Jurnal Kejuruteraan 36(4) 2024: 1483–1493
https://doi.org/10.17576/jkukm-2024-36(4)-14

Quay Crane Performance Improvement and Lifecycle Extension: Retrofit Determination – A Case Study

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Received 28 July 2023, Received in revised form 29 March 2024
Accepted 29 April 2024, Available online 30 July 2024

ABSTRACT

Quay cranes (QCs) are critical equipment in Container Terminals and their performance determines the port operation efficiency in meeting operational Key Performance Indicators (KPIs). Considering 30-year lifespan of QCs and deteriorating reliability of the electrical control system, planning for timely retrofit of the QCs is critical. The paper aims to present a case study on how the performance of a batch of QCs, having more than 50% remaining lifespan, were analyzed and concluded to be retrofitted to address their deteriorating performance, high maintenance cost and obsolescence. The study methodology is based on quantitative data and employed a prospective longitudinal panel research design over sixteen years. eleven years of pre-retrofit and five years of post-retrofit operations, maintenance and financial data were collected. Convenient sampling technique was selected in this study as the QCs identified as samples were having reliability issues. The Correlation Analysis indicates strong positive correlation of more than 90% between Mean Time Between Failure, Mean Move Between Failure and Reliability KPIs. These KPIs have moderate positive correlations of about 50% with Availability KPI. These 4 KPIs have strong negative correlation of between -50% and -85% with Mean Time to Repair, Maintenance and Breakdown Repair Cost indicating performance degradation but increased maintenance and repair costs as shown by Trend Analysis. The 11-year pre-retrofit data has identified parameters to determine the QC retrofit prediction. The KPIs, obsolescence status, maintenance and breakdown repair cost can be used as the inputs to the future QC Retrofit Prediction Model development.

Keywords: Quay Crane; rtrofit; maintenance; obsolescence; container terminal

INTRODUCTION

International trade has steadily increased since the end World War II due to liberation of trade policies. Almost 80% of the international trade is carried by sea (Pekih et al. 2021; Jo & Kim 2020). Container Terminal is a specialized port facility for containerships to load and unload shipping containers (Azimi et al. 2011). The movement of containers from the yard to the containerships for loading and from the containerships to the yard for storage in a discharging operation is performed by quay cranes (QCs), terminal tractors (TTs) and yard cranes (YCs) (Bartošek & Marek 2013). The QCs' speed of handling of containers per hour is generally attributed towards the performance of a container terminal on a particular vessel and, also the overall performance of a container terminal (Premathilaka 2018; Budiprianto et al. 2017), which is commonly indicated as Moves per Hour (MPH). As such, QCs with high reliability and availability are paramount to ensure uninterrupted operations for the desired container handling performance is achieved (Pekih et al. 2021; Szpytko & Salgado 2019; Wen et al. 2017). Container Terminals are paying more and more attention to improving and ensuring high reliability, availability and operational efficiency of QCs (Pekih et al. 2021; Jo & Kim 2020; Haoyuan & Sun 2017). Container terminals' significant investments in physical assets especially procurement quay cranes necessitate a sizeable maintenance budget as reliability and availability are a critical requirement (Eti et al. 2006).

Generally, periodic and condition-based maintenance (Gama et al. 2012) are carried out on the QCs to ensure continued availability, reliability and lifecycle extension (Abdullah et al. 2006). Predictive maintenance is commonly used to estimate remaining useful life (RUL) of components (Cheng et al. 2022). Wear and tear take its toll on the QCs and maintenance alone is not able to sustain the reliability requirements. As condition worsens, long-term approaches such as refurbishments or retrofits must be considered. Refurbishment involves dismantling of an equipment, carry out inspection, cleaning of certain component and selective renewal of critical component of that equipment (Gothandapani & Ab Rahman 2021; Ajao et al. 2016). Refurbishment process restores the system to meet its original specifications without replacing parts of the system (Zacharaki et al. 2021). Retrofit of a QC involves the complete replacement of an equipment, component or legacy devices (Dietrich et al. 2021). The cost of refurbishment or retrofit of a QC may run between few hundred thousand of Ringgits for a refurbishment to few millions of Ringgits for a retrofit (Bello 2009). The cost relates to the degree of refurbishment or retrofit carried out (Gupta & Majumdar 1989). The cost will be much higher if any physical dimensional increase of the QC such as lifting height or boom length are carried out. As such, it is paramount that the decision to carry out refurbishment or retrofit of a QC is substantiated with its performance data. It is also very important to execute the refurbishment or retrofit at the right timing to minimize operational impact (Falamarzi et al. 2019). There are no guidelines or recommendations currently available to assist ports in determining the refurbishment, retrofit and replacement process. At the same time there is no specific mechanism or framework that can assist in identifying the quay crane performance deterioration and availability added with the increasing maintenance cost. This study focuses on analyzing the operational, maintenance and financial data and methods used to determine the deterioration in performance and increase in maintenance cost (Mobley 2004) that led to the retrofitting of few QCs purchased in same year from same manufacturer. The study also will discuss on how the decision of the retrofit assisted in improving the performance and reliability of the QCs and at the same time managed the obsolescence challenges in the electrical control system lifecycles. In current port operation practice, there is no predetermined method in timing the retrofit execution due to lack in long term maintenance data management policy. Currently, at the most the data is retained for seven years based on ISO 9001 requirement. As of now there is no specific analysis tools or formulas that can assist in retrofit planning.

This paper is structured to first provide a comprehensive review of the relevant literature. Subsequently, the research methodology employed in this study will be delineated in detail. Following this, the results garnered from the data analysis will be presented in a tabular format. Thereafter, a thorough discussion will be undertaken to elucidate the implications of these results. Finally, the paper will culminate in a robust conclusion that summarizes the key findings and their contributions to the field.

LITERATURE REVIEW

The literature survey reveals the types of periodic and conditional based maintenance (Gama et al. 2012) and the long-term improvement works carried out on QCs to ensure continued high performance by the QCs (Li et al. 2020). Due to the high utilization rate of the QCs, it is in evitable that the QCs' components will have wear and tear and deterioration in characteristics (Jalal et al. 2023) which decreases the availability and reliability of the QCs and increase unexpected losses (Lee et al. 2019). One of the areas where the container terminals encounter such problems is the electrical control system of the QCs (Blomquist 2010). This paper presents a case study of a retrofit project that was carried out on a batch of QCs procured in 1998 by a container terminal in Malaysia. The QCs experienced deteriorating performance of their electrical control system even though the container terminal has done early detection and implemented all the maintenance strategies and Performance Improvement Rectification Works (PIRW) to avoid breakdowns (Cheng et al. 2022) but unable to achieve the desired and lasting reliability and availability levels. The QCs experienced degradation in reliability, increased downtime due to both planned maintenance and breakdowns, obsolescence of the electronics boards and increased maintenance and repair costs (Lapin 2021; Bello 2009).

This paper aims to analyze on how the operational performance data, maintenance and breakdown data and financial data could be employed to determine that long term improvement works such as refurbishment or retrofit must be planned and executed before the performance deteriorates to the levels that will impact the overall performance of the container terminal.

METHODOLOGY

The retrofit project undertaken at the container terminal involved the complete replacement of the electrical control system due to degradation in reliability, downtime getting longer, obsolescence of the electronics boards and increased maintenance and repair costs (Lapin 2021; Vuojolainen 2015). The justification for the retrofit to be carried out was based on operational, maintenance performance and financial data of the QCs. The various data were originally collected to carry out maintenance activities such as preventive maintenance, predictive maintenance, and overhauls (Gothandapani & Ab Rahman 2021). The accumulated data, collected over many years, were then used to investigate the degradation in performance of the QCs and to initiate the retrofit justification. In order to gauge the performance of the QCs after the retrofit, similar data were collected for analysis.

The study methodology is based on quantitative data and has employed a prospective longitudinal panel research design over sixteen years. eleven years of pre-retrofit and five years of post-retrofit data was collected. The interval of data collection was daily for breakdown hours and frequency, weekly for operating hours and downtime hours, monthly for container moves, maintenance cost and breakdown repair cost. The breakdown hours, frequency, downtime, and operation hours data are keyed in by technical supervisors. The container moves, maintenance cost and breakdown repair cost are system generated. A convenient sampling technique was selected in this study as the QCs identified as samples were having reliability issues. The QCs were purchased at the same time and fabricated by the same QC manufacturer. Furthermore, the QCs are identical in terms of structure, mechanical, electrical and hydraulic system.

TYPES OF DATA AND COLLECTION MECHANISM

The types of data collected were based on the past maintenance team practice to evaluate the equipment performance. The maintenance team recommended operational, maintenance, performance and financial data to be collected in the interval stated above. The identified data is defined and detailed to support its importance in the analysis.

QC operations or utilization hours is the time between the beginning of the boom lowering operation to the ending of the boom raise operation. This data was collected from two sources, the maintenance department that keeps track of the utilization of the QC and operations department that considers operating hours as the time between the first container lift and the last container landing. Number of Container Moves is the number of containers handled either discharge or loading containers (Plousios 2009). The container moves data is provided by operations department and verified by maintenance department.

Breakdowns are stoppages causing halting in loading or unloading of containers during vessel operation. Breakdown hours is the amount of time a QC stops work while loading or unloading a containership as a result of crane system failure (Bello 2009). Downtime of a QC is categorized in two parts, planned downtime which are for maintenance activities and unplanned downtime are for corrective work due to breakdowns. Maintenance Cost is related to all types of maintenance costs incurred but, in this study, only the costs related to electrical control system are considered. Breakdown repair costs are incurred to rectify a breakdown and put the QC back into operating condition. The Breakdown Frequency, Breakdown Hours, Downtime Hours, Maintenance Cost and Breakdown Repair Cost information are extracted from the Maintenance Management System (MMS) which is used to record, analyze, plan and execute maintenance activities (Ismail et al. 2016).

Considering the complexity in collecting the different types of data from different departments over 16 years a careful data collection and storage mechanism has been instituted.

DATA ANALYSIS

Case study and statistical analysis research method was selected to determine the requirement to execute the retrofit of the QCs. The QCs' breakdown hours, breakdown frequency, downtime, maintenance cost and breakdown repair cost data together with operating hours and number of container moves collected over sixteen years will be basis of the analysis of this case study. In order to have a comparable value or ratio, KPIs such as Mean Time Between Failure (MTBF) which is function of operating hours and breakdown frequency, Mean Move Between Failure (MMBF) (operating hours and container moves), Reliability (operating hours and breakdown hours), Availability (total time and downtime) and Mean Time To Repair (MTTR) (breakdown hours and breakdown frequency) are used to compare and analyze the performance of the QCs. Key performance indicators are used by container terminals to assess the performance of their equipment and consistent quality of equipment work (Pekih et al. 2021). The KPIs used in the QC performance measurement can be categorized to equipment condition and the time taken in maintaining this equipment as detailed below.

MTBF is the average time between subsequent running failure or breakdown of a QC. MTBF can be used to check reliability of individual system or component of a QC. MTBF is a reliability factor and it can be used to support the decision to determine options for refurbishment, retrofit or replacement of a QC. MTBF is calculated as below:-

$$MTBF = \frac{Tot\ Operation\ Hrs}{Bdown\ Frequency} \quad (1)$$

MMBF is a numerical representation of average number of container loading or unloading moves performed between subsequent failure or breakdown of a QC (Pekih et al. 2021; Plousios 2009). MMBF is a reliability factor and is one of the KPIs used to monitor reliability of a QC, thus it can be used to support the decision to determine options for refurbishment, retrofit or replacement of a QC. MMBF is calculated as below:-

$$MMBF = \frac{Tot\ Container\ Moves}{Bdown\ Frequency} \quad (2)$$

Reliability of an equipment is the measure of quality of that equipment performing well consistently over a long period of time (Rokke 2017) and trouble-free while on operation (Bello 2009). Equipment Reliability is a critical KPI that should be used to determine options for refurbishment, retrofit or replacement of a QC. Reliability is calculated as below:-

$$Reliability = \frac{Operation\ Hrs - Bdown\ Hrs}{Operation\ Hrs} X\ 100 \quad (3)$$

Availability of any equipment is the percentage of time within a given time either day, week, month or year that equipment is readily available to be operated (Rokke 2017). Maintenance activities are planned such that they do not strongly affect the availability of the QCs (Burhanuddin et al. 2014). Equipment Availability data of a QC is currently not used to determine the execution of refurbishment, retrofits or replacement of the QC. Availability is calculated as below:

$$Availability = \frac{Tot\ Hrs\ per\ Mth - Tot\ Dtime\ Hrs}{Tot\ Hrs\ per\ Mth} X\ 100 \quad (4)$$

MTTR is the average time taken to put the QC back into operating condition when the QC is faulted during operations causing a stoppage and unable to perform container loading or unloading operations (Pekih et al. 2021 & Bello 2009). MTTR is another KPI that can be used to support the decision to determine options for refurbishment, retrofit or replacement of a QC. MTTR is calculated as below:-

$$MTTR = \frac{Tot\ Bdown\ Hrs}{Bdown\ Frequency} \quad (5)$$

The stated KPIs are used in correlation analysis of the pre and post retrofit operational performance of the selected equipment.

RESULTS

This case study is on the operational performance decline, analysis and remedial actions taken and final decision taken to address further deterioration of five QCs purchased in year 1998. The estimated lifespan of the QCs is between 25 to 30 years (Vuojolainen 2015: Bartošek & Marek 2013) based on 3 million container handling cycles considered in the design for steel structure fatigue calculation. However, the actual lifespan duration depends on the annual container handling cycles or moves, the QCs accumulate throughout their operational life (Vuojolainen 2015). The analysis of this case study is focused on the performance of the QCs' electrical control system and the PIRW undertaken. The focus is on electrical control system as it has the highest impact on the operational performance of the QCs and susceptible to obsolescence compared to steel structure, mechanical and hydraulic components which are still functioning well (Lapin 2021).

The KPI values were calculated using the operations, maintenance, breakdowns, and financial data as explained under Types of Data and Collection Mechanism utilizing formulas as described in Data Analysis. The calculated KPI values of MTBF, MMBF, Reliability, Availability and MTTR, and the Maintenance Cost and Breakdown Repair Cost for each year are tabulated below in Table 1. The MTBF, MMBF, Reliability and Availability KPIs indicates performance drop over the years with the lowest performance in year 2010 and 2011 before the retrofit was carried out in 2012 and 2013. The MTTR, Maintenance Cost and Breakdown Repair Cost on the other end increased, with highest values recorded in 2010 and 2011. The detailed explanation on the KPI data as tabulated in Table 1 is discussed individually with bar charts for each of the KPIs as per Figure 1 to Figure 7.

Tables 2, 3 and 4 indicate the Correlation Analysis of the KPI data tabulated in Table 1. Table 2 is the Correlation Analysis over the sixteen years which indicates strong positive correlations among MTBF, MMBF, Reliability and Availability but strong negative correlations with MTTR, Maintenance Cost and Breakdown Repair Cost. Table 3 is the Correlation Analysis for the period before the retrofit which again indicates strong positive correlations among MTBF, MMBF, Reliability and Availability but strong negative correlations with MTTR, Maintenance Cost and Breakdown Repair Cost and Table 4 is the Correlation Analysis after the retrofit which as before the retrofit, indicates strong positive correlations among MTBF, MMBF, Reliability and Availability. These four KPIs still indicate negative correlations with MTTR, Maintenance Cost and Breakdown Repair Cost but, the strong negative correlation has weakened or become less pronounced. The retrofit has addressed deterioration and improved the QC performance which influenced the relationship between the KPIs, resulting in a reduction in the strength of the negative correlation.

TABLE 1. KPI values calculated from 16 years of data

Year	MTBF (hrs)	MMBF	Reliability (%)	Availability (%)	MTTR (hrs)	Mtce Cost (RM'000)	Bd Cost (RM'000)
2003	190	4191	99.61	93.97	0.49	613	147
2004	174	4013	99.64	95.22	0.50	698	153
2005	139	2880	99.53	94.54	0.49	913	204
2006	146	3022	99.45	92.52	0.57	665	163
2007	128	2696	99.50	94.24	0.56	865	233
2008	89	1595	99.07	87.32	0.58	1051	376
2009	105	2016	99.19	91.08	0.59	828	287
2010	68	1301	99.14	85.18	0.53	883	325
2011	71	1639	99.16	81.95	0.54	809	326
2012	113	2344	99.34	67.12	0.62	658	233
2013	108	2041	99.25	74.54	0.55	618	198
2014	173	4179	99.62	88.90	0.49	448	113
2015	175	4215	99.66	94.00	0.47	443	124
2016	199	4788	99.72	95.50	0.46	478	103
2017	217	6015	99.71	94.14	0.48	413	117
2018	207	5892	99.70	93.13	0.47	442	112

TABLE 2. Correlation Analysis - Overall (2003 to 18)

	MTBF (hrs)	MMBF	Reliability (%)	Availability (%)	MTTR (hrs)	Mtce Cost (RM'000)	Bd Cost (RM'000)
MTBF (hrs)	1						
MMBF	0.97466	1					
Reliability (%)	0.95172	0.92027	1				
Availability (%)	0.58140	0.54354	0.58142	1			
MTTR (hrs)	-0.76404	-0.78443	-0.78702	-0.63812	1		
Mtce Cost (RM'000)	-0.79044	-0.81845	-0.75496	-0.14207	0.62555	1	
Bd Cost (RM'000)	-0.92205	-0.87933	-0.93789	-0.41401	0.72089	0.87809	1

TABLE 3. Correlation Analysis - Pre-Retrofit (2003 to 13)

	MTBF (hrs)	MMBF	Reliability (%)	Availability (%)	MTTR (hrs)	Mtce Cost (RM'000)	Bd Cost (RM'000)
MTBF (hrs)	1						
MMBF	0.98643	1					
Reliability (%)	0.92424	0.94359	1				
Availability (%)	0.50491	0.50609	0.48844	1			
MTTR (hrs)	-0.52106	-0.56887	-0.57444	-0.58562	1		
Mtce Cost (RM'000)	-0.52186	-0.53604	-0.47390	0.26996	0.09469	1	
Bd Cost (RM'000)	-0.88220	-0.87113	-0.88766	-0.25220	0.44385	0.76191	1

TABLE 4. Correlation Analysis - Post-Retrofit (2014 to 18)

	MTBF (hrs)	*MMBF*	*Reliability (%)*	*Availability (%)*	*MTTR (hrs)*	*Mtce Cost (RM'000)*	*Bd Cost (RM'000)*
MTBF (hrs)	1						
MMBF	0.95467	1					
Reliability (%)	0.84234	0.69344	1				
Availability (%)	0.54075	0.37066	0.88446	1			
MTTR (hrs)	-0.23310	-0.09601	-0.69548	-0.88284	1		
Mtce Cost (RM'000)	-0.35004	-0.51632	0.05067	0.13529	-0.45529	1	
Bd Cost (RM'000)	-0.33511	-0.16442	-0.42063	-0.14608	0.18962	-0.65355	1

The port's target for MTBF is 120 hours based on the previous 5-year average. Figure 1 indicates slight deterioration of MTBF of the QCs starting in year 2004. As it is still above the targeted MTBF of 120 hours, the performance was monitored without any intervention. However, due to continued drop in MTBF in 2005, PIRW involving calibration of feedback electronics boards, replacement of thyristor firing cards and, for some QCs, the thyristors were replaced due to low insulation. The DC motors were serviced to improve their insulation resistance (IR) value. The above PIRW improved the QCs' performance in year 2006. However, the MTBF dropped below the target of 120 hours in 2008. The above-mentioned PIRW were again carried out including some additional work. The second PIRW improved the MTBF in 2009 but not meeting the MTBF target of 120hours. Beyond that, the MTBF continued to slip and was not recoverable mainly due to deterioration of the electronics boards of the Programmable Logic Controller (PLC) and the Direct Current Speed Drive (Drive) causing repeated faults.

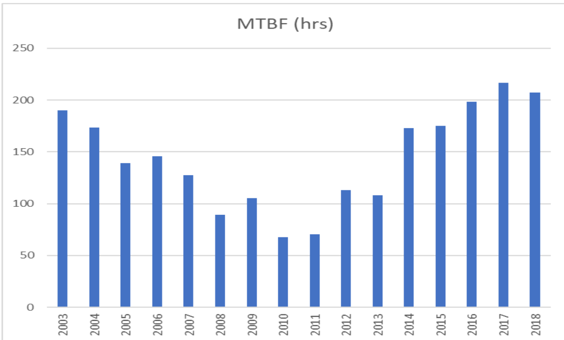

FIGURE 1. Mean Time Between Failure (MTBF)

It is also notable that the Original Equipment Manufacturer (OEM) of the Drive has declared the drive installed on the QCs as obsolete in 2005. When a product is declared as obsolete, the OEM will no longer provide any support for the product, the product is no longer available and no lifecycle services available. While the OEM will not carry any stocks of electronics boards, third party suppliers may still have some new, repaired or remanufactured electronics boards (Pingle 2015; Darley & Liang 1998). Procurement period of these electronics boards will be rather long, first-come first-serve basis and on exchange basis only causing them to be very expensive and difficult to source (Rojo et al. 2009). In some cases, container terminals devise methods for reverse engineering and refabricate the broken components (Thulasy et al. 2022) or modify other components to suit the requirements. As a last resort, OEMs normally recommend users that migration to active product generation as the only possibility, which is to retrofit the QCs with the latest generation of electrical control system (ABB Industry 2011).

The MMBF chart as per Figure 2 is almost similar to the MTBF graph. The port's target for MMBF is 3000 container moves based on previous 5-year average. The similarity is due to the denominator (Breakdown Frequency) is the same for MMBF and MTBF. The slight difference is due to operator's skills in handling containers and operational efficiency. The main reason to monitor the MMBF is to check on the performance of the QC when the QC is executing loading and unloading operations (Pekih et al. 2021). This offsets the effect of idling time of QCs in the calculation of MTBF due to waiting for containers for loading operations or waiting for prime movers during unloading operations. Since the trends for the MMBF and MTBF graphs are similar, analysis for MMBF is similar to MTBF. The Correlation Analysis shows a strong positive correlation of more than 97% between MTBF and MMBF for overall and before the retrofit analysis, which indicates a reliable QC will provide the basis for good operational performance.

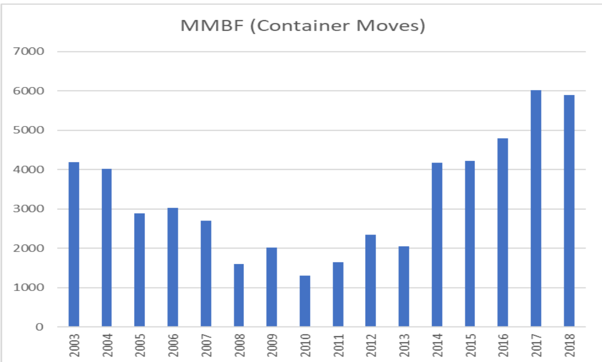

FIGURE 2. Mean Move Between Failure (MMBF)

Figure 3 indicates the Reliability of the QCs for 16 years. The port's target for Reliability is 99.50% based on previous 5-year average. The target is to ensure the breakdown repair time is as minimum as possible. PIRW carried out in 2005 did not improve Reliability in 2006, possibly due to long breakdown repair time but in 2007 the MTBF has improved. In 2008 the reliability dropped again, as did MTBF causing another round of PIRW to be undertaken in 2008. Reliability improved in 2009 but did not meet the target. The QCs continued to experience higher number of breakdowns and long repair time which causes the Reliability to drop in the 2010 and 2011.

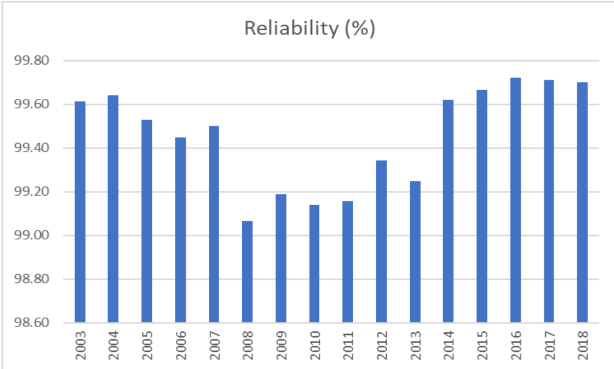

FIGURE 3. Reliability

The Reliability KPI has strong positive correlation of more than 90% with MTBF and MMBF for overall and before the retrofit analysis, which indicates a reliable QC will provide the basis for good operational performance as per Tables No 2 and 3.

The port's target for Availability is 92.50% based on the previous 5-year average. The Availability graph as per Figure 4 indicates the slide in Availability from year 2005. This is due to the PIRW carried out in 2005 which spilled into early 2006 and again another round of PIRW carried out in 2008. The QCs need to be grounded in order to carry out the PIRW, thus not readily available to be operated. The availability improved in 2009 due to the PIRW in 2008 but again dropped in 2010 and 2011. The Availability was the lowest in 2012. This is due to the retrofit of three QCs were carried out in 2012 and the balance two QCs in 2013 which also sees low availability. The Availability KPI has moderate positive correlation of about 50% with MTBF, MMBF and Reliability for overall and before the retrofit analysis, which indicates that availability of QC is crucial for good operational performance.

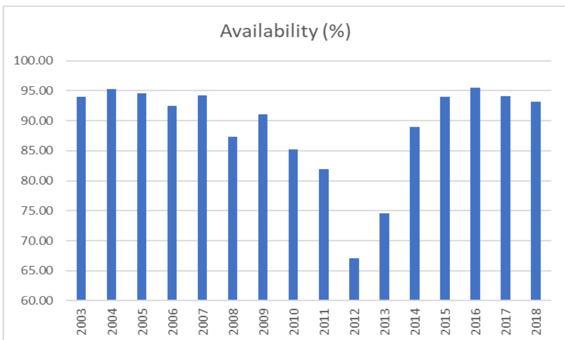

FIGURE 4. Availability

The port's target for MTTR is 0.50 hours or less based on the previous 5-year average. As per Figure 5, low MTTR is desirable as it indicates that the average repair time is short and high MTTR indicates longer average repair time which is not good. The MTTR from year 2006 onwards is high indicating that the breakdowns are taking longer time to rectify. This agrees with the Reliability chart as per Figure 3 which indicates low reliability from year 2006 onwards. The long breakdown time is due to most of the breakdowns requires replacements of spare parts. The MTTR for 2012 and 2013 is high due to longer time taken to rectify faults on the newly retrofitted QCs. The breakdown repair crew is still on the learning curve to rectify faults on the newly retrofitted QCs.

The MTTR for the subsequent years have improved and below the target. On the correlation analysis, the MTTR KPI has strong negative correlation of between -50% and -78% with MTBF, MMBF, Reliability and Availability KPIs for overall and before the retrofit analysis. This indicates that low MTTR due to reduced average QC breakdown time will provide reliable and readily available QCs with good operational performance.

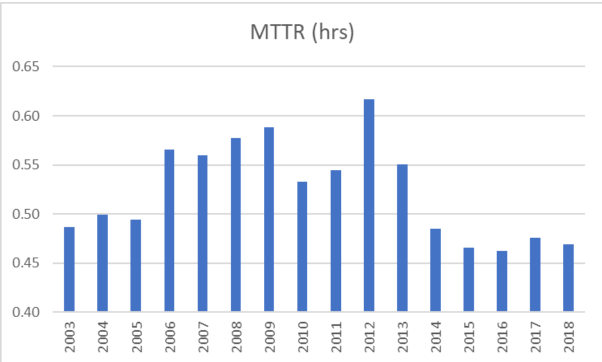

FIGURE 5. – Mean Time To Repair (MTTR)

The overall annual budget for Maintenance Cost is RM500,000.00. The maintenance cost is normally budgeted to carry out all planned maintenance which includes preventive maintenance, predictive maintenance, and replacement of components due to wear and tear in order to ensure the reliability of the QCs are maintained at the highest levels. The annual Maintenance Cost of the QCs will be about the same in normal cases with spikes in certain years when there are planned overhauls to be carried out. However, the Maintenance Cost as per Figure 6 indicates continuous high maintenance cost but the reliability did not meet the target. The maintenance cost is highest in 2005 and 2008 to carry out the PIRW. It is also evident from Figure 6 that the maintenance cost is still high in year 2009, 2010 and 2011 which is due to rectification works, in addition to the normal planned maintenance, to ensure the QCs can be operated but the reliability of the QCs did not improve significantly.

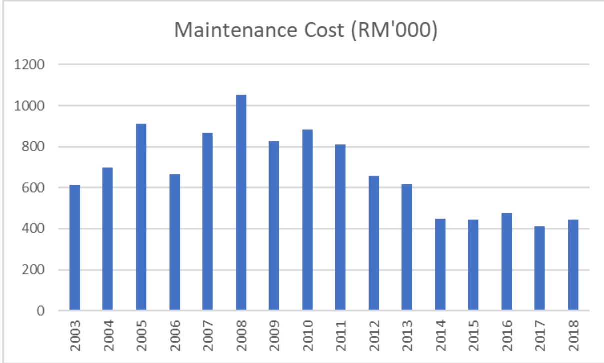

FIGURE 6. Maintenance Cost

Figure 7 indicates the Breakdown cost that increases beyond year 2007. The breakdown cost was due to repair or replace faulty components when the QCs were faulted during operations. The breakdown cost remains high until year 2011 as rectification works were carried out to improve the QCs' reliability but without significant improvements. The Maintenance Cost and Breakdown Repair Cost has strong negative correlation of about between -50% and -87% with MTBF, MMBF, Reliability and Availability KPIs for overall and before the retrofit analysis. This indicates that when the QCs experience reliability issues the maintenance repair cost is high in order to continue operating the QCs.

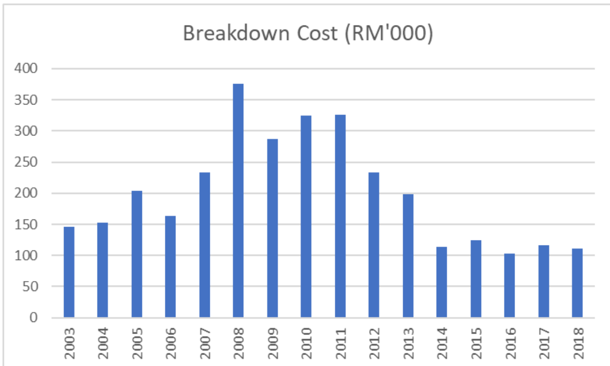

FIGURE 7. Breakdown Repair Cost

The above analysis of MTBF, MMBF, Reliability, Availability, MTTR, Maintenance Cost and Breakdown Repair Cost is on the conditions of the QCs before the retrofit was carried out in 2012 and 2013. By year 2010, the QCs are 12 years old and the steel structure and mechanical components are still functioning well (Lapin 2021), but the reliability of the electrical control system is very much below targets and incurring high maintenance and repair costs. There are still about 13 to 18 years of useful life of the QCs based on structural design of the QCs which can be operated for between 25 to 30 years

(Vuojolainen 2015; Bartošek & Marek 2013). The QCs cannot continue to be operated with such low performance for the rest of their lifespan (Bello 2009). Due to the deteriorating performance of the QCs as per the above analysis, the increasing maintenance and repair costs, the obsolete status of the drives installed on the QCs and the long remaining useful life of between 52% and 60% of the original lifespan, a decision was made to retrofit the complete electrical control system of the QCs (Vuojolainen 2015; Blomquist 2010) including the replacement of DC motors that powers the main motions with AC motors which are cheaper to maintain (Achterberg 2012) and inclined towards latest technology and optimization (Mughal 2024). The retrofit was completed by middle of year 2013.

The overall performance of the QCs in year 2012 and 2013 improved from previous years but still below the set targets as retrofit of few remaining QCs are still not executed but the QCs are continued to be utilized for container loading and unloading operations. However, by the fourth quarter of 2013, the overall performance of the QCs has improved and started to stabilize. There were tremendous improvements in the performance of the QCs after the retrofit. It is notable that from year 2014 onwards all KPIs have shown uptrend. The MTBF and MMBF improved from the lowest of 68 hours to 217 hours and from 1300 container moves to more than 6000 container moves respectively which only means that breakdowns of the QCs are reduced. The Reliability of the QCs improved from the lowest of 99.07% to 99.72% due to less number of breakdowns and shorter breakdown repair time. The downtime of the QCs has reduced as the QCs are not taken out from operations to carry out performance improvement work. The downtime is only to carry out preventive or predictive maintenance and replacement of wear and tear parts. The decision to replace the DC motors with AC motors to power up the main drives of the QCs during the retrofit has reduced the maintenance on the motors (Mahmoud et al. 2020; Pingle 2015). The reduced planned downtime to maintain the AC motors has contributed towards the increase of Availability from 87.12% to 95.50%. MTTR was also reduced as number of breakdowns are lesser and repair time is shorter. The maintenance cost and breakdown repair cost were also reduced due to no improvement works required to be carried out and breakdowns do not require replacement of expensive spare parts.

DISCUSSION

QCs are the frontline equipment in a container terminal and its performance in container loading and/or unloading operations per hour, namely Mover per Hour (MPH) is generally taken as the performance of the overall terminal operations. As such the QCs need to be in the most reliable condition to perform the container loading and unloading operations without interruptions. The analysis in this study is based on 16 years of operational and maintenance data of a Container Terminal. The results and analysis have indicated that the electrical control system reliability is the single most important determinant in the overall performance of the QCs (Blomquist 2010; Bello 2009). The electrical control system breakdowns are major contributor of QCs under performance which constitute between 75% and 80% of all breakdowns and about 70% of overall breakdown time. Downtime due to electrical control system failure is between 60% and 65%. The repeated breakdowns necessitated for PIRW which incurred additional cost to the planned maintenance cost. Breakdown costs are also high due to high number of breakdowns (Yap 2023) requiring for electronics board replacement. The obsolete status of the Drives has caused difficulty in sourcing for replacement electronic boards and its high procurement cost (Pingle 2015; Darley & Liang 1998). The analysis also indicates that PIRW could improve the reliability of the QCs for a short term but will not have lasting impact especially when the electronic boards conditions are deteriorating and made worst by the obsolescence status of the electrical control system.

The results and analysis also indicate that the reliability and performance of the QCs cannot be determined by evaluating one or two KPIs (Sukhadeva 2023). In order to make an informed decision, it is very important to evaluate at least 4 KPIs to arrive at that decision. The Correlation analysis indicates strong positive correlation among the MTBF, MMBF, Reliability and Availability KPIs. These 4 KPIs have strong negative correlation with MTTR, Maintenance Cost and Breakdown Repair Cost. Based on the results and analysis of the various KPIs which indicates deteriorating performance of the QCs, increase in maintenance and repair costs, the obsolescence of the electrical control system of the QCs and the long remaining useful life of between 52% and 60% of the original lifespan, the port decided to retrofit all the five QCs that were purchased in the same year and from the same manufacturer.

The port also has other equipment, namely Rubber Tyred Gantry Cranes (RTG Cranes) that are fitted with similar electrical control system and facing similar reliability and obsolescence issues with remaining design lifespan of about five years. Based on above considerations, the port decided to retrofit all five QCs and utilize all the serviceable electronics boards harvested from the QCs as spares (Pingle 2015: Rojo et al. 2009; Meyer et al. 2004; Singh et al. 2002) for the RTG Cranes.

The study indicates that in general the QC designed lifespan is about twice longer than the electrical control system lifespan which is not identified in previous studies. By analyzing the 16 years of raw data and developing the KPIs values, it provides the ability to identify the decline in performance, increase in maintenance and repair cost in order to decide the appropriate short term and long-term actions to be taken.

CONCLUSION

QC is the single most expensive piece of equipment in a container terminal, and it determines the overall performance of a container terminal, thus the operational reliability of a QC is very critical. A batch of QCs purchased from the same manufacturer were experiencing reliability issues which impacted operational performance. This prompted an analysis to be conducted on the batch of QCs which still had more than 50% of their design lifespan but were having performance degradation which could not be arrested by conducting periodic maintenance and PIRW. The analysis identified an array of QC operational and maintenance data, namely operating hours, number of container moves, breakdown hours, number of breakdowns, downtime hours that can be utilized to determine the condition of the QCs. KPIs calculated from these data were tabulated and analyzed to determine the QC reliability. Apart from the KPIs, the maintenance cost and breakdown repair cost provided information on the total cost to achieve the desired reliability. The analysis concluded that the periodic maintenance and the PIRW could only improve the reliability of the electrical control system for a short period of time but increases the maintenance cost drastically, and coupled with the obsolescence status of the electrical control system, the best approach for long-term solution is to carry out retrofit of the electrical control system. Based on the case study, the QCs' performance, reliability management and lifecycle monitoring of the electrical control system is crucial and that a retrofit prediction model can play a significant role in establishing a timely retrofit plan to replace unreliable, ageing, and obsolete electrical control system that will ensure the reliability of the QCs. The KPIs, obsolescence status, the maintenance cost and breakdown repair cost can be used as the inputs to the future QC Retrofit Prediction Model development efforts. The developed prediction model can be trained for equipment in other industries by identifying the operational, maintenance and financial data, calculate the KPIs and other information relevant to the industry and re-train the prediction model to cater their retrofit needs.

ACKNOWLEDGMENT

The authors would like to thank the Department of Mechanical and Manufacturing Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia for their support.

DECLARATION OF COMPETING INTEREST

None

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