Optimization and Evaluation of Tandem Quay Crane Performance

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Abstract—**To meet the challenges of mega-vessels, i.e. those vessels that have capacity of 18,000 Twenty-foot Equivalent Units (TEUs) or more, tandem lift quay cranes have become more and more popular in container terminals. Theoretically these cranes may double the productivity of loading and unloading operations at the quayside. However, many factors in real operations affect the throughput of such cranes. The existing performance evaluations of these cranes involve yard operations which may end up with inaccurate results. They also do not consider hatch covers, intra-bay crane movements, and the time needed by the crane to change spreader between tandem lifts and single lifts. We propose a method to plan the operations of tandem quay cranes to handle the containers in a 40-foot bay. This includes grouping containers into tandem lifts and sequencing all lifts (tandem and single) in a 40-foot bay to optimize crane performance. Our evaluation of crane performance is based on the quay crane systems only and we use real vessel stowage plans to show what can be achieved by these cranes in real operations.**

Keywords - tandem quay cranes; single-lift quay cranes; container vessels; optimization;

I. Introduction

Quay cranes are container handling equipment in charge of loading/unloading containers onto/from vessels in container terminals. The number of containers they can handle per hour is critical to the length of time a vessel has to berth at a terminal which is referred to as vessel turnaround time. Vessel turnaround time is one of the most important indicators of the performance of container terminals. In order to meet the challenge of Mega-vessels which carry up to 18,000 TEUs (the largest vessel can carry 20,000 TEUs at the moment) of containers and keep the vessel turnaround time low, crane manufacturers continuously offer new designs of quay cranes to increase crane productivity.

A conventional quay crane (CQC) which has been used for many years has a single trolley which can move one 20-foot, or one 40-foot or two 20-foot containers in one cycle of movements of the trolley between a vessel and the shore. This type of cranes is referred to as single lift cranes. In the double trolley design of a quay crane a container is moved in a pipelined fashion by one trolley moving between a vessel and the lashing platform in the crane and another trolley between the lashing platform and the loading/unloading point on the shore. Quay crane productivity is increased because of the parallel operations of the two trolleys. This type of cranes is in operation at the CTA in Hamburg (Germany).

Another type of new quay cranes is called tandem quay crane (TQC) or tandem lift cranes. This type of cranes has two trolleys moving together. With two trolleys the crane can carry two 40-foot containers, or one 40-foot and two 20-foot containers, or four 20-foot containers in one cycle of movements of the spreaders between a vessel and the shore. The crane can still move one 40-foot or two 20-foot or one 20-foot container at a time. This crane has the potential of doubling the number of containers handled per hour which means half the vessel turnaround time. However, whether a tandem crane can achieve the theoretical operational rate depends on many factors. In this paper we present our optimization and evaluation of tandem quay crane performances. Our study is based on real stowage plans on real vessels from a shipping line. The realistic operations of single-lift quay cranes and tandem-lift quay cranes are simulated. This includes the intra-bay and inter-bay movements of cranes, the handling of hatch covers and the change between single spreader and twin spreaders. We do not include the other subsystems of a container terminal, i.e. yard trucks and yard cranes, like many other studies, so we believe our results about tandem quay cranes will not be affected by the efficiency of the other subsystems in a container terminal.

The rest of the paper starts with the descriptions of vessel bay structures and quay crane operations in Section II. Section III presents related work. Section IV presents the method to optimize tandem cranes operations in one vessel bay. The evaluation of the tandem cranes performance is given in Section V and the paper ends with conclusions in Section VI.

II. Vessls, Containers and Quay Cranes

Figure 1 shows the side view of the structure of a container vessel. Containers are stacked longitudinally in a number of 40-foot bays. Figure 2 shows the cross section view of a bay. In each bay, containers are stacked latitudinally in a number of rows. At each bay and row, containers are stacked vertically in a number of tiers. Two 20-foot containers can occupy one 40-foot slot in a bay. Each 40-foot bay is labeled by an even bay number, shown as 02, 06, .. in Figure 1. Within 40-foot bays, the two 20-foot positions are labeled by odd bay numbers, shown as 01, 03, 05, 07, ... in Figure 1. Figure 2 also shows the two 20-foot bays which sit at the left half and the right half of a

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40-foot bay respectively. The container stacks above deck are supported by hatch covers shown by the three horizontal line segments between Tier 82 and Tier 14 in Figure 2 (tier numbers 82 – 90 and 02 – 14 are just the conventional way of numbering tiers in vessels). This means after unloading containers from above deck and before unloading containers below deck, there will be one or more quay crane operations to remove hatch cover(s) to shore. Similarly, after loading containers below deck and before loading containers above deck, hatch cover(s) have to be put back from shore to vessel.

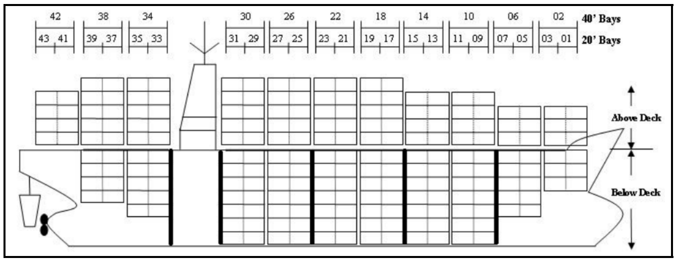

Figure 1. Side view of the structure of a vessel.

In a 40-foot bay, 40-foot containers have to be stowed on top of 20-foot containers both above deck and below deck. Generally, a row in a bay may have containers filled up to its highest tier. There are three possibilities. (i) From the lowest tier upwards it may be occupied completely by 40-foot containers. For example Row 01 of Bay 22 in Figure 2 may have 40-foot containers from Tier 82 till Tier 90. (ii) A row may also be completely occupied by 20-foot containers. For example, Row 02 of Bay 22 in Figure 2 may contain 20-foot containers only. A scenario may be Bay 21 and Bay 23, which form Bay 22, are occupied by 20-foot containers from Tier 82 to Tier 90. Another scenario may be Bay 21 and Bay 23 are occupied by 20-foot containers from Tier 82 to Tier 86 and only Bay 21 is occupied from Tier 88 to Tier 90. (iii) A row may also be occupied in both odd-numbered bays by 20-foot containers for several lower tiers and by 40-foot containers in upper tiers.

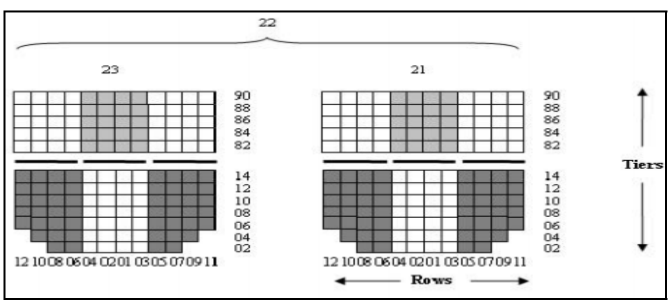

Figure 2. Cross section view of bay 22 formed by bay 21 and bay 23 of a vessel.

When a TQC picks up/puts down two 40-foot or four 20-foot from/into a vessel bay, these containers must be in two neighbouring rows at the same tier. This is called a tandem lift. However if due to the stowage plan of a vessel, a tandem crane does not find a tandem lift to perform, it will just perform single lift operation which means one 40-foot or two 20-foot or one 20-foot container. It also means sometimes, a tandem crane performs tandem lift operations and sometimes single lift operations. According to Jin et al. [6], there needs to be a change of spreaders between tandem lift and single lift operations which will take 90 seconds. Bartosek and Marek [1], Bose [2] and Kemme [7] provided detailed descriptions of these tandem cranes.

When performing tandem lifts or single lifts of one 40-foot container or two 20-foot containers, the trolley of a crane has to be aligned to the centre of a 40-foot bay. When loading or unloading a single 20-foot container, the trolley of the CQC or TQC has to be aligned to the centre of a 20-foot bay (an odd numbered bay). When removing a hatch cover or putting back a hatch cover, the trolley of a crane has to be aligned to the centre of a 40-foot bay. The different alignments cause intra-bay crane movements.

III. RELATED WORK

Choi et al. [4] compared the waiting times of quay cranes and that of yard cranes in container terminals using conventional quay cranes (single-lift and twin-lift), or tandem quay cranes at quayside and double-stack trailers or serial dual trailers. They showed that waiting time of quay cranes decreases and waiting time of yard cranes increases with the increase of tandem ratio. They also showed that waiting time of trailers generally increases with the increase of tandem ratio. We believe that these increases or decreases in waiting times point to the need to have well synchronized operations between the quay cranes, trailers and the yard cranes. The synchronization is more critical when the quay crane operation rate increases by the use of tandem quay cranes and when tandem ratio increases.

Phan-Thi et al. [11] proposed statistical models to estimate the cycle times of two advanced types of quay cranes: (1) a crane with a vessel side trolley and a land side trolley with a lashing platform for transfer of containers between the two trolleys; (2) a crane with two trolleys at vessel side and land side respectively taking containers up and down and a traverser making horizontal movement between vessel and shore. Each trolley and the traverser is represented by a random variable of a normal distribution. Their simulation of quay cranes cycles showed that the statistical models are quite good. However, the performance of quay cranes is also affected by intra-bay movements and changing spreaders so the sequence of the containers to be handled in a bay will also be important.

Yang et al. [12] analyzed the productivity of multi-lift quay cranes. Their theoretical model computes the productivity of quay cranes based on the ratio of containers that can be handled in multi-lifts. The simulation model to assess quay cranes included the yard trucks and yard cranes. Such simulation results may be inaccurate because yard performance may significantly impact the quay crane operation rates.

Two other studies [9] [13] investigate the benefits of optimizing dual-cycle quay crane operations. In dual-cycle mode of operation, a crane carries containers in its trolley movements both from vessel to shore and from shore to vessel. Productivity is increased because the empty trolley movement is eliminated.

Quay crane scheduling which is to partition the loading and unloading operations of a vessel among a number of quay cranes is not the focus of this study. Interested readers may refer to, for example, [3], [5], [8] and [10].

IV. Optimization of Operations of a Tanden Quay Crane in a Bay

Given the list of containers to unload and the list of containers to load in a 40-foot bay, the subtasks of a crane are

(1) unloads containers above deck,

(2) removes those hatch covers which prevent the crane from reaching the containers below deck,

(3) unload containers below deck,

(4) load containers below deck,

(5) put back the hatch covers,

(6) load containers above deck.

For each of the subtasks (1), (3), (4) and (6), a tandem quay crane has to group the containers into tandem lifts and to sequence the tandem lifts and single lifts. To maximize the benefits of tandem cranes, the number of tandem lifts should be maximized and the number of changes of spreaders between tandem lifts and single lifts should be minimized. The intra-bay crane movements should also be minimized. Simply unloading (or loading) tier by tier within a bay will incur some intra-bay movements as well as spreader changes between single lifts and tandem lifts which can otherwise be avoided. The outline of the planning algorithm for the tandem crane operations is given in Figure 3.

1. Identify tandem lift and single lift operations.
2. Sequence the lift operations for unloading above deck.
3. Remove hatch covers that block the containers below deck.
4. Sequence the lift operations for unloading below deck.
5. Sequence the lift operations for loading below deck.
6. Put back hatch covers.
7. Sequence the lift operations for loading above deck.

Figure 3. Outline of planning for TQC.

The algorithm to identify tandem lift and single lift operations is given in Figure 4. It takes in the list of containers, referred to as taskL in Figure 4. The algorithm is executed separately for unloading tasks above deck, unloading tasks below deck, loading tasks below deck and loading tasks above deck. It produces

- the list of tandem lifts, TL,
- the list of single lifts of 40-foot containers and two 20-foot containers, SL40,
- the list of single lifts of 20-foot containers in the lower odd-numbered bay, SL20L
- the list of single lifts of 20-foot containers in the higher odd-numbered bay, SL20H.

Each of the lists above is in fact an array of lists, each element in the array is the list for one row. The list for each row is in decreasing order of tiers if the algorithm is handling unloading lists of containers and in increasing order if it is loading.

```
taskL = list of containers to be handled in the bay
For each tier t in the bay
   For (row r = row at the port side; till r = last row at the starboard)
       If there is no container at tier t row r
           r = next row
       Else if r = last row at the starboard
           Put the container(s) into SL40[r], SL20H[r] or SL20L[r] as fit
           Remove the container(s) from taskL
       Else if there is a 20-foot container at tier t row r
          Put the container into SL20H[r] or SL20L[r] as fit
          Remove the container from taskL
          r = next row
       Else  // there is a 40-foot or two 20-foot containers at tier t row r
           If there is a 40-foot or two 20-foot containers at tier t row r+1
               Put the containers in the 2 rows as one task into TL[r]
               Remove the containers from taskL
           Else if there is a 20-foot container at tier t row r+1
               Put the container(s) in row r as one task into SL40[r]
               Put the container in r+1 into SL20H[r+1] or SL20L[r+1]
as fit
               Remove the container(s) from taskL
           Else // no container in row r+1
               Put the container(s) in row r as one task into SL40[r]
               Remove the container(s) from taskL
           r = the row after next
```

Figure 4. Algorithm to identify tandem lift and single lift operations.

Figure 5 gives an illustration of the result of the algorithm in Figure 4 as an example. The numbers on the left of each array are the row numbers as shown in Figure 2.

The algorithm to sequence the lift operations in a bay that minimizes the number of intra-bay movements and the number of spreader changes between tandem lift and single lift is shown in Figure 6 (for unloading). The algorithm is executed for unloading above deck and then for unloading below deck. The algorithm to sequence the lift operations in a bay for loading is similar.

Using Figure 5 as an example, the two tasks at Tiers 90 and 88 of Row 11 in SL20L are blocking a task at Tier 86 of Row 11 in SL40 so they will be handled and removed from Sl20L by Statement 1 in Figure 6. After this, the task at Tier 88 of Row 5 in SL20L will be handled and removed from SL20L by Statement 2 in Figure 6. A task at Tier 86 of Row 11 in SL40 is blocking a task at Tier 84 of Row 11 in TL so it will be handled and removed from SL40 by Statement 4 in Figure 6. The task at Tier 88 of Row 03 will then be handled and removed from SL40 by Statement 5. Two tasks at Tier 84 and Tier 82 of Row 11 and two tasks at Tier 90 and Tier 88 of Row 01 will be handled and removed from TL by Statement 6. Next the task at Tier 86 of Row 02 will then be handled and removed from SL40 by Statement 7. Last the two tasks at

Tiers 86 and 84 of Row 01 in SL20L will be handled and removed from SL20L by Statement 8.

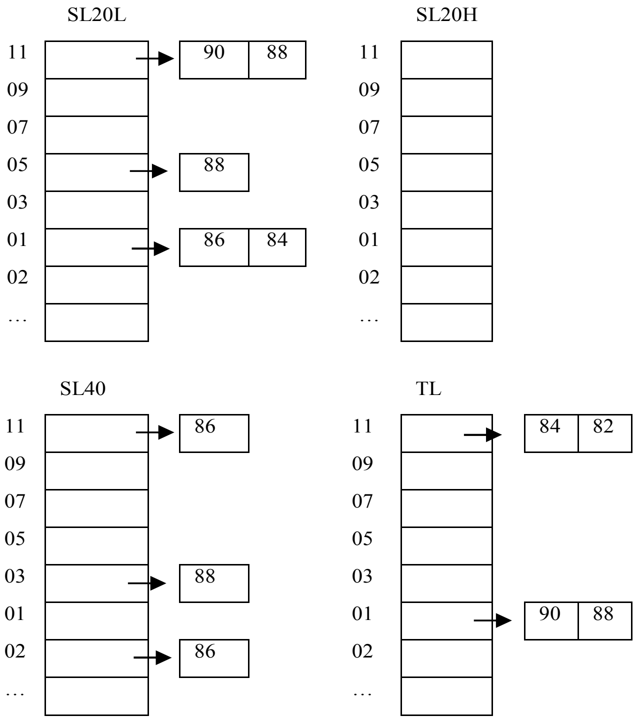

Figure 5. An illustration of results of the algorithm in Figure 4.

1. While a task in SL20L blocks a task in SL40 or a task in TL
   Move crane to align with the 20-foot bay if needed;
   Perform single lift for this task;
   Remove this task from SL20L;
2. If there are tasks in SL20L that are not blocked
   Perform these tasks in SL20L;
   Remove these tasks from SL20L;
3. Repeat Statements 1 & 2 for SL20H;
4. While a task in SL40 blocks a task in TL,
   Move crane to align with the 40-foot bay;
   Perform single lift of this task;
   Remove this task from SL40;
5. If there are tasks in SL40 that are not blocked
   Perform these tasks in SL40;
   Remove these tasks from SL40;
6. If there are tasks in TL
   Move crane to align with the 4-foot bay if needed;
   Change spreader; // single lift to tandem lift
   Perform these tasks;
   Remove these tasks from TL;
7. If SL40 is not empty
   Change spreader; // tandem lift to single lift
   Perform these tasks and remove them from SL40;
8. If SL20L is not empty
   Move crane to align with the 20-foot bay
   Perform these tasks and remove them from SL20L;
9. Repeat Statement 8 for SL20H;

Figure 6. Algorithm to sequence of lift operations for unloading.

V. COMRISON OF PERFORMANCES

We used real vessel loading and unloading lists for vessels from a shipping line to compare the performances of tandem quay cranes. So the numbers and the locations of 40-foot containers, 20-foot containers on vessel are not generated artificially. The need to remove and put back hatch covers also arises from the real scenarios. The lists of container loading and unloading operations for quay cranes serving a vessel are computed by a quay crane scheduling algorithm which has shown to be effective in balancing workload among quay cranes [8]. We experimented with 19 vessels and used difference number of quay cranes (4, 5 or 6) serving a vessel. We assume that both tandem quay crane and single-lift crane will take 2 minutes to complete one cycle of trolley movements between a vessel and the shore. It takes 5 minutes to move from one even bay to the next even bay. When a crane needs to move across the vessel bridge, it will take an extra 5 minutes for the crane to lift its boom and later lower it.

A. *Performance of Tandem Cranes for Whole Vessels*

We first present the results regarding the whole vessels. Table 1 shows the percentage in reduction of vessel completion time when a vessel is served by tandem quay cranes instead of single-lift quay cranes. The last row in the table is the average for each column. The percentage in reduction of vessel completion time is

$$\frac{VCT_s - VCT_t}{VCT_s} \times 100\%$$

where VCT_s = vessel completion time with single-lift QCs, VCT_t = vessel completion time with tandem QCs. Vessel completion time is the amount of time for all quay cranes to complete their operations. It can be seen from Table 1 that using tandem quay cranes it will save more than 40% of the time that vessels have to wait at berths for exchanging containers with a terminal.

TABLE I. VESSEL COMPLETION TIME REDUCTION.

4 QCs	*5 QCs*	*6 QCs*
43.67%	47.55%	40.75%
44.61%	41.15%	46.27%
43.99%	35.67%	47.72%
32.74%	37.40%	47.83%
37.57%	41.26%	41.31%
41.50%	42.74%	42.29%
42.83%	42.44%	46.95%
43.22%	41.40%	47.85%
42.32%	41.36%	46.53%
48.16%	41.44%	43.12%
44.04%	43.97%	39.68%
39.65%	44.54%	47.13%
43.50%	44.97%	43.47%
43.02%	45.35%	44.83%
39.23%	41.63%	39.73%
43.20%	45.00%	46.45%
23.91%	47.39%	36.47%
38.01%	44.82%	39.54%
41.83%	**43.46%**	**44.39%**

Table II compares the number of containers moved per hour per crane when CQCs are used and when TQCs are used for a vessel. It is calculated by

$$\frac{\text{total number of containers loaded/unloaded for the vessel}}{\text{total time for all loading and unloading operations * no. of cranes}}$$

for TQC served vessels and CQC served vessels respectively. The total number of containers is the sum of the number of 40-foot and that of 20-foot containers. The total time for all loading and unloading operations is the time the last crane completes its loading and unloading operation. From the results in Table II we find that the number of containers moved per hour per crane in the TQC case is 1.75 ± 0.03 times that of the CQC case with 95% confidence.

TABLE II. COMPARISON OF THE NUMBER OF CONTAINERS MOVED PER HOUR PER CRANE*.

Single lift			*Tandem lift*		
4 QCs	*5 QCs*	*6 QCs*	*4 QCs*	*5 QCs*	*6 QCs*
25.07	25.72	25.23	44.50	49.04	42.59
22.79	29.66	31.28	41.15	50.40	58.22
23.95	27.82	31.48	42.76	43.24	60.21
32.28	29.66	31.68	47.99	47.38	60.73
32.07	29.42	30.59	51.37	50.09	52.13
30.83	28.75	27.87	52.70	50.21	48.30
33.00	28.74	31.16	57.73	49.93	58.74
14.62	29.58	30.76	25.75	50.48	58.98
32.62	29.73	33.09	56.56	50.70	61.88
22.97	29.42	31.43	44.31	50.23	55.26
25.28	32.76	22.50	45.17	58.48	37.30
33.13	30.96	30.69	54.89	55.81	58.05
32.28	31.06	27.41	57.13	56.44	48.48
32.26	30.36	28.58	56.61	55.56	51.81
28.43	30.93	31.31	46.78	53.00	51.94
32.16	26.98	24.55	56.62	49.06	45.84
16.85	27.13	27.46	22.14	51.57	43.23
29.40	27.83	28.14	47.42	50.44	46.54
29.45	31.06	32.29	47.55	56.44	56.92

Time for inter-bay and intra bay crane movement is included

B. *Performance of Tandem Cranes for Single Bays*

The performance of tandem cranes for single 40-foot bays are presented in Figures 7-9.

In Figure 7, the horizontal axis shows the ratio of the number of lift operations of TQC to that of CQCs. In other words, this is the number of lift operations if the bay is served by a TQC divided by the number of lift operations if the bay is served by a CQC. It shows that when the number of lifts of TQC is about half of the number of lifts of CQCs to handle the containers in a bay, the reduction of bay completion time is about 50%. When the number of lifts of TQC is about the same as that of CQC, the reduction in completion time drops to zero.

In Figure 8, the horizontal axis shows the proportion of the number of containers involved in tandem lifts in the total number of containers to be handled in a bay. So when the number of containers involved in tandem lifts is very small (ration is close to zero), the reduction in completion time is almost zero. When almost all containers are involved in tandem lifts, the reduction is about 50%.

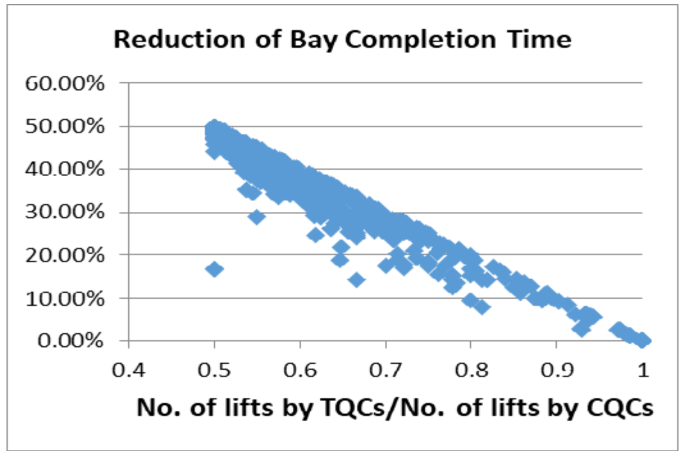

Figure 7. Reduction in bay completion time against number of lifts by TQC/number of lifts by CQC.

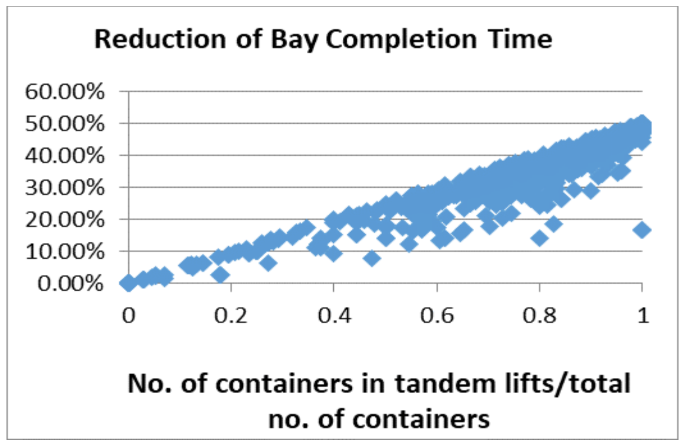

Figure 8. Reduction in bay completion time against number of containers by tandem lifts/total number of containers by tandem QC.

In Figure 9, the horizontal axis is the percentage of tandem lifts in the total number of lifts by the TQC. The total number of lifts by the TQC is the sum of the number of tandem lifts and the number of single lifts by the TQC. The results is similar to those in Figures 7 and 8.

VI. CONCLUSIONS

We have proposed a method to plan the operations of tandem quay cranes to handle the containers in a 40-foot bay that observe the precedence relationships among the tandem lift and single lift operations because they can be blocking each other. The number of spreader changes between tandem lift and single lift operations and the number of intra-bay crane movements are kept to a minimum. The performance of the tandem crane is evaluated by real loading and unloading list of vessels between tandem cranes and conventional cranes.

Generally, we obtain 40-50 % reduction in vessel completion time. This means if a vessel needs 50 hours for exchanging containers with a terminal using conventional quay cranes, it can finish in 25-30 hours using tandem cranes.

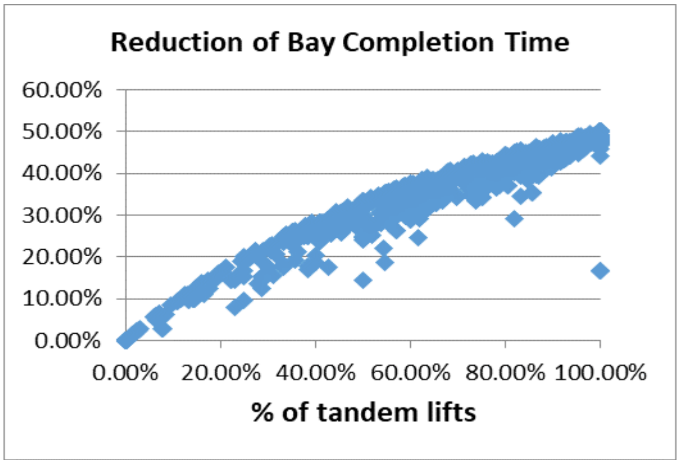

Figure 9. Reduction in bay completion time against percentage of tandem lifts.

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