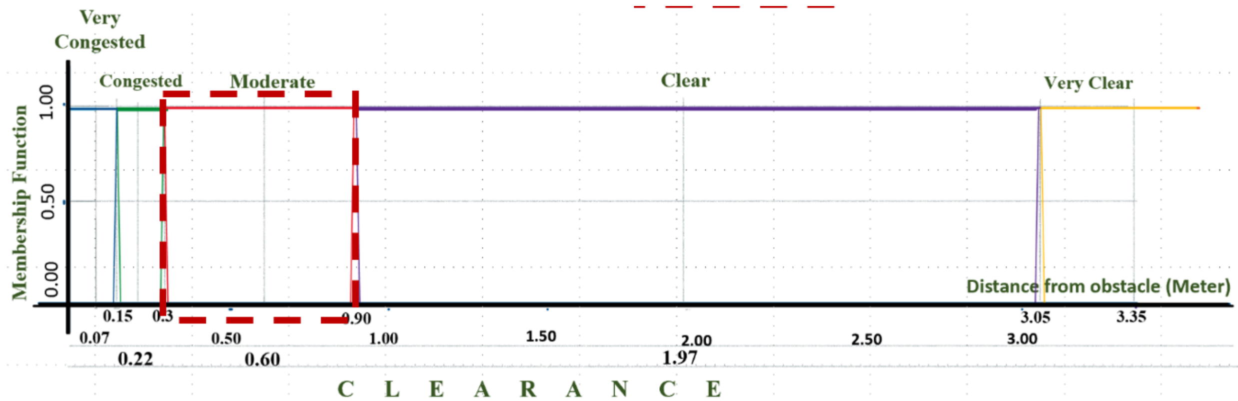


Fig. 5. Fuzzification of clearance classes

All influential factor functions need to be built in fuzzy logic to process the fuzzy logic system. However, wind paraments and the way their effect is used in crane motions need to be identified. To do so, a lift analysis is conducted as follows:

3.2 Lift Analysis

Calculating a mobile crane's cycle time of an operation within the context of heavy modular construction can be done if the satisfaction of the following criteria in terms of safety and efficiency is met.

i. Safety factor confirmation

ii. Crane capacity assessment

iii. Satisfaction of clearance

iv. Wind assessment confirmation

To have a complete lift analysis, different wind parameters within the crane realm need to be identified:

- $\boldsymbol{V_{Current}}$ which is the average wind speed at the height of 10 meters above the ground
- $\boldsymbol{V_{Max-TAB}}$ which is the average wind speed specified for the load values in the load chart
- $\boldsymbol{V_{Max}}$ which is the effect of wind speed based on a load's weight, shape, and dimensions according to the Eq. (3)
- $\boldsymbol{V_{final}}$ which is the checkpoint that if wind speed exceeds it, the operation is canceled. It is the minimum value of $V_{Max-TAB}$ and V_{Max}
- $\boldsymbol{V_Z}$ which is wind gust speed at the tip of crane boom [50].

In order to better understand the process of applying the identified wind parameters to the mobile crane, Fig. 6 illustrates the flowchart of steps that need to be taken.

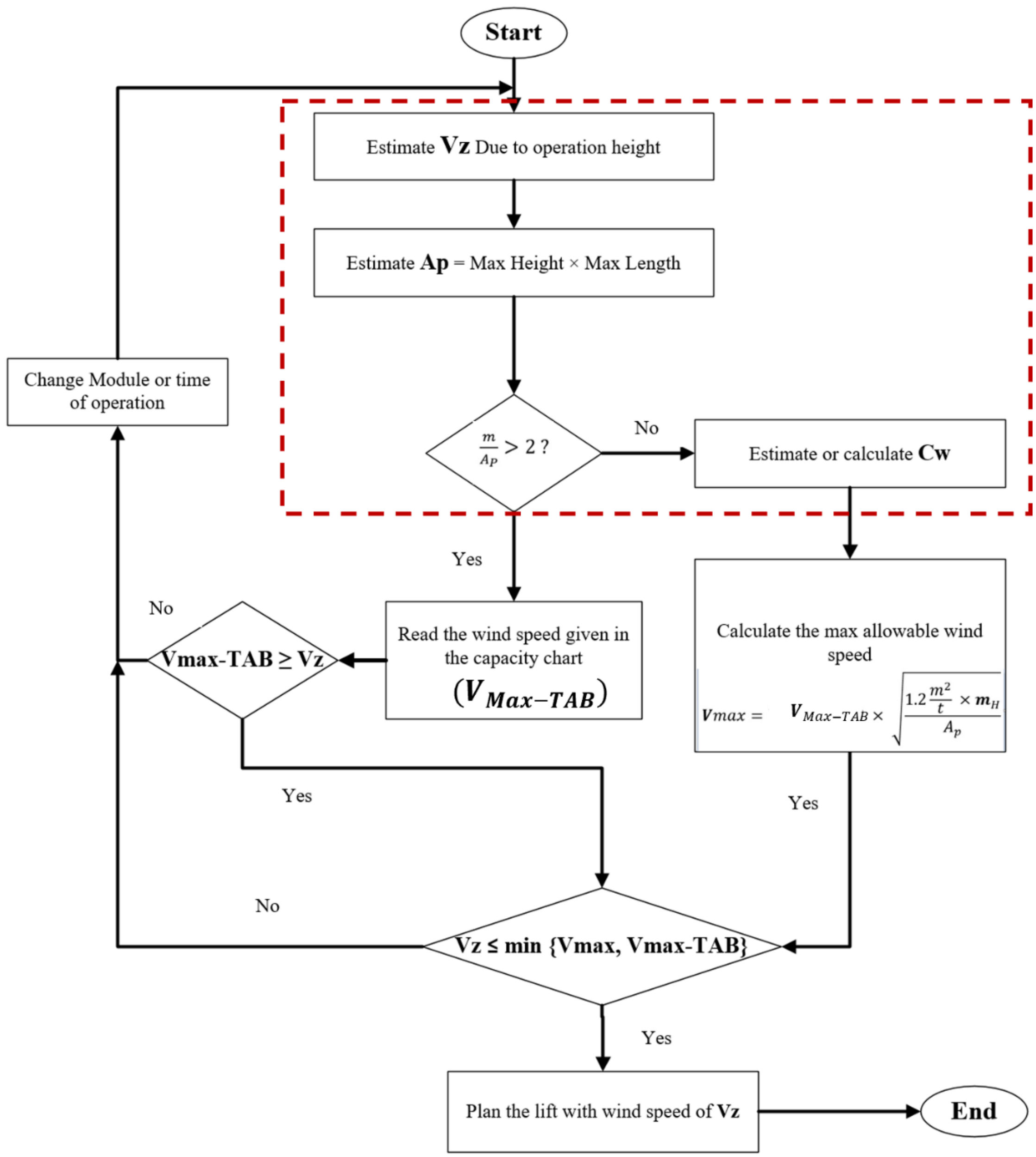


Fig. 6. Flowchart to determine the allowable wind speed

The present study assesses wind speed and its effect on motions as a factor in lift analysis; other factors (i.e., SFs, and collision-free paths) were already evaluated in the previous studies in detail [[2], [51]]. The crane wind assessment is mainly performed in two steps:

i. Calculating the maximum permissible wind speed for the selected crane.

ii. Measuring the maximum wind speeds at the highest boom tip throughout an operation.

Computing the maximum allowable wind capacity is carried out to determine whether the wind capacity setting obtained from the wind capacity chart of the crane would meet given constraints [50]. Manufacturer typically provides the wind capacity of a given crane based on different parameters (e.g., boom lengths, and standards) [50]. It indicates all permitted wind-related capacities; any wind blows during operation should be less or equal to the maximum permissible wind. The calculation of wind speed, taking to account the weight, dimensions of the load, the height at which the operation is performed, and the crane's wind chart, is done using the Eq. (3) [50].

$$Vmax = V_{Max-TAB} \times \sqrt{\frac{1.2\frac{m^2}{t} \times m_H}{A_w}} \quad (3)$$

Where:

- $\boldsymbol{A_W}$ is the surface area exposed to the wind (m^2) according to the module information
- $\boldsymbol{m_H}$ is the W_{Total}, including rigging system weight, hook block weight, lifted weight, and ropes weight according to the project database.

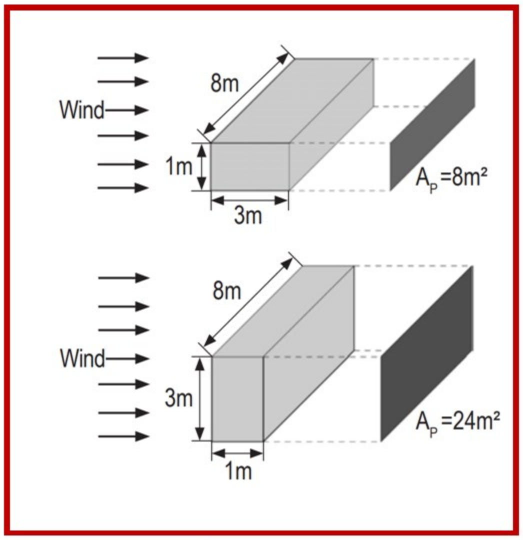
To calculate A_W, the value of A_p must be determined, which indicates the maximum projected surface area of the module to the wind. Fig. 7 illustrates the maximum projected area and drag coefficient of different shapes. Eq. (4) introduces the formula for calculating A_W.

$$A_w = A_P \times C_w \quad (4)$$

Where:

- $\boldsymbol{A_P}$ is the maximum projected surface area
- $\boldsymbol{Cw}$ is the coefficient of resistance, which is defined according to the lifted object shapes as shown in Fig. 7. The minimum value of $Vmax$ and $V_{Max-TAB}$ is considered as the checkpoint that no wind speed should exceed that during operation. It is calculated due to Eq. (5):

$$V_{final} = Min\left\{V_{Max-TAB}\ ,\ V_{Max-TAB}\ (\frac{1.2\ m_i}{C_{w.}A_p}) \times 1^{0.5}\right\} \tag{5}$$



Type of body		Drag coefficient C_w
Cube	D	1.05
	D	0.8
Solid hemisphere	D	→ 0.42 ← 1.17
Hollow hemisphere	D	→ 0.38 ← 1.42
Thin disk	D	1.1
Circular disk	D	20.4/Re 1
Sphere	D	24.0/Re 0.45 0.2
Streamlined body	l	0.04

Working height	Factors for available wind speed determined over a period of 10 minutes at a height of 10 m	Factors for available wind gust speed determined at a height of 10 m
10	1,400	1,000
20	1,502	1,073
30	1,566	1,119
40	1,614	1,153
50	1,653	1,181
60	1,685	1,204
70	1,713	1,224
80	1,738	1,241
90	1,760	1,257

Fig. 7. Maximum surface area presentation, *Cw,* and height adjustment coefficient

It should be noted that any wind speed associated with crane operations should pertain to wind gusts. Although cranes are equipped with an anemometer to measure the wind force flow, before any operation, the local wind measurement resources should be carefully evaluated for the following reasons [50]:

i. A crane's anemometer measures momentary wind force; however, for any lift operation, the wind speed should be considered throughout the operation.

ii. A crane's anemometer should not be considered fully reliable since it can have potential technical issues.

iii. It is essential to compare the crane's anemometer's wind speed with other local measurement resources to avoid unwanted errors.

Wind speeds are typically measured at the height of ten meters above the ground. Two steps must be taken to achieve a correct and reliable wind speed.

i. Calculate the maximum height of operation from ground level.

ii. Calculate actual wind gust speeds (V_z) due to operation's height by utilizing a wind gust table.

When heavy lifting is required, wind force at the boom tip should be considered as effective wind speed. Fig. 7 illustrates 3-second wind gusts and their height coeficient for calculating the (V_z) at the cranes' boom tip. In practice, wind information needs to be updated from reliable local resources or valid online websites such as www.windfinder.com. Lift analysis considers the module and crane information so that project personnel can better identify when wind errors occur. When the (V_z) or anticipated wind velocity levels exceed the acceptable value, three safer alternatives should be considered:

i. Change the time of operation so that the minimum of $\mathrm{V}_{Max}$and $V_{Max-TAB}$ is higher than V_Z.

ii. Select different modules that can be lifted with the existing wind speeds.

iii. Chang crane type with the higher wind speed capacity.

Prior to processing any lift operation, a complete lift analysis needs to be done according to the wind evaluation to ensure a safe and reliable operation.

3.3 Development of Wind Function

The wind has the most significant impact on a crane's operations [1]. To reiterate, this study is designed to assess cane operation from when the lifting work commences to the moment of load discharging. The survey indicates the wind sets and wind speed ranges of any sets. Outcomes organize the wind speeds (m/s) into five gradual sets, as shown in Table 3.

Table 3. Wind sets and their ranges, taken from the survey

Linguistic range	Very Weak	Weak	Moderate	Strong	Very Strong
Unit	m/s	m/s	m/s	m/s	m/s
Wind Speed	X ≤ 6	6 < X ≤ 8	8 < X ≤ 10	10 < X ≤ 14	14 < X

Any crane must cease operation when the wind speed exceeds a maximum defined value associated with a couple of factors (i.e., the manufacturer's specifications, standards, local job-site regulations, and safety issues [50], [52]). Two types of wind are recorded and registered in local wind logs: $V_{Current}$ and V_Z. Indeed, researchers have stressed the importance of monitoring V_Z during crane operations since it can either decrease crane motion speeds or, in severe cases, stop all operations [52]. As a result, V_Z is considered as a wind parameter pointed out in designed functions for wind during an operation as effective wind.

Moreover, Beaufort wind force scales are globally used to classify wind speeds based on visual estimation of the wind. Beaufort has 13 scales (i.e., calm wind scale, which is wind speed range 0-0.2 m/s, to hurricane wind scale, which is wind seed over 32.6 m/s). The maximum acceptable wind speed in the crane realm due to the survey ranges is lower than the upper threshold of the Beaufort scale 7. Survey wind speed sets are adjusted with wind speeds from scale 0 to scale

7 of Beaufort. The “Very Weak” set corresponds to the wind scale of 0 to 3 in the Beaufort scale. The rest of the survey sets correspond a scale from 4 to 7, respectively, as illustrates in Fig. 8.

Survey classification | **Beaufort Scale**

Very weak
Weak
Moderate
Strong
Very strong

Maximum acceptable range of wind

Beaufort scale	Class	Characteristics and impacts	Wind speed m.s^{-1}	km.h^{-1}	mile.h^{-1}
0	Calm	No wind, smoke billowing upright	0-0.2	1	1
1	Light Air	The direction of the wind is visible in the direction of smoke, there is no breeze	0.3-1.5	1-5	1-3
2	Light breeze	The wind felt on the face, the leaves lightly rocked	1.6-3.3	6-11	4-7
3	Gentle wind	The leaves and twigs continue to sway	3.4-5.4	12-19	8-12
4	Moderate wind	Dust and paper blowing, twigs and small branches sway	5.5-7.9	20-28	13-18
5	Fresh breeze	Small trees sway, white foam in the sea water	8.0-10.7	29-38	19-24
6	Strong wind	The big branches swayed, the sounds of the electric wire	10.8-13.8	39-49	25-31
7	High wind	The whole tree rocked	13.9-17.1	50-61	32-38
8	Gale	The branches of a broken tree, walking against the wind are quite heavy	17.2-20.7	62-74	39-46
9	Severe gale	The roof of the house is blown and thrown	20.8-24.4	75-88	47-54
10	Strong storm	Trees are uprooted, houses are severely damaged	24.5-28.4	89-102	55-63
11	Violent storm	Storm damage large areas	28.5-32.6	103-117	64-72
12	Hurricane force	Big trees uprooted, houses collapsed	>32.6	>117	>72

Fig. 8. Beaufort wind scale and corresponding survey sets

Wind speeds are highly variable and change dramatically over a short period of time. Therefore, assessing wind speeds because of the fluctuating nature of wind is complex. To overcome this limitation, and process the safest operation, the highest V_ZValue during an operation is applied in the designed fuzzy function. In modular-based heavy construction, cranes are routinely required to deal with large-sized modules in terms of dimensions and weights. Thus, based on the calculation of effective wind formulas on lifted loads, any changes in wind speed would have a considerable impact on crane loads [50]. Therefore, the selected function needs to reflect the sensitivity of crane speeds toward wind speed changes. As a result, in this study, different function forms, the triangular form is selected to construct the wind functions in fuzzy logic. To verify the precision of the triangular form of function while building the wind function, a verification process is conducted to test the effects of two types of functions (see Fig. 9). The triangular form of function leads to gradual changes in the motion speeds. In contrast, with the trapezoidal wind function, the DOMs is accorded unchanged value while wind speeds increase in part of wind different sets so that even though wind speeds are changing, changes in output motions' speeds (e.g., slewing) shifts only slightly or remains steady. In actuality, however, any change in wind speeds has the potential to change crane motions significantly.

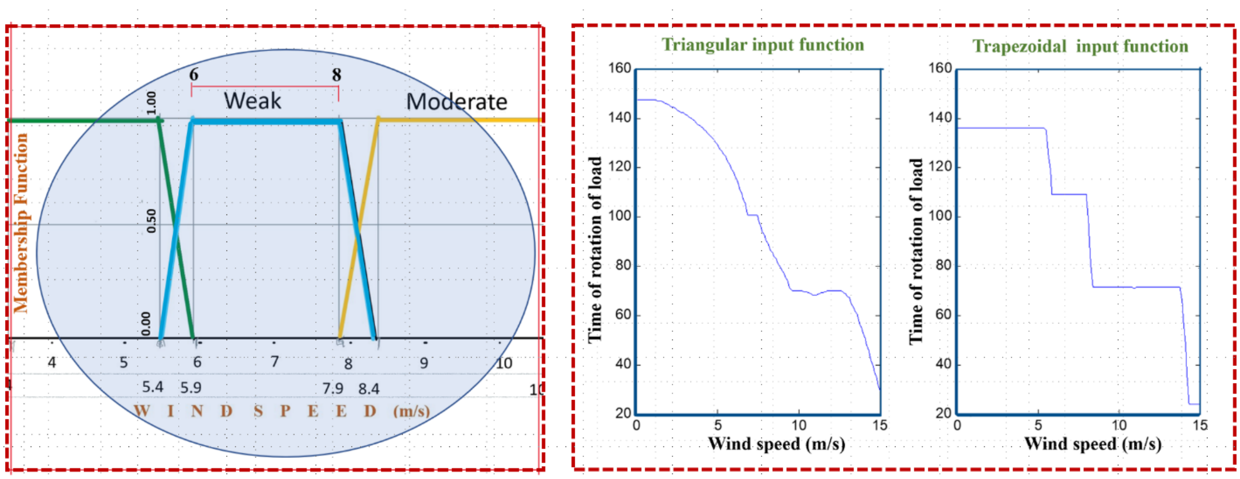


Fig. 9. Impact of the two DOMs presentation on output

For example, DOMs of wind speeds ranging from 6 (m/s) to 8 (m/s) are assigned a value of 1, which means that within this range, all winds would be considered absolute "Weak"; accordingly, its impact on output motions remains the same. In contrast, the sensitivity of crane motions' speeds in relation to wind speeds is significantly higher than remaining the same in 2 (m/s) of wind speeds. As shown in Fig. 9, data simulation indicates that motion changes (e.g., time of rotation of load) resulted from trapezoidal MFs of wind are stair shape while changes in crane motions are continuous, not stair changes.

To build-up wind function, the average value of the scale 3 (i.e., the upper Beaufort scale in the set of 0, 1, 2, and 3), which is 4.4 (m/s), is identified as the point at which any preceding values are assumed to be “Very Slow”. For the other sets, the mean value of sets corresponding to Beaufort scale ranges are calculated and selected to assign an MF of 1 As shown in Fig. 10 (e.g., 9.35, which is the mean of 8 and 10.70 in the scale five on the Beaufort corresponds “Moderate” in the survey). Since the vertex of the triangle that makes any set function gets the value of 1, two adjacent sets get the value of zero at this point according to the fuzzy logic regulation to build a linear function. This process continues to build all wind sets’ function as illustrates in Fig. 10.

Wind Set ID	**Set Ranges**	**Set Ranges**	**Mean Value**	**Lower Limit**	**Upper limit**
Scale source	Beaufort (m/s)	Survey (m/s)	Beaufort	Beaufort	Beaufort
Very Weak	3.40 – 5.40	$X \leq 6$	4.40	0.00	6.70
Weak	5.50 – 7.90	$6 < X \leq 8$	6.70	4.40	9.35
Moderate	8.00 – 10.70	$8 < X \leq 10$	9.35	6.70	12.30
Strong	10.80 – 13.80	$10 < X \leq 14$	12.30	9.35	15.50
Very Strong	13.90 – 17.10	$14 < X$	15.50	12.30	unlimited

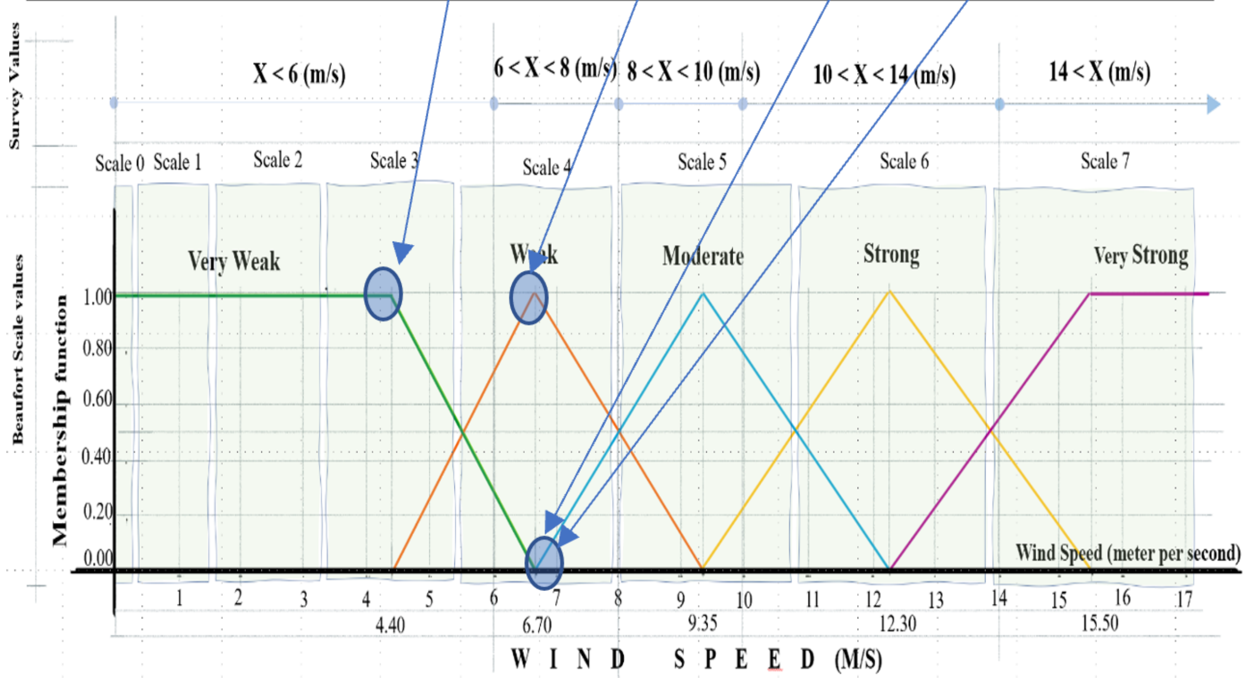


Fig. 10. MF of wind speed, presentation of Beauford scale values, and survey of corresponding values.

3.4 Model Expansion

Three variables (i.e., SF, wind, clearance) are selected to form functions of fuzzy logic inputs.

Maximum values of the operation SFs, maximum wind speed during operation, and minimum clearance value are pointed out to be applied in the designed functions to determine DOM values of any. To complete the model in fuzzy logic, output functions which are motion speeds and time of rotation of load, need to be designed. Fig. 11 illustrates the steps to be taken in the process of estimating the cycle time. In the fuzzy section, before inferencing system determination, building output functions and rule identifications are needed.

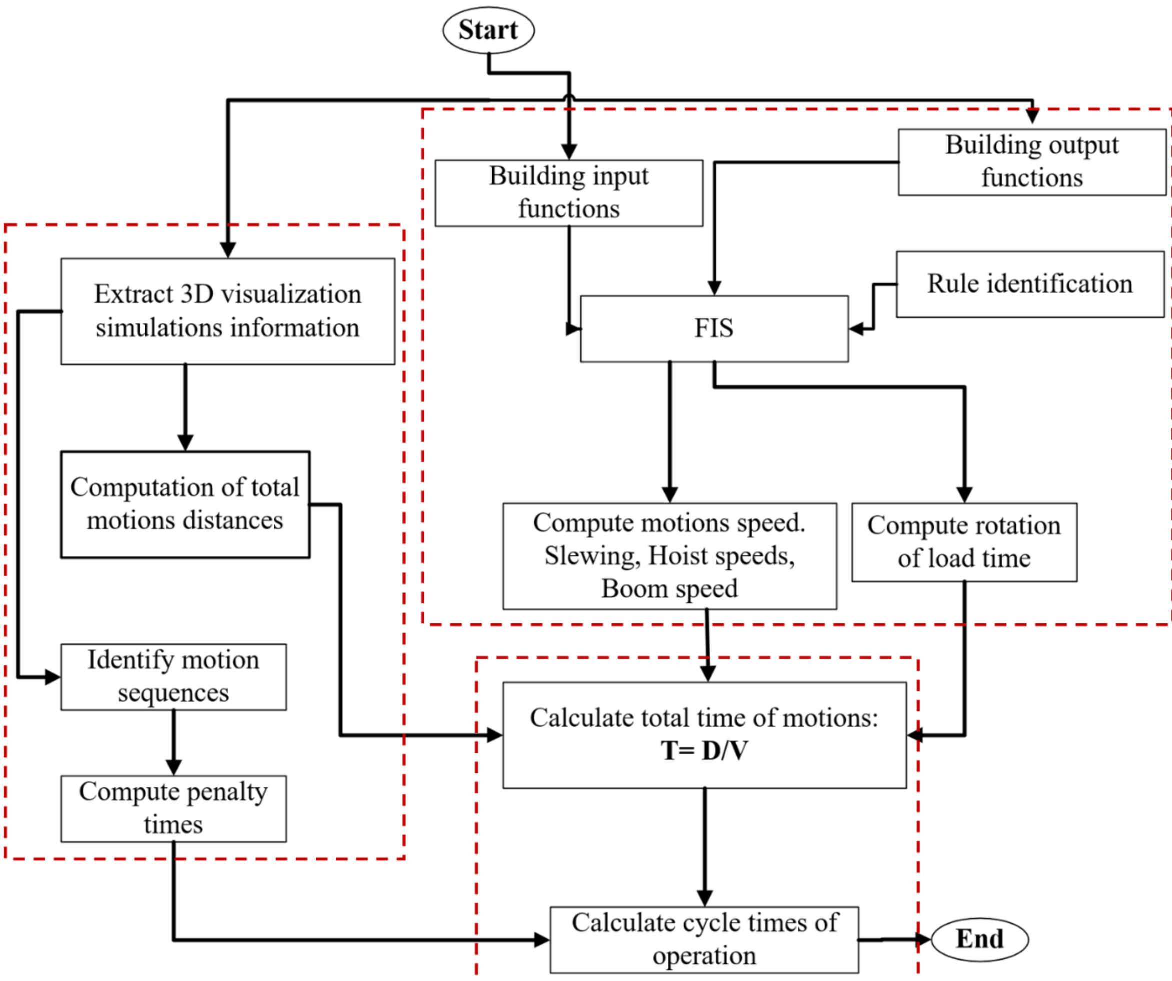


Fig. 11. Flowchart of steps to calculate the cycle time

Table 4. District boundaries of crane motions

		Motion Sets (Linguistic Values)				
		Very Fast	**Fast**	**Moderate**	**Slow**	**Very Slow**
Crane Motions	**Slewing Angles (% of rpm)**	>70%	60% - 70%	40%-60%	20%-40%	<20%
	Boom up (% of m/min Winch speed)	>90%	60% - 90%	40%-60%	10%-40%	<10%
	Boom down (% of m/min Winch speed)	>90%	60% - 90%	40%-60%	10%-40%	<10%
	Hoist up (% of m/min Winch speed)	>90%	60% - 90%	40%-60%	10%-40%	<10%
	Hoist Down (% of m/min Winch speed)	>90%	60% - 90%	40%-60%	10%-40%	<10%
	Rotation of load (Min)	< 4	4 < X < 8	8 < X < 14	14 < X < 20	20 < X

All motion speeds follow the speed velocity profile, involving the determination of (1) acceleration, (2) maximum velocity, (3) deceleration, as shown in Fig. 12 [53]. All cranes are equipped with an anti-swing system to control their movement to avoid oscillation in the lifted load, particularly at the start or stop point of the motion to overcome inertia [54]. It does not matter how fast an operator presses the lever or joystick; the motion control system applies its anti-swing system to achieve the operator's desired speed. After overcoming the initial inertia, the motion continues at a stable speed [53]. With some joysticks, the operator can select different speeds using a gearing method, enabling the operator to select and jump from speed to speed—higher or lower. For this study, to avoid the complexity effect of acceleration and deceleration, the motion speeds are deemed stable; thus, motions' average speed is taken into account.

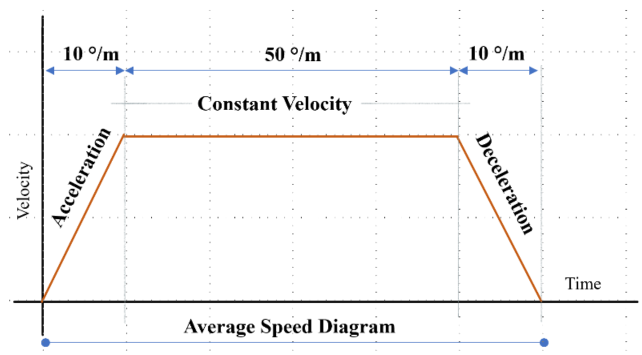


Fig. 12. Speed velocity profile [14]

To build up six motion functions (i.e., boom up/down, slewing, hoist up/down, time of rotation of load) in fuzzy logic, survey ranges are used, which illustrate in Table 4. The survey determines linguistic sets and their correspondent ranges. The motions in cranes are usually achieved using levers or joysticks. In some cranes, motions can also be accomplished by manually entering the desired numerical speeds. This practice implies that even though motions change gradually. However, they follow the trapezoidal form of the speed velocity profile. For example, five first and last seconds of any motion operation, the crane is increase and decrease the motion speed respectively; however, for the rest of the time of motion operation, the speed remains steadily at its highest acceptable speed. According to this argument, in part of any set of a motion, the sets' DOM is 1. therefore, the DOM of 1 happens at more than one point. As a result, the function form for motion speeds is trapezoidal. For instance, any speed from 45 to 55 percent of the maximum slewing speed should be considered absolute "Moderate". For presenting the motion functions of sex motions, the same logic would be applied. For all six motions in mobile cranes, five sets are determined to represent a specific speed range according to the percentage of maximum speed. It should be noted that the manufacturers of mobile canes determine the maximum speed for any motion (e.g., 0.7 (round per minute) RPM for slewing angle). For instance, for 40% to 60% for moderate ranges of slewing, it is calculated that the slewing speed ranges are 0.28 RPM to 0.42 RPM if the maximum manufacturer speed is 0.7 RPM. In other words, slewing movement speed can range from 100.8° to 151.2° per minute.

Fig. 13 illustrates the final designed form of output functions which is trapezoidal for all motions. These functions are used in the fuzzy logic system to decide the behaviour of motion speeds toward input variables.

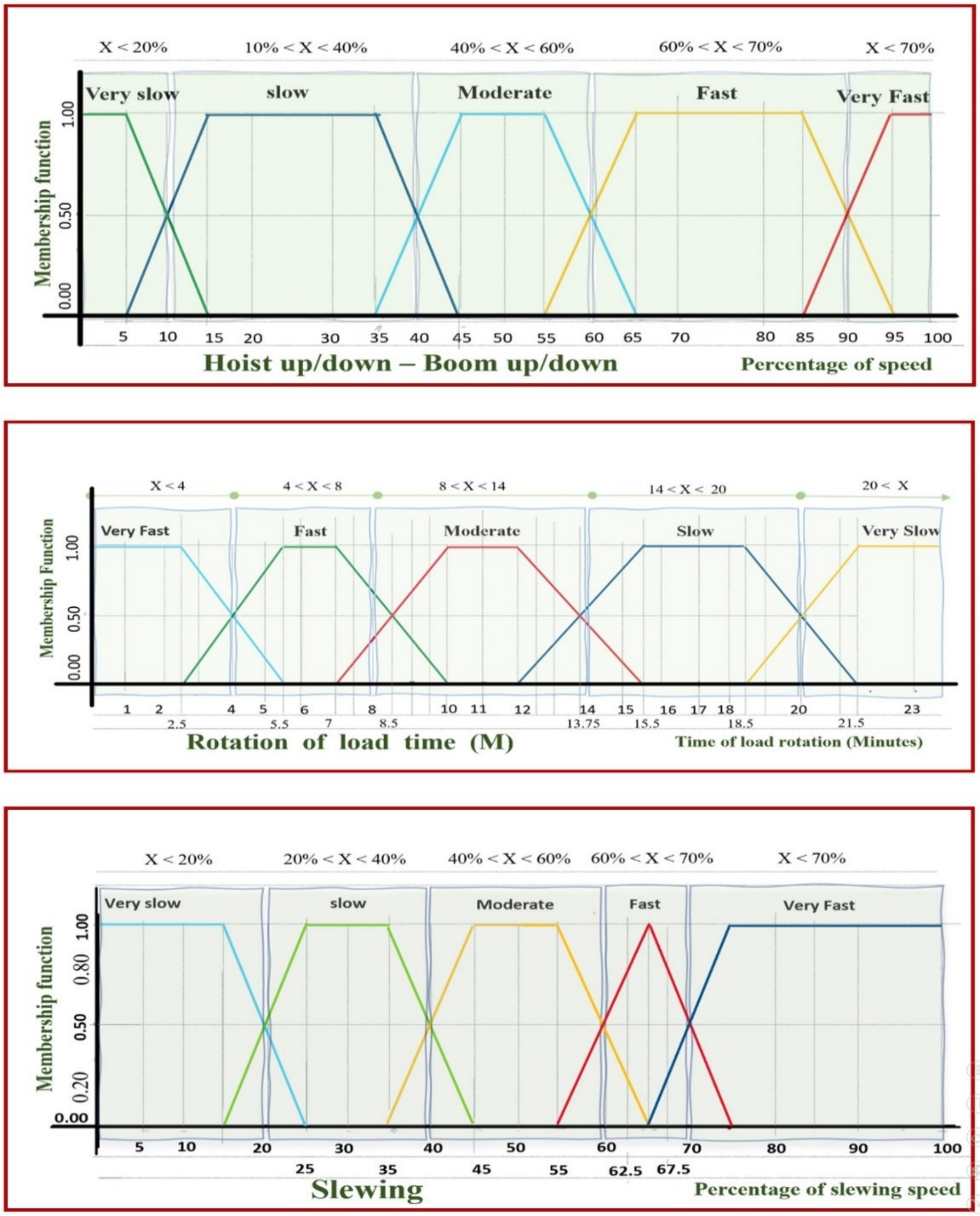


Fig. 13. Fuzzy logic-based functions of time-consuming motions.

3.4.1 Motion Matrix

The survey identifies 125 if-then rules that show the relation among inputs and outputs for any motion. Since there are six motions to be evaluated, 750 rules are identified, covering all possible moods of rules that determine relationships among inputs and outputs variables. For example, if SF is “Light”, and wind is “Strong”, and clearance is “Congested” then slewing speed is “Slow” as illustrates in Fig. 14.

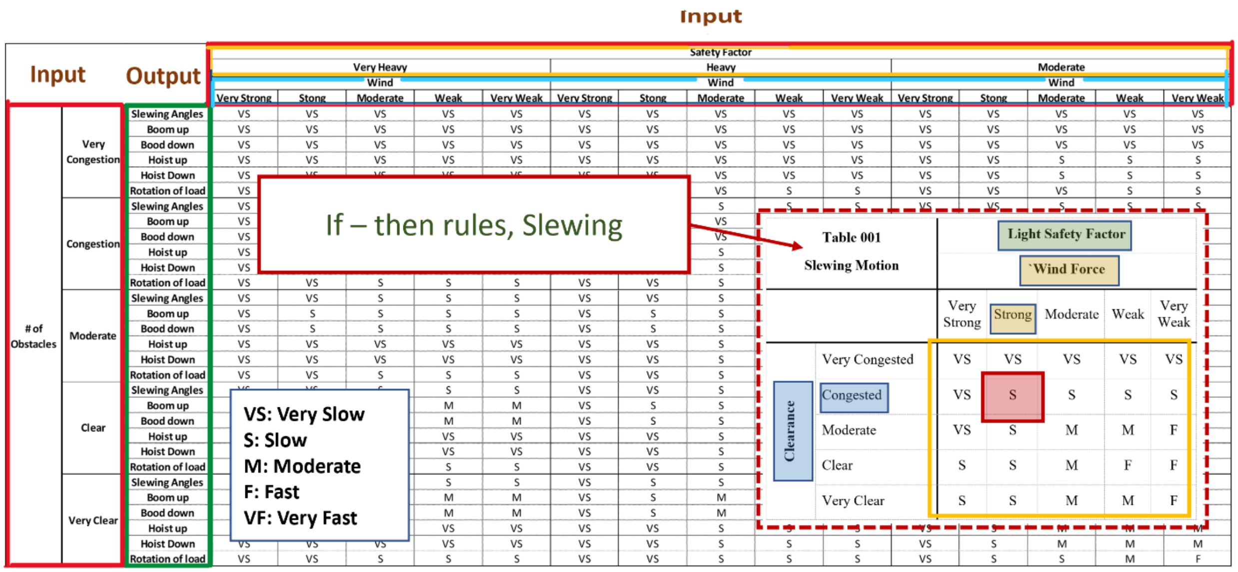


Fig. 14. Presentation matrix for if-then rules-illustration of slewing motion

This means that slewing should be at the range of 20% - 40% of the maximum speed due to survey ranges presented in the Table 4. Since the if-then rule outcomes are a range of crane motion speed which is a linguistic value, mining a single value is needed by defuzzification of result. To do so, the Mamdani inference system, which is using the T-norm and centroid method, is applied. This process is illustrated in Fig. 15 and Fig. 16. T-norm method is applied in which selection of the smallest operator value of input aggregation is used to accomplish the process of a fuzzy logic system. In addition, the centroid method to compute the DOMs aggregation is utilized in defuzzification. All steps are designed and written using MATLAB programming as part of the study completion.

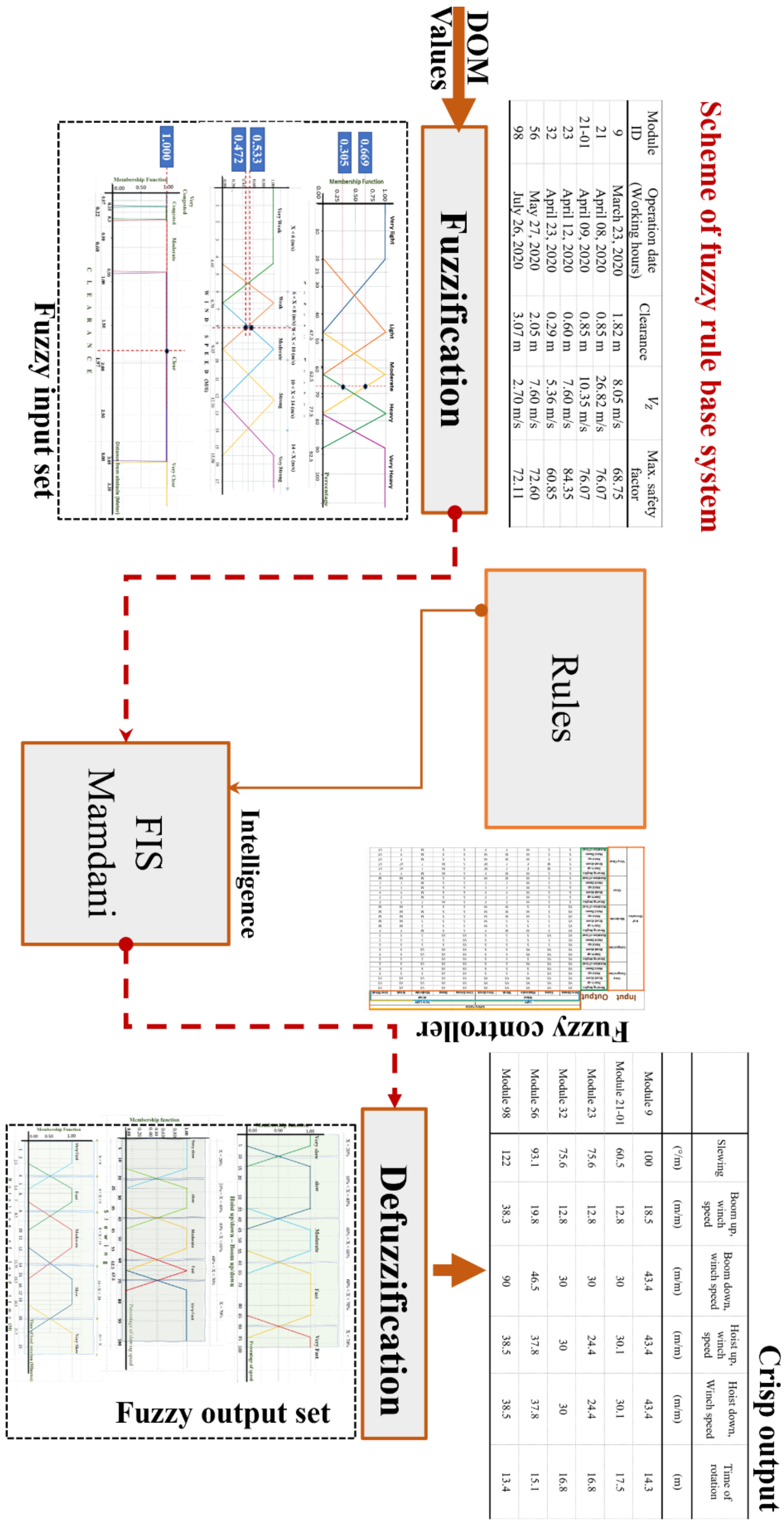


Fig. 15. Fuzzy logic diagram process considering three inputs and six output motions

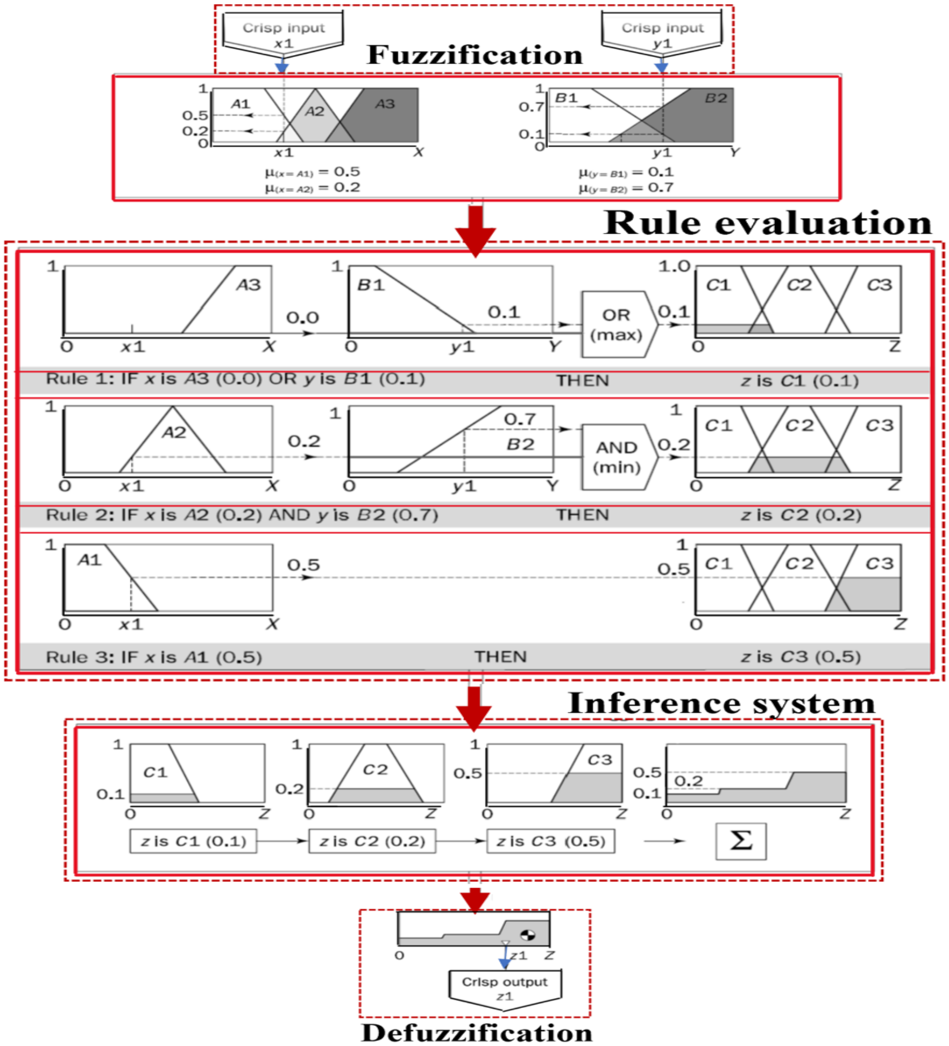


Fig. 16. Steps in applying fuzzy logic using Mamdani and centroid technique

3.5 Time Computation

To calculate cycle time of crane operation by utilizing fuzzy logic approach, which estimates motion speeds, and 3D visualization of operation, which measures the motion relocations, the following steps are implemented:

i. Develop a motions' matrixes in which by using if-then rules degree of efficacy of inputs are determined on outputs

ii. Select proper inference techniques for interpreting input data and distribute rules on output data by considering output data functions

iii. Measure the position change for motions during operation

iv. Measure radius of operation and boom length

v. Record the sequences of motions engaged in the operation.

After having the mentioned information, the time calculation of the operation is done. In physical quantities and units, time is calculated by measuring the change in position of an object divided by the speed of position changing. In the process of this study, by utilizing a fuzzy logic algorithm, crane motion speeds are calculated. To complete the distance measurement, a 3D evaluation of motions is utilized. Therefore, the time is calculable by applying the two obtained values. In addition, it should be noted that during a crane operation, the number of switching times from one motion into another motion called (penalty time (T_P)) should be considered in the cycle time of operation. Studies have investigated T_P between crane different motion changes, as shown in Table 5. A modified version of penalty time has been provided by Han (2014) [12]. Adding penalty time calculated by the provided table with the time calculated by utilizing 3D evaluation with fuzzy logic is resulted into the total time of operation. This process illustrates in Fig. 17 as a flowchart.

All operations are visualized using the 3Ds-max application. Information obtained from the 3Ds-max simulations indicates motions' distances in either meters or degrees of movement depending on the linear or rotational nature of the movement. In all cases, penalty time is calculated due to the number of motion changes and the sequences of motions. Aggregation of all data results in a crane's cycle time. All data processing is done by utilizing Fuzzy-MATLAB programming.

Table 5. Modified Penalty time for switching between motions [[2], [55]]

Crane motion	Boom up or down	Slewing	Hoist up	Hoist down
Boom up or down	0.00	0.75	1.00	0.50
Slewing	0.75	0.00	0.50	0.75
Hoist up	0.75	1.00	0.00	0.00
Hoist down	0.50	0.75	0.00	0.00

Note: Unit is minute.

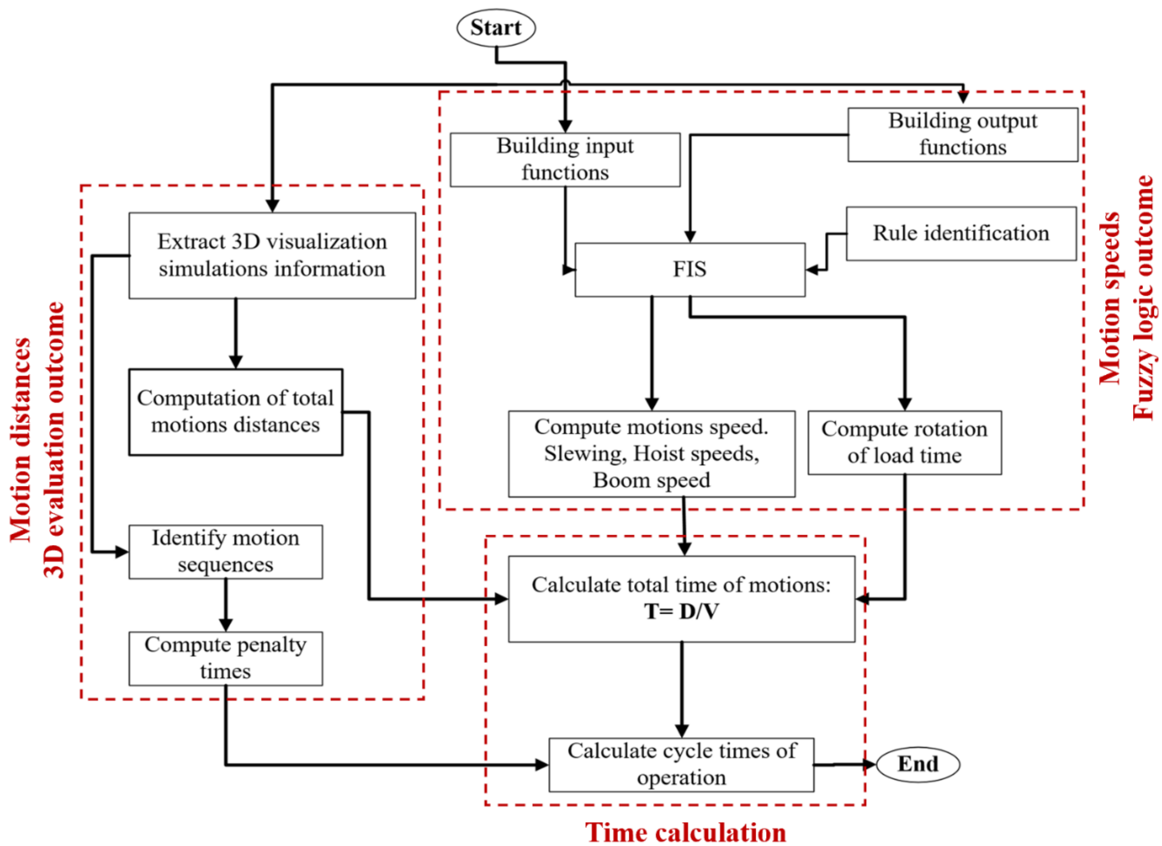


Fig. 17. Flowchart of cycle-time computation process

Chapter 4: Case Study.

To validate and demonstrate the effectiveness of the methodology's process and its components, 6 cases of crawler crane operations out of more than 200 operations are selected from a modular-based construction project by PCL industrial management Inc., in Alberta, Canada. In heavy industrial projects, modules are prefabricated off-site in factory environments and are transferred on-site to be installed by cranes.

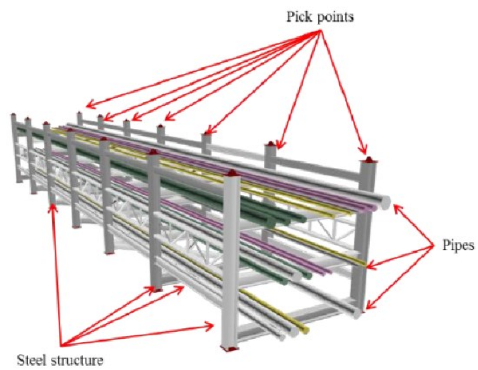


Fig. 18. Typical Pipe rack module [12]

As illustrated in Fig. 18, pipe rack modules include steel structure, pipes, and pick points to connect and disconnect the rigging system to lift the module. Modules will be considered box-shaped in this study because of their quasi-box shapes and to avoid complex calculations. These assumptions are to help to assess and analyze the wind effect on the module. Due to the proposed methodology in this study, all operations being investigated are from crane fixed positions (CFPs). The crane path checking (i.e., clearance) and three-dimensional (3D) evaluation simulation developed respectively by lei et al. [9], and Han et al. [2], are used to select crane locations, motions' sequences, measurement of motions' movements, determining clearance values, and determining safety factors (SFs) in operations.

The crane selected is the Demag CC 2800 crawler crane equipped with 660 imperial ton super-lift, a lattice boom length of 84 m (276 ft), and the super lift counterweight length of 15 m (49 ft). The module information and site layout come from a Microsoft Excel file readable by MATLAB programming as the initial platform for calculations. Dimensions of all modules are unique as 5.99 × 29.99 × 6.74 m, and the weight of the modules ranges from about 215 metric tons (MT) to 343 MT. According to the different classes identified in this study, clearance takes any value of 0.075 m to over 3.05 m. In practice, lift engineers provide input data such as allowable SFs, allowable wind speed, and minimum clearance values. Based on the crawler crane specifications, as shown in Fig. 19, the maximum motion speeds, including slewing speed, the boom up and down winch speed, and the hoist up and down winch speed, are calculated in the model and considered as input data in MATLAB. All data processing and software evaluations are done on a laptop with an intel® core(TM) i7-8650 CPU @ 1.90GHz. All necessary information for the identified crawler is illustrated in Fig. 19.

Both the crane specifications and the survey record the boom and hoist speeds based on their winch speed. In this study, in favour of computing the motions' times, since the load relocation speeds depend on the number of hoisting ropes, Eq. (6) is used to calculate the load relocation speeds.

$$Laod/boom\ movement\ speed\ (\frac{m}{m}) = \frac{Winch\ rotational\ speed\ (\frac{m}{m})}{Number\ of\ pulling\ lines} \qquad (6)$$

For instance, for a 120 meters per minute (m/m) winch speed with four rope lines, the load movement is 30 (m/m).

Load radius	Boom length (m)						Boom angle (°)
	24	36	48	60	72	84	
6	600						
7	561	567					
8	506	499	494				
9	410	407	405	404			
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
12						212	81.80
14						181	80.40
16						145	79.02
18						120	77.62
20						101	76.70
22						86	74.82
24						74.5	73.34
26						65	71.10
28						57	70.53
30						50	69.08
34			[illegible]	[illegible]	[illegible]	39.1	66.13
38			39.9	38.7	33.8	30.5	63.11
42			34.1	30.2	27.2	23.8	60.00
46				25.1	21.9	18.4	56.80
50				21	17.6	14	53.47
54				17.8	14.1	10.4	50.00
58					11.2	7.4	46.33

Mechanisms	Speed	Single line pull	Hoist rope length	Rope Diameter
Hoist 1	Max. 120 m/min	16519.83 kg	900 m	28 mm
Hoist 2	Max. 120 m/min	16519.83 kg	900 m	28 mm
Boom derrick	Max. 120 m/min	-	800 m	28 mm
Boom hoist	Max. 52 m/min	-	2 × 275 m	30 mm
Slewing (RPM)	Max. 0.7 1/min	-	-	-
Driving speed	Max 1.2 km/h	-	-	-

Note: Speeds of boom and hoist are based on the top layer of the winch pully.

Fig. 19. Load capacity chart, Demag CC- 2800, crawler crane- motor speeds specifications

MATLAB serves as the initial platform for the implementation of the methodology.

In terms of SFs, data retrieved from a study of a three-dimensional-base crane evaluation system (3D-CES) developed by Han et al. [2] is used to filter the responsive operations of modules so that all selected operations are feasible scenarios. Thereafter, this research points out the SFs of the built membership functions (MFs) in fuzzy logic to determine the SFs degree of memberships (DOMs). Module lifting has different SFs during the operational time, resulting in altering load radiuses required to accomplish the operations[2]. It should be noted that the maximum created safety factor in operations is applied in the fuzzy logic function since it gives the safest operation. Table 6 presents the maximum SFs for operations of module IDs 9, 21, 23, 32, 56, and 98 according to the crane's total weight (W_{Total}) and gross capacity (GC). Fig. 20 presents an indication of the DOM of module 9's SF. The crawler crane is positioned at the start points (SPs) of the crane from CFPs in the database to perform operations. Due to equal module sizes and connection point numbers, in all operations, rigging system weight (i.e., the weight of the hook, slings, spreader bars, and hoist ropes) is assumed to be 26799 kgs. Fig. 23 and Fig. 24 illustrate module 98's operation process by considering the motions' sequences.

Table 6. Maximum SFs of 6 module operations

Module ID	Weight of payload (kg)	W_{Total} (kg)	Radius of operation (m)	GC kg	Safety factor %
9	343252.35	370051.35	27.4	538200	68.75
21	313925.85	340724.85	36.2	447900	76.07
23	327222.00	354021	39.9	419700	84.35
32	215560.80	242359.8	42.1	398300	60.85
56	318776.85	345575.85	33.80	476100	72.6
98	338379.30	365178.3	30.14	506400	72.11
32 - 001	0.00	26799	42.1	398300	6.72

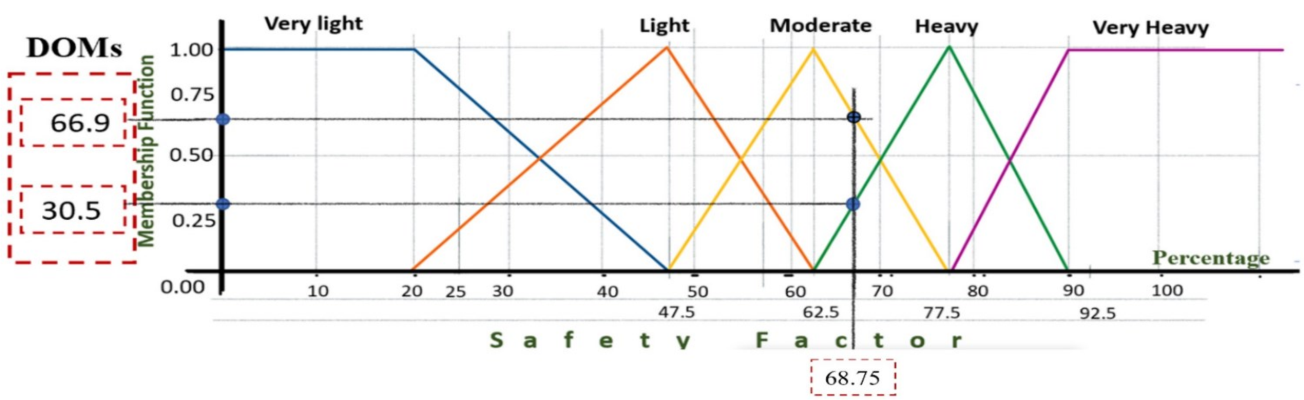
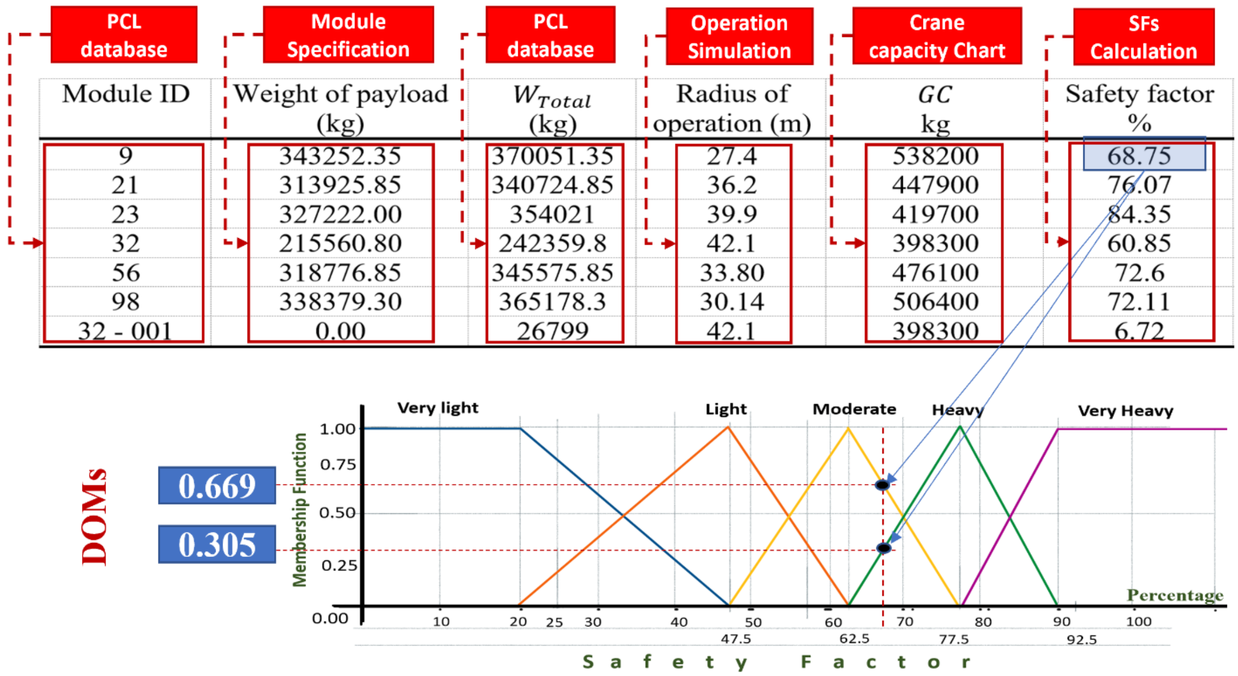


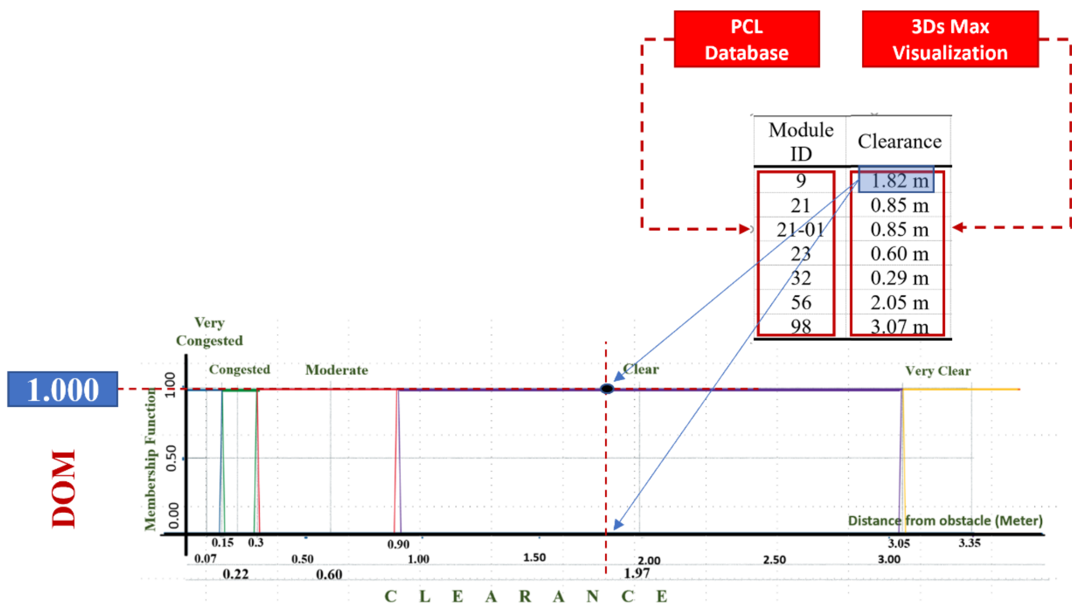
Fig. 20. Illustrating the safety factor value and DOMs for Module ID 9.

Moreover, to calculate the clearance of the operations, due to measurements from 3D evaluation of any operation, the values are calculated and entered the Microsoft Excel. Fig. 21, and Fig. 22 illustrate designed functions. Theses also show the sources of any part of the information which is used to calculate the values.



Module ID	Weight of payload (kg)	W_{Total} (kg)	Radius of operation (m)	GC kg	Safety factor %
9	343252.35	370051.35	27.4	538200	68.75
21	313925.85	340724.85	36.2	447900	76.07
23	327222.00	354021	39.9	419700	84.35
32	215560.80	242359.8	42.1	398300	60.85
56	318776.85	345575.85	33.80	476100	72.6
98	338379.30	365178.3	30.14	506400	72.11
32 - 001	0.00	26799	42.1	398300	6.72

Fig. 21. DOM calculation of SF by applying calculated SF value into designed function



Module ID	Clearance
9	1.82 m
21	0.85 m
21-01	0.85 m
23	0.60 m
32	0.29 m
56	2.05 m
98	3.07 m

Fig. 22. DOM calculation of Clearance by applying measured clearance value from 3D evaluation into designed function, module 9

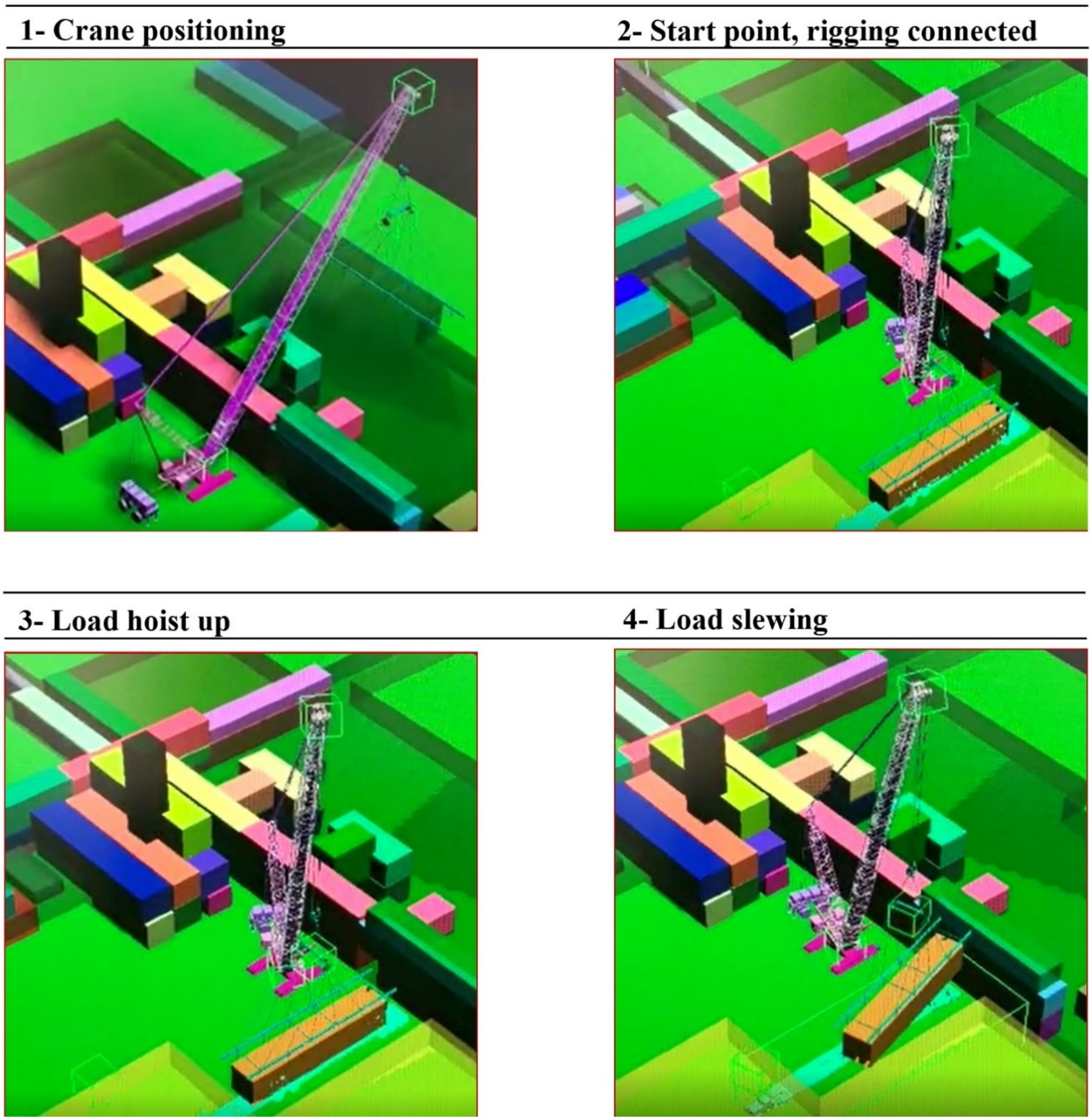


Fig. 23. Operation of module ID 98, including seven sequential motions.

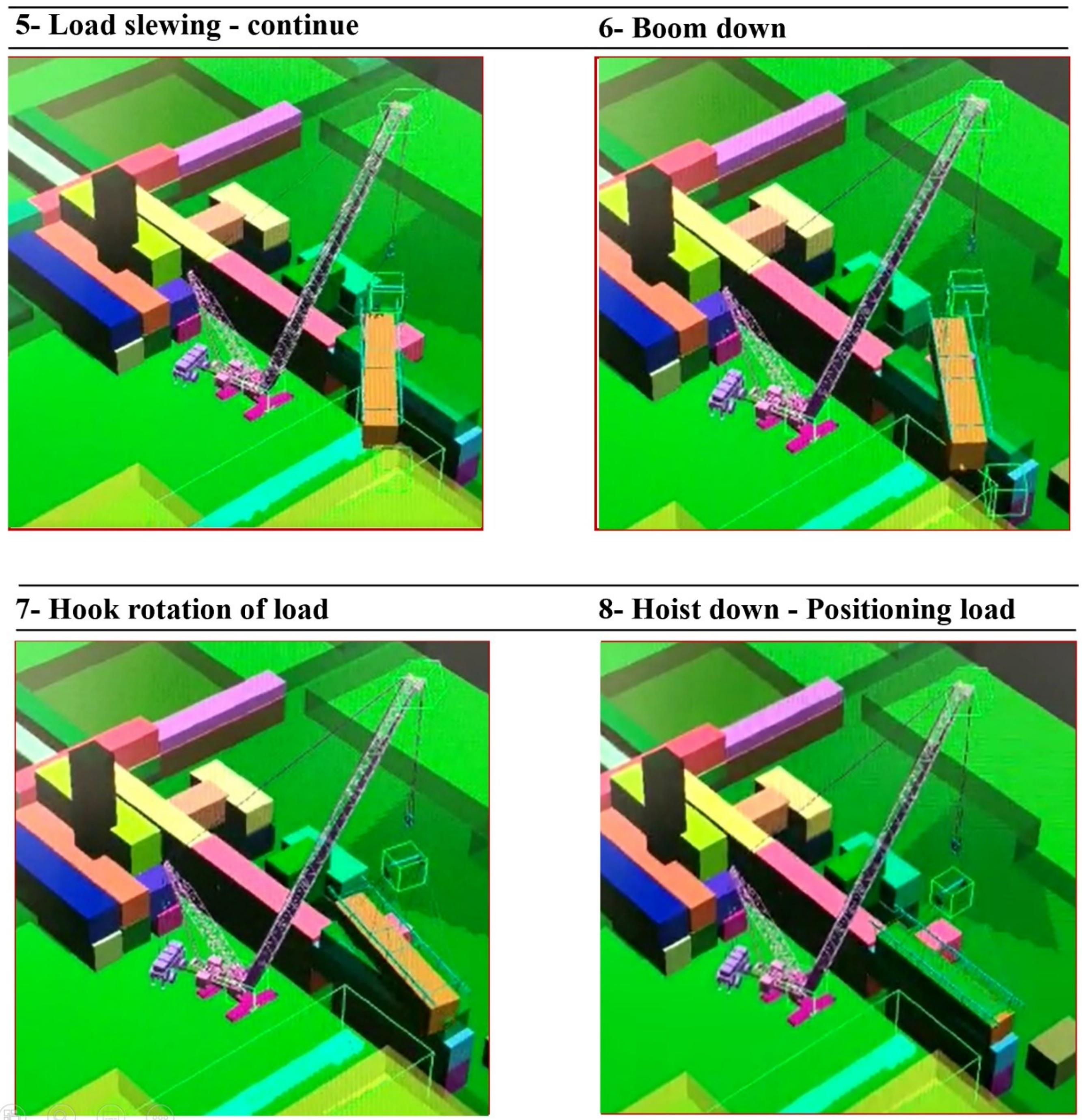


Fig. 24. Sequences of operation of module ID 98

In practice, wind prediction is assessed for the whole duration of a lifting operation [50]. Afterward, maximum wind speed is implemented during the operation time. For calculation of motions' speeds of single crane operations, the following steps are needed:

i. Selecting acceptable operations in terms of SFs according to SF calculation. Feasible operation data is saved in Microsoft Excel software

ii. Taking the maximum safety factor value of module lifting throughout the operation from the pick point to the position point

iii. Measuring minimum distance of crane configuration from existing obstacles during any single operation

iv. Considering maximum wind speed during the operation time due to wind prediction of the operation day

v. Calculating of maximum working height due to the boom length and working radius at operation and determine effective wind by considering wind height coefficient as shown in Table 7

vi. Checking the Actual wind (V_Z) with the maximum allowed wind speed (Vmax) and wind speed of crane capacity chart ($V_{Max-TAB}$)

vii. Pointing out the safety factor value, the wind speed at the boom highest point (V_{act}) value, the clearance value into the fuzzy logic functions in MATLAB

viii. Apply rules between input variables and motions according to the prepared speed rule's matrix

ix. Identifying fuzzy inference system (FIS) to interpret rules by considering input variables.

Table 7. Maximum $V_{\max\_TAB}$ Corresponding to the crane boom length, Demag CC-2800

Min boom length	$V_{\max\_TAB}$	Permitted dynamic pressure
(m)	(m/sec)	(N/m2)
Up to 36	15.0	140
42-66	13.8	120
72-84	11.3	80
Above 84	9.8	60

All six lifting operations in this study are scheduled from March 23, 2020, to July 26, 2020. Working hours are considered from 8:00 AM to 5:00 PM. In practice, crane managers or engineers need to update wind current speed ($V_{Current}$) and define maximums by acquiring data from the closest local wind prediction sources. Table 8, and Table 9. show the corresponding $V_{Current}$s and gust wind (V_Z) during the operation date and working hours for 6 cases. In addition, Table 10 shows different wind speed types which need to be considered in cranes. To calculate the V_Z, Eq. (7) is applied:

$$V_Z = V_{Current} \times working\ height\ coef\ factor \tag{7}$$

Where:

- $\boldsymbol{V}_{Current}$ is the wind gust speed value at the height of 10 meters above ground according to the local wind speed prediction.

Table 8. Daily prediction of wind speed and working hours. (www.windfinder.com)

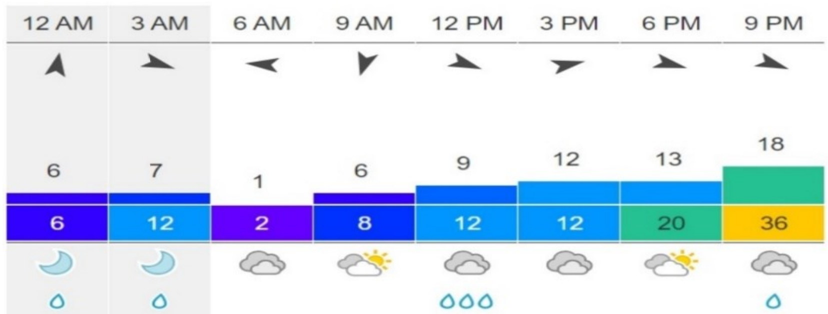
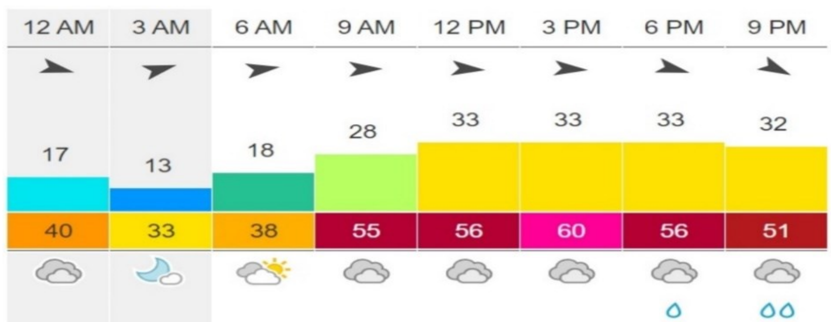
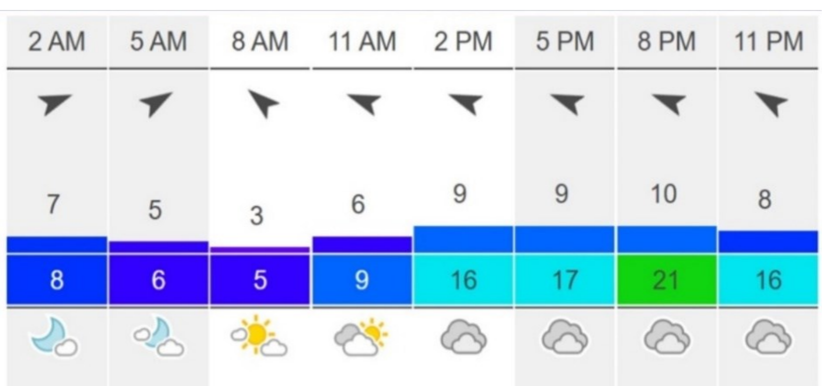
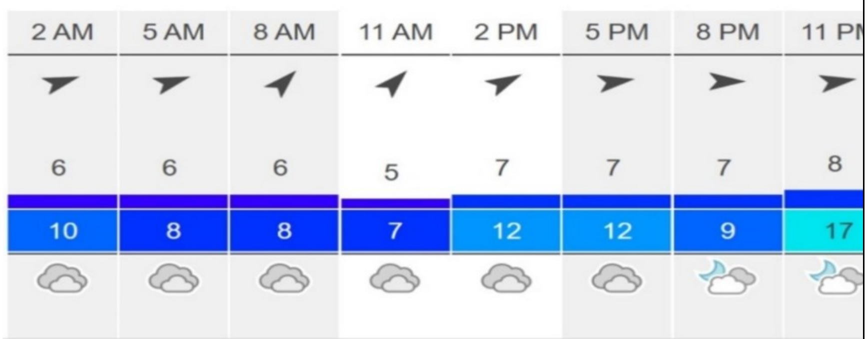
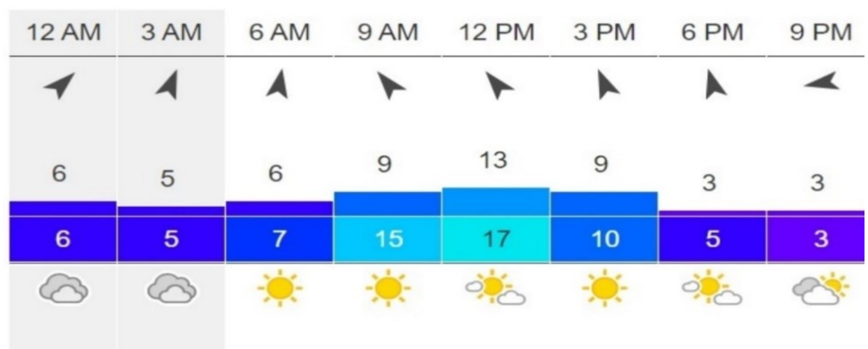
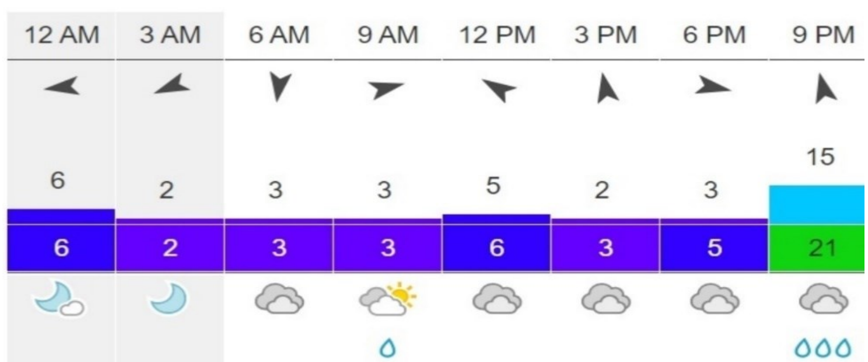
Module no	Operation date	Max. wind (m/s)	Wind prediction
9	March 23, 2020	8.05	
21	April 08, 2020	26.82	
23	April 12, 2020	7.60	

Table 9. Daily prediction of wind speed and working hours. (www.windfinder.com)

Module no	Operation date	Max wing (m/s)	Wind prediction
32	April 23, 2020	5.36	
56	May 27, 2020	7.60	
98	July 26, 2020	2.70	

To assure the safe operation, wind calculation needs to be done by considering the shapes and dimensions of modules and comparison with the values from closest wind prediction centres. The maximum surface area exposed to the wind between 2 values of the module dimensions will be selected, 202.132 m. According to the drag coefficients and based on Eq. (6) and Eq. (7), the V_{max} value is calculable for the modules, presented in Table 10. Based on the crawler crane specifications, $V_{max-TAB}$ for an 84 meters boom should be less than 11.3 m/s. As shown in Table 11, unless V_Z for modules 21, which exceeds the permissible value of wind, in comparison with $V_{max-TAB}$ and V_{Max} , all other operations are allowed. In this case, the operation is deemed to be canceled and shifted to another time of operation is decided in which the V_Z is less than or equal to the minimum of $V_{Max-TAB}$ and V_{Max}.

In the executive phase of projects, to update all information regarding the SFs and wind values, new information according to the lift analysis toward the wind effects must be updated and saved in databases.

Table 10. Wind calculation to determine allowable wind and applicable wind for fuzzy logic

CC-2800 Crawler crane

Module ID	Vmax-TAB	Vmax (m/s)	Working height (m)	Height coef	$V_{Current}$ (m/s)	V_Z (m/s)
9	11.3	16.75	72.53	1.224	6.58	8.05
21	11.3	16.06	78.73	1.241	21.61	26.82
23	11.3	14.95	76.85	1.241	6.12	7.60
32	11.3	12.37	75.63	1.241	4.32	5.36
56	11.3	14.20	79.82	1.241	6.124	7.60
98	11.3	14.60	81.34	1.241	2.176	2.70

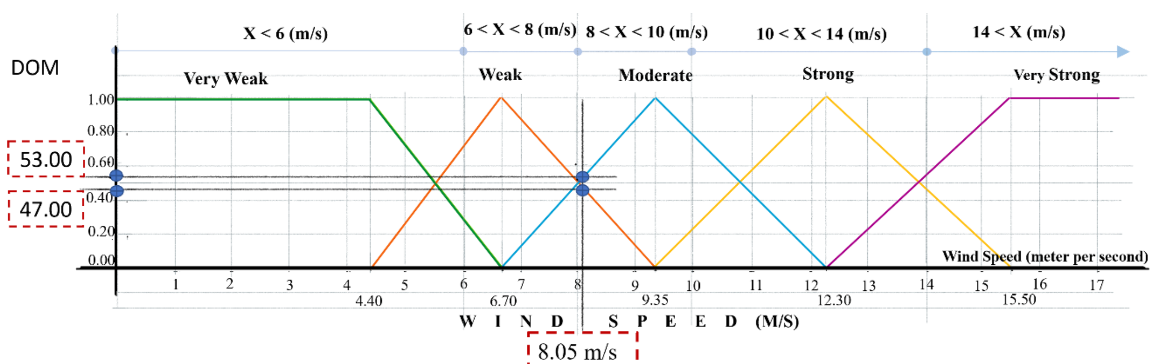


Fig. 25. DOM of wind, module 9.

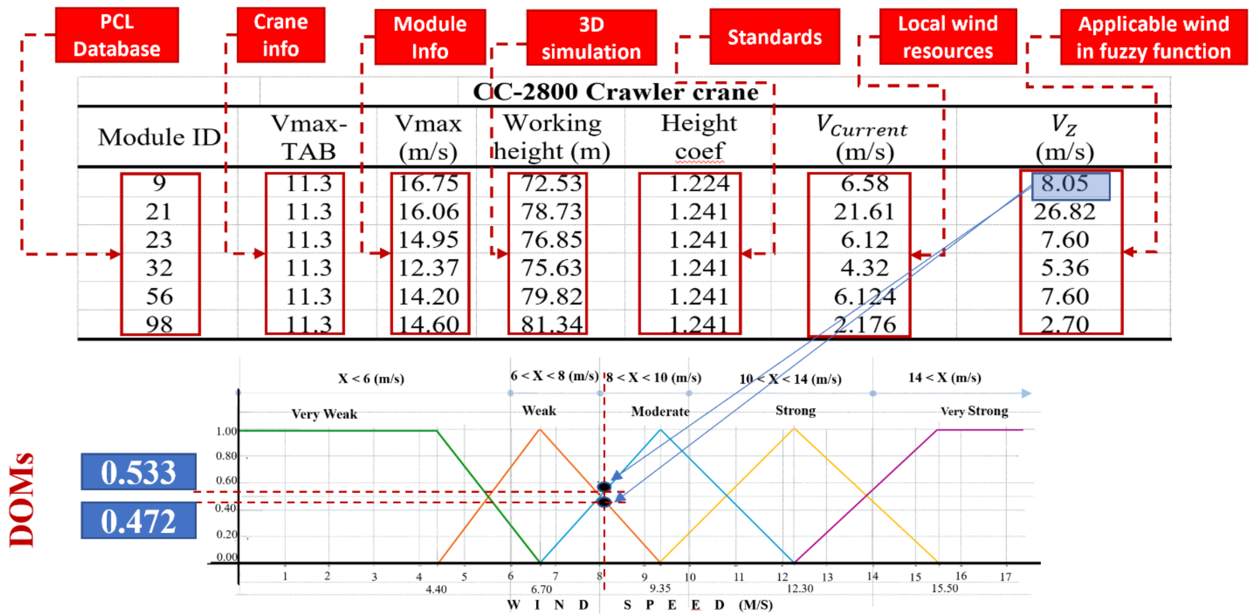


Fig. 26. DOM calculation of wind by applying V_Z value into designed function, Module 9

Table 11 illustrates calculated input variables (i.e., wind speeds, safety factor values, and clearance values), applied in the fuzzy functions to determine the DOMs.

Table 11. Input variables in fuzzy logic

Module ID	Operation date (Working hours)	Clearance	V_Z	Max. safety factor
9	March 23, 2020	1.82 m	8.05 m/s	68.75
21	April 08, 2020	0.85 m	26.82 m/s	76.07
21-01	April 09, 2020	0.85 m	10.35 m/s	76.07
23	April 12, 2020	0.60 m	7.60 m/s	84.35
32	April 23, 2020	0.29 m	5.36 m/s	60.85
56	May 27, 2020	2.05 m	7.60 m/s	72.60
98	July 26, 2020	3.07 m	2.70 m/s	72.11

In the fuzzy logic technique, if-then rules are needed to interpret the efficacy of inputs variable on output variables. In this study, due to the survey results, 750 different if-then rules (i.e., 125 rules for every motion) have been identified and classified in tables for any motion. Fig. 27 shows part of identified rules according to the survey.

Input		Output	Very Heavy: Very Strong	Very Heavy: Stong	Very Heavy: Moderate	Very Heavy: Weak	Very Heavy: Very Weak	Heavy: Very Strong	Heavy: Stong	Heavy: Moderate	Heavy: Weak	Heavy: Very Weak	Moderate: Very Strong	Moderate: Stong	Moderate: Moderate	Moderate: Weak	Moderate: Very Weak
			Safety Factor														
			Very Heavy					Heavy					Moderate				
			Wind					Wind					Wind				
			Very Strong	Stong	Moderate	Weak	Very Weak	Very Strong	Stong	Moderate	Weak	Very Weak	Very Strong	Stong	Moderate	Weak	Very Weak
# of Obstacles	Very Congestion	Slewing Angles	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
		Boom up	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
		Bood down	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
		Hoist up	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S
		Hoist Down	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S
		Rotation of load	VS	VS	VS	VS	VS	VS	VS	VS	S	S	VS	VS	VS	S	S
	Congestion	Slewing Angles	VS	VS	VS	S	S	VS	VS	S	S	S	VS	VS	S	S	S
		Boom up	VS	VS	VS	S	S	VS	VS	VS	S	S	VS	VS	VS	S	S
		Bood down	VS	VS	VS	S	S	VS	VS	VS	S	S	VS	VS	VS	S	S
		Hoist up	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	S	S	S
		Hoist Down	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	S	S	S
		Rotation of load	VS	VS	S	S	S	VS	VS	S	S	S	VS	VS	S	S	S
	Moderate	Slewing Angles	VS	VS	S	S	S	VS	VS	S	S	S	VS	S	S	S	S
		Boom up	VS	S	S	S	S	VS	S	S	S	S	VS	S	S	S	S
		Bood down	VS	S	S	S	S	VS	S	S	S	S	VS	S	S	S	S
		Hoist up	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Hoist Down	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Rotation of load	VS	VS	S	S	S	VS	VS	S	S	S	VS	VS	S	M	M
	Clear	Slewing Angles	VS	VS	S	S	S	VS	VS	S	S	S	VS	S	S	M	F
		Boom up	VS	S	S	M	M	VS	S	S	M	M	VS	S	M	M	F
		Bood down	VS	S	S	M	M	VS	S	S	M	M	VS	S	M	M	F
		Hoist up	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Hoist Down	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Rotation of load	VS	VS	S	S	S	VS	VS	S	S	S	VS	VS	S	M	M
	Very Clear	Slewing Angles	VS	S	S	S	S	VS	S	S	S	M	VS	S	S	M	M
		Boom up	VS	S	M	M	M	VS	S	M	M	F	VS	S	M	F	F
		Bood down	VS	S	M	M	M	VS	S	M	M	F	VS	S	M	F	F
		Hoist up	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Hoist Down	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Rotation of load	VS	VS	S	S	S	VS	VS	S	S	S	VS	S	S	M	F

Fig. 27. Typical if-then rules for slewing motion: VS= very slow, S= slow, M= moderate, F= fast, and VF= very fast

Thereafter by entering the calculated values of input variables and selecting the Mamdani inference system in MATLAB, and inserting rules, the numeric values of speeds are calculated as illustrated in Fig. 28

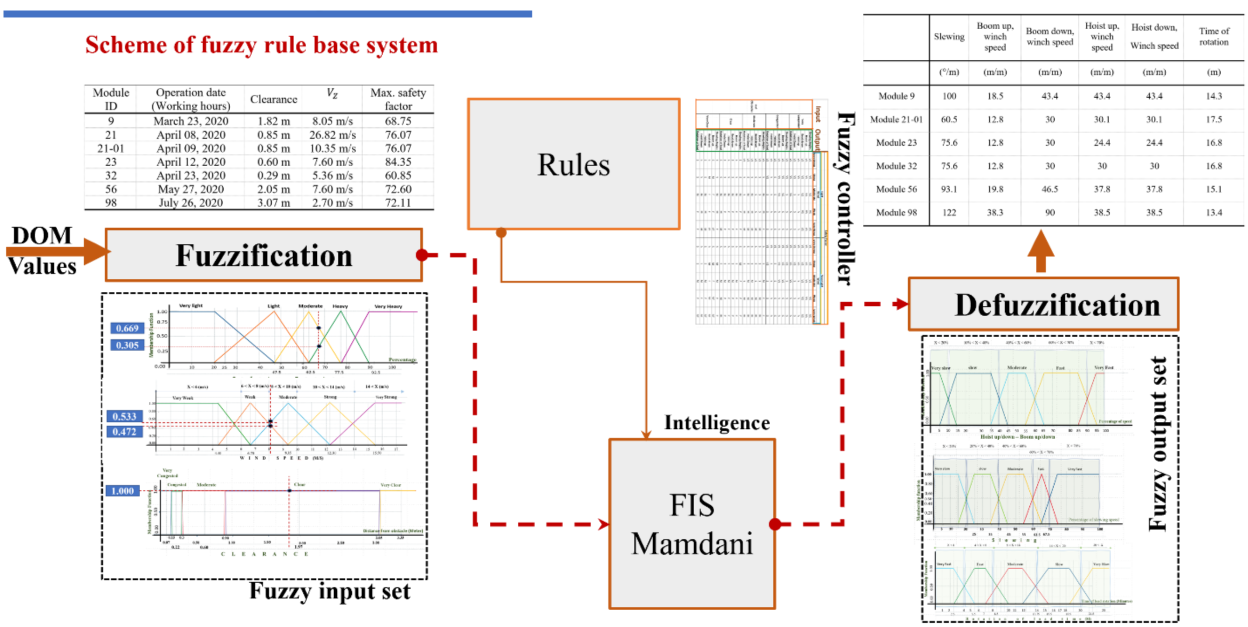


Fig. 28. Scheme of fuzzy logic application to calculate the speed of motions for module 9

After applying rules, as shown in Table 12, there are six motions' speeds for any module operation, computed by running the Fuzzy-MATLAB program. Then, outputs of this step are saved and presented in a Microsoft Excel data sheet. Crane's specifications for boom movement are based on winch speed. Winch unwinds ropes to prepare more cable length to feed big frame for the sake of decreasing boom ale and increasing working radius. The same operates to increase boom angle is done conversely. To convert the winch speeds to the applicable speed toward time calculation of boom and hoist motions, two steps are needed:

i. Calculation of boom tip movement using Eq. (8).

ii. Calculation of the boom tip movement based on the trigonometric degree using Eq. (9).

$$Boom\ tip\ movement\ speed\ (\frac{m}{m}) = \frac{winch\ speed\ (\frac{m}{m})}{rope\ lines\ number} \tag{8}$$

$$Boom\ tip\ movement\ (°) = \frac{Boom\ tip\ movement\ (m)}{1.46} \tag{9}$$

Table 12. Output motions

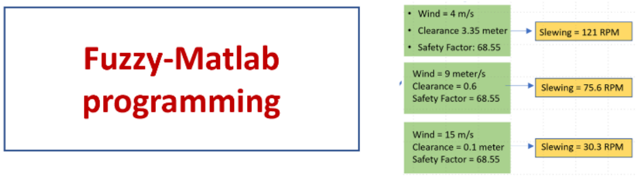
	Slewing	Boom up, winch speed	Boom down, winch speed	Hoist up, winch speed	Hoist down, Winch speed	Time of rotation
	(°/m)	(m/m)	(m/m)	(m/m)	(m/m)	(m)
Module 9	100	18.5	43.4	43.4	43.4	14.3
Module 21-01	60.5	12.8	30	30.1	30.1	17.5
Module 23	75.6	12.8	30	24.4	24.4	16.8
Module 32	75.6	12.8	30	30	30	16.8
Module 56	93.1	19.8	46.5	37.8	37.8	15.1
Module 98	122	38.3	90	38.5	38.5	13.4

For example, in the CC-2800 crawler crane, the boom-up winch speed is 52.12 (m/m). If 4 rope lines change the boom angle, the boom tip movement speed and boom tip movement in degree are respectively 13.03 m/m and 8.92 (°). This approach is applicable for speed calculation of boom down, hoisting up, and hoisting down (i. e., 30 (m/m) and 20.55 (°/m) respectively).

Table 13. Distance's data retrieved from 3Ds max, their conversions, and motions' sequences

Case No	Module ID	Slewing angle	Hoist up	Hoist down	Boom up	Boom down	Clearance	Hook rotation
		(°)	(m)	(m)	(°)	(°)	(m)	(°)
9	**Module 9-410**	2- 20.71 4- 1.98 6- 42.34	1- 2.13 3- 6.26 5- 5.26	9- 15.36	7- 0.39	-	1.82	8- 24.95
21	**Module 21-2068**	2- 17.83 4- 35.37	1- 2.13 3- 5.36	7- 9.09	-	5- 3.39	0.85	6- 53.194
23	**Module 23-2330**	2- 10.62 4- 4.83 6- 50.05 8- 41.95	1- 2.13 3- 13.37 5- 2.82 7- 0.90	11- 20.85	-	9- 12.29	0.85	10- 38.826
32	**Module 32-3453**	2- 22.96 4- 11.41 6. 21.33	1- 2.13 3- 4.77 5- 0.35	9- 1.22		7- 12.58		8- 55.71
56	**Module 56-5631**	2- 158.30 4- 6.919 6- 86.49	1- 2.13 3- 11.39 5- 1.70	9- 16.85	7- 11.98	-	2.05	8- 98.713
98	**Module 98-11834**	2- 15.79 4- 37.05	1- 2.13 3- 12.39	7- 4.71	-	5- 2.37	3.07	6- 37.256

Note: Boom length = 84 meters.



3Ds Max information

Case No	Module ID	Slewing angle	Hoist up	Hoist down	Boom up	Boom down	Clearance	Hook rotation
		(°)	(m)	(m)	(°)	(°)	(m)	(°)
9	**Module 9-410**	2- 20.71 4- 1.98 6- 42.34	1- 2.13 3- 6.26 5- 5.26	9- 15.36	7- 0.39	-	1.82	8- 24.95
21	**Module 21-2068**	2- 17.83 4- 35.37	1- 2.13 3- 5.36	7- 9.09	-	5- 3.39	0.85	6- 53.194
	23-2330	2- 10.62 4- 4.83 6- 50.05 8- 41.95	1- 2.13 3- 13.37 5- 2.82 7- 0.90	11- 20.85	-	9- 12.29	0.85	10- 38.826
	32-3453	2- 22.96 4- 11.41 6. 21.33	1- 2.13 3- 4.77 5- 0.35	9- 1.22		7- 12.58		8- 55.71
	56-5631	2- 158.30 4- 6.919 6- 86.49	1- 2.13 3- 11.39 5- 1.70	9- 16.85	7- 11.98	-	2.05	8- 98.713
	98-11834	2- 15.79 4- 37.05	1- 2.13 3- 12.39	7- 4.71	-	5- 2.37	3.07	6- 37.256

= 84 meters.

Fuzzy logic result

Module 9	Total movement Distance	Total movement Distance	Winch Speed of motion	Applicable movement Speed	Applicable movement Speed	Hook Load Rotation	Time of motion
	(m)	(°)	(M/M	(M/M)	(°/m)	(°)	(Minute)
Hoist up	13.66	-	43.4	10.85	-		1.25
Hoist down	15.366	--	43.4	10.85	-	-	1.42
Boom Up	0.572	0.392	12.8	3.20	-	-	0.18
Boom down	-	-	-	-	-	-	-
Slewing	-	65.03	-	-	100	-	0.65
Hook Load Rotation	-	-	-	-	-	-	14.3
Total motions time	-	-	-	-	-	-	**17.80**

Motions' distances information retrieved fromm 3ds max are updated and saved to Microsoft Excel according to module IDs as shown in Table 13. This data is computed into the readable and proper input information to MATLAB programming. Table 14, and Table 15 shows the process of units' exchange and time of motions' calculation for selected modules separately. Finally, after time calculation of 6 motions for 6 cases, by adding the $T_{Penalty}$s, the $T_{Cycle\ time}$ is resulted. $T_{Penalty}$ calculation according to the motions sequences is presented in Table 16.

Table 14. Calculations of motions' times -001

Module 9	Total movement Distance	Total movement Distance	Winch Speed of motion	Applicable movement Speed	Applicable movement Speed	Hook Load Rotation	Time of motion
	(m)	(°)	(M/M	(M/M)	(°/m)	(°)	(Minute)
Hoist up	13.66	-	43.4	10.85	-		1.25
Hoist down	15.366	--	43.4	10.85	-	-	1.42
Boom Up	0.572	0.392	12.8	3.20	-	-	0.18
Boom down	-	-	-	-	-	-	-
Slewing	-	65.03	-	-	100	-	0.65
Hook Load Rotation	-	-	-	-	-	-	14.3
Total motions time	-	-	-	-	-	-	**17.80**

Module 21-01	Total relocation Distance	Total Relocation Distance	Winch Speed of motion	Applicable Relocation Speed	Applicable Relocation Speed	Hook Load Rotation	Time of motion
	(m)	(°)	(M/M	(M/M)	(°/m)	(°)	(Minute)
Hoist up	7.49	-	30.1	0.684	-		10.95
Hoist down	9.09	-	30.1	0.684	-	-	13.29
Boom Up	-	-	-	-	-	-	-
Boom down	4.95	3.39	30	0.682	-	-	7.26
Slewing	-	53.20	-	-	60.50	-	0.88
Hook Load Rotation	-	-	-	-	-	53.194	17.5
Total motions time	-	-	-	-	-	-	**49.88**
Total motions time	-	-	-	-	-	-	**21.242**

Table 15. Calculations of motions' times

Module 23	Total relocation Distance	Total Relocation Distance	Winch Speed of motion	Applicable Relocation Speed	Applicable Relocation Speed	Hook Load Rotation	Time of motion
	(m)	(°)	(M/M	(M/M)	(°/m)	(°)	(Minute)
Hoist up	18.32	-	24.4	6.10	-		3.01
Hoist down	20.85	-	24.4	6.10	-	-	3.42
Boom Up	-	-	-	-	-	-	-
Boom down	17.94	12.29	30	7.5	-	-	2.39
Slewing	-	107.45	-	-	75.60	-	1.42
Hook Load Rotation	-	-	-	-	-	-	16.8
Total motions time	-	-	-	-	-	-	**27.04**

Module 32	Total relocation Distance	Total Relocation Distance	Winch Speed of motion	Applicable Relocation Speed	Applicable Relocation Speed	Hook Load Rotation	Time of motion
	(m)	(°)	(M/M	(M/M)	(°/m)	(°)	(Minute)
Hoist up	7.25	-	30	7.50	-		0.97
Hoist down	1.22	--	30	7.50	-	-	0.163
Boom Up					-	-	
Boom down	18.37	12.58	30	7.50	-	-	2.44
Slewing	-	55.70	-	-	75.60	-	0.74
Hook load Rotation	-	-	-	-	-	55.71	16.8
Total motions time	-	-	-	-	-	-	**17.54**

Module 56	Total relocation Distance	Total Relocation Distance	Winch Speed of motion	Applicable Relocation Speed	Applicable Relocation Speed	Hook Load Rotation	Time of motion
	(m)	(°)	(M/M	(M/M)	(°/m)	(°)	(Minute)
Hoist up	15.22	-	37.80	9.45	-		1.61
Hoist down	16.85	--	37.80	9.45	-	-	1.78
Boom Up	17.49	11.98	19.80	4.95	-	-	3.53
Boom down	-	-	-	-	-	-	-
Slewing	-	251.71	-	-	93.1	-	2.70
Hook load Rotation	-	-	-	-	-	-	15.1
Total Motions time	-	-	-	-	-	-	**24.72**

Module 98	Total relocation Distance	Total Relocation Distance	Winch Speed of motion	Applicable Relocation Speed	Applicable Relocation Speed	Hook Load Rotation	Time of motion
	(m)	(°)	(M/M)	(M/M)	(°/m)	(°)	(Minute)
Hoist up	14.52	-	38.50	9.625	-		1.51
Hoist down	4.71	--	38.50	9.625	-	-	0.49
Boom Up					-	-	-
Boom down	3.46	2.37	90	22.50	-	-	0.154
Slewing	-	52.84	-	-	122	-	0.43
Hook load Rotation	-	-	-	-	-	-	13.40
Total Motions time	-	-	-	-	-	-	**16.984**

Although the speed interval assists in the calculation of process times of motions near to those observed in practice, these process times are not still realistic because other aspects of crane operations, such as preparation time when the movement of the crane with a heavy load is changed vertically and/or horizontally, are not considered. To address this, the time penalty ($T_{Penalty}$) matrix developed by Olearczyk. (2010)[55] and modified by Han et al. (2017)[2] is applied to the processing time of each motion. Table 17 describes the time penalties for crane movement changes.

Table 16. Penalty time of motions [[2], [55]]

Crane motion	Boom up or down	Slewing	Hoist up	Hoist down
Boom up or down	0.00	0.75	1.00	0.50
Slewing	0.75	0.00	0.50	0.75
Hoist up	0.75	1.00	0.00	0.00
Hoist down	0.50	0.75	0.00	0.00

Note: Unit is minute.

The process times for each motion of crane operation, taking into account time penalties, are calculated using Eq. (10) and Eq. (11).

$$T_{Motion} = \frac{L_{Angle}\ or\ L_{Height}}{V_{Motion}} \tag{10}$$

Where:

- $\boldsymbol{L_{Angle}}$ is the lift angle for a given motion.
- $\boldsymbol{L_{Height}}$ is lifting height for a given motion.
- $\boldsymbol{V_{Motion}}$ is the speed of the given motion.

$$T_{Cycle\ time} = T_{Motions} + T_{Penalty} \tag{11}$$

Where:

- $\boldsymbol{T_{Penalty}}$ = time penalty for a crane movement change from a preceding motion to a subsequent motion.

Following the calculation of cycle time of the crane operation motions and penalty time. All information, including module IDs, motions sequences, motions IDs with their process times and speeds, are delivered to Microsoft Excel. The sequences of crane motions and motions' distances in this study are built using 3ds max. All calculations are done by MATLAB programming. Fig. 29, and Fig. 30 provide the pseudocode for the detailed MATLAB programming used to compute the crane cycle time for the given modules.

Although this study uses the fuzzy logic-based technique in MATLAB programming as a deterministic model to assess the cycle time of crane operation in the project's planning phase, it is also adjustable to different mobile cranes in different heavy modular industrial projects in the planning and executive phases of the projects. Thus, the Fuzzy-MATLAB programming can improve decision-making to assist project managers and lift engineers in selecting the best crane based on the crane specifications and selecting the best crane operation by comparing the cycle times of various alternatives for each module lifting.

Table 17. Motions' Total $T_{Penalty}$ **(m)** calculation

Module 9	
Motion sequences	$T_{Penalty}$ **(m)**
Hoist up - slewing	1.00
Slewing to hoist up	0.50
Hoist up to slewing	1.00
Slewing to hoist up	0.5
Rotate to boom up	0.75
Boom up to hook rotation	-
Hook rotation to hoist down	-
Total $T_{Penalty}$ **(m)**	**4.75 (m)**

Motion 21-01	
Motion sequences	$T_{Penalty}$ **(m)**
Hoist up to slewing	1.00
Slewing to hoist up	0.50
Hoist up to slewing	1.00
Slewing to boom down	0.75
Boom down to hook rotation	-
Hook rotation to hoist down	-
Total $T_{Penalty}$ **(m)**	**3.25 (m)**

Motion 23	
Motion sequences	$T_{Penalty}$ **(m)**
Hoist up to slewing	1.00
Slewing to hoist up	0.50
Hoist up to slewing	1.00
Slewing to hoist up	0.50
Hoist up to slewing	1.00
Slewing to hoist up	0.50
Hoist up to slewing	1.00
Slewing to boom down	0.75
Total $T_{Penalty}$ **(m)**	**6.25 (m)**

Module 32	
Motion sequences	$T_{Penalty}$ **(m)**
Hoist up - slewing	1.00
Slewing to hoist up	0.50
Hoist up to slewing	1.00
Slewing to hoist up	0.5
Hoist up to slewing	1.00
Slewing to boom down	0.75
Total $T_{Penalty}$ **(m)**	**4.75 (m)**

Motion 56	
Motion sequences	$T_{Penalty}$ **(m)**
Hoist up to slewing	1.00
Slewing to hoist up	0.50
Hoist up to slewing	1.00
Slewing to hoist up	0.50
Hoist up to slewing	1.00
Slewing to boom up	0.75
Total $T_{Penalty}$ **(m)**	**4.75 (m)**

Motion 98	
Motion sequences	$T_{Penalty}$ **(m)**
Hoist up to slewing	1.00
Slewing to hoist up	0.50
Hoist up to slewing	1.00
Slewing to boom down	0.75
Total $T_{Penalty}$ **(m)**	**3.25 (m)**

Table 18. $T_{Cycle\ time}$ of modules' operation

Crane cycle time			
Module ID	Total's $\boldsymbol{T}_{Motions}$ (M)	Operation's $\boldsymbol{T}_{Penalty}$ (M)	Operation's $\boldsymbol{T}_{Cycle\ time}$ (M)
9	17.80	4.75	22.55
21-01	21.242	3.25	24.492
23	27.04	6.25	33.29
32	17.54	4.75	22.29
56	24.72	4.75	29.47
98	16.984	3.25	20.234

```
A_p = 202          %cross section aria of the load
c_w = 1.2
booml = 84
r_p = 44           %rope line number
% v_mc = 18        %v_max chart
m_i = 370.05135    %sum of the load, hook and the hoist mass total weight
% z = 84             %the hight that the load is transporting(for calculation the wind speed at the hight)
% v_f = 8.05         %wind speed at 10m hight from the ground(the weather forcast)

c_c = 538.200             %crane capacity
safety_factor = m_i / c_c *100;
% safety_factor = 60 %
clearance = 1.82
seq = [4 1 4 1 4 1 2 6 5]           %sequence vctor: slewing=1, boom up=2, boom down=3, hoist up=4, hoist down=5, walking=6
dist = [2.13 20.71 6.26 1.98 5.26 42.34 0.39 24.95 15.36]          %operated distances vector in sequence

if booml<=39
    v_mc = 15;
elseif booml<=69
    v_mc = 13.8;
elseif booml<=84
    v_mc = 11.3;
else
    v_mc = 9.8;
end

v_p = min(v_mc,v_mc*(1.2*m_i/(c_w*A_p))^0.5);   %v_p max. allowed wind speed

fis=readfis('project-three inputs and six outputs4');
% if v_p<fis.input(2).mf(3).params(1)
%     error('the v_p is lower than the intial range of very strong mf')
% else
%     fis.input(2).mf(3).params(2) = v_p; %assigning the very strong mf
%     fis.input(2).mf(4).params(3) = v_p; %assigning to strong mf
% end

% v_z = ((z/10)^.14+0.4)*v_f;     %wing speed at hight z
v_z = 8.05;

if v_z>v_p
    error('the wind speed is higher than maximum allowable wind speed. stop the operation')
end


input = [safety_factor v_z clearance];
```

Fig. 29. MATLAB pseudocode for cycle time of mobile crane.

```
fisout = evalfis(input,fis);

speeds(1) = fisout(1); %slewing angle
speeds(2) = fisout(2)/r_p/1.46; %boom up
speeds(3) = fisout(3)/r_p/1.46; %boom down
speeds(4) = fisout(4)/r_p;      %hoist up
speeds(5) = fisout(5)/r_p;      %hoist down
speeds(6) = fisout(6);          %time of rotation of load

t_operation = 0;
t_penalty = 0;
for i=1:length(seq)
    t_operation=t_operation + dist(i)/speeds(seq(i));
    if i==length(seq)
        break
    end
    switch seq(i)
        case 1

            switch seq(i+1)
                case {2,3,5}
                    t_penalty=t_penalty+0.75;
                case 4
                    t_penalty=t_penalty+0.5;
                case 6
                    t_penalty=t_penalty+0;
                    t_operation = t_operation + speeds(6);
            end
        case {2,3}
            switch seq(i+1)
                case 1
                    t_penalty=t_penalty+0.75;
                case 4
                    t_penalty=t_penalty+1;
                case 5
                    t_penalty=t_penalty+0.5;
                case 6
                    t_penalty=t_penalty+0;
                    t_operation = t_operation + speeds(6);
            end
        case 4
            switch seq(i+1)
                case 1
                   t_penalty=t_penalty+1;
                case{2,3}
                  t_penalty=t_penalty+0.75;
                case 6
                    t_penalty=t_penalty+0;
                    t_operation = t_operation + speeds(6);

            end
        case 5
            switch seq(i+1)
                case 1
                    t_penalty=t_penalty+0.75;
                case {2,3}
                    t_penalty=t_penalty+0.5;
                case 6
                    t_penalty=t_penalty+0;
                    t_operation = t_operation + speeds(6);

            end
        case 6
            t_penalty=t_penalty+0;
%             t_operation = t_operation + speeds(6);

    end
end

t_total = t_operation + t_penalty;
```

Fig. 30. MATLAB pseudocode for cycle time of mobile crane.

Chapter 5: Future Works

Due to some limitations in the proposed framework, future development is required. The present constructed context considers safety factors (SFs) as a static input variable. However, other factors such as weather, especially wind, may act as a dynamic force which might impact SFs during operations. This results in SFs becoming dynamic factors. Wind force changes the load radius either to decrease or increase working radius. Respectively, it changes the crane's gross capacity. In addition, load swinging, caused by wind and/or motion speeds acceleration or deceleration, increases momentum load and can change the force of lifted load on the boom and grooves of sheaves. This matter can be addressed by proposing the pendulum effect of wind on the lifted load.

Another limitation of this proposed framework is that mobile cranes are supposed to operate from fixed positions (CFPs). However, a crane's pick and walk operation (CPW), in modular-based industrial construction, must be considered. It should be noted that based on the studies, some operations cannot be done without CPWs method. CPWs are also more complex operations. Moreover, utilizing crawler cranes in projects offers the possibility of mobile capability in lift engineering. To overcome this drawback, future research should focus on the CPWs approach of lifting.

another constraint of the proposed framework is that clearance in current study is deemed to be a crisp value which is applied as an input as (0 and 1) at the planning stage of cycle time assessment, instead of being [0, 1]. Besides load swinging created by acceleration and deceleration of motions, wind intensity especially gust wind, makes clearance uncertain from time to time due to the load's uncontrollable horizontal movement. So, the uncertain nature of clearance in congested industrial projects needs to be considered. In this respect, future efforts to include multi-values of clearance during the planning stages of projects are required to increase preciseness and efficiency of clearance and respectively of crane cycle times.

To cover more areas of mobile crane cycle times, future research should also include pre-lifting and after positioning operations. In this respect, evaluating several motions (e.g., super lift (SL) counterweight times to guarantee floating SL tray, switching times to change SL counterweights between lifts, job site ground conditions, rigging exchange between lifts, crane manufacturing restrictions and capabilities such as simultaneous motions) need to be considered.

Chapter 6: Conclusion

Modular-based construction is an appealing approach for congested sites to achieve better productivity and lower costs while maintaining high-quality builds in the construction industry. In practice, the industry relies heavily on timely crane planning in which large numbers of modules can be lifted and positioned manually in congested sites. Efficient methods to improve the accuracy of project schedules and rapid reaction toward changes in heavy industrial projects are essential to increase efficiency and productivity. However, available methods that evaluate work cycles are not fully introduced yet into the modular-based construction sector. To do so, researchers and engineers must evaluate crane cycle times by identifying influential factors and major motions that affect the cranes' cycle time. This thesis proposes a fuzzy logic-based approach to adjust for the subjectiveness of the influential factors and motions when estimating the cycle times of crane operations in construction projects. A survey is conducted to ask experts to indicate mobile crane motion speeds and their effective factors to meet these goals. The proposed method consists of mainly four components: *(i)* model initiation to build up safety factor (SFs) and clearance functions; *(ii)* a lift analysis to study wind parameters and its effect on module shape, weight, and dimension; *(iii)* development of wind function; *(iv)* model expansion to build up crane motion speeds function, and implementation of fuzzy if-then and inference system to complete the fuzzy-bases designed model ; *(v)* time computation to estimate the crane cycle time. The proposed method of this thesis offers the following benefits: *(i)* improve the project schedule related to mobile crane activity, which is essential as crane operations are common in the critical path of the projects; *(ii)* prepare accurate numerical information that helps project practitioners and engineers to proceed with faster decision-making which eliminates wasted time during operations; *(iii)* estimation of total motion time to improve accuracy of project schedule by designing a computer program that has been simplified to be applied at the project sites by project participants. However, some limitations are included in the proposed methodology: *(i)* this method does not cover walking with load operations (CPWs) which are utilized when lifting from a fixed position (CFPs); *(ii)* effective factors are presumed to be static while in practice, they may act as dynamic factors; *(iii)* there are still several factors which may affect the crane operations beside other motions that are not considered in this research.

References:

[1] M. Jung, M. Park, H.-S. Lee, and H. Kim, "Weather-Delay Simulation Model Based on Vertical Weather Profile for High-Rise Building Construction," *J. Constr. Eng. Manag.*, vol. 142, no. 6, p. 04016007, 2016, doi: 10.1061/(asce)co.1943-7862.0001109.

[2] S. Han, A. Bouferguene, M. Al-Hussein, and U. (Rick) Hermann, "3D-Based Crane Evaluation System for Mobile Crane Operation Selection on Modular-Based Heavy Construction Sites," *J. Constr. Eng. Manag.*, vol. 143, no. 9, p. 04017060, 2017, doi: 10.1061/(asce)co.1943-7862.0001360.

[3] N. Kayhani, H. Taghaddos, A. Mousaei, S. Behzadipour, and U. Hermann, "Heavy mobile crane lift path planning in congested modular industrial plants using a robotics approach," *Autom. Constr.*, vol. 122, no. December 2020, p. 103508, 2021, doi: 10.1016/j.autcon.2020.103508.

[4] A. Shapira, G. Lucko, and C. J. Schexnayder, "Cranes for Building Construction Projects," *J. Constr. Eng. Manag.*, vol. 133, no. 9, pp. 690–700, 2007, doi: 10.1061/(asce)0733-9364(2007)133:9(690).

[5] Z. Lei, S. Han, A. Bouferguène, H. Taghaddos, U. Hermann, and M. Al-Hussein, "Algorithm for mobile crane walking path planning in congested industrial plants," *J. Constr. Eng. Manag.*, vol. 141, no. 2, pp. 1–10, 2015, doi: 10.1061/(ASCE)CO.1943-7862.0000929.

[6] H. Taghaddos, A. Eslami, U. Hermann, S. AbouRizk, and Y. Mohamed, "Auction-based Simulation for Industrial Crane Operations," *Autom. Constr.*, vol. 104, no. April, pp. 107–119, 2019, doi: 10.1016/j.autcon.2019.03.015.

[7] A. Nekouvaght Tak, H. Taghaddos, A. Mousaei, and U. (Rick) Hermann, "Evaluating industrial modularization strategies: Local vs. overseas fabrication," *Autom. Constr.*, vol. 114, no. March, p. 103175, 2020, doi: 10.1016/j.autcon.2020.103175.

[8] A. Shapira and A. Elbaz, "Tower Crane Cycle Times: Case Study of Remote-Control versus Cab-Control Operation," *J. Constr. Eng. Manag.*, vol. 140, no. 12, p. 05014010, 2014, doi: 10.1061/(asce)co.1943-7862.0000904.

[9] Z. Lei, H. Taghaddos, U. Hermann, and M. Al-Hussein, “A methodology for mobile crane lift path checking in heavy industrial projects,” *Autom. Constr.*, vol. 31, pp. 41–53, 2013, doi: 10.1016/j.autcon.2012.11.042.

[10] “An Algorithm for optimizing Tower Crane Location and Operation,” pp. 1–26.

[11] C. M. Tam, A. W. T. Leung, and D. K. Liu, “Nonlinear models for predicting hoisting times of tower cranes,” *J. Comput. Civ. Eng.*, vol. 16, no. 1, pp. 76–81, 2002, doi: 10.1061/(ASCE)0887-3801(2002)16:1(76).

[12] S. H. Han, “BIM-based Motion Planning of Mobile Crane Operation in Modular-based Heavy Construction Sites,” 2014.

[13] L. For, R. Around, B. C. M. Tam, T. K. L. Tong, and W. K. W. Chan, “O s l t c,” vol. 127, no. 4, pp. 315–321, 2002.

[14] K. Tantisevi and B. Akinci, “Simulation-Based Identification of Possible Locations for Mobile Cranes on Construction Sites,” *J. Comput. Civ. Eng.*, vol. 22, no. 1, pp. 21–30, 2008, doi: 10.1061/(asce)0887-3801(2008)22:1(21).

[15] H. Safouhi, M. Mouattamid, U. Hermann, and A. Hendi, “An algorithm for the calculation of feasible mobile crane position areas,” *Autom. Constr.*, vol. 20, no. 4, pp. 360–367, 2011, doi: 10.1016/j.autcon.2010.11.006.

[16] Z. Lei, S. Han, A. Bouferguène, H. Taghaddos, U. Hermann, and M. Al-Hussein, “Algorithm for Mobile Crane Walking Path Planning in Congested Industrial Plants,” *J. Constr. Eng. Manag.*, vol. 141, no. 2, p. 05014016, 2015, doi: 10.1061/(asce)co.1943-7862.0000929.

[17] J. K. W. Yeoh and D. K. H. Chua, “Optimizing Crane Selection and Location for Multistage Construction Using a Four-Dimensional Set Cover Approach,” *J. Constr. Eng. Manag.*, vol. 143, no. 8, p. 04017029, 2017, doi: 10.1061/(asce)co.1943-7862.0001318.

[18] S. M. Bagheri, H. Taghaddos, A. Mousaei, F. Shahnavaz, and U. Hermann, “An A-Star algorithm for semi-optimization of crane location and configuration in modular construction,” *Autom. Constr.*, vol. 121, no. October 2020, p. 103447, 2021, doi: 10.1016/j.autcon.2020.103447.

[19] M. Al-Hussein, S. Alkass, and O. Moselhi, “D-CRANE: A database system for utilization of cranes,” *Can. J. Civ. Eng.*, vol. 27, no. 6, pp. 1130–1138, 2000, doi: 10.1139/l00-039.

[20] V. S. S. Kumar and A. S. Hanna, “A Fuzzy logic approach to selection of cranes,” *J. Struct. Eng.*, vol. 30, no. 4, pp. 215–224, 2004.

[21] A. Sawhney and A. Mund, “Adaptive Probabilistic Neural Network-based Crane Type Selection System,” *J. Constr. Eng. Manag.*, vol. 128, no. 3, pp. 265–273, 2002, doi: 10.1061/(asce)0733-9364(2002)128:3(265).

[22] M. Al-Hussein, S. Alkass, and O. Moselhi, “An algorithm for mobile crane selection and location on construction sites,” *Constr. Innov.*, vol. 1, no. 2, pp. 91–105, 2001, doi: 10.1108/14714170110814532.

[23] M. Al-Hussein, S. Alkass, and O. Moselhi, “Optimization Algorithm for Selection and on Site Location of Mobile Cranes,” *J. Constr. Eng. Manag.*, vol. 131, no. 5, pp. 579–590, 2005, doi: 10.1061/(asce)0733-9364(2005)131:5(579).

[24] D. Wu, Y. Lin, X. Wang, X. Wang, and S. Gao, “Algorithm of Crane Selection for Heavy Lifts,” *J. Comput. Civ. Eng.*, vol. 25, no. 1, pp. 57–65, 2011, doi: 10.1061/(asce)cp.1943-5487.0000065.

[25] U. H. Hermann, S. Hasan, M. Al-Hussein, and A. Bouferguene, “Innovative System for Off-the-Ground Rotation of Long Objects Using Mobile Cranes,” *J. Constr. Eng. Manag.*, vol. 137, no. 7, pp. 478–485, 2011, doi: 10.1061/(asce)co.1943-7862.0000309.

[26] M. Behm, “Linking construction fatalities to the design for construction safety concept,” *Saf. Sci.*, vol. 43, no. 8, pp. 589–611, 2005, doi: 10.1016/j.ssci.2005.04.002.

[27] iifstaff, “Crane-Related Occupational Fatalities,” no. July, 2006.

[28] S. Hasan, M. Al-Hussein, U. H. Hermann, and H. Safouhi, “Interactive and Dynamic Integrated Module for Mobile Cranes Supporting System Design,” *J. Constr. Eng. Manag.*, vol. 136, no. 2, pp. 179–186, 2010, doi: 10.1061/(asce)co.1943-7862.0000121.

[29] S. Tamate, N. Suemasa, and T. Katada, “Analyses of Instability in Mobile Cranes due to Ground Penetration by Outriggers,” *J. Constr. Eng. Manag.*, vol. 131, no. 6, pp. 689–704,

2005, doi: 10.1061/(asce)0733-9364(2005)131:6(689).

[30] W. Sochacki, “The dynamic stability of a laboratory model of a truck crane,” *Thin-Walled Struct.*, vol. 45, no. 10–11, pp. 927–930, 2007, doi: 10.1016/j.tws.2007.08.023.

[31] A. Golabchi, S. Han, A. R. Fayek, and S. Abourizk, “Stochastic Modeling for Assessment of Human Perception and Motion Sensing Errors in Ergonomic Analysis,” *J. Comput. Civ. Eng.*, vol. 31, no. 4, pp. 1–11, 2017, doi: 10.1061/(ASCE)CP.1943-5487.0000655.

[32] S.-C. Kang and E. Miranda, “Computational Methods for Coordinating Multiple Construction Cranes,” *J. Comput. Civ. Eng.*, vol. 22, no. 4, pp. 252–263, 2008, doi: 10.1061/(asce)0887-3801(2008)22:4(252).

[33] K. C. Lai and S. C. Kang, “Collision detection strategies for virtual construction simulation,” *Autom. Constr.*, vol. 18, no. 6, pp. 724–736, 2009, doi: 10.1016/j.autcon.2009.02.006.

[34] K. Tantisevi and B. Akinci, “Automated generation of workspace requirements of mobile crane operations to support conflict detection,” *Autom. Constr.*, vol. 16, no. 3, pp. 262–276, 2007, doi: 10.1016/j.autcon.2006.05.007.

[35] M. Al-Hussein, M. Athar Niaz, H. Yu, and H. Kim, “Integrating 3D visualization and simulation for tower crane operations on construction sites,” *Autom. Constr.*, vol. 15, no. 5, pp. 554–562, 2006, doi: 10.1016/j.autcon.2005.07.007.

[36] K. Tantisevi and B. Akinci, “Transformation of a 4D product and process model to generate motion of mobile cranes,” *Autom. Constr.*, vol. 18, no. 4, pp. 458–468, 2009, doi: 10.1016/j.autcon.2008.10.008.

[37] Y. C. Chang, W. H. Hung, and S. C. Kang, “A fast path planning method for single and dual crane erections,” *Autom. Constr.*, vol. 22, pp. 468–480, 2012, doi: 10.1016/j.autcon.2011.11.006.

[38] H. AlBahnassi and A. Hammad, “Near Real-Time Motion Planning and Simulation of Cranes in Construction: Framework and System Architecture,” *J. Comput. Civ. Eng.*, vol. 26, no. 1, pp. 54–63, 2012, doi: 10.1061/(asce)cp.1943-5487.0000123.

[39] S. Han, Z. Lei, A. Bouferguene, M. Al-Hussein, and U. (Rick) Hermann, “3D Visualization-Based Motion Planning of Mobile Crane Operations in Heavy Industrial Projects,” *J. Comput. Civ. Eng.*, vol. 30, no. 1, p. 04014127, 2016, doi: 10.1061/(asce)cp.1943-5487.0000467.

[40] P. Cai, Y. Cai, I. Chandrasekaran, and J. Zheng, “Parallel genetic algorithm based automatic path planning for crane lifting in complex environments,” *Autom. Constr.*, vol. 62, pp. 133–147, 2016, doi: 10.1016/j.autcon.2015.09.007.

[41] H. J. Zimmermann, “Fuzzy set theory,” *Wiley Interdiscip. Rev. Comput. Stat.*, vol. 2, no. 3, pp. 317–332, 2010, doi: 10.1002/wics.82.

[42] W. Siler and J. J. Buckley, *Fuzzy Expert Systems and Fuzzy Reasoning*. 2004.

[43] A. Golabchi, S. Han, and A. R. Fayek, “An Application of Fuzzy Ergonomic Assessment for Human Motion Analysis in Modular Construction,” pp. 257–264.

[44] P. Venkata Subba Reddy, “Fuzzy logic based on Belief and Disbelief membership functions,” *Fuzzy Inf. Eng.*, vol. 9, no. 4, pp. 405–422, 2017, doi: 10.1016/j.fiae.2017.12.001.

[45] N. Bagheri and S. S. Hashemin, “A New Bell Shape Fuzzy Number,” *Int. J. Math. Trends Technol.*, vol. 54, no. 5, pp. 377–382, 2018, doi: 10.14445/22315373/ijmtt-v54p544.

[46] F. Omar, F. Karray, O. Basir, and L. Yu, “Autonomous overhead crane system using a fuzzy logic controller,” *JVC/Journal Vib. Control*, vol. 10, no. 9, pp. 1255–1270, 2004, doi: 10.1177/1077546304042038.

[47] F. Topaloğlu and H. Pehlivan, “Comparison of Mamdani type and Sugeno type fuzzy inference systems in wind power plant installations,” *6th Int. Symp. Digit. Forensic Secur. ISDFS 2018 - Proceeding*, vol. 2018-Janua, pp. 1–4, 2018, doi: 10.1109/ISDFS.2018.8355384.

[48] J. Vaughan, D. Kim, and W. Singhose, “Control of Tower Cranes With Double-Pendulum Payload Dynamics,” vol. 18, no. 6, pp. 1345–1358, 2010.

[49] B. Kim and R. R. Bishu, “Evaluation of fuzzy linear regression models by comparing

membership functions,” vol. 100, 1998.

[50] P. G. Cranes and L. Equipment, “‘ Safety Issues in Wind Turbine Installation and Transportation ’ Windkrafta nlagen ” transport d ’ éoliennes ",” pp. 1–26, 2017.

[51] Y. Lin, D. Wu, X. Wang, X. Wang, and S. Gao, “Lift path planning for a nonholonomic crawler crane,” *Autom. Constr.*, vol. 44, pp. 12–24, 2014, doi: 10.1016/j.autcon.2014.03.007.

[52] “A Methodology to The Safe Operation of Mobile Crane in Erection of Wind Turbine,” vol. 16, no. 7, pp. 6–10, 2019, doi: 10.7537/marslsj160719.02.Keywords.

[53] K. H. Low, “COMPENDIUM MOTION ANALYSIS OF A SUSPENDED ATTACHED TO A CRANE,” vol. 52, no. I, 1994.

[54] D. Safarzadeh, S. Sulaiman, F. Abdul Aziz, and D. Bin Ahmad, “An Approach to Determine Effect of Crane Hook on Payload Sway,” *Int. J. Mech. Appl.*, vol. 1, no. 1, pp. 30–38, 2012, doi: 10.5923/j.mechanics.20110101.04.

[55] J. Olearczyk, “Crane Lifting Operation Planning and Lifted Object Spatial Trajectory Analysis,” 2010.

Appendix

Appendix 1: Survey explanation and tables

Study Title: Development of a prediction model for mobile crane operation

Crane type: Crawler cranes with lattice boom

1. Please check the factors affecting the time of crane operation. The crane operation means only motions of crane operation except other factors such as installation.

Safety Factor (%)	
Slewing angle (°)	
Boom up (°)	
Boom down (°)	
Hoist up (m)	
Hoist down (m)	
Walking (m)	
Weather (wind)	
Number of motion change	
Number of obstacles	
Rotation of load (°)	

- Safety Factor (%) = (Weight of the payload / Gross capacity (lifting capacity setting)) * 100.
- Number of obstacles mean existed objects which block the paths of crane operation. We may consider both above ground obstacles and the obstacles around the crane body including tracks and (SL) counterweight tail swing path.
- Number of motions is to count on the number of motions (slewing, hoist up and down etc.) during crane operation.

2. Please provide any other factors affecting to the time of crane operation if you have other opinions.

Crane configuration: For example: super-lift counterweight will take more time to operate to ensure SL tray floats, clear of obstacles for the tail swing, setup time for change of SL counterweight between lifts.

Weight of the load: The heavier the load, the more hoists line required. This affects the hoist speed.

Site Conditions – For example, crane operating in live unit VS green field/brown field environment. It will be a lot more controls over crane operation such as temporary evaluation of personnel along the crane path.

Low temperature operation - Most of the time cranes in Canada are winterized but still will relatively take longer time for pre-work inspections and for preparations and de-icing in the case where ice built up on the boom sections.

Rigging changes between lifts – this comes down to engineering and equipment/module setting sequence.

Crane re-configurations between lifts

Ground allowable pressure or U/G utilities capacity – Crane motion may need to be engineered in order to avoid boom orientation or crane working radius that causes high pressure below the crawler. Also, any crane re-location may require crane complete or partial dis-assembly IF the ground allowable GBP is so low to support the crane to travel without suspended load.

Project site safety policies – lifting plan review and approval procedure.

Incorrect engineering data (i.e., COG location) – re-configure of rigging arrangement or even crane configuration such as super-lift counterweight

Number of cranes involved in a lift – Tandem or multiple crane lift

Setting location of the load:

- If the load setting location has low or no visibility (blind lift) to the operator, there will be longer time to communicate through radio.
- If the load is set at elevated location, rigging detachment after installation can be time consuming.

Crane manufacturer restrictions- for example, not all the cranes can be slew and walk at the same time if super-lift counterweight is mounted.

3. Please define the discrete boundaries of linguistic variables with times represented below.

3.1. Safety factor between 0 % and 100%, **What is your maximum allowable safety factor in your experience?**

Appendix 2: influential variables sets and ranges

3.1. Safety factor between 0 % and 100%, **What is your maximum allowable safety factor in your experience?**

	Very Light	Light	Moderate	Heavy	Very Heavy
SF (Percentage)	X ≤ 40	40 < X ≤ 55	55 < X ≤ 70	70 < X ≤ 85	85 < X

3.2. Weather (wind speed) – **What is the maximum allowable wind speed in your experience?**

Linguistic range	Very Congested	Congested	Moderate	Clear	Very Clear
Unit	Meter	Meter	Meter	Meter	Meter
Clearance	X ≤ 0.15	0.15 < X ≤ 0.3	0.3 < X ≤ 0.9	0.9 < X ≤ 3.05	3.05 < X

3.4 Number of Obstacles - Clearance

Linguistic range	Very Congested	Congested	Moderate	Clear	Very Clear
Unit	Meter	Meter	Meter	Meter	Meter
Clearance	X ≤ 0.15	0.15 < X ≤ 0.3	0.3 < X ≤ 0.9	0.9 < X ≤ 3.05	3.05 < X

Appendix 3: Penalty time-table

3.3. Number of motion changes

The table blow is to add time whenever crane motion is changed. Please confirm the time or modify the time if you have different opinions.

	Boom up or down	Rotate (Arc)	Hoist-up	Hoist-down
Boom up or down	0	0.5	0.5	0.5
Rotate (Arc)	0.5	0	0.75	0.75
Hoist-up	0.5	0.75	0	0
Hoist-down	0.5	0.75	0	0
Walking	1.0	0.5	0.75	0.75
unit = minute				

Appendix 4: Crane motion speed sets and ranges

3.5 Please define the discrete boundaries at each factor. What is the maximum allowable speed

		Motion Sets (Linguistic Values)				
		Very Fast	**Fast**	**Moderate**	**Slow**	**Very Slow**
Crane Motions	**Slewing Angles (% of rpm)**	>70%	60% - 70%	40%-60%	20%-40%	<20%
	Boom up (% of m/min Winch speed)	>90%	60% - 90%	40%-60%	10%-40%	<10%
	Boom down (% of m/min Winch speed)	>90%	60% - 90%	40%-60%	10%-40%	<10%
	Hoist up (% of m/min Winch speed)	>90%	60% - 90%	40%-60%	10%-40%	<10%
	Hoist Down (% of m/min Winch speed)	>90%	60% - 90%	40%-60%	10%-40%	<10%
	Rotation of load (Min)	< 4	4 < X < 8	8 < X < 14	14 < X < 20	20 < X

Appendix 5: If-then rules

3.6. Please use the linguistic variables which are Very fast (VF), fast (F), moderate (M), slow (S) and very slow (VS) defined in section 3.5

			Safety Factor														
			Very Heavy					Heavy					Moderate				
			Wind					Wind					Wind				
			Very Strong	Stong	Moderate	Weak	Very Weak	Very Strong	Stong	Moderate	Weak	Very Weak	Very Strong	Stong	Moderate	Weak	Very Weak
# of Obstacles	Very Congestion	Slewing Angles	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
		Boom up	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
		Bood down	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
		Hoist up	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S
		Hoist Down	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS	S	S	S
		Rotation of load	VS	VS	VS	VS	VS	VS	VS	VS	S	S	VS	VS	VS	S	S
	Congestion	Slewing Angles	VS	VS	VS	S	S	VS	VS	S	S	S	VS	VS	S	S	S
		Boom up	VS	VS	VS	S	S	VS	VS	VS	S	S	VS	VS	VS	S	S
		Bood down	VS	VS	VS	S	S	VS	VS	VS	S	S	VS	VS	VS	S	S
		Hoist up	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	S	S	S
		Hoist Down	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	S	S	S
		Rotation of load	VS	VS	S	S	S	VS	VS	S	S	S	VS	VS	S	S	S
	Moderate	Slewing Angles	VS	VS	S	S	S	VS	VS	S	S	S	VS	S	S	S	S
		Boom up	VS	S	S	S	S	VS	S	S	S	S	VS	S	S	S	S
		Bood down	VS	S	S	S	S	VS	S	S	S	S	VS	S	S	S	S
		Hoist up	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Hoist Down	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Rotation of load	VS	VS	S	S	S	VS	VS	S	S	S	VS	VS	S	M	M
	Clear	Slewing Angles	VS	VS	S	S	S	VS	VS	S	S	S	VS	S	S	M	F
		Boom up	VS	S	S	M	M	VS	S	S	M	M	VS	S	M	M	F
		Bood down	VS	S	S	M	M	VS	S	S	M	M	VS	S	M	M	F
		Hoist up	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Hoist Down	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Rotation of load	VS	VS	S	S	S	VS	VS	S	S	S	VS	VS	S	M	M
	Very Clear	Slewing Angles	VS	S	S	S	S	VS	S	S	S	M	VS	S	S	M	M
		Boom up	VS	S	M	M	M	VS	S	M	M	F	VS	S	M	F	F
		Bood down	VS	S	M	M	M	VS	S	M	M	F	VS	S	M	F	F
		Hoist up	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Hoist Down	VS	VS	VS	VS	VS	VS	VS	S	S	S	VS	S	M	M	M
		Rotation of load	VS	VS	S	S	S	VS	VS	S	S	S	VS	S	S	M	F

			Safety Factor									
			Light					Very Light				
			Wind					Wind				
			Very Strong	Stong	Moderate	Weak	Very Weak	Very Strong	Stong	Moderate	Weak	Very Weak
# of Obstacles	Very Congestion	Slewing Angles	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
		Boom up	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
		Bood down	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
		Hoist up	VS	VS	S	S	S	VS	VS	S	S	S
		Hoist Down	VS	VS	S	S	S	VS	VS	S	S	S
		Rotation of load	VS	VS	VS	S	S	VS	VS	VS	S	S
	Congestion	Slewing Angles	VS	VS	S	S	S	VS	VS	S	S	S
		Boom up	VS	VS	VS	S	S	VS	VS	VS	S	S
		Bood down	VS	VS	VS	S	S	VS	VS	VS	S	S
		Hoist up	VS	S	S	S	S	VS	S	S	S	S
		Hoist Down	VS	S	S	S	S	VS	S	S	S	S
		Rotation of load	VS	VS	S	S	S	VS	VS	S	S	S
	Moderate	Slewing Angles	VS	S	M	M	F	S	S	M	F	F
		Boom up	VS	S	S	S	M	S	S	S	M	M
		Bood down	VS	S	S	S	M	S	S	S	M	M
		Hoist up	VS	S	M	M	M	S	S	M	M	M
		Hoist Down	VS	S	M	M	M	S	S	M	M	M
		Rotation of load	VS	S	S	M	M	S	S	S	M	M
	Clear	Slewing Angles	S	S	M	F	F	S	M	F	F	F
		Boom up	S	S	M	F	F	S	S	M	F	F
		Bood down	S	S	M	F	F	S	S	M	F	F
		Hoist up	S	S	M	F	F	S	S	M	F	F
		Hoist Down	S	S	M	F	F	S	S	M	F	F
		Rotation of load	S	S	M	M	M	S	S	M	M	M
	Very Clear	Slewing Angles	S	S	M	M	F	S	M	M	F	F
		Boom up	S	M	F	F	VF	S	M	F	VF	VF
		Bood down	S	M	F	F	VF	S	M	F	VF	VF
		Hoist up	S	S	M	M	M	S	S	M	F	VF
		Hoist Down	S	S	M	M	M	S	S	M	F	VF
		Rotation of load	S	S	M	F	F	S	S	M	F	VF