CRANE DOUBLE CYCLING IN CONTAINER PORTS: PLANNING METHODS AND EVALUATION

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ABSTRACT. In this paper we look at the longer term impact of double cycling on port operations including crane, vessel, and berth productivity. Double cycling is a technique by which empty crane moves are converted into productive ones. We use a double cycling sequence that is operationally convenient, easy to model, and nearly optimum. We compare the performance of this sequence to those determined by a greedy and a mathematical programming strategy. A framework is developed for analysis, and a simple formula is developed to predict the impact on turn-around time. The formula is an accurate predictor of performance. We show that double cycling can reduce the requirements for yard tractors and drivers. The paper also comments on strategies for altering port operations to support double cycling such as segmenting vessel storage, and streamlining traffic flows. We show that double cycling can reduce operating time by 10%, improving vessel, crane, and berth productivity. It can reduce by about 20% the requirement for yard tractors and drivers. Further, for wheeled operations, we suggest a method to reduce the requirement for chassis by about 25%. We estimate the financial impact of the these benefits, which total approximately $65.00 per container moved.

Introduction

Double cycling is an operating technique that can be used to improve the utilization of quay cranes by converting empty crane moves into productive ones. Instead of using the current method, single cycling, where all relevant containers are unloaded before any are loaded, with double cycling, containers are loaded and unloaded simultaneously. This allows the crane to carry a container while moving from the apron to the ship (one move) immediately after moving a container from the ship to the apron; doubling the number of containers transported in one cycle (or two moves).

In 2004, peak levels of container traffic through major US West Coast ports jumped approximately 15% from the previous year. This caused significant port congestion, for example, containers required an additional week just to be moved from vessels through the marine terminals [8]. In 2005, container volumes at the ports of Oakland and the Pacific Northwest have grown by about 20% inbound, while the Southern California complex is up about 5 to 6% [9]. There is no reason to believe this growth will not continue, except that our inland transportation infrastructure will be unable to move it. This growth in container volumes will require additional capacity on the freight transportation network and through ports in particular. In contrast to terminal expansion and information technology deployments, double cycling is a low cost method to increase capacity; it does not require new technology or infrastructure. Although double cycling on its own may not solve the capacity problem, it can be more quickly implemented than other solutions, and can be used to complement other strategies.

In [5] we defined and evaluated efficient algorithms for determining a double cycling sequence, and demonstrated the benefits of double cycling over the status quo (where all containers are unloaded from the vessel before any are loaded). In this paper we define a simpler strategy that is more operationally convenient. The results of this strategy compare well with those of the greedy and mathematical programming strategies of [5]. Based on this strategy, we develop tools to quantify the long-term impact of double cycling on crane productivity and other aspects of port operations. We consider three main operational improvements; reduction in crane operating time per vessel, reduction in the number of landside vehicles and drivers, and reduction in the amount of storage equipment required. We also suggest supporting operational changes for container storage and transportation.

In addition, we estimate the financial impact of these benefits. Of course, the financial impact will depend on the choices a port makes regarding what to do with the productivity improvements; for example, will an improvement in crane productivity be used to increase vessel throughput, or to reduce labor requirements? These choices depend on the details of each port such as current and expected traffic in peak and off-peak seasons, current labor contracts, and current operational bottlenecks. While we provide estimates as to the magnitude of financial benefits, we stop short of providing a very detailed analysis because this should be done on a case by case basis.

While problems of port design and operation are the subject of much academic research and currently the subject of much political attention (California State Assembly Bill 2650, 2002-03 and 2042, 2003-04), to date no study except on double cycling except [5] has appeared in a scholarly journal. We believe the tools presented in this paper will be particularly useful for those considering implementation of double cycling, and performing long-range planning. Modern ports use computer programs to sequence loading and unloading operations and schedule daily port operations. Double cycling could be easily incorporated into these tools. The ideas presented in this paper are not meant to substitute for detailed terminal planning programs, which are well suited to managing a specific vessel and terminal configuration, but to provide portable insights into double cycling at a more general level. Results can be used to suggest how a port should be configured and operated.

In Section 1 of this paper we define the new strategy and compare its performance to those of other double cycling strategies. In Section 2 we develop a methodology and formula to determine the long-term improvement in crane productivity, and compare the results using this formula to simulation. In Section 3 we look at the impact of double cycling on the requirements for landside vehicles and drivers. In Section 4 we consider how the number of containers in port during loading and unloading operations is affected by double cycling, and the ramifications for chassis and storage space requirements. Section 5 presents operational changes that could be undertaken to support double cycling. In Section 6 we estimate the financial impact of the benefits described in the paper. The paper concludes with a discussion.

1. The Proximal Stack Strategy

As demonstrated in [5] the benefits of double cycling depend on the sequence with which loading and unloading operations are carried out. The goal of double cycling is to increase port throughput. Port throughput is the number of forty foot containers (FEUs), or twenty foot containers (TEUs) that enter and exit the port per gate hour. Port throughput can be increased by improved utilization of port resources, in particular the quay crane as this is typically the bottleneck when unloading and loading the vessel, and the most expensive single piece of port equipment. With double cycling quay crane utilization is increased by converting wasted crane moves into productive ones. Through improved crane productivity we are also able to improve vessel productivity. A key metric is the number of cycles required to complete loading and unloading operations on the vessel. While initially we will consider the benefits of double cycling in terms of number of cycles, we will also take advantage of a method to convert these benefits from cycles to time, as suggested in [5].

The layout of containers on a ship can be modelled as a 3-dimensional matrix. Containers are stacked on top of one another, and arranged in rows. Each row stretches across the width of the ship. Large container vessels typically hold up to 20 stacks of containers across the width of the ship, and up to 20 stacks (FEUs) along the length of the ship. Each stack can hold up to about 8 containers above deck and about 8 containers below deck. Let R be the number of rows on a vessel, and let C_i be the number of stacks in row i. Rows are numbered $i = 1..R$ starting from the bow.

Let $\{1...C_i\}$ be the set of stack numbers, c, in one row of a vessel. The first number, $c = 1$ is the stack closest to the shore, and C_i the stack nearest the water. In this paper we will consider sequences of stack operations determined by the following strategy:

Definition 1.0.1 (Proximal Stack Strategy)**.** The crane processes rows one at a time in order of increasing i. For each row it:

(1) Unloads all containers in the stack closest to the shore, $c = 1$, then all containers in stacks $c = 2, 3$, etc. until all stacks in the row have been unloaded.
(2) Loads the stacks using the same ordering. Loading can start in a stack as soon as it is empty or contains just containers that should not be unloaded at this port. Once loading has begun in a stack it is continuously loaded until complete.

We choose to focus on this strategy because it is operationally and mathematically convenient, and is used by shipping companies to a limited extent. By operating on each row individually we do not require the crane to move laterally along the ship within one cycle.

1.1. **Simulation Results.** We use simulation results to compare the benefits from the proximal stack strategy to the benefits of single cycling, the mathematical programming strategy, and the greedy strategy. Our comparison considers double cycling within one row of the ship. The mathematical programming and greedy strategies are defined in [5]. Ship data were generated using a simulation program. The number of containers to load and unload in each stack were assumed to be independent and uniformly distributed between 0 and 10. The simulation counts the number of cycles required to complete loading and unloading operations on a vessel for various sequences. For more details on the simulation program see [4]. These results are shown in figure 1.

As expected, the benefits using the proximal stack strategy are smaller than the benefits using the greedy or mathematical programming strategies. For a row of 20 stacks, there is a 26% reduction in number of moves over single cycling for the mathematical programming strategy, 25.5% for the greedy strategy, and 25% for the proximal stack strategy. Notice the scale of the benefits axis has been reduced to allow closer comparison of the strategies, that benefits above 23% are commonplace, and that the benefits of using any of the three strategies are essentially equivalent.

2. Estimation of Long-Term Reduction in the Number of Cycles

Before adopting double cycling, terminal operators will need to understand its impact on requirements for land-side vehicles, quay cranes, stevedores, etc.. Instead of understanding the expected turn-around for an individual vessel, they would like to base estimates on the entire fleet calling, and expecting to call, at their terminal for some relevant time horizon. In this analysis we assume knowledge only of the distribution of the number of containers to load and unload in each stack, and the number of stacks on the vessel. We now develop formulae for the expected number of cycles using double cycling given just this distributional information.

Definition 2.0.1 (Demand)**.** Introduce random variables $u_{c,i}$ to denote the number of containers to unload in stack $c \in \{1..C_i\}$ of row $i \in \{1..R\}$, and $l_{c,i}$ the number of containers to load in stack c of row i. [1] The random variables in sets $\{l_{c,i}\}$, and $\{u_{c,i}\}$ are mutually independent. The variables in set $\{u_{c,i}\}$ are identically distributed with mean μ_u and variance $\sigma_u^2$and so are the random variables in $\{l_{c,i}\}$ with mean μ_l and variance σ_l^2.

Definition 2.0.2 (Cumulative Demand)**.** Define $Y_i = \sum_{c=1}^{C_i} u_{c,i}$ the total number of containers to unload in row i and $\Lambda_i = \sum_{c=1}^{C_i} l_{c,i}$, the total number of containers to load in row i.

2.1. **Expected Number of Cycles Using Single Cycling.** We require one cycle for each container, so the expected number of cycles to unload and load in row i using single cycling is equal to the expected number of containers:

$$E[\Lambda_i] + E[Y_i] \tag{1}$$

[1] If a container on the vessel needs to be moved to access another container, but it is not to be unloaded at this port, this move will be considered an unload, and a load if it is handled again, for simplicity.

These expectations are: $E[Y_i] = E[\sum_{c=1}^{C_i} u_{c,i}] = \sum_{c=1}^{C_i} E[u_{c,i}] = C_i\mu_u$, $E[\Lambda_i] = E[\sum_{c=1}^{C_i} l_{c,i}] = \sum_{c=1}^{C_i} E[l_{c,i}] = C_i\mu_l$.

It should be noted that while mathematically it is satisfactory to consider the number of cycles necessary to unload and load a row, in current operations, all containers from *the vessel* are unloaded before any containers are loaded onto the vessel.

2.2. **Expected Number of Cycles Using Double Cycling.** Figure 2a shows a queuing diagram for the loading and unloading processes for an example problem; one row with four stacks. In this example, $u_{1,1} = u_{2,1} = 3$, $u_{3,1} = u_{4,1} = 2$, $l_{1,1} = 2$, $l_{2,1} = 5$, $l_{3,1} = 0$, and $l_{4,1} = 3$. The diagram shows two curves; one that documents the loading process, and one that documents the unloading process. The figure shows the number of stacks completed for any number of cycles completed. When both loading and unloading, we operate on the stacks in the order $c = 1, 2, 3, 4$. The loading operations begin on stack 1 as soon as the unloading operations are complete in stack 1. Note the loading operations are delayed by one cycle before starting to operate on stack 2, as unloading operations on stack 2 are not yet complete. Define:

$$M_i(c) = \sum_{2\leq j\leq c} \{u_{j,i} - l_{j-1,i}\} \,\forall c \in \{2..C_i\} \tag{2}$$

Also define $M_i(1) = 0$. Then,

$$M_i = \max_{c=1\ldots C_i} \{M_i(c)\} \tag{3}$$

If we delay the loading of stack 1 by M_i time units (see figure 2b), we eliminate all future delay caused by waiting and loading operations are completed at time $\{u_{1,i} + M_i\}+ \Lambda_i$. The number of cycles required to unload and load the row using the proximal stack strategy is thus:

$$u_{1,i} + \Lambda_i + M_i \tag{4}$$

Then on average:

$$E[u_{1,i}] + E[\Lambda_i] + E[M_i] \tag{5}$$

The first two terms are easy to estimate; the expected number of containers to unload in the first stack, and the expected number of containers to load in row i. Since the $u_{j,i}-l_{j-1,i}$ are independent, identically distributed random variables, $M_i(c)$ is a diffusion process with the stacks completed, c, as time. Thus, we can use diffusion formulae for $E[M_i]$. The drift is:

$$d = \frac{E[M_i(c)]}{c} = \mu_u - \mu_l \tag{6}$$

and the variance rate is:

$$D = \frac{var(M_i(c))}{c} = \sigma_u^2 + \sigma_l^2 \tag{7}$$

Definition 2.2.1 (First Passage Time)**.** Let $T_i(z)$ be the time (number of stacks completed) at which $M_i(c)$ first reaches z cycles, assuming the process starts from $z = 0$.

According to [3] the formula for the probability density function of $T_i(z)$ evaluated at c is:

$$f(c|z) = \frac{z}{\sqrt{2\pi Dc^3}} e^{\frac{-(z+dc)^2}{2Dc}} \tag{8}$$

The cumulative distribution function is therefore:

$$\Pr\{T(z) \leq c\} = F(c|z) = \int_0^c \frac{zdy}{\sqrt{2\pi Dy^3}} e^{\frac{-(z+dy)^2}{(2Dy)}}. \tag{9}$$

We are interested in $F(C_i|z)$. Where C_i is the number of stacks in row i. Note, however, that

$$Pr\{T(z) \leq C_i\} \equiv Pr\{M_i > z\}. \tag{10}$$

The expectation of a non-negative random variable is obtained by integrating the complementary cumulative distribution function. Hence, the expected maximal excursion is;

(11)

$$E[M_i] = \int_0^\infty dz \int_o^{C_i} dy \left\{ \frac{z}{\sqrt{2\pi Dy^3}} e^{\frac{-(z+dy)^2}{(2Dy)}} \right\} = \frac{2D}{d}[\Phi(\frac{d\sqrt{C_i}}{\sqrt{D}}) - \frac{1}{2} + \int_{\frac{-d\sqrt{C_i}}{\sqrt{D}}}^0 y\Phi(y)dy]$$

where $\Phi(x) = \int_{-\infty}^x \frac{dw}{\sqrt{2\pi}} e^{\frac{-w^2}{2}}$. This result is obtained by interchanging integrals and variable substitution. An estimate for the number of cycles to unload and load a row is thus:

$$\mu_u + C_i\mu_l + \frac{2D}{d}[\Phi(\frac{d\sqrt{C_i}}{\sqrt{D}}) - \frac{1}{2} + \int_{\frac{-d\sqrt{C_i}}{\sqrt{D}}}^0 y\Phi(y)dy] \tag{12}$$

where $\Phi(x) = \int_{-\infty}^x \frac{dw}{\sqrt{2\pi}} e^{\frac{-w^2}{2}}$, and $E[u_{c,i}] = E[u_{1,i}] = \mu_u$ because $\{u_{c,i}\}$ all identically distributed. Notice that for $d = 0$, the value of M_i is undefined. We expect that in these cases, the value of M_i would be small. In fact, if we define $x = \frac{d\sqrt{C_i}}{\sqrt{D}}$ then the reader can verify from equation (11) that $\lim_{x \to 0} E[M_i] = 0$. The formula allows us to estimate the number of cycles to insert before beginning loading operations so we can avoid future delay and thus estimate the total number of cycles to complete loading and unloading operations.

Formula (12) tells us that only μ_u, μ_l, C_i and $D = \sigma_u^2 + \sigma_l^2$ influence crane time; all other ship configuration data are irrelevant. One could not get this insight with simulation alone. Figure 3a shows the percentage reduction in the number of cycles required to complete loading and unloading operations below deck on a row for different values of D. In this example $C = 20$, and $\mu_u = \mu_l$. Figure 3b shows the same information, but for a vessel where $\mu_l = 0.5\mu_u$. As we expect, benefits decrease with increasing variance (values of D). Given that C_i is fixed, increasing values of μ_u imply a larger total number of containers, and so as a percentage, benefits are greater with increasing μ_u.

2.3. **Comparison of Formula and Simulation Results.** Given the central limit theorem, we know formula (12) will provide a good estimate for the number of cycles for a large number of stacks, but it is unclear how well the expression will match reality for realistic numbers (up to 20 per row in current ships). We therefore compare the estimated values using the formula to the average of a set of simulation runs. A simulation program was used to generate ship data according to a distribution of imports and exports, and count the number of cycles required to turn around each row. For details of the simulation see [4]. The inputs to the simulation are parameters p and q of the beta distribution for both the number of imports and number of exports in one stack, the number of stacks, the maximum height of an import stack and the maximum height of an export stack. Inputs to the formula, d, D, C_i, μ_u, and μ_l can be determined uniquely from the simulation inputs.

Figure 4 shows the number of moves necessary to turn around the vessel versus the number of stacks on the vessel. Each square represents the estimated number of cycles using formula (12). Each diamond shows the average result of 30 simulation runs. We see the estimate and average are very close even for small numbers of stacks. For the data shown, the average difference between the estimate and the simulation average was 1.93%. The estimate is worst for the case of 35 stacks, where there is almost a 6% difference. It is similarly different for the smallest case of 5 stacks, where there is a 5.3% difference. We have thus developed a formula to estimate long-run crane and vessel productivity improvements as a result of double cycling. These results can be converted into time and money savings as per [5].

3. Impact on Landside Transportation Operations

In addition to improving crane and vessel productivity, the use of double cycling provides an opportunity to increase the utilization of landside equipment such as yard tractors or straddle carriers. Loading and unloading the vessel simultaneously means that after a yard tractor or straddle carrier delivers a container to the apron, it can then carry a container from the apron to local storage, instead of returning to the local storage without transporting a container.

Figure 5a shows a schematic of the landside transportation system when single cycling. In this figure we have shown only one crane operating on the vessel, but the analysis is also applicable to the case where we have many cranes operating per vessel. The diagram shows, with arrows, the flow of landside vehicles with containers in solid lines, and vehicles without containers with dashed lines. We will refer to these trips without containers as empty trips, and would like to reduce their number. Figure 5b shows a schematic for double cycling, where the two empty trips of single cycling have been replaced by one empty trip between the storage locations of import and export containers.

In both the single and double cycling cases, we model the flow of landside vehicles as a closed queueing system, with two server stations and many customers. The server stations are 1) the quay crane and 2) landside vehicle drivers at the local storage areas. The customers are landside vehicles, such as yard tractors or straddle carriers. The system is closed because the landside vehicles shuttle between server stations, visiting the quay crane and then the local storage facilities, until the vessel unloading and loading operations are complete.

3.1. **Modelling the Quay Crane.** The quay crane is modelled as a single server with deterministic service times. This server station is labelled I in figure 5. The crane serves its customers; landside vehicles. In the case of single cycling the following tasks make up service by the quay crane:

- While loading: pick up a container from a landside vehicle or the ground beneath the crane, carry it to the vessel, drop the container, and return to the apron.
- While unloading: drop a container onto a landside vehicle or the ground, return to the vessel, pick up a container, return to the apron.

In the case of double cycling service by the quay crane requires the crane to pick up a container from a landside vehicle or the ground, carry it to the desired location on the vessel, drop the container, move to the location of the container to unload, pick-up the container, carry it to the apron, and drop the container onto a landside vehicle or the ground.

Service times are $1/\lambda$ and $1/\lambda'$ minutes per customer for the single and double cycling cases, respectively. In practical operations quay crane cycle times are very consistent, so we assume no variance in these service times. Cycle times are typically longer for double cycling than for single cycling, as demonstrated in [2].

3.2. **Travel Times Between Servers.** After being served by the quay crane, the landside vehicle will travel to either the import or export storage facility. We assume the travel time between the apron and the local import storage is a minutes, with $var(a) = 0$. We assume the travel time between the local export storage and the apron is b minutes, with $var(b) = 0$. We assume the travel time between the local import and local export facilities is e minutes, with $var(e) = 0$.

3.3. **Modelling the Local Storage.** Service in this case is the movement of containers from their landside vehicle to the appropriate storage location or vice-versa. Service is provided by the landside vehicle driver. If containers are being stored on a chassis, with single cycling, service is defined by the driver finding the storage location, and either attaching or detaching the chassis. With double cycling, the driver must find the location of the import, detach the chassis, find the location of the export, and attach the chassis. If the landside transportation is being provided by straddle carriers, the driver must find the appropriate location, and drop-off and/or pick-up the container. The container may then be moved again by a reach stacker or gantry crane, but this is not considered part of the service time as the straddle carrier driver can move on to another task while this operation takes place. For both the single and double cycling cases, we assume there are infinitely many servers at the local storage facility. This allows us to model the situation where service is always available; once the driver arrives at the local storage facility he/she can always be looking for the storage location or dropping/picking-up a container, but the amount of time it takes to complete this operation varies; the driver may have difficulty locating the position or dropping/picking-up the container. We will label the local storage location II.

Although in reality with double cycling the landside vehicles pick-up and drop-off containers at different instants in time, and at different locations, we consider these two events part of the same mathematical server. Call the service time at II with single cycling w, and the service time at II with double cycling, w'. With single cycling, we consider picking up or dropping off a container to have the same service time. We assume $E[w] = E[w^u] = E[w^l]$ where $E[w^l]$ is the service time during loading (picking up) and $E[w^u]$ is the service time for unloading (dropping-off). With double cycling, the driver must drop-off and pick-up a container, so $E[w'] = E[w^u] + E[w^l]$. It is therefore reasonable to estimate that $E[w'] = 2E[w]$. To calculate the number of landside vehicles required, we will assume distributional information is available about w and w'.

3.4. **Estimating the Number of Landside Vehicles Required.** Given the framework described above, we can estimate the number of customers required in the system such that a server is almost never waiting for a customer. In practical terms we would like to supply just enough landside vehicles for each crane in service, such that the crane is never idle. If we have excess vehicles, we assume they are in queue at I. We use Little's Formula to determine the number of vehicles in transit and at server station I. Given the nature of our system, the rate at which customers, or landside vehicles arrive at I is determined by the quay crane's service time (assuming we have enough vehicles). The expected arrival rate for single cycling is λ, and for double cycling, λ'. An estimate for the number of landside vehicles required per crane *when single cycling* is:

$$\lambda(2a+2b)+1+\lambda E[w]+2\sqrt{\lambda E[w]\left\{1-\frac{E[min(w_1,w_2)]}{E[w]}\right\}} \tag{13}$$

The first two terms, $\lambda(2a+2b)$, reflect the number of vehicles in transit between the apron and the local storage at any instant in time. The third term, 1, is the number of landside vehicles in service at I. The remaining terms are the expected number of landside vehicles in service at II, plus two standard deviations. The expression for the standard deviation is taken from an approximation derived in [11] for D/G/∞ service systems.

Similarly, an estimate for the number of landside vehicles required per crane when double cycling is:

$$\lambda'(a+b+e)+1+\lambda' E[w']+2\sqrt{\lambda' E[w']\left\{1-\frac{E[min(w_1',w_2')]}{E[w']}\right\}} \tag{14}$$

Here the first two terms, $\lambda'(a+b)$, are the number of vehicles in transit between the apron and local storage, and the third term, $\lambda' e$, is the number of landside vehicles in transit between the local storage facilities.

3.4.1. *Evaluation.* It would not be difficult for the port to determine reasonable values of the required parameters, in order to evaluate these expressions. We require only ballpark estimates of the parameters as one of the strengths of our method is that sensitivity analysis could be easily carried out.

While terminals vary widely in their size, crane service rates do not. For single cycling an average cycle time of 1 minute and 45 seconds was recorded at the Efficient Marine Terminal Trial at the Port of Tacoma in 2003. The average double cycle took 2 minutes and 50 seconds. For this data, $\lambda = .57$ landside vehicles per minute and $\lambda' = .35$. See [2] for further information. Values of $a = 1$ minute, $b = 2$ minutes, and $e = 1$ minute were estimated based on the current storage plan for, and the dimensions of, the Ben E. Nutter terminal at the Port of Oakland and a yard tractor speed of 15 miles per hour.

If w follows an exponential distribution $E[min(w_1, w_2)]/E[w] = 1/2$, and $E[min(w_1', w_2')]/E[w'] \geq 1/2$ so choosing $1/2$ for this value is conservative. Figure 6 shows the number of drivers required for different values of $E[w']$, where $E[w'] = 2E[w]$. For example with $E[w'] = 5$ minutes we estimate 7.5 yard tractors required per crane with single cycling but only 6 required with double cycling. The main contributor to the reduction is the increased cycle time with double cycling. Not only do we reduce the number required, but we improve their productivity per mile travelled or hour driven. The Ben E. Nutter terminal at the Port of Oakland typically deploys 7 yard tractors per crane. At this level, double cycling could offer a reduction of about 1.5 drivers and tractors required, a reduction of about 22%.

4. Impact on Storage Space and Storage Equipment

In this section we consider the impact of double cycling on the requirements for storage space and storage equipment in the terminal. A storage space is a location within the terminal where an import or export container can be stored for a period of time. For an import container this time period includes some time after the vessel departs. For an export container this includes some time before the vessel arrives. With respect to storage equipment, we will consider the need for chassis in wheeled operations (where containers are stored on chassis while in the terminal, rather than of the ground or on top of another container).

With single cycling, just after the unloading operations have been completed on a vessel, all containers to load and unload on that vessel are sitting in the terminal. With double cycling, we never have all loads and unloads sitting in the terminal because almost as soon as we start unloading the vessel, we begin loading the vessel. We can exploit this fact and reduce the storage equipment required.

4.1. **Impact on Storage Spaces.** Containers for import and export are typically stored in different locations on the terminal. In this case, the use of double cycling will not reduce storage space requirements. There will be fewer containers in port during loading and unloading operations, and this may be of some benefit as space is freed for maneuvering, but this benefit is difficult to quantify without empirical data. We will discuss the efficiencies of sharing import and export storage in section 5.3.

4.2. **Impact on Storage Equipment.** While wheeled operations are becoming less common due to the need for greater land utilization, many terminals still have some, or a significant portion of their containers stored temporarily on chassis, so in addition to the storage location a chassis must be provided. The difference between chassis and storage spaces is that chassis can be shared between imports and exports.

We would like to accommodate the entire fleet of vessels calling at a terminal, so should plan to provide enough chassis for the largest vessel. When a container is in the terminal, it requires a chassis, therefore, we can think of the number of chassis required as equal to the total number of containers to load and unload on the vessel, less the minimum number of containers on the ship at any time during the loading and unloading operations. The number of containers in port per vessel at any point in time during the loading and unloading operations can be seen in figure 2a. Interpret the curves of unloads and loads as the cumulative number of containers added to and removed from the terminal. The picture is just a conventional queueing diagram for the landside of the terminal.

With single cycling, the minimum number of containers on the ship at any time during the loading and unloading operations is 0 (when unloading is complete), so with wheeled operations the number of chassis required (k_s) equals the number of containers:

$$k_s = \sum_{i=1}^{R} \Lambda_i + \sum_{i=1}^{R} Y_i \tag{15}$$

So on average, for the largest ship that repeatedly calls at the berth,

$$E[k_s] = E[\sum_{i=1}^{R} \Lambda_i + \sum_{i=1}^{R} Y_i] = \sum_{i=1}^{R} C_i \left\{\mu_u + \mu_l\right\} \tag{16}$$

and,

$$var(k_s) = var(\sum_{i=1}^{R} \Lambda_i + \sum_{i=1}^{R} Y_i) = \sum_{i=1}^{R} C_i \left\{var(u_{c,i}) + var(l_{c,i})\right\} \tag{17}$$

If we plan to almost always have enough chassis, the number required is given by:

$$E[k_s] + 2\sqrt{var(k_s)} = \sum_{i=1}^{R} C_i \{\mu_u + \mu_l\} + 2\sqrt{\sum_{i=1}^{R} C_i \{var(u_{c,i}) + var(l_{c,i})\}} \tag{18}$$

We can significantly reduce the number of chassis required by choosing to single cycle within one row. Instead of unloading the entire vessel before loading, unload just one row, and load that row, before moving on to the next row on the vessel. The number of containers on the ship at any one time can be approximated by:

$$(R-1) \min_{i \in 1..R} \{\min\{E[Y_i], E[\Lambda_i]\}\} \tag{19}$$

We estimate the number of chassis required when using the single cycle by row as:

$$\sum_{i=1}^{R} C_i \{\mu_u + \mu_l\} - (R-1) \min_{i \in 1..R} \{\min\{E[Y_i], E[\Lambda_i]\}\} \tag{20}$$

Any additional reduction in number of chassis required when double cycling is small, and these benefits are of minor economic significance (see section 6). In an evenly loaded vessel (where $E[\Lambda_i] = E[Y_i] \forall i$), we could reduce the number of chassis required by approximately $(R-1)E[\Lambda_i]$.

5. Operational Changes to Support Double Cycling

While many of the following strategies will not measurably impact the benefits of double cycling, their implementation will simplify double cycling planning and implementation.

5.1. **Loading Plans.** In this section we discuss changes to existing load planning that may create more significant opportunities to benefit from double cycling. Our goal is not to provide a simulation tool for determining a loading plan for a specific set of data (as these tools already exist), but to provide general principals upon which loading plans that support double cycling should be based. When developing a ship loading plan there are many considerations; weight balancing, storage of hazardous materials, storage of refrigerated containers, and storage of both 20 and 40 foot units. These considerations are relevant for both single and double cycling, so will be ignored. We assume the total number of imports and exports at each port is determined by market demand and that vessel utilization should be maximized.

5.1.1. *Balance the number of containers to load and unload in each stack.* This reduces the possibility of delay caused by the loading operations waiting for the unloading operations to be completed. Ideally we want to have at least as many loads as unloads in each stack. This is easy to achieve if there are more total loads than unloads, but in the case where total unloads exceed total loads, we want to smooth the differences out as much as possible across the stacks, so we avoid having a greater difference in any one stack $\{u_{j,i} - l_{j,i}\}$ than the total difference $\{Y_i - \Lambda_i\}$.

5.1.2. *Put stacks for one destination in as few rows as possible.* This will reduce the time required to unload and load the vessel by keeping the distance between stacks upon which we operate within one cycle small. It will also reduce the number of times we pay the initial unloading stack penalty, thereby reducing total crane moves.

5.1.3. *Segment space on the vessel by origin-destination pairs.* Assume vessel stops can be enumerated, as shown in figure 7. This can represent any tour with n stops including shuttle services ($n = 2$), as well as more typical routes with $n = 3$ or more. The example in figure 7 has $n = 4$ stops. The vessel has just called at port 4 and is sailing for port 1. The vessel is divided into 6 segments, one for each of the 6 OD pairs represented on the ship. Each segment is labelled with an OD pair, for example $4 - 1$ indicates containers loaded at port 4 and destined for port 1. Notice there is no segment labelled $3-4$, $2-4$, or $1 - 4$ as these containers would have just been unloaded at port 4. Similarly, notice there are no segments labelled $2 - 3$, $1 - 3$, or $1 - 2$ as these containers would only be on board on the segments between ports 1 and 3. At any one time, containers for only a subset of all OD pairs appear on board.

Let m be the number of stacks on the vessel below deck, or, if double cycling above deck, m is the number of stacks above deck plus the number of stacks below deck. Let n be the number of different stops on the vessel tour. $N = (n - 1) + (n - 2) + ... + 1$. An OD pair is a single origin matched with a single destination.

If the demand for service is equivalent for all OD pairs, then we require m/N stacks for each OD pair on the vessel. At any sailing time we have $(n - 1)m/N$ cells for the next destination, $(n - 2)m/N$ for the second destination, etc.. Although desirable, it is not possible to ensure that all segments for a single destination are in co-located segments. With even demand, we divide the ship up into evenly sized segments for each OD pair on the vessel. With N segments each has $1/N$% of the total number of stacks. With uneven demand, the percentage of stacks allocated to an OD pair on the vessel should equal the percentage of total demand that appears for that OD pair.

Generally, demand to move freight is not well balanced across a vessel's route; Asian ports operate as export terminals, while US ports are essentially import terminals. The vast majority of trans-Pacific containers are loaded onto the vessel at an Asian port and discharged at a US terminal. That said, empty containers must be returned to Asia, so over time the flow of containers out of a terminal almost balances the flow in.

5.1.4. *For any OD pair with stacks in a row, leave one stack empty.* By doing this we can avoid waiting to begin the loading operations, since there will always be space available to begin loading as soon as we begin unloading. Unfortunately this reduces the utilization of the vessel so is not practical.

5.2. **Load Sequencing.** In modern port operations, information is given to landside vehicle drivers regarding the destination of their load, or which load to pick-up, from a terminal operating system and delivered through a mobile data device. Terminal operation software programs decide which container should be served next, or where the container should be stored, based on the information it has received from other drivers, and port planners. These programs could easily be changed to accommodate the new sequencing rules of double cycling, thus continuing to provide drivers with clear instructions.

A further benefit of double cycling is that internal port traffic flows can be significantly simplified. Figures 8a and 9a show typical traffic flows for straddle carriers and yard tractors operating single cycling. Figures 8b and 9b show typical traffic flows for straddle carriers and yard tractors operating double cycling. Before implementing double cycling, a port will need to reconsider traffic flow patterns. Each port will do this based on the specifics of the port. Although it may initially seem traffic flows would be complicated by double cycling, these figures demonstrate double cycling's simplifying nature.

5.3. **Yard Storage Locations.** Figures 8 and 9 show hypothetical terminal traffic patterns and storage locations for export containers, import containers, and empty chassis. These figures clearly simplify reality, where, for example, empty chassis may be segregated by carrier, and imports and exports may be stored in several different locations, but the general results still hold. While the introduction of double cycling has removed the wasted trips between the storage facilities and the apron, it has added the wasted trip between the import and export storage facilities. To minimize the distance of this trip, containers for import and export should be placed as close together as possible, or co-located. The ability of a port to do so will depend on existing storage strategies. Typically, terminals consider the shipping line, storage mode, destination, outbound transportation mode, weight, importer and/or size of the container when determining the storage location.

In fact, more significant benefits can be generated by not segregating imports and exports at all, and using the same storage locations for either import containers or export containers. This has two benefits:

- Reducing to zero the distance between the expected location of an export and the expected location of an import ($e = 0$ in equation (14)). This reduces the requirements for landside vehicles and drivers.
- Achieving higher utilization of the storage facility by pooling the storage facilities and smoothing demand. When segregating storage we need to provide $E[\sum_{i=1}^{R} Y_i] + 2\sqrt{var(\sum_{i=1}^{R} Y_i)}$ locations for imports and $E[\sum_{i=1}^{R} \Lambda_i] + 2\sqrt{var(\sum_{i=1}^{R} \Lambda_i)}$ locations for exports. When pooling storage facilities we only require, $E[\sum_{i=1}^{R} Y_i] + E[\sum_{i=1}^{R} \Lambda_i] + 2\sqrt{var(\sum_{i=1}^{R} Y_i) + var(\sum_{i=1}^{R} \Lambda_i)}$. By getting higher utilization out of the storage facility the port can reduce it's land requirements for the same throughput.

5.4. **Stevedores.** Stevedores are present on the vessel when containers are being loaded and unloaded. They do not guide containers into position, but ensure that containers are lashed down correctly and stored in the correct positions. Given this, we do not expect that additional staff will be required when carrying out double cycling. The same gang of Stevedores will be asked to monitor containers being placed on and retrieved from the vessel.

5.5. **Container Handling Equipment.** With double cycling, containers are being placed in short-term storage and retrieved from short-term storage, simultaneously. With single cycling, containers are placed in local storage before any containers are retrieved. Depending on how the port operates, additional container handling equipment, for example, top picks or reach stackers, may be required to move containers between the landside vehicle and the correct storage position, so that machines are available to both retrieve and store containers simultaneously.

6. Economic Evaluation

In this section we provide estimates as to the order of magnitude of the financial impact of double cycling. As mentioned, ports vary distinctly in their ownership and fee structures, so a more detailed analysis should be carried out on a case by case basis.

We provide a very rough estimate of the opportunity costs assuming that the freed resources can be usefully employed. In practical terms this means the new capacity can be used to move additional containers. This assumption reflects current market conditions, where demand is expected to exceed capacity during the peak season.

Using equation 6 of [5] we can convert the benefits from a number of cycles to an amount of time. Using the same parameter values as in section 6.3 of [5] we would expect a reduction by 25% in the number of moves to equate to a time reduction of 9.5%. In the following subsections we will consider the economic impact of a 10% reduction in operating time. We assume a typical vessel, capable of carrying 6000 TEUs, unloads and loads 1500 containers in 50 hours using single cycling and 45 hours using double cycling. This equates to moving 30 containers per hour with single cycling, and 33 with the proximal stack strategy. We compare all of the benefits in dollars per container moved in table 1 below.

In table 1, under extra revenue we list the value, in dollars per container moved, of employing the resources that are freed with double cycling. Detailed assumptions for each resource are described in the sections below. In the case of chassis and landside vehicles the extra revenue would be obtained by renting out or selling off unused resources. In the case of berth utilization - dockage fees, this benefit comes from reduced expenses. Under extra cost, we list the cost of using the resource for the time saved. In the case of vessel productivity this cost is incurred by consumption of fuel, in the case of container handling equipment this includes the equipment, operator, fuel and maintenance cost of the new machine.

Notice the order of magnitude difference in the net benefits on the waterside (approximately $20.00) as compared to the benefits landside (on the order of $1.00). The greatest benefits come from higher utilization of the vessel, crane, and berth. Also notice that if the operation is ”on wheels”, where containers are stored on chassis rather than on the ground, there is an additional $4.00 benefit per container moved using double cycling, over operations that are ”grounded”. Also notice that a significant portion of the benefits of double cycling are experienced by parties who are not responsible for implementing the operation. These results highlight the distributed nature of the benefits of double cycling. If a larger portion of the benefits were experienced by those responsible for its implementation, we may see more widespread use of the technique.

Major shipping lines APL and P&O Nedloyd experienced average revenue of almost $3000 per FEU in 2004 [1], [10]. If double cycling can save the vessel operator approximately $25.00 per FEU at each port this would be a reduction of approximately 1.5% of the total transportation cost.

6.1. **Vessel Productivity.** Given a reduction in idle time (while unloading and loading), a vessel has the opportunity to increase productive time (transporting containers). We assume this productive time is used to transport containers further.

6.1.1. *Revenue.* Using freight rates from [12], we estimate the revenue generated for an average vessel at $54000 (assuming a 6000 TEU vessel can travel 200 km in the 5 hours saved). This is a value of $36.00 per container moved. We ignore the benefit of reduced dwell times on the vessel, and therefore somewhat underestimate the value of double cycling.

6.1.2. *Cost.* We only incur the additional cost of operating the vessel as the cost of ownership and staffing are not increased. We consider only the cost of fuel, and ignore the increase in maintenance cost as this value is much smaller. We estimate the cost of fuel at $100 per km for a 6000 TEU vessel and again assume the vessel could travel 200 km in the 5 hours saved. This would cost the vessel operator $20000 in fuel, or $13.33 per container moved.

The net benefit of $22.67 per container moved or about $750 an hour compares well with the benefits when calculated using the profit per TEU experienced in the industry in 2004. These profits fall within the range of $100 to $500 per FEU or $11.00 to $55.00 per container moved [1],[10].

6.2. **Crane Productivity.** We have ignored any additional cost increase due to increased fuel consumption or maintenance caused by a greater percentage of the crane's time spent moving containers versus moving empty. Terminals are typically paid for each container moved, and although these cost structures are complicated, average rates are on the order of $200 per container [7]. In the 5 hours of crane time freed for a typical vessel we could generate $33,000, or $22.00 per container moved.

6.3. **Berth Utilization.** Again we do not incur any additional cost, but there is the opportunity to increase revenue if additional capacity is used to move containers. Shipping lines typically pay both warfage and dockage fees to the terminal or the port authority, depending on the particular port's structure. Dockage fees are paid by the vessel operator to the port authority on a daily or hourly basis. Therefore, revenue to the port authority will not increase but cost per vessel will decrease. Warfage rates are also paid by the vessel operator to the port authority, but on a container basis. Therefore, rates for the same vessel will not decrease, but total revenue to the port authority will increase.

6.3.1. *Dockage Fees.* Dockage fees at the Port of Oakland are $12000 per day for the largest vessels (more than 1200 feet long) and $3000 per day for smaller vessels (640 - 700 feet). A vessel that transfers 1500 containers during a 50 hour port visit, currently pays about $24000 in dockage fees. This could be reduced by $2400 using double cycling, or $1.60 per container move.

6.3.2. *Warfage Fees.* Warfage rates are typically paid by the container, and are on the order of $200 per container. Income would increase from warfage fees to the port authority or terminal operator by about $22.00 per container moved.

6.4. **Landside Vehicles and Drivers.** Requirements for provision of landside vehicles and drivers are reduced, so there is an opportunity to reduce staffing and sell or rent the vehicles. Yard tractor or straddle carrier operators are typically unionized and earn close to $100000 annually [6]. A new yard tractor costs about $50000. We amortize this cost over 20 years, operating 40 hours a week, 52 weeks a year. We assume $10.00 per hour for fuel and maintenance. This provides a benefit of $.18 per container moved. In a typical operation we might be able to save 3 drivers and tractors per crane.

6.5. **Chassis.** Requirements for provision of chassis will be reduced. The chassis provider could therefore utilize these chassis in another way. Assume a yard chassis costs about $20000. Amortized over 20 years, the chassis costs $0.12 per hour (excluding maintenance and management costs). On a large vessel with 1500 containers to move we remove the need for chassis for 5 hours, and it would not be atypical reduce our chassis requirement by 25% for the 45 hours during which the vessel was being loaded and unloaded. This could provide a savings of almost $2.00 per container moved.

6.6. **Additional Container Handling Equipment.** With double cycling, we will be storing containers for import, and retrieving containers for export, simultaneously. If the operations at the terminal require top picks, or other container handling equipment for storage and retrieval, the use of double cycling will double the need for this equipment. The number of handlers required depends on the layout of storage in the terminal. At a cost of about $400000, amortized over 20 years, operating 40 hours a week, 52 weeks a year, each handler costs almost $9.62 per hour. We expect maintenance and fuel costs are approximately $10.00 per hour. In addition, vehicle operators will be required at approximately $50.00 per hour. The additional cost of container handling equipment is thus about $2.00 per container moved.

7. Discussion

We have quantified the key operational and financial benefits of double cycling; increased crane productivity, berth utilization, and vessel utilization. Double cycling does not require significant capital investment beyond additional container handling equipment; only additional planning and modifications to the terminal operating system. We have made suggestions to streamline traffic flows and integrate double cycling into existing operations. Outside of double cycling we have made suggestions for improving storage yard utilization and reducing chassis requirements. The next step in our research is to understand how other port resources, such as gate time and rail capacity can accommodate this additional traffic. We will also continue to work on understanding the distributed nature of the benefits of double cycling and its affect on implementation. We will examine remuneration schemes and other cost models, as tools to encourage implementation of operational improvements for different port management paradigms.

Through the work presented in this paper we have provided port planners with tools and insights as to the impact of double cycling on requirements for port resources.

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References

1. APL, *Annual report*, Report available at www.apl.com, 2004.
2. TranSystems Corporation, *Efficient Marine Terminal Full Scale Demonstration*, Report available at www.ccdott.org, 2003.
3. William Feller, *Probability Theory and its Applications*, John Wiley & Sons, London, 1950.
4. A. V. Goodchild, *Port Productivity Enhancements through Implementation of Double Cycling Crane Operations*, Ph.D. thesis, University of California at Berkeley, Department of Civil and Environmental Engineering, 2005.
5. A.V. Goodchild and C. F. Daganzo, *Crane Double Cycling in Container Ports: Effect on Ship Dwell Time*, The Institute for Transportation Studies Report UCB-ITS-RR-2005-5, 2005.
6. E. Johnson, *L.B. and L.A. Port Wages Top $100k*, Long Beach Press Telegram **Wednesday March 30** (2005).
7. C. May, *Personal Conversations*, Manager of the Ben E. Nutter Terminal, Port of Oakland, 2005.
8. B. Mongelluzzo, *LA Won't See Peak Repeat*, The Journal of Commerce **6 (24)** (2005), 12.
9. ———, *A Peek at the Peak*, The Journal of Commerce **6 (26)** (2005), 16.
10. P&O Nedloyd, *Annual report*, Report available at www.ponl.com, 2004.

11. G. F. Newell, *Approximate Stochastic Behavior of n-Server Service Systems with Large n*, Springer-Verlag, Berlin, Heidelberg, New York, 1987.
12. T. Notteboom, *Container Shipping and Ports: An Overview*, Review of Network Economics **3(2)** (2004), 86–106.

	Proximal Stack Strategy	Extra revenue ($/container moved)	Extra cost ($/container moved)	Benefactor
Waterside	Vessel Productivity	$36.00	$13.33	Vessel Operator
	Crane Productivity	$22.00	$0.00	Terminal Operator
	Single Berth Utilization – Warfage Fees	$22.00	$0.00	Port Authority
	Single Berth Utilization – Dockage Fees	$1.60	$0.00	Vessel Operator
Landside	Container Handling Equipment (per vehicle and driver if grounded)	$0.00	$2.00	Terminal Operator
	Landside Vehicles (per vehicle and driver)	$0.18	$0.00	Terminal Operator
	Chassis (on wheels)*	$2.00	$0.00	Chassis Provider

Table 1. Comparison of the economic benefits of double cycling. *The benefits of reduced chassis are for single cycling within one row.

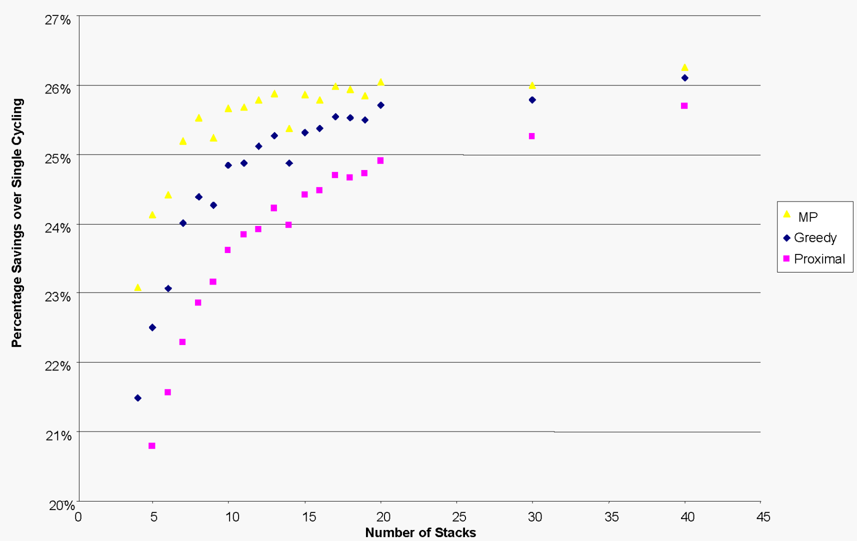

Figure 1. Performance comparison of greedy, proximal, and mathematical programming (MP) strategies

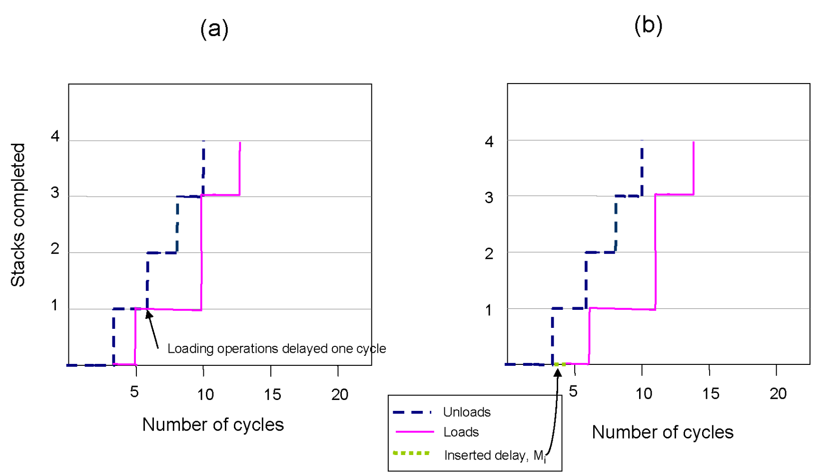

Figure 2. (a) Example queuing diagram for loading and unloading operations. Notice delay of one cycle to loading operations after completing stack 1. (b) Delay, M_i inserted before any loading operations start to avoid later delay.

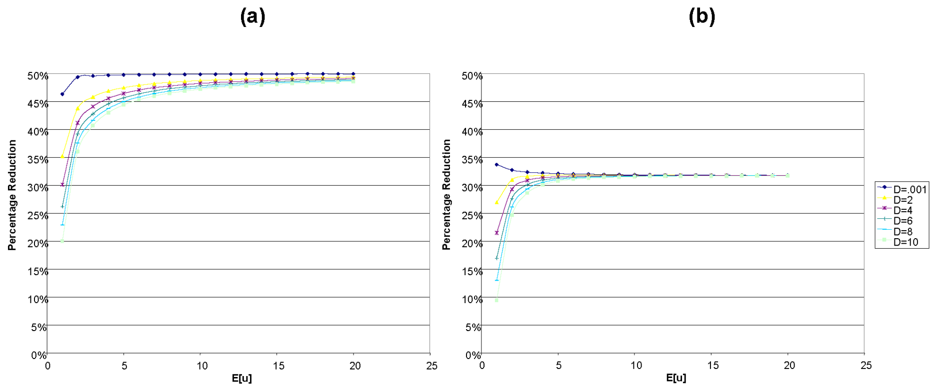

Figure 3. (a) Percentage reduction in number of cycles to complete loading and unloading operations below deck using the proximal stack strategy for varying values of D. C_l=20, and Y=Λ. (b) Percentage reduction, Y=0.5Λ.

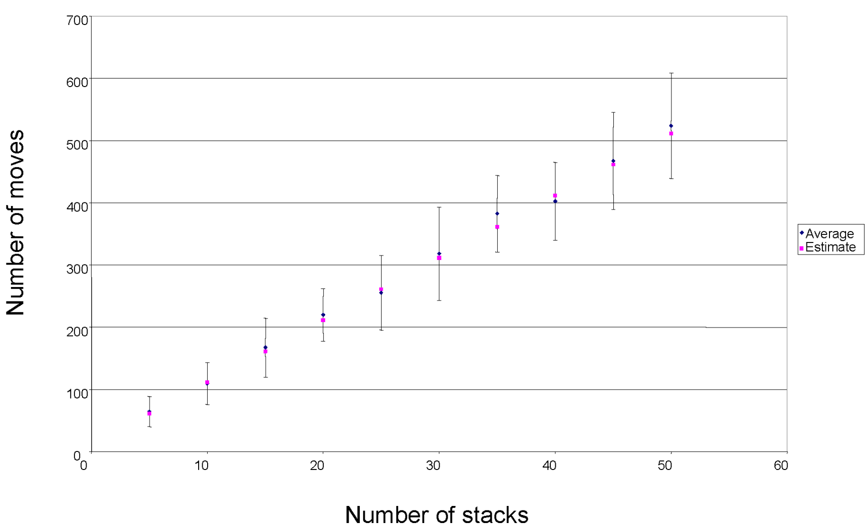

Figure 4. Comparison of estimate of number of moves to complete unloading and loading operations on a row from formula and simulated runs. Each error bar corresponds to 30 simulation runs.

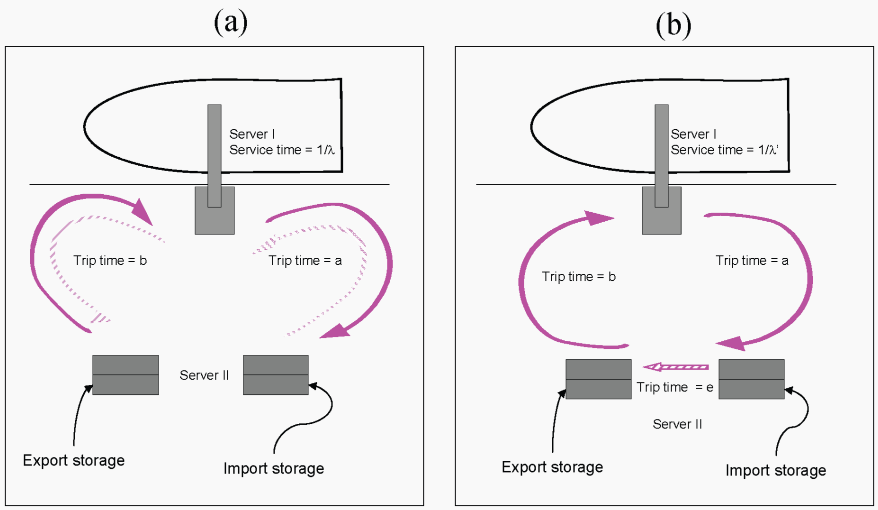

Figure 5. (a) Schematic diagram of landside operations when single cycling. (b) double cycling.

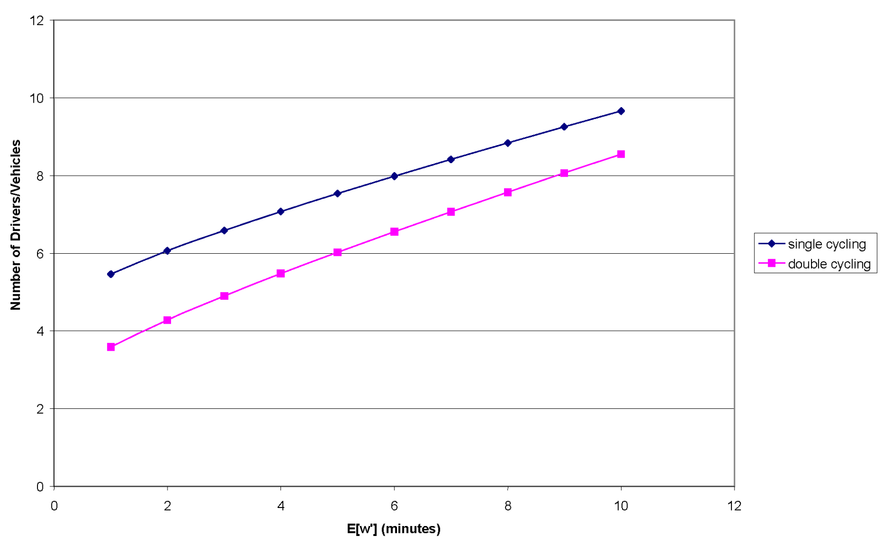

Figure 6. Number of landside vehicle drivers required for single and double cycling, against expected wait time at II.

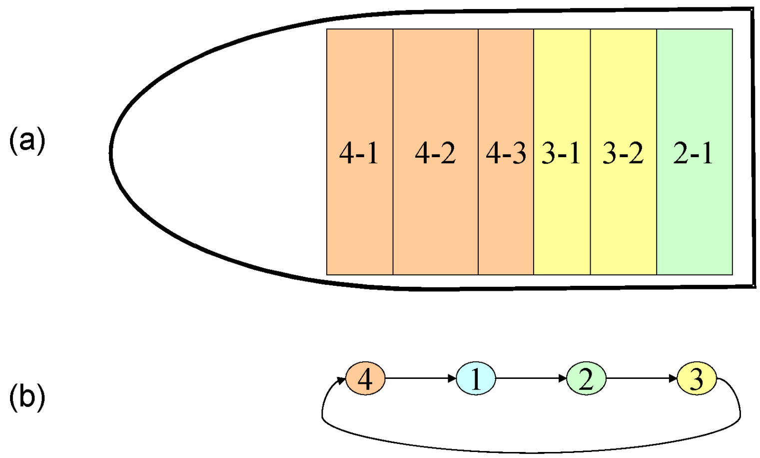

Figure 7. (a) Vessel storage segregated by origin-destination pairs (labelled O-D). (b) This example vessel calls at four ports labeled by number. The vessel has just left port 4, sailing for port 1.

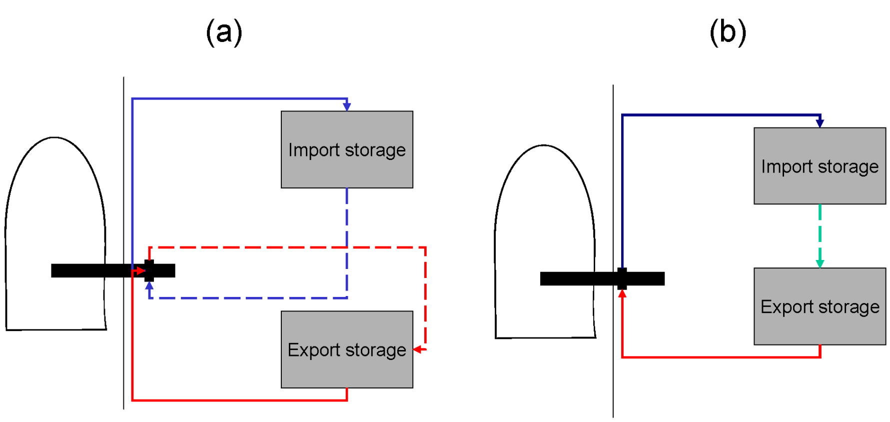

Figure 8. (a) Traffic flows for straddle carriers when single cycling. (b) double cycling.

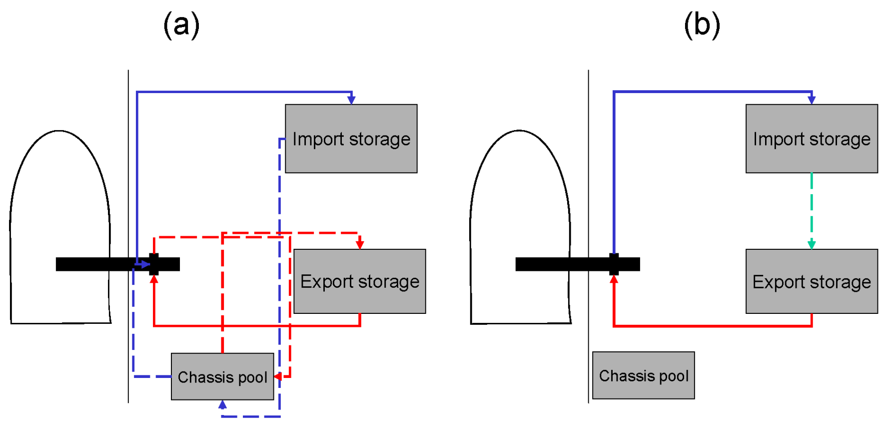

Figure 9. (a) Traffic flow pattern for yard tractors single cycling. If imports are stored “on-wheels” it is necessary for the driver to stop at the empty chassis pool. (b) Landside traffic flow patters for yard tractors when double cycling. With double cycling, trips to the empty chassis pool are not typically required.