Preventative maintenance of straddle carriers

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Background: Robotic vehicles such as straddle carriers represent a popular form of cargo handling amongst container terminal operators.

Objectives: The purpose of this industry-driven study is to model preventative maintenance (PM) influences on the operational effectiveness of straddle carriers.

Method: The study employs historical data consisting of 21 273 work orders covering a 27-month period. Two models are developed, both of which forecast influences of PM regimes for different types of carrier.

Results: The findings of the study suggest that the reliability of the straddle fleet decreases with increased intervals of PM services. The study also finds that three factors – namely resources, number of new straddles, and the number of new lifting work centres – influence the performances of straddles.

Conclusion: The authors argue that this collaborative research exercise makes a significant contribution to existing supply chain management literature, particularly in the area of operations efficiency. The study also serves as an avenue to enhance relevant management practice.

Introduction

Global sea cargo operations are expanding rapidly and testing global cargo infrastructures to their limits (Choi *et al*. 2012; Fransoo & Lee 2013; United Nations Conference on Trade and Development 2013). Along with this growth has been an associated increase in the demand for more efficient movement of cargo by container terminal operators. There are a number of types of equipment available for cargo handling; these include yard cranes, forklifts and straddle carriers (Avery 1999). Over the last few years, however, robotic vehicles such as straddle carriers (shown in Figure 1) appear to have gained popularity amongst container terminal operators for the movement and handling of cargo (Huang & Chu 2003).

According to Huang and Chu (2003) a noted problem in the utilisation of straddle carriers is their poor record in terms of reliability, maintenance, and operational costs. Straddle carriers also have relatively short economic life spans (compared to their initial purchase cost). However, despite this demand for them continues to be high, due to their flexibility compared to other cargo-handling equipment such as yard cranes and forklifts. Within that context the pursuit of efficiency within container terminal operations has become paramount for maritime logistics researchers (Panayides 2006; Pallis, Vitsounis & De Langen 2010; Woo *et al*. 2011). To date such research has been largely concerned with efficiency quantification (see Cullinane, Song & Gray 2002; Tongzon & Heng 2005): yet what efficiency means for maritime cargo infrastructure is contestable.

Striving for greater efficiency might simply mean minimising financial and time costs, perhaps also adjusting for risk. Looking at the issue from a broader perspective, greater efficiency may encompass the pursuit of 'agility', such that cheaper and quicker shifts in usage become possible for a broader range of task parameters. It might also encompass the pursuit of 'resilience', such that poor weather conditions or skill shortages become less likely to hamper intensive or varied use of infrastructure. Building resilience might also entail minimising downtime required for equipment maintenance, repair or replacement.

When ships dock at cargo terminals, quay cranes are used to move containers from ship to quayside. Straddles then move the containers to stack areas where they can be picked up by trains or trucks for further onward movement (Roso, Wosenius & Lumsden 2009). Straddle carriers are regarded as the most effective means of moving containers to stack areas (Avery 1999; Huang & Chu 2003; Hadjiconstantinou & Ma 2009), and each carrier consists of two components: a lower

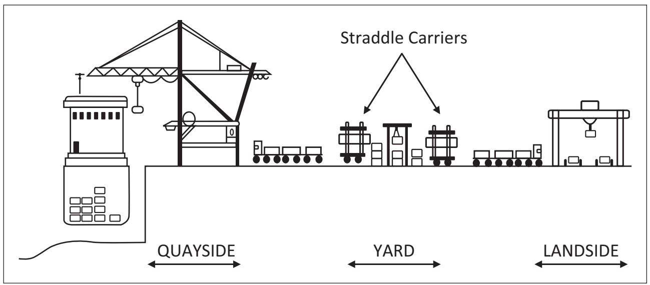

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FIGURE 1: Straddle carrier workplaces.

chassis on which flexible wheels are mounted and an upper chassis which carries a moveable rectangular load lift. As they usually run on wheels, and under their own power, they are versatile in terms of where they can be situated within cargo terminals. Although popular amongst terminal operators (Stahlbock & Voß 2007), a noted problem is their poor record in terms of reliability. Due to their heavy utilisation of hydraulic components straddle carriers are known to be notoriously maintenance-intensive, needing a substantial amount of preventative maintenance (PM), and are frequently subject to breakdowns, requiring often intensive repair (Goel & Meisel 2013; Pascual, Meruane & Rey 2008).

Maintenance is conceptualised by scholars such as Sarker and Haque (2000) as a service endeavour of a dynamic nature which aims at delivering continuous and cost-effective operations. From a review of literature (see Nakagawa & Mizutani 2009; Moghaddam & Ushe 2011; Lynch *et al*. 2013) maintenance may be categorised into two types: (1) *corrective* maintenance, which refers to that undertaken primarily to restore or 'correct' a particular item to an original manufactured standard or quality, and (2) *preventative* maintenance, which focuses on proactive prevention of item failures. Planning and designing an optimised PM strategy can be a complex endeavour for a number of reasons, including management pressures to minimise operational downtime and cost (Goel & Meisel 2013; Pascual *et al*. 2008) and the limited availability of historical data, which may impede performance forecasting (Silver & Fiechter 1995). A more detailed review of available literature on maintenance management and optimisation has been undertaken by Garg and Deshmukh (2006) and, more recently, by Sharma, Yadava and Deshmukh (2011).

This study therefore examines the impact of PM services on the maintenance system of straddle carriers. To support the study objective the rest of the article is organised as follows. In section two we provide background information on the operations of the case organisation and also address the generation of regression models which enable us to explore the relationships between the mean time between failures (MTBF) and mean time between maintenance (MTBM). This is followed by section three, where we develop simulation models for working processes for the repair and lifting systems, the objective being to forecast straddle-fleet reliability against different PM service intervals. Section four focuses on the assessment of different straddle performance scenarios, and in the penultimate section we discuss the findings of the study, followed by the conclusion in section six.

The case organisation

Organisation A's operations

With a fleet of 88 straddles grouped into 12 batches, the complexity and scale of the operations of the case organisation (herein referred to as organisation 'A') are vast. Founded in the 1980s, organisation A is one of the largest container terminal operators in the United Kingdom. Since 2008 the company has had to adapt to increases in container numbers of between 5% and 10% each year. Workloads are usually concentrated heavily around September and October, when goods ordered for the coming December holiday shopping period are processed through the port.

Organisation A's straddle fleet

The company's operational managers are expected to ensure that available straddles are picked for container handling every 12 hours. For ease of operations the available 88 straddles are classified into 12 batches, based on age, manufacturer and type. The company currently owns 33 straddles manufactured by Kalmar Ltd and 55 manufactured by Noell Mobile Systems. Straddles designated '3H' refers to those which are able to lift containers up to three times the height of a container, whilst '4H'-designated straddles are able to lift containers up to four times the height of a container. The company has 543H-designated straddles and 344H-designated straddles.

Referring to Figure 2, which shows the registry of organisation A's straddles, the 'year' column denotes the purchase date of the straddle. For instance, in the first batch, V01 is a 3H straddle bought in 2005 from Noell Mobile Systems.

Organisation A's maintenance programme

A total of eight technicians working two shifts from Monday to Thursday are assigned to the preventive maintenance repair team. Both mechanical and electrical maintenance is based on two shift periods that cover a day shift from 7 am to 7 pm and a night shift from 7 pm to 7 am Mechanical maintenance focuses on oil and filter changes, and tyres. Electrical maintenance focuses on components such as circuits and reverse alarms. Part of the maintenance challenge faced by organisation A is to minimise downtime through the well-known approach of optimising PM (see Moghaddam & Ushe 2011; Lynch *et al*. 2013).

There are three constituent elements of the straddle maintenance system being employed by the case organisation: (1) PM services, (2) remedial (REM) services and (3) breakdown (BD) services. PM generally focuses on preserving and restoring the reliability of straddles by proactively replacing components which may be worn before they

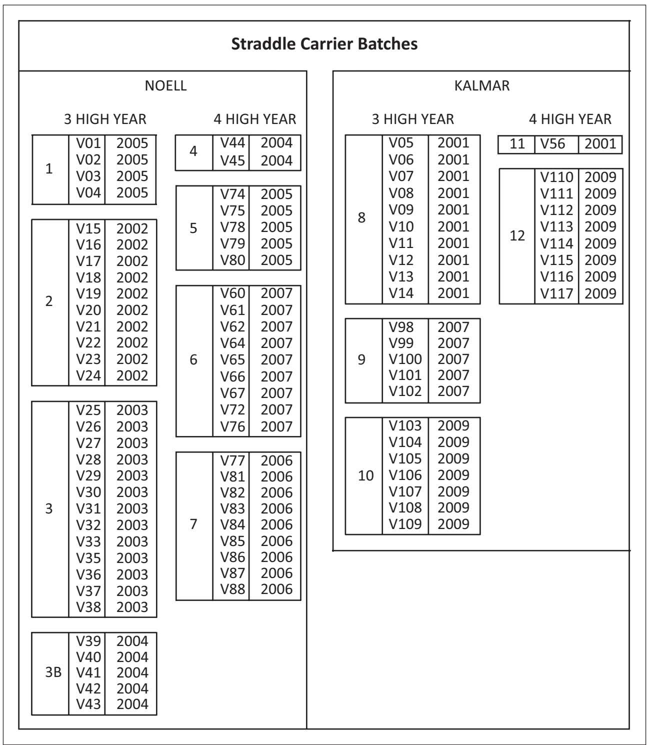

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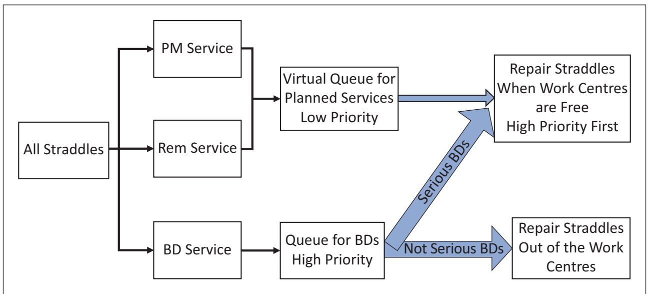
FIGURE 2: Registry of straddles.



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PM, preventative maintenance; BD, breakdown.

FIGURE 3: Workflow of maintenance.

actually break down or fail unexpectedly. The company generally carries out two main types of PM services, one focused on mechanical services and the other on electrical services.

REM services involve corrective maintenance, whilst BD services represent emergency maintenance. Generally BD services do have an impact on the reliability of the straddle fleet. Currently there are five bays for PM services and four bays for REM services. In the repair system there are no real queues for PM service and REM services as, during waiting time, straddles remain operational. BD services are divided into two types: those that are serious and those that are not deemed as such by operators and managers. For non-serious breakdowns, such as no lights, repair work is undertaken outside the bays. Only serious BD services are carried out in designated work centres.

In Figure 3 we show the workflow for organisation A's maintenance programme.

TABLE 1: Related categories for analysis.

Repair services	Related services
PM services	Work order number
	Sub-services: Only consider mechanical and electrical services
	Status: Overdue and finished
	Actual start time
	Actual finish time
BD services	Work order number
	Sub-services: All types of sub-services
	Status: Finished
	Reported time
	Actual finish time

PM, preventative maintenance; BD, breakdown.

Development of simulation models for working processes

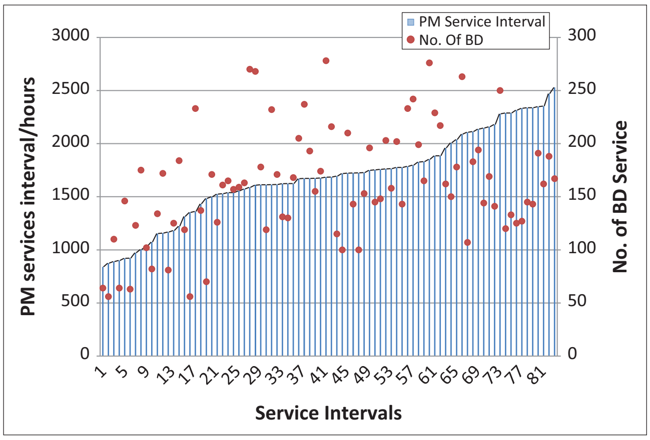
Data collection

The study employs real-life data obtained via participant observation and action research as described by Argyris and Schon (1991). Data for the study were collected between May 2008 and July 2010 from the database of the Engineering Department in organisation A. In total data covered 21 273 work orders recorded for repair services against each straddle. For each work order there were 56 different categories covering service descriptions, issues report time, and actual start and finish time for each repair service. In addition, 55 094 records on actual working hours for 84 target straddles were obtained in order to understand the time stamp for each work order.

Our first step was to separate the original data into small categories. We then selected the most relevant categories, as displayed in Table 1. Next we identified correlations between the MTBF and the MTBM and, in the process, generated regression equations for the straddle carrier fleet. The second stage involved data categorisation, with the main indices of this stage being the average durations for BD and PM services. Whilst the first and second steps were undertaken using MS Excel worksheets, for the third step we employed MS Excel worksheets and Minitab (Ver. 15).

There were three stages to the data handling; the first involved separating the original data into small categories by classifying data into groups depending on different services and batches. The second stage involved data categorisation, with the main indices of this stage being the average durations for BD and PM services. The final stage involved identifying correlations between the MTBF and the MTBM, and generating the regression equations for the straddle fleet.

As changes in the status of a straddle generate work orders, these orders were utilised to search corresponding run time. In terms of the status of BD services, we focused on finished services. Maximum run time for each straddle before PM is 1800 hours; however, some operators are known to overrun this parameter. We therefore analysed PM services with status options of 'overdue' and 'finished'. Thus we represent



Source: Authors' own creation
PM, preventative maintenance; BD, breakdown.

FIGURE 4: Breakdown against preventative maintenance service intervals.

service durations as time periods between $(n+1)^{\text{th}}$ service and n^{th} serivce. For instance, V01 had mechanical PM services on 23 July 2009 and a second service on 16 September 2009. This calculates as a serviceduration of 1320 hours. We represent PM (PM) intervals by equation 1 (below) using original data, whilst equation 2 represents MTBM. As MTBMs differ for older straddles, we make special provision for the 70 straddles in the older batch with reference to equation 3. We use equation 4 to estimate the duration for each BD service. Another index at this stage is the MTBF, which denotes the average hours between $(n-1)^{\text{th}}$ BD services and n^{th} BD services. We show the MTBF in equation 5:

$$\text{PM Service Duration} = \text{Actual Finish Time - Actual Start Time} \quad \text{[Eqn 1]}$$

$$\text{MTBM} = \frac{1}{t}\sum_{i=1}^{t}\left(\text{PM Service Duration}\right)_i \quad \text{[Eqn 2]}$$

$$\text{MTBM for Old Straddles} = \frac{1}{n}\sum_{j=1}^{9} \text{m} \times \left(\text{PM Intervals}\right)_j \quad \text{[Eqn 3]}$$

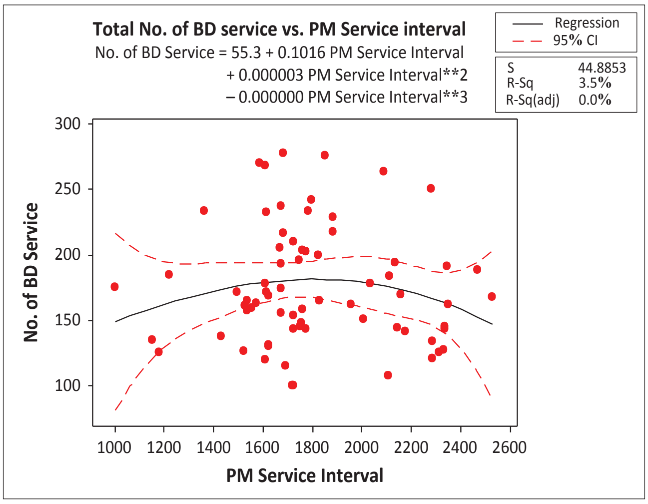
$$\text{BD Service Duration} = \text{Actual Finish Time - Report Time} \quad \text{[Eqn 4]}$$

$$\text{MTBF} = \frac{\text{TOC}}{\text{Total Number of BD Services}} \quad \text{[Eqn 5]}$$

Where: t denotes the total number of PM services, n denotes the total number of straddles in the old group, m denotes the total number of straddles in each batch, j denotes the batch number, and TOC denotes total operating time of the straddles.

It is then expected that, as PMs increase, BDs will decrease.

In Figure 4 we show this relationship, with the blue bars denoting PM services intervals, whilst the red points stand for BD services between May 2008 and July 2010. Outcomes from regression modelling are shown in Figure 5 and Table 2. The value of *R*-square is 3.5% and correlations between the variables are -0.052, suggesting that with increasing intervals of PM services, the number of BDs will decrease. From this, we propose the hypothesis:



Source: Authors' own creation
PM, preventative maintenance; BD, breakdown.

FIGURE 5: Regression of breakdown and preventative maintenance service intervals.

TABLE 2: Analysis of variance of breakdown and preventative maintenance service intervals.

Source	*df*	SS	MS	*F*	*P* value
Regression	3	4825	1608.33	0.8	0.499
Error	66	132 969	2014.69	-	-
Total	**69**	**137 794**	-	-	-

df, degrees of freedom; SS, sum of squares; MS, mean square; *F*, ratio of two mean square values.

- H_0: $\mu_{(\text{no of BD service})} = \mu_{(\text{PM service interval})}$
- H_1: $\mu_{(\text{no of BD service})} \neq \mu_{(\text{PM service interval})}$
- $F_{0.05}(3,80) = 2.744 > 0.8$

so we accept H_0 which provides that the population means of the total number of BD services and PM services intervals are the same.

From regression models for the 3H and 4H straddles, the *R*-square value for the 3H straddles is 2.8%, which is higher than that for the 4H straddles. Additionally, 3H straddles have a higher prediction level than 4H straddles. For the 3H straddle, when the MTBM is less than 1200 hours or greater than 2000 hours, the MTBF decreases with increases in the MTBM.

In terms of the relationship between the MTBF and the MTBM of straddles built by different manufacturers (in this case, Noell and Kalmar), the prediction of the MTBF for Noell straddles was 23.6% higher than for Kalmar straddles. For Noell-built straddles, when the MTBM is less than 1200 hours or greater than 2100 hours, the MTBF was observed to decrease as the MTBM increased.

In terms of regression models for straddles purchased before and after 2005, we find that *R*-square for straddles purchased after 2005 is 19.1% higher than those purchased before 2005. For straddles purchased after 2005, when the MTBM is less than 1200 hours or greater than 2000 hours, the MTBF decreases with increases in the MTBM. Finally, in terms of regressions for the MTBF and the MTBM, the *R*-square value is 6.3%, which means that only 6.3% of the

TABLE 3: Analysis of variance for the mean time between failures and the mean time between maintenance.

Source	*df*	SS	MS	*F*	*P* value
Regression	3	1187.9	395.965	1.79	0.156
Error	80	17711.5	221.394	-	-
Total	**83**	**18899.4**	-	-	-

df, degrees of freedom; SS, sum of squares; MS, mean square; *F*, ratio of two mean square values.

original data can be identified by this equation. Moreover, the correlation coefficient between the MTBM and the MTBM is 0.212, which represents the fact that the MTBM increases with the increasing value of the MTBM. In Table 3 we show the analysis of variance (ANOVA) scores for the MTBF and the MTBM.

The hypothesis is:

- H_0: $\mu_{MTBF} = \mu_{MTBM}$
- H_1: $\mu_{MTBF} \neq \mu_{MTBM}$
- $F_{0.05}(3,80) = 2.719 > 1.79$

so we accept H_0, which means the population means of MTBF and MTBM are the same.

In summary, in terms of expected outcomes of the analysis, we found that: (1) MTBF decreases with straddle age, (2) at the same age, the MTBF of the 3H straddles is higher than the 4H straddles, (3) for old straddles (over 2 years old) decreasing values for MTBM directly correlate to increases in age, (4) MTBFs for 3H straddles are more predictable than for 4H straddles, (5) MTBFs for straddles purchased after 2005 are more predictable than for those purchased before 2005, (6) the MTBFs of straddles purchased from the Noell Company are more predictable than for those purchased from Kalmar and (7) for new straddles, MTBM does not impact upon MTBF.

On the other hand, in terms of unexpected outcomes, we found that: (1) a positive correlation (0.212) emerged between MTBF and MTBM, (2) a negative correlation emerged between the number of BD services and PM services intervals, (3) for 3H straddles, unexpected results were observed with MTBM less than 1200 hours or greater than 2000 hours, (4) for 4H straddles, unexpected results were observed with MTBM less than 1400 hours, (5) for straddles purchased before 2005, unexpected results were observed with MTBM less than 1200 hours or greater than 2000 hours and (6) for Noell's straddles, unexpected results were observed for MTBM less than 1200 hours or greater than 2100 hours.

Assessment of different straddle performance scenarios

Estimation of reliability

Here we employ queuing theory to develop simulation models and forecast fleet reliability against different PM services intervals. Historical data on old straddles covered the period between August 2008 and July 2010, whilst for new straddles historical data covered the period between May 2009 and July 2010. From queuing theory we know the inter-arrival time is the time between $(n-1)^{th}$ and n^{th} work items. In terms of the theory, each node stands for the 'customer' (i.e. the straddles), the total number of which is fixed. λ is the arrival rate; u is the service rate; m is the number of technicians available in the system, and n is the number of straddles in the queuing system. For the PM services, the inter-arrival time changes depended on different maintenance systems within organisation A. Service time is a time-scale for completing a certain job. Table 4 shows time stamps for TEM (total hours of BD services), TCM (total hours of REM services), TPM (total hours of PM services), and TOC (total hours of lifting work). As indicated earlier, when breakdowns are reported downtime commences straight away; thus waiting time should be included in TEM, although for TOC, because PM services are planned beforehand, waiting time is not included.

TABLE 4: Time stamp for each index.

Index	Time stamp
TOC	From enter WCs† to exit WCs
TPM	From enter WCs to exit WCs
TCM	From enter WCs to exit WCs
TEM	From enter queue for BD WCs to exit WCs

TOC, total hours of lifting work; TPM, total hours of preventative maintenance services; TCM, total hours of remedial services; TEM, total hours of breakdown services, WC, work centre.
†, denotes work centre in the simulation model.

TABLE 5: Values and distributions for main indices in simulation models.

Indices	Distribution	Values
Inter-arrive time for containers	Fixed	0.005
Service time for lifting	Normal	Mean: 0.118184 SD: 0.034267
Inter-arrivetime for REM services	Normal	Mean: 6.3292 SD: 3.7489
Service time for REM	Normal	Mean: 54.445 SD: 30.7071
Inter-arrive time for BD services	Normal	Mean: 0.8762 SD: 0.4031
Service time for BD	Normal	Mean: 1.7222 SD: 1.7166
Service time for PM	Normal	Mean: 40.9036 SD: 19.6748

REM, remedial; BD, breakdown; PM, preventative maintenance; SD, standard deviation.

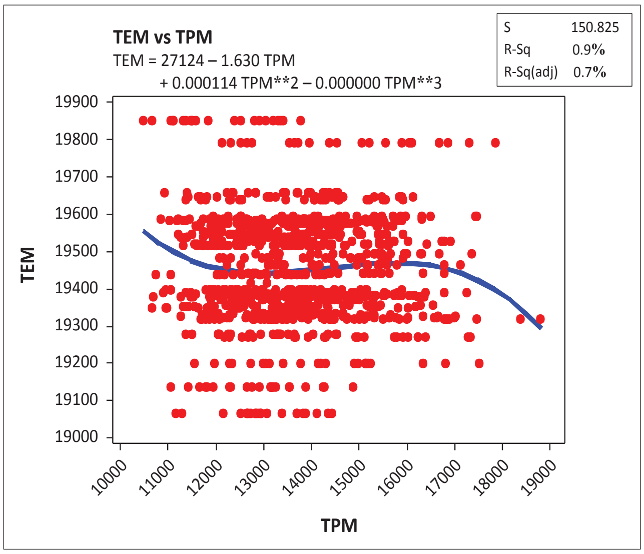
In Table 5 we show the distributions and values for both inter-arrival time and service time. The inter-arrival time of containers refers to the time when containers arrive at the quayside.

We make the following modelling assumptions. In the first place, we assume that the working efficiency for each straddle and labour resource is 100%. We also assume that the waiting time for PM services is not included in the TPM. It is also assumed that the waiting time for REM services is not included in the TCM; nor is the waiting time for lifting included in the TOC. We also assume that inspections in the repair system are perfect. This implies that only straddles requiring repair are housed in the work centres at any one time. Finally, we assume that straddles in the repair system cannot undergo multiple services simultaneously. The model is also limited by the following considerations: (1) the total number of straddles in the system is 84, (2) PM intervals for old straddles range from 1000 hours to 3000 hours, (3) the average queuing time for each BD work centre cannot exceed 0.1 hours whilst utilisations for each repair team must be less than 100% and (4) the maximum number of straddles employed in the lifting system is 66.

We developed two modelling solutions for estimating the inter-arrival time of PM services. One focused on individual performances of straddles whilst the other concentrated on groups of straddles, divided into old and new groups. For the first solution, actual working hours of each straddle is tracked and managed by Visual Logic codes only. PM services also have a lower priority level than the lifting work. The straddle is sent to the PM work centres, when the working hour for the straddle equals the PM interval and the straddle is in the waiting-for-work list. For the second solution, PM services have a higher priority level than lifting work. During the data collection period, the total number of containers lifted is 2 228 179 with 75% (1 645 789 containers) from the old group and 26% (582 390 containers) from the new group. We used Simul8 to auto-adjust the replicated straddle levels. We also (1) set the maximum number of new and old lifting work centres to 10 and 56 respectively and (2) set up 84 resources to represent the 84 straddles, of which 70 were old and 14 were new. Cumulative working hours for each straddle were then calculated and recorded in a spreadsheet. For every user-defined hour (1800 hours), a straddle is sent to the PM service storage bin. In terms of the second solution, during the 24 months between June 2008 and June 2010 there were 538 recorded cases of PM services, 483 of which emanated from the old group and 55 from the new group. The service period for the old group was 24 months (average PM interval of 1804 hours; inter-arrival time 35.78 hours), but for the new group, purchased in June 2009, it was 13 months (average PM interval of 1064 hours; inter-arrival time 157.01 hours).

For our basic PM model, when sufficient technicians are not available other time slots are booked for maintenance. However, to minimise straddle occupancies within repair centres, high priority is usually given to BD services. There are two expected results from the two simulation models. In the first place, with increased intervals reliability will obviously decrease. The second expected result is a negative correlation between TPM and TEM. We found that the reliability change against increasing PM service intervals for the first model was 94.3%, whilst the figure recorded for the second model was 93.75%. Hence, as the first model outperformed the second model, we utilise data from the first model to undertake regression using Minitab (Ver. 15). In Figure 6 we show the regressions for TEM and TPM from the first model.

When the TPM is less than 12000 hours (PM services intervals for the old straddles = 2500 hours), we observe that TEM



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TEM, total hours of BD services; TPM, total hours of PM services.

FIGURE 6: Regressions for total hours of breakdown services and total hours of preventative maintenance services from the first model.

decreases with increasing values for TPM. At the same time, when the TPM is greater than 16 000 hours (PM services time intervals for the old straddles = 1300 hours), TEM also decreases with the increasing TPM values. Hence, when PM services intervals are less than 1300 hours, TEM decreases with the shorter intervals; when PM services intervals are greater than 2500 hours, TEM increases with increasing intervals. As *R*-square is only 0.9%, we are not able to generate a formula for predicting TEM by changes to TPM. In terms of reliability ratios of each service, we observe that values of the total hours of lifting containers (TOC) do not change due to either the inter-arrival time or the service time for each container which is fixed. TPM changes also appear to be dependent on differences in maintenance regimes.

In summary, for the reliability estimation (against changes in PM intervals), we find that (1) simulation models perform better when focusing on individual straddles, (2) impacts of PM intervals on straddle fleet reliability are limited, (3) there appears to be no relationship between TEM and TPM and (4) the optimal decision intervals for PM services are between 1000 hours and 1300 hours and between 2500 hours and 3000 hours.

Current performances of straddles in organisation A

Description of current performance

Having developed simulation models and forecast fleet reliability against different PM service intervals, here we evaluate the current performances of straddles in the case organisation. In Table 6 we show the index values of the first model. Reliability for the straddle fleet is 94.3%. For 131 408 containers there were 339 cases of delay to PM services. Delayed PM services are different from overdue PM services; delays commence 24 hours after a straddle has been booked in for servicing, whenever work centre space or technicians are unavailable. Table 7 shows the routine policy for each work centre.

TABLE 6: Index values for the first model: Results of main indices.

Index	Performances
Reliability	94.3%
TOC	303 693.3 hours
TPM	20 500.53 hours
TEM	19 453.38 hours
TCM	14 991.16 hours
Utilisation of whole fleet	69%
Utilisation of PM team	66%
Utilisation of contractor team	96%
Utilisation of REM and BD team	47%
Average queuing time for BD services	0.058 hours
Containers in the queue	131 408
Delay PM services	339

TOC, total hours of lifting work; TPM, total hours of preventative maintenance services; TEM, total hours of breakdown services, TCM, total hours of remedial services; PM, preventative maintenance; BD, breakdown.

TABLE 7: Routine policies for work centres.

Work centre	Routine policies
PM Arrival WCs	Circulate
Dummy WC for REM	Shortest queue
Dummy WC for BD	Circulate
Dummy WC for lifting	26% for new lifting WCs; 74% for old lifting WCs

PM, preventative maintenance; WC, work centres; REM, remedial; BD, breakdown.

TABLE 8: Scenarios for preventative maintenance service changes: Changes caused by adding two preventative maintenance technicians.

Index	Performances
Reliability	93.6%
TOC	270 880.3 hours
TPM	22 542.73 hours
Utilisation of PM team	70%
Containers in the queue	25 571
Delay PM services	72
Description	Labour resources
PM repair team: Day shift	10
PM repair team: Night shift	10
Distributions for PM team	[1,2] For 1 PM WC, [2,2] For 2 PM WCs, [2,4] For 2 PM WCs

TOC, total hours of lifting work; TPM, total hours of preventative maintenance services; PM, preventative maintenance; WC, work centre.

Outcomes from different queries

In terms of the different scenarios, we show that changes solely in PM service intervals are only likely to increase reliability by 0.5%. If we set PM service intervals to 1800 hours and add two extra technicians to the PM team, as shown in Table 8, we are only likely to reduce the lifecycle for PM services. Again, there will be no increase in reliability. Similarly, as shown in Table 9, a reduction of the shift period of PM technicians, from Monday to Thursday to Monday to Wednesday, will result in an increased number of 'delayed PM services'. We also find –as shown in Table 10 – that if we extend the work shift for technicians to five days a week, the performance of the straddles will improve, whilst in Table 11 we show that if we add two extra new straddles to the lifting system there is likely to be a decrease in the queue size for the new lifting work centres. Finally, as shown in Table 12, an increase in the proportion of new straddles will result in a decrease in the number of containers waiting in the queue; however, the reliability of the straddles will also reduce.

TABLE 9: Shorter shifts for preventative maintenance technicians.

Index	Performances
Reliability	93%
TOC	272 779.6 hours
TPM	178 364.87 hours
Utilisation of PM team	100%
Containers in the queue	82 963
Delay PM services	366

TOC, total hours of lifting work; TPM, total hours of preventative maintenance services; PM, preventative maintenance.

TABLE 10: Outcomes of longer shifts for preventative maintenance technicians.

Index	Performances
Reliability	93.5%
TOC	213 404.5 hours
TPM	24 279.61 hours
Utilisation of PM team	72%
Containers in the queue	192 670
Delay PM services	204

TOC, total hours of lifting work; TPM, total hours of preventative maintenance services; PM, preventative maintenance.

TABLE 11: Outcomes for adding two new straddles in lifting system.

Index	Performances
Reliability	94.5%
TOC	319 688.6 hours
TPM	21 283.87 hours
Utilisation of whole fleet	70%
Utilisation of PM team	72%
Containers in the queue	73 328

TOC, total hours of lifting work; TPM, total hours of preventative maintenance services; PM, preventative maintenance.

TABLE 12: Outcomes for increasing proportion of new lifting work centres.

Index	Performances
Reliability	94.1%
TOC	290 965 hours
TPM	22 589.35 hours
Utilisation of whole fleet	71%
Utilisation of PM team	86%
Containers in the queue	88 764

TOC, total hours of lifting work; TPM, total hours of preventative maintenance services; PM, preventative maintenance.

Results and proposed models

Based on the above, we propose two generalised models developed utilising MS Excel. These focus on: (1) decisions at operational level (strategy one) and (2) decisions at a strategic level (strategy two). An increase in the number of PM technicians is needed to reduce service cycles, which in turn reduces the number of hours that straddles will occupy the PM work centres. For strategy one the decision had been to: (1) retain the current situation for both repairing and lifting systems, (2) focus on individual straddle performance and (3) operate available straddles based on optimal portfolios. An interface for this scenario was constructed/built in MS Excel. Data were collected from different batches of straddles, with key indices of TEM, TOC, TPM and TCM, and the reliability for each group estimated using equation (6):

$$\text{Coefficient} = \frac{\text{average PM intervals}}{\text{arrival time for PM services}} \quad \text{[Eqn 6]}$$

Input

Group number	1	2	3	3B	5	6	7
Straddle needed	0	0	0	0	0	0	0

Group number	8	9	10	12
Straddle needed	0	0	5	5

Output

Total working SCs	10
Average PM time for Old	1011.428571
Number of 3H	5
Number of 4H	5
Reliability of the system	0.968933672

Group 1 is OK
Group 2 is OK
Group 3 is OK
Group 3B is OK
Group 5 is OK
Group 6 is OK
Group 7 is OK
Group 8 is OK
Group 9 is OK
Group 10 is OK
Group 12 is OK

Source: Authors' own creation
PM, preventative maintenance.

FIGURE 7: Reliability for applying only new straddles.

TABLE 13: Outcomes for strategy two.

Index	Performances
Reliability	94.70%
TOC	318 147.08 hours
TPM	24 595.26 hours
TEM	19 318.86 hours
TCM	14 991.83 hours
Utilisation of whole fleet	72%
Utilisation of PM team	66%
Containers in the queue	0
Delayed PM services	207

TOC, total hours of lifting work; TPM, total hours of preventative maintenance services; TEM, total hours of breakdown services, TCM, total hours of remedial services; PM, preventative maintenance.

In the MS Excel interface the reliability of the straddle fleet will change against different numbers of straddles. For instance, if five 3H and five 4H straddles are required for lifting containers, when five new straddles from group 10 and group 12 are chosen, the reliability of the straddle fleet is 96.89% (see Figure 7). Using this strategy only the static situation of the straddle fleet was taken into consideration, which meant that the reliability for each batch did not change with time.

The second strategy represents decisions taken at a strategic level where: (1) there are two new straddles in the lifting system and (2) there is an increase in the number of PM technicians to ten for each shift. In Table 13 we show that compared against current performances of the straddle fleet, with this strategy the reliability of the straddle fleet will increase by 0.4%. At the same time, there will be a 38% reduction in the number of delayed PM services.

In future, however, it will be necessary to classify BD services in more detail, and to rank the emergency and critical levels for each BD service work order. After that, inter-arrival time for machinery BD services must be applied in simulation models and a contrast drawn with outcomes from this study. In the current maintenance regime of the case organisation the PM services obey the 'first come, first served' principle; however, because both reliability and availability of straddles differ, it is necessary to build models for solving issues around the scheduling of maintenance services.

Heuristic techniques and deterministic operational research approaches are useful for future models on prioritising certain straddles, and for ensuring that all PM are completed during the maintenance team shifts. Furthermore, as straddles are the main handling equipment in the case organisation, the logistics of containers are essential considerations when evaluating straddle fleets. With reduction in unproductive moves and empty travel time, the productivity of loading and unloading systems can be expected to reflect positively in academic evaluations of carriers.

Since the working and repairing processes of straddles are full of uncertainty, variability and complexity, a number of factors would affect the reliability of the straddle fleet and predictions of BD services. For this study only PM service intervals are considered; we do, however, suggest that more exhaustive efforts are needed to map out all of the variables that, taken together, can be said to comprise straddle agility and resilience. How maintenance regimes affect straddle resilience and agility certainly merits further study.

Conclusion

Following slight improvements in the global economic environment, the largest container terminal operators are experiencing increasing demand for cargo handling. Operators generally have a number of options in responding to increasing demand for their services. One is to enhance their competitive standing by promoting higher productivity. This strategy requires a high level of reliability in container handling. However, managers face the reality that their handling equipment stocks continue to age and may need replacing. As such, this study identifies two major factors of concern to managers, relating to how changes in maintenance intervals may impact on reliability and how to evaluate performance in order to achieve higher rates of reliability.

This study, that seeks to examine the reliability of equipment and the possible impact of preventative intervals on maintenance programmes, serves as an important means of informing major customers and stakeholders on how equipment maintenance may be optimised. The study is of particular relevance to managers as it represents a collaborative endeavour between academia and industry.

For this project original data about BD services may reflect both human factors and machinery defaults. In future it will be necessary to classify BD services in more detail and to rank the emergency and critical levels for each BD service work order. After that, inter-arrival time for machinery BD services must be applied in simulation models and a contrast drawn with outcomes obtained from this study.

In the current maintenance regime of organisation A the PM services obey the 'first come, first served' principle. However, because both reliability and availability of straddles differ, it is necessary to build models for solving the scheduling of maintenance services issues. Heuristic techniques and deterministic operational research approaches are useful for future models on prioritising certain straddles and ensuring that all PM services are completed during the maintenance team shifts. Furthermore, as straddles are the main type of handling equipment in organisation A, logistics of containers are essential for a straddle fleet. A reduction in unproductive moves and empty travel time will increase the productivity of the loading and unloading systems.

In the general simulation model the assumption has been made that work efficiency for straddles and labour resources is 100% and that the inspections in the repair system are perfect. In fact, due to the fact that straddles are a type of manual handling equipment, working efficiencies in real operations are usually less than 100%. Also, inspections for straddles are not perfect, because of technological restrictions.

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Competing interests

The authors declare that they have no financial or personal relationships which may have inappropriately influenced them in writing this article.

Authors' contributions

S.L. (University of Southampton), T.H. (APM Terminals AME), Y.W. (University of Southampton), U.O. (British University in Dubai), and A.M. (University of Southampton) all made equal conceptual contributions that led to the development of this article.

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