

Factors to Determine Quay Crane Lifecycle: Retrofit and Replacement Policy

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Abstract

Container Terminal is a specialized port facility for container vessels to load and unload shipping containers. Yard cranes, terminal tractors and quay cranes are used to transport container between wharf and yard and vice-versa. Quay cranes' container handling speed is considered as the performance of container terminals commonly indicated as Moves per Hour (MPH). As such, quay cranes with high reliability and availability is paramount to ensure desired container handling performance is achieved. However, in many container terminals the performance of quay cranes is impacted due to lack of maintenance, spare parts and timely refurbishment, retrofitting or replacement of deteriorating components or the quay cranes itself. This paper attempts to propose the appropriate maintenance activities to be carried out and the performance of the quay cranes are monitored to detect impending performance deterioration and action to be taken. The approach is based on evaluation of 12 months operational data of breakdown frequency, breakdown hours, operating hours, container moves and downtime. The correlation analysis for reliability has good negative correlation (-0.75) with breakdown frequency and breakdown hours has strong correlation (0.93) with breakdown frequency. The study will explore 60 months data to establish a quay crane reliability prediction model.

Keywords

Quay crane, Retrofit, Lifecycle, Equipment, Maintenance.

1.0 Introduction

International trade has contributed immensely to the rise in welfare since the end of WWII. As almost 80% of trade is carried by sea (Jo and Kim 2020). Container Terminal is a specialized port facility for container vessels to load and unload shipping containers. The movement of containers from the yard to the vessel for loading and from the vessel to the yard in a discharging operation is performed by yard cranes, terminal tractors and quay cranes. The quay cranes' speed of handling of the containers is generally attributed towards the performance of a container terminal on a particular vessel, which is commonly indicated as Moves per Hour (MPH). As such, quay cranes with high reliability and availability are paramount to ensure uninterrupted operations so that the desired container handling performance is achieved. Container Terminals are paying more and more attention to improving the reliability, availability and operational efficiency of quay cranes (Jo and Kim 2020, Haoyuan and Sun 2017). While the main motions and shape of quay cranes generally remains the same, quay cranes have had evolved tremendously in terms of dimensions, speed of the main motions, lifting capacity and most importantly the electrical control system. The outreach and lifting height have doubled and similarly the speed of the main motions has also doubled (Zrni ü and Hoffmann 2004). since the first purpose-built quay crane for container operations was built and commissioned for operations in Jan 1959 (Zrni ü and Hoffmann 2004). The main electrical control system consists of hardwired direct-on-line (DOL) systems and DC Motor control with analog Ward-Leonard system evolved to PLC based main control system with DC Motor control using digital DC Drives. The digital DC Drives and the DC Motors are now replaced with digital AC Drives and AC Motors which are much easier and cheaper to maintain. The evolution in the quay cranes is due to meeting the needs of the shipping lines as the volume of cargo transportation through containers has increased tremendously (Abourraja et al).

The advancements in science and technology have had enabled such giant quay cranes weighing in excess of 2,000 metric tonnes to be designed, built and operated. The quay cranes are designed and constructed to the required specifications of the container terminals (Zrnić and Hoffmann 2004) to ensure durability, availability and reliability under the varying operating conditions. However, due to repeated heavy load (containers) and high-speed operations, the quay cranes will eventually break down and the frequency of the breakdowns happening will gradually increase over time. Comparing the type and number of breakdowns or failures in the early stages of the quay crane utilization against the type and number of breakdowns after five, ten or fifteen years a quay crane in operation, it will be obvious that repeated operation will inevitably lead to increased breakdown rates (Jo and Kim 2020) due to component deterioration in electrical system and fatigue builds up in quay crane structures and mechanical components.

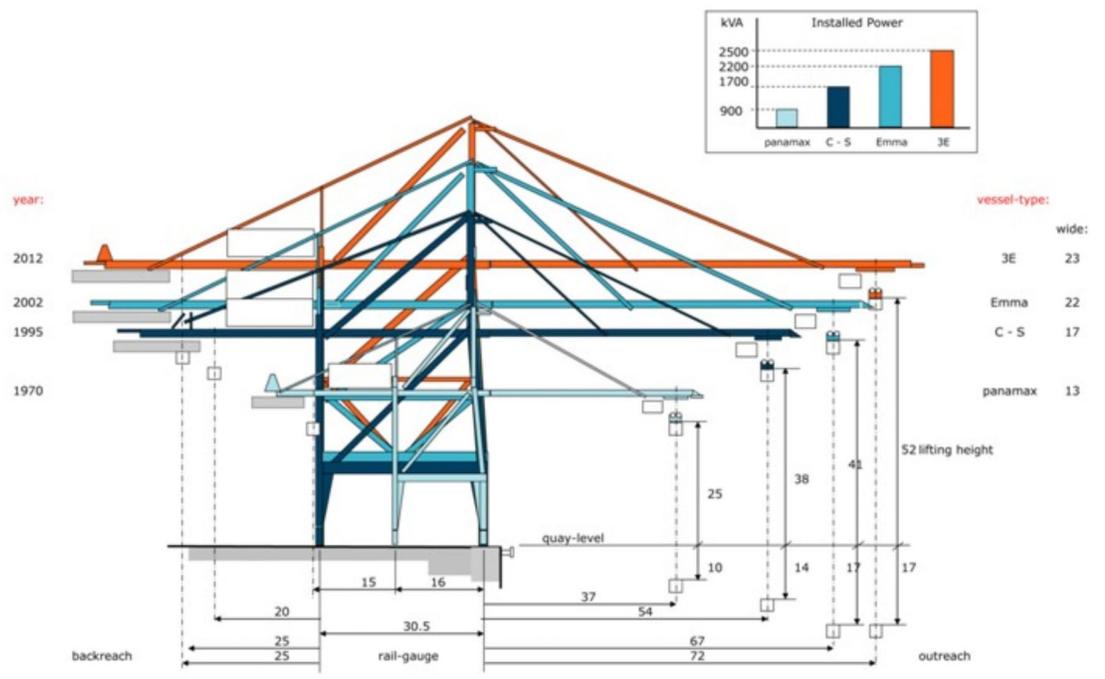


Figure 1. Evolution of Quay Crane's General Dimension & Power Requirements (Adapted : APM Terminals)

As such, in order to ensure deterioration of quay cranes' performance is contained, it is paramount to identify the type, frequency of breakdowns and any related patterns in the breakdowns to create standardized performance indicators and proactive actions are taken. The proactive actions to be taken will be standard actions such as preventative maintenance or any specialized actions unique to the type of breakdown and their frequency. Two of the most important performance criteria of a quay crane that any container terminal keeps track is the equipment availability and equipment reliability.

1.1 Equipment Reliability

Reliability in equipment performance context is a measure of quality of that piece of equipment performing consistently well over a long period of time without breakdowns that causes stoppages. Reliability of an equipment is the measure of its trouble-free time while on operation. Reliability is expressed in terms of percentage of time the equipment is operating without stoppage in a given operating time. The term equipment reliability and maintenance (ERM) encompass not only the equipment, but also the technical, operational, and management activities, ranging from equipment specifications to daily operation and maintenance, required to sustain the performance of manufacturing equipment throughout its useful life. Substantial capital investments, in the form of facilities and equipment, are required for operating a port, and procurement of quay cranes is one of the biggest investments (National Research Council 1991). The productivity of these investments is a

fundamental element of competition among ports and nations. Breakdowns that slow or interrupt the operations impair the competitiveness of a container terminal.

1.2 Equipment Availability

As the quay crane is the most expensive piece of equipment in a container terminal, the return of investment (ROI) takes many years for a terminal. As such, the quay crane must be available to be used at all time (except during planned maintenance) and highly reliable. Availability of an equipment is the percentage of time within a given time either week, month or year that equipment is readily available to be operated. This measurement expresses the percentage that the asset can perform or performed its intended function satisfactorily when needed in a fully operational condition (Jo and Kim 2020) and not experiencing any downtime, planned or otherwise. Based on above, availability is an equipment's uptime. To characterize the availability of an equipment or an asset, it is therefore important to identify the occurrences of downtime or durations when operations are stopped. Downtime consists of planned or unplanned maintenance. While downtime is a necessary step to perform preventive maintenance activities, monitoring downtime would provide useful insights to identify and compare how much it is contributing to the overall performance of the equipment (www.onupkeep.com 2021)

1.3 Quay Crane Characteristic and Structure

As this paper will be concentrated on the performance of container handling quay cranes, an introduction of the steel structure, motions and systems that makes up a quay crane will be explained in order to understand its operations and maintenance.

The entire quay crane is fabricated of steel. Steel plates of different sizes and grades are used in the construction of a quay crane depending the location they are used to meet the quay crane steel structure design criteria. The structure is subjected to cyclic loads throughout its entire life when the quay cranes are utilized to load and unload containers from a container ship. Terminals specify the fatigue design criteria in their technical specification during tendering stage by indicating number of cycles and load spectrum expected from the quay cranes. A hoisting cycle of a quay crane is the complete sequence of operations from the instance a container is hoisted from a prime mover, loaded onto a vessel and ends at the moment when the quay crane's spreader lands on the next container, locks itself to the container and ready to hoist that container (Verschoof 2002, FEM 1998). The load spectrum is a distribution function that characterizes the magnitude or various mass of loads hoisted during the entire life of a quay crane (Verschoof 2002, FEM 1998). The higher the number of cycles and load spectrum for the fatigue design criteria, the more containers the quay crane is able to handle in its entire life without having any fatigue failure to its structure. Generally, the higher the number of cycles the longer the cranes can be utilized or operated at the terminal. Typically, the number of cycles ranges between 2,000,000 to 4,000,000 cycles which translates to lifespan of the quay crane between 20 to 30 or 35 year of operations depending the number of containers a quay crane handles in a year. It is normal that quay cranes located in the middle of a container wharf of a container terminal handles more containers than quay cranes located at the ends of quay line.

Mechanical components consist of all the reducers, actuators, wheels, wire rope drums, couplings and cable reels to name a few. The mechanical components are driven by electric motors. The major mechanical components such as main reducers, wire rope drums and wheels are normally sized to last the designed fatigue life of the quay cranes. However, minor mechanical components such as small reducers, actuators and coupling have much shorter lifespans and may need to be replaced based on wear and tear or it is uneconomical to repair and maintain thereafter.

The electrical system of a quay crane consists of the medium voltage (MV) devices such as the switchgears and power transformers and, low voltage devices such as air circuit breakers, speed drives, main motion motors, programmable logic controller (PLC), other minor electrical components and circuit breakers. The MV switchgears and power transformers could be operated the entire lifespan of the quay cranes with adequate sizing during design stages and proper maintenance program. However, the electrical control system which consist of the programmable logic controller and the speed drives have shorter lifespan. As in other industry, this is mainly due to scarcity of the electronics boards and eventual obsolescence of the hardware and support

service. This requires for the control system to be maintained properly to extend their useful life, their performances monitored for any abnormality and replacement is planned at an appropriate time to avoid prolonged low reliability and long downtime to get the old control system replaced with newer and more reliable system.

Hydraulic systems on quay cranes are confined to trolley rope tensioner and main motion braking system (thruster operated). Hydraulic systems used for the multi-functional system to control and adjust the angle of trim, list and skew of the container lifted by the quay crane and boom structure hook system are nowadays being replaced by electromechanical system, which are easier to maintain and much more reliable.

In general quay cranes are consist of four main motions, namely main hoist, trolley traverse, gantry travel and boom hoisting (Jo and Kim 2020). Each of these motions are activated by the operator which sends the speed reference to the PLC which does some processing and send the processed signal to the respective speed drives which powers the main motors. The main hoist, trolley traverse and boom hoisting motors are connected to their respective reducers which in turn rotates wire rope drums to wind or unwind wire ropes wound on it. This action will cause the container to be lifted or lowered, the trolley traverses forward or reverse and the boom structure to be lifted or lowered. In quay cranes with direct driven trolley traverse system, the trolley motors are connected to the trolley wheels via reducers. The gantry travel motors are connected to the gantry travel wheels via reducers.

Apart from the above main motion systems and components, there are also auxiliary systems and components such as trim-list-skew system, festoon system, rope tensioner system, cable reel system, braking system, load weighing system and emergency drive system. Based on above, the quay crane consists of many types of systems and components which are of custom designed and also off-the-shelf systems and components. They have different lifecycle and maintenance needs.

This paper attempts to study the electrical control system of a quay crane, with the emphasis on monitoring its performance, propose the appropriate major maintenance activities to be carried out, identify markers for impending obsolescence and propose the potential actions that can be taken to overcome obsolescence such as refurbishment and retrofitting/modernization and its impact on the cost, reliability and availability. Refurbishment involves selective renewal of critical component of an equipment (Ajao et al 2016) such as deep cleaning of windings, revarnishing and replacement of bearings of a motor. In refurbishment example, the motor winding, rotor and casing are retained. Retrofit of a quay crane involves the complete replacement of an equipment, component or device. This is done to increase efficiency and performance, reduce operating and maintenance cost or to overcome obsolescence of the replaced equipment, component or device.

2.0 Materials and Method

This paper is focusing on one-year (2018) data collected in a seaport terminal on quay crane performance. The maintenance team has tabulated the breakdown frequency, breakdown hours, operating hours and container moves and most importantly the quay crane downtime for 32 quay cranes. The descriptive statistics of the 32 cranes has been tabulated in Table 1.

Table 1. Descriptive Statistics of 32 Quay Cranes

Events	Min	Max	Mean	Median	STD	Variance
Operating Hours	0.00	470.00	244.48	260.68	112.43	12640.19
No of Moves	0.00	15532.00	6699.25	6914.50	3467.01	12020153.61
Breakdown Hours	0.00	22.33	1.98	1.17	2.54	6.43
Breakdown Frequency	0.00	35.00	2.72	2.00	3.36	11.28
Downtime	0.17	767.88	106.83	61.54	153.33	23509.34

The quay cranes operational reliability framework introduced in this study is represented as per the fishbone diagram in Figure 2.

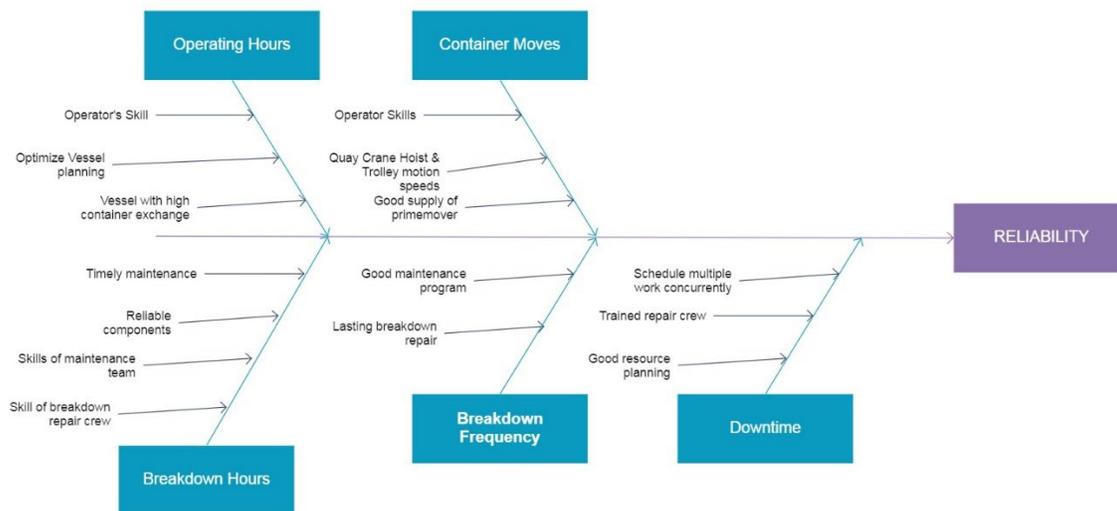


Figure 2. Quay Crane Reliability Framework

In identifying the reliability of the electrical control system in the quay crane the above five parameters were considered. There is a good negative correlation between operating hours and breakdown hours compared the other parameters. The relationship between these two variables can be expressed by the following equation:

$$\text{Reliability (\%)} = \frac{(\text{Total Operating Hours} - \text{Total Breakdown Hours})}{\text{Total Operating Hours}} \times 100$$

The derived reliability was further explored to identify the dependent and independent parameter and the result has been discussed in the next section.

3.0 Result and Discussion

In this study, the emphasis is on the performance of quay cranes' electrical control system. The focus is on electrical control system due to past experience of the maintenance team in attending to repeated electrical control system related breakdowns. The box plot in Figure 3, represents the parameter selected for quay crane reliability framework development. Some general observations from box plot analysis: -

- The box plot for breakdown time and frequency is comparatively short. This suggests that in overall the quay cranes have a high level of agreement with breakdown time and frequency.
- The box plot for operating hours and container moves is comparatively tall. This suggests the individual quay cranes operating hours and container moves are vastly difference and hold quite different opinions among the same manufacturer or similar age.
- The obvious difference between box plots for operating and breakdown hours, or breakdown frequency and container moves is worthy of further investigation on the other available parameters relevant to the formation of the quay crane reliability framework.

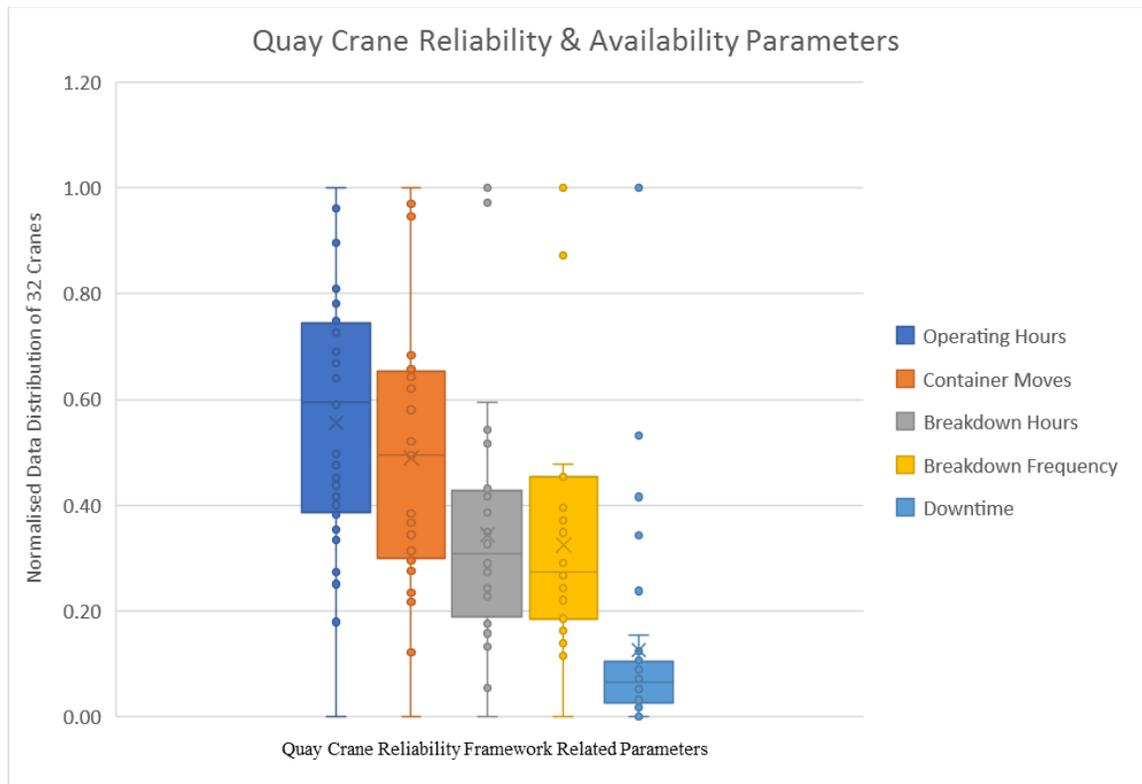


Figure 3, Representation the Parameters Selected for Quay Crane Reliability

- **The general observation of the box plot is as below: -**

Operating Hours. The tall box plot shows that the operating hours of the quay cranes are highly varied. Some of the quay cranes are highly utilized compared to some other quay cranes. Generally, this is due to the location of the quay cranes in the terminal, size of the quay cranes, the draft of the seabed and size of the ships calling at the berths where the quay crane is located and availability of the quay cranes. The shorter upper whisker and smaller Quartile Group 3 denotes that half of the quay cranes are utilized more often than the other half of the quay cranes.

Container Moves. The tall box plot shows that the container moves performed by the quay cranes are **highly** varied. The median and average which is about the same indicates the data is evenly distributed. A comparison against box plot of operating hours indicates that some quay cranes may have moved more containers in the same or shorter operating hours compared to other quay cranes. This is possible as some of the newer quay cranes are much faster than the older quay cranes, thus able to achieve higher moves per hour (MPH) than the older quay cranes with lower operating speeds.

Breakdown Hours. The shorter box plot indicates that the breakdown hours of the quay cranes are less varied. The median which is lower than the mean indicates that quay cranes with low breakdown hours are more than those quay crane with high breakdown hours. This is evident from the two upper outliers at the top of the scale. Low number of quay cranes with high breakdown hours will provide the opportunity to concentrate maintenance and improvement works on these quay cranes.

Breakdown Frequency. The box plot for Breakdown Frequency indicates that many of the quay cranes have similar number of breakdowns at certain parts of the scale, but number of breakdowns of some quay cranes are more varied in other parts of the scale. The short upper whisker denotes that number of breakdowns are about the same for quay cranes with high breakdown frequency and the longer lower

whiskers indicates that number of breakdowns are varied amongst the quay cranes with low breakdown frequency.

Down time. The comparatively short box plot denotes that the quay cranes in general have high level of similarities or agreement in total downtime hours. However, the downtime of 5 quay cranes are upper outliers and highly varied. The average which is in the upper whisker area indicates that there are some quay cranes with very high downtime but bulk of the quay cranes are with low downtime. This could be due to major works such as refurbishments or retrofits were carried out or the quay cranes were inoperable due to breakdowns that requires spare parts which are not in the inventory. This needs further examination and evaluation of the quay cranes downtime data.

The average which is higher than median for both Breakdown hours and Breakdown frequency are consistent which indicates that there is high potential that same group of quay cranes are having reliability issues. This will provide the opportunity to concentrate maintenance and improvement works on these group of quay cranes.

This analysis is based on 12 months operational and maintenance data. The electrical control system breakdowns are consisting of 75% of the total breakdowns' frequency and breakdown time. The analysis has indicated that the breakdown hours of the electrical control system are between 10 to 20 minutes per breakdown. It is also identified that the frequency of breakdown has strong negative correlation (75%) with the reliability of the quay crane. The frequency of breakdowns has positive correlation with the age of the quay cranes. This corresponds to the lifecycle of the electrical control system. As the quay crane structures last twice longer than the electrical control system lifecycle, maintenance managers have to plan for the retrofit of the quay crane's electrical control system. The analysis outcome of this study has identified the frequency of breakdown and duration of each breakdown as some of the indicators that can be used in developing the retrofit prediction system.

4.0 Conclusion

The 12 months data has identified the first step parameters for quay crane reliability prediction. The study is expected to explore further with 60 months or longer data in identifying more parameters to establish a quay crane reliability prediction model. As the quay crane is the most expensive piece of equipment in a container terminal and determines the overall performance of a container terminal, the operational reliability of the quay cranes is very critical. Breakdown of any one of the quay cranes assigned to a vessel will impact the performance of other quay cranes assigned to the vessel as well. As such the performance, reliability and lifecycle monitoring of the electrical control system and timely retrofit planning will have high contribution in overall quay crane lifecycle management. A retrofit predictive model can play a significant role in establishing the electrical control system replacement policy that can ensure the reliability of the equipment.

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Biographies

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