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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 evaluate the performance of this sequence over single cycling. 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, in some cases, 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. We identify additional benefits on the landside, but these are typically much less significant.

Keywords: Container terminal; Terminal operations; Port operations

1. 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. In contrast to a more commonly used strategy, single cycling (where all relevant containers are unloaded before any are loaded), with double cycling, containers are loaded and unloaded in the same crane cycle. A cycle is a complete round-trip of the crane trolley from ship to shore and back, or from shore to ship and back. This allows the crane to carry a container by 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).

Double cycling has been a recognized operating strategy for some time, and is used to a limited extent in many ports, but given the benefits described in Goodchild and Daganzo (2006), it is not used to the extent

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expected, in a large part due to the perception that double cycling complicates landside port operations. This perception provided the motivation for this research; to provide a rigorous analysis of the impact of double cycling on landside port operations.

In 2004, peak levels of container traffic though 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 marine terminals (Mongelluzzo, 2005a). In 2005, container volumes at the ports of Oakland and the Pacific Northwest grew by about 20% inbound, while the Southern California complex was up about 5–6% (Mongelluzzo, 2005b). This growth in container volumes is expected to continue and will require additional capacity on the freight transportation network and through ports in particular. Some of this additional capacity may be acquired through the increased use of double cycling. In contrast to terminal expansion and information technology deployments, double cycling is a low cost method to increase capacity. 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.

While the freight transportation industry is currently focussed on increasing port capacity, and these issues have recently been the subject of much political attention (California State Assembly Bill 2650, 2002–03 and 2042, 2003–04), to date no academic study on double cycling except Goodchild and Daganzo (2006) has appeared in a scholarly journal. Goodchild and Daganzo (2006) defines and evaluates efficient algorithms for determining a double cycling sequence. Here we shall define a simpler strategy, the proximal stack strategy, that is more operationally convenient and nearly as efficient. Based on this strategy, the paper will develop tools to quantify the long-term impact of double cycling on crane productivity and other aspects of port operations. It will consider three operations 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. The paper also suggests operational changes for container storage and transportation.

Modern ports use computer programs to sequence loading and unloading operations and schedule daily port operations. The ideas presented in this paper are not meant to substitute for detailed terminal operating programs (although rules to incorporate double cycling could be easily added to these programs), but to provide insights into double cycling at a more general level for long-range planning. Results can be used to suggest how a port should be configured and operated.

Section 2, below, defines the proximal stack strategy for double cycling and evaluates its efficiency. Section 3 develops an approximate statistical formula to determine the long-term improvement in crane productivity from planning data, and compares the results of the formula with simulations. Section 4 looks at the impact of double cycling on the requirements for landside vehicles and drivers. Finally, Section 5 discusses the impact of double cycling on other landside features, such as storage equipment and space.

2. The proximal stack strategy

As demonstrated in Goodchild and Daganzo (2006) the benefits of double cycling depend on the sequence with which loading and unloading operations are carried out. One of the goals of double cycling is to increase port throughput (the number of 40 foot equivalent units, FEUs, or two 20 foot equivalent units, 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 main port bottleneck. With double cycling quay crane utilization and vessel productivity are improved because wasted crane moves are converted into productive ones. Therefore, the metric used in this paper to evaluate benefits is the number of cycles required to turn around a vessel. A method to convert this number into time is provided in Goodchild and Daganzo (2006).

The layout of containers on a ship can be modelled as a 3-dimensional matrix (see Fig. 1). Containers are stacked on top of one another (in stacks), 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 eight 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 $i = 1 \ldots R$ starting from the bow.

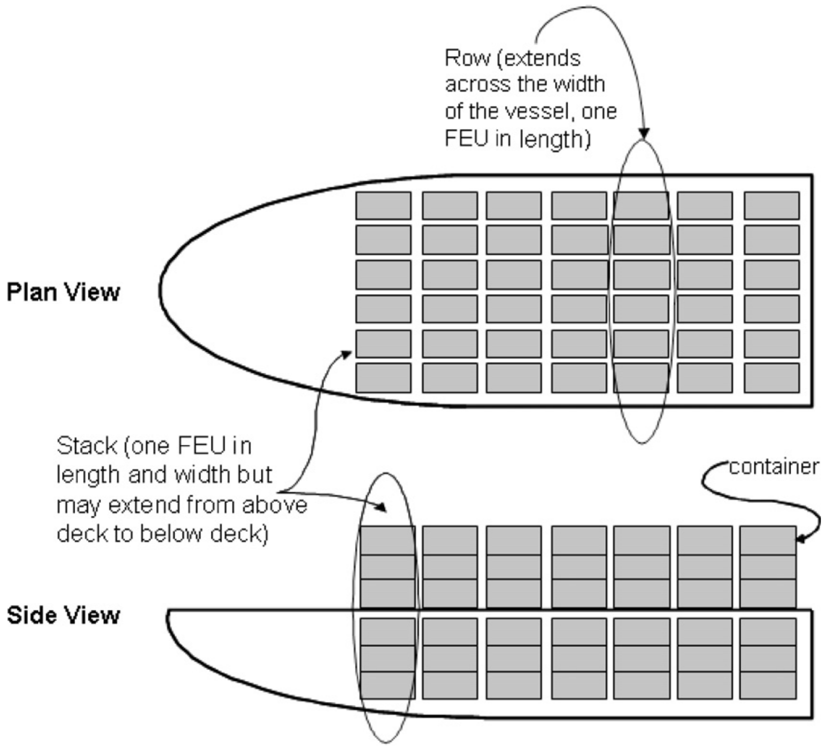

Fig. 1. Containers on a vessel can be modelled as a 3-dimensional matrix. A row is one FEU in length, and stretches across the width of the vessel. A stack is one FEU that may continue above and below deck.

Let $\{1 \ldots C_i\}$ 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 double cycling strategy:

Definition 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 sequential stacks 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 the strategy used in practice due to its operational simplicity. By operating on each row individually we do not require the crane to move laterally along the ship within one cycle.

2.1. Simulation results

We use simulation to compare the benefits of the proximal stack strategy to single cycling, while loading and unloading containers from one row of the ship. Single cycling is defined as using one complete cycle for either unloading a container or loading a container, and unloading all relevant containers from the row before loading any containers. The number of stacks in the row is specified, and the number of containers to load and unload in each stack are assumed to be independent and uniformly distributed between 0 and

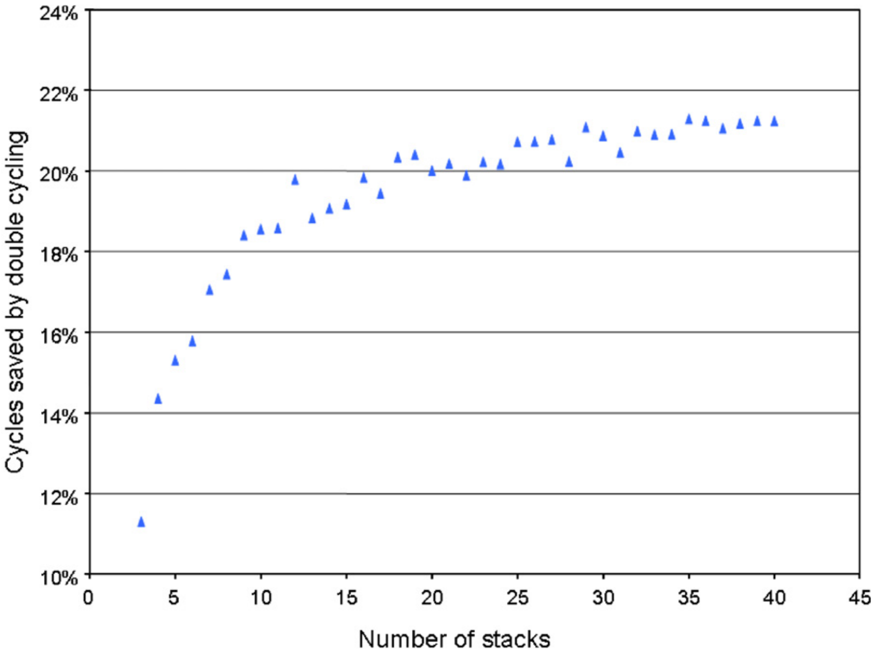

Fig. 2. Performance comparison of the proximal stack strategy and single cycling. Double cycling only takes place below deck.

10. The simulation counts the number of cycles required to complete loading and unloading operations on a vessel for the two strategies. For single cycling it is one cycle for each container (both loads and unloads). We assume that double cycling only takes place below deck, as this is common practice. In this case, all containers to unload above deck are removed using single cycling. Then the hatch covers are removed and double cycling is carried out below. Finally, hatch covers are replaced, and containers are loaded above deck using single cycling. The results are shown in Fig. 2.

For a row of 20 stacks, there is approximately a 20% reduction in the number of cycles. Notice that benefits above 15% are commonplace. Of course, it would be possible to achieve more significant savings by double cycling both above and below deck. In this case, only containers from atop the first hatch would be removed, double cycling would be completed below deck for this hatch. Then double cycling would be carried out above deck by unloading containers atop the second hatch while loading the first. We would then double cycle under the second hatch and would proceed in this fashion until the row is complete.

3. Estimation of long-term reduction in the number of cycles

Here, we provide formulae to estimate the expected number of cycles based on the distribution of ship types calling at a terminal.

Definition 2 (*Demand*). Introduce random variables $u_{c,i}$, to denote the number of containers to unload in stack $c \in \{1 \ldots C_i\}$ of row $i \in \{1 \ldots R\}$, and $l_{c,i}$ the number of containers to load in stack c of row i.[1] All the 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 σ_u^2 and so are the random variables in $\{l_{c,i}\}$ with mean μ_l and variance σ_l^2.

Definition 3 (*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.

[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 both an unload and a load.

3.1. 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, $E[T_{I,i}]$, is equal to the expected number of containers:

$$E[T_{I,i}] = E[\Lambda_i] + E[Y_i] = C_i\{\mu_u + \mu_l\} \quad (1)$$

Fig. 3 shows a queueing 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 $l_{4,1} = 3$. For consistency, we will always assume the crane starts and ends on the shore. The diagram shows two curves; one that documents the loading process, and one that documents the unloading process. 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 4. The number of cycles required to unload and load the vessel is 20. It should be noted that while mathematically it is satisfactory to consider the number of cycles necessary to unload and load in a row, in current operations, often all containers from a *vessel* are unloaded before any containers are loaded onto the vessel.

3.2. Expected number of cycles using double cycling

Fig. 4a shows a queuing diagram for the same data as Fig. 3, but using double cycling. 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 stack 2 still contains containers for unloading. This delays the completion time. Note also, that the total number of cycles required to complete unloading and loading operations is significantly reduced over single cycling. Define:

$$M_i(c) = \sum_{2 \leqslant j \leqslant c} \{u_{j,i} - l_{j-1,i}\} \quad \forall c \in \{2 \ldots C_i\} \quad (2)$$

Also define $M_i(1) = 0$, and

$$M_i = \max_{c=1 \ldots C_i} \{M_i(c)\} \geqslant 0 \quad (3)$$

It should be clear that if we delay the loading of stack 1 by M_i time units (as shown in Fig. 4b), then we eliminate all future delay caused by waiting and the operations are completed at time $T_{II,i} = u_{1,i} + M_i + \Lambda_i$. In

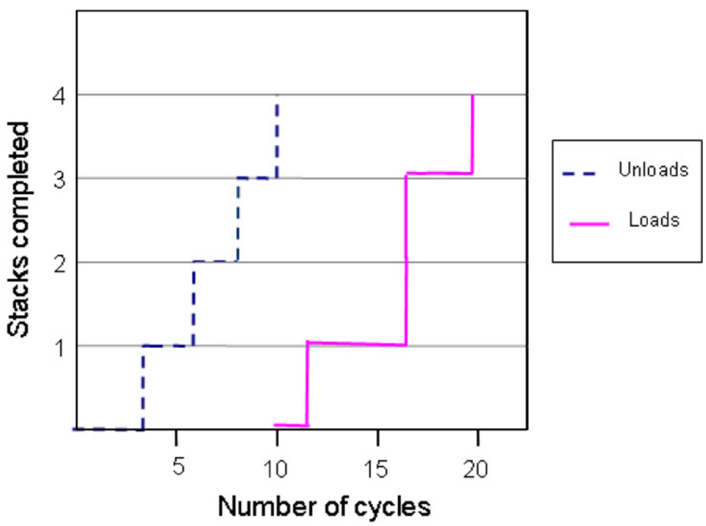

Fig. 3. Queueing diagram for the unloading and loading operations of one row, using single cycling.

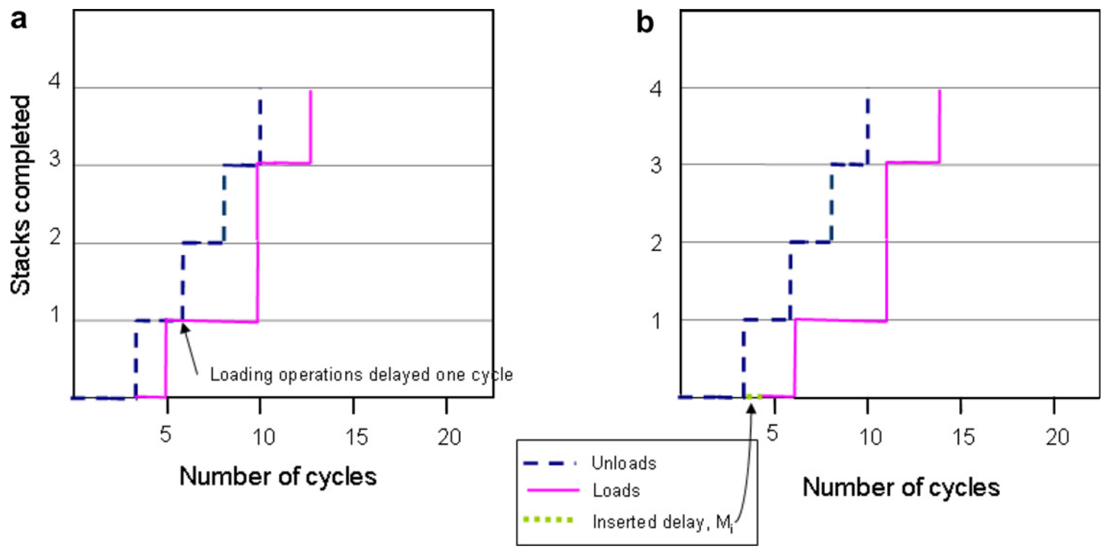

Fig. 4. (a) Example queuing diagram for loading and unloading operations. Notice delay of one cycle to loading operations after completing stack 1. (b) Delay, M_i, inserted before any loading operations start.

practice, one would not actually delay the start of the loading operations, but defining M_i this way allows us to develop an expression for the expected number of cycles to complete the row.

On average, the loading operations with double cycling are completed at time:

$$E[T_{\mathrm{II},i}] = E[u_{1,i}] + E[\Lambda_i] + E[M_i] \tag{4}$$

The first two terms are easy to estimate: the expected number of containers to unload in the first stack, μ_u, and the expected number of containers to load in row i, $C_i\mu_l$. Since the $u_{j,i} - l_{j-1,i}$ are independent, identically distributed random variables, $\{M_i(c)\}$ can be modeled as a diffusion process with the stacks completed, c, as time, and $E[M_i]$ as the expected maximal excursion of this process in time C_i. The drift of process $\{M_i(c)\}$ is

$$d = \frac{E[M_i(c)]}{c} = \mu_u - \mu_l \tag{5}$$

and its variance rate is

$$D = \frac{\mathrm{var}(M_i(c))}{c} = \sigma_u^2 + \sigma_l^2 \tag{6}$$

Appendix A shows that:

$$E[M_i] = \int_0^\infty \mathrm{d}z \int_0^{C_i} \mathrm{d}y \left\{ \frac{z}{\sqrt{2\pi D y^3}} \mathrm{e}^{\frac{-\{z-dy\}^2}{2Dy}} \right\} = \frac{2D}{d}\left[\Phi\left(\frac{d\sqrt{C_i}}{\sqrt{D}}\right) - \frac{1}{2} + \int_0^{\frac{d\sqrt{C_i}}{\sqrt{D}}} z\Phi(z)\,\mathrm{d}z\right] \tag{7}$$

where $\Phi(x) = \int_{-\infty}^{x} \frac{\mathrm{d}w}{\sqrt{2\pi}} \mathrm{e}^{\frac{-w^2}{2}}$. An estimate for the number of cycles to complete the row is thus

$$E(T_{\mathrm{II},i}) \simeq \mu_u + C_i\mu_l + \frac{2D}{d}\left[\Phi\left(\frac{d\sqrt{C_i}}{\sqrt{D}}\right) - \frac{1}{2} + \int_0^{\frac{d\sqrt{C_i}}{\sqrt{D}}} z\Phi(z)\,\mathrm{d}z\right] \tag{8}$$

Notice that for $d = 0$, the value of $E[M_i]$ is undefined. In this case we use the limit, $\lim_{d\to 0} E[M_i] = \mu_u + C_i\mu_l + \sqrt{\frac{2}{\pi} D C_i}$. Analysis shows that (8) is a convex function of d, with a global minimum at $d = 0$.

Eq. (8) tells us that only μ_u, μ_l, C_i, d and D influence the required number of crane cycles; all other ship configuration data are irrelevant. One could not get this insight with simulation alone.

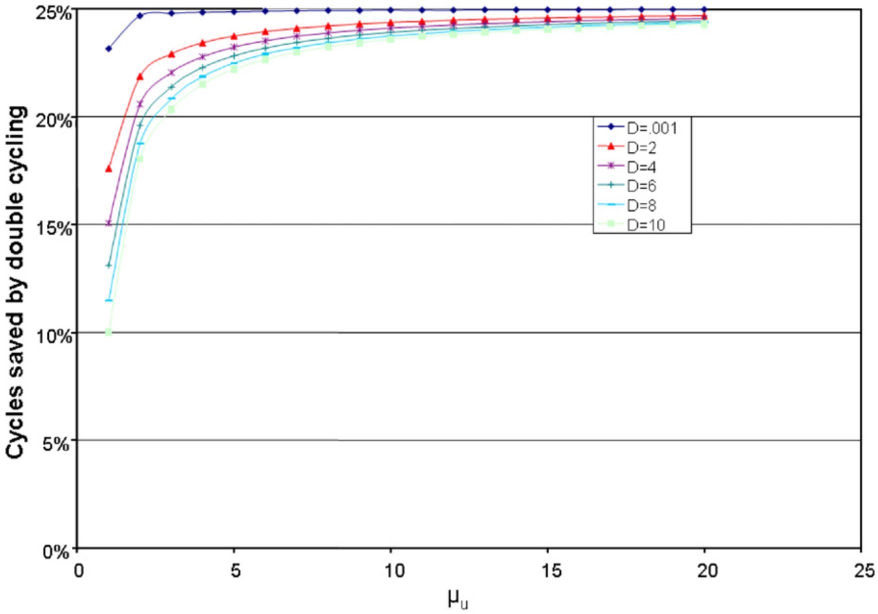

Fig. 5. Percentage reduction in number of cycles to complete loading and unloading operations below deck using the proximal stack strategy for varying values of D. $C_i = 20$, and $Y_i = \Lambda_i$.

Fig. 5 shows the percentage reduction $\left(\frac{E[T_{\mathrm{I},i}]-E[T_{\mathrm{II},i}]}{E[T_{\mathrm{I},i}]}\right)$ 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, $C_i = 20$, and $\mu_u = \mu_l$. Fig. 6 shows the same information, but for vessels where $\mu_l = 0.5\mu_u$. As we expect, benefits decrease with increasing variance (values of D). Interestingly, as a percentage, benefits are greater with increasing μ_u, and the effect of variance declines. By comparing Figs. 5 and 6 we also see that benefits are greater in 5, where vessels have an even balance of imports and exports, as expected.

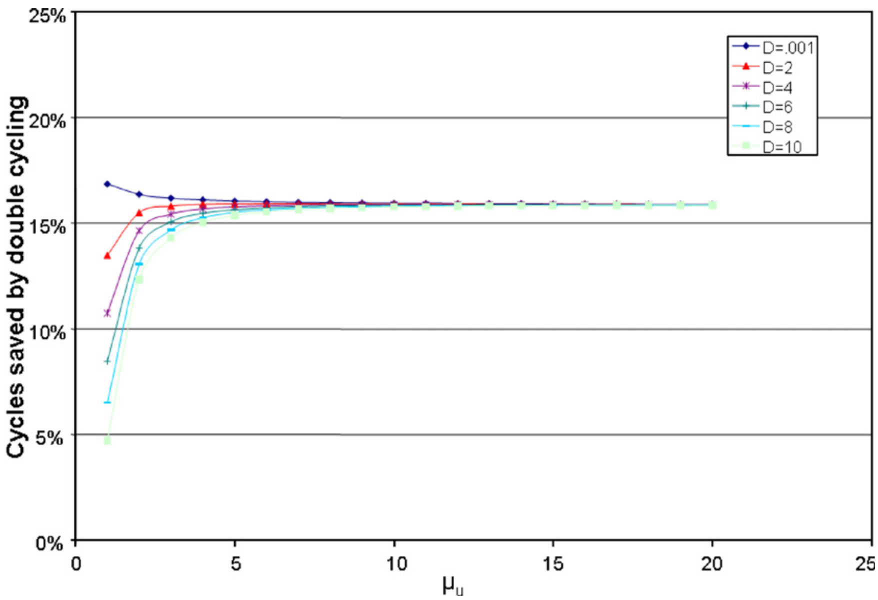

Fig. 6. Percentage reduction in number of cycles to complete loading and unloading operations below deck using the proximal stack strategy for varying values of D. $C_i = 20$, and $Y_i = 0.5\Lambda_i$.

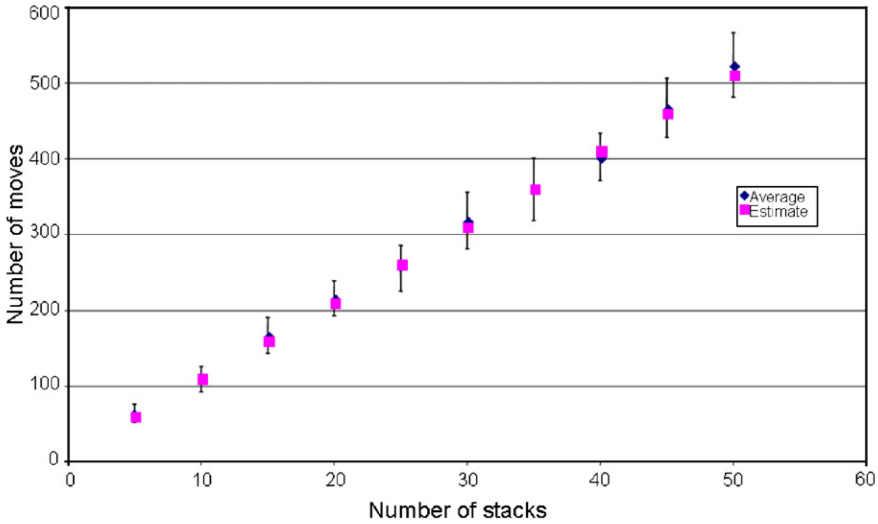

Fig. 7. Comparison of estimate of number of moves to complete unloading and loading operations on a row from formula and simulated runs. Each error bar corresponds to 30 simulation runs.

3.3. Comparison of formula and simulation results

Given the Central Limit Theorem we know that (8) will provide a good estimate for the number of cycles for large C_i, but it is unclear how accurate the expression will be for realistic values of C_i (up to 20 stacks per row in current ships). We therefore compare the estimated values using the formula to the average number of cycles for a set of randomly generated ships. The number of containers to load and unload in each stack were randomly drawn from a beta distribution. The inputs to the simulation are the parameters p and q of the beta distribution for both the number of imports and exports in one stack, the number of stacks, the maximum height of an import stack, and of an export stack. The inputs to (8), d, D, C_i, μ_u, and μ_l, can be determined uniquely from the simulation inputs.

Fig. 7 plots the number of moves necessary to complete a row vs the number of stacks in the row. Each square represents the estimated number of cycles according to (8). Each diamond shows the average result of 30 generated rows. The error bars show one standard deviation of the simulated data on each side of the mean. The predicted and simulated averages are very close even for small numbers of stacks, and the discrepancies are statistically insignificant. The average difference between the estimate and the average was 1.13%.

Eq. (8) applies to a single row. To estimate the number of cycles to turn around the entire vessel, one only need sum over the rows of the vessel. These results can be converted into time savings as per Goodchild and Daganzo (2006). We have thus developed a formula to estimate long-run crane and vessel productivity improvements as a result of double cycling.

4. Impact on landside transportation operations

In addition to improving crane, vessel, and berth productivity, double cycling can increase the productivity of container handling equipment on the landside. There are many different methods by which containers can be transferred from the apron to the local storage area, and then placed in local storage. We are interested in two varieties:

(1) Transfer methods that require two pieces of equipment: a vehicle for transportation and another piece of equipment to remove the container from the vehicle (or place a container on the vehicle) at the local storage area. In one such method, containers are transported by yard tractors on chassis, but stored on the

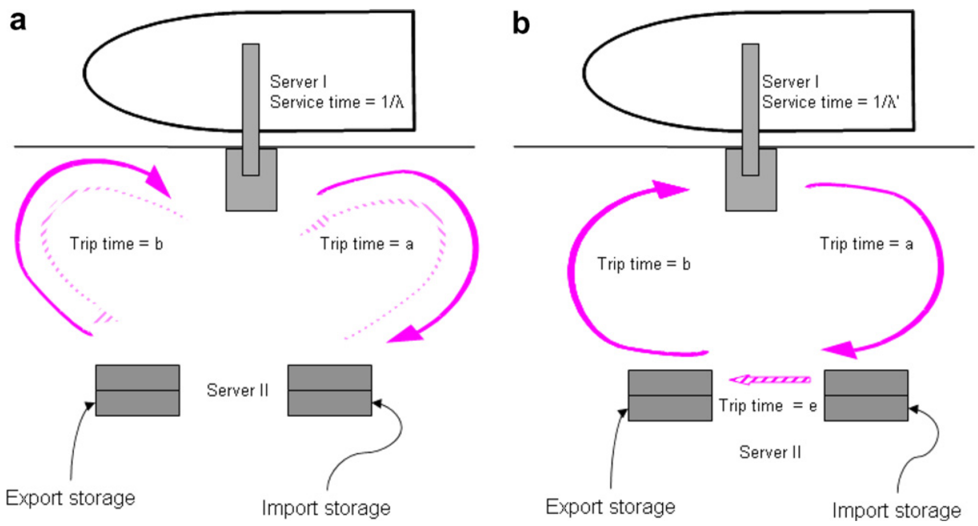

Fig. 8. (a) Schematic diagram of landside operations when single cycling. (b) Double cycling.

ground. In this case another machine, such as a top-pick, is used to move the container from the chassis to the ground.

(2) Transfer methods that use a single piece of equipment for the whole operation. For example, containers may be transferred by yard tractors with chassis and stored on chassis, or containers can be transferred by straddle carriers, which can pick and place the containers on the ground without help.

The analysis here is appropriate for the second case, which is common.

Loading and unloading a vessel simultaneously means that after a vehicle deposits a container on the apron, the driver can pick-up an unloaded container and take it to local storage, instead of returning empty to the local storage.

Fig. 8a 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 if we assign cranes to non-overlapping segments of the 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. Fig. 8b 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. These schematics are not meant to fully describe the flow of traffic, but to capture the main elements common to most systems.

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) the local, self-service storage areas. The customers are the 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. We assume the queueing system has reached steady state after some time.

We now develop simple expressions for the number of landside vehicles required with and without double cycling. We assume vehicle travel times are independent, and ignore congestion.

4.1. The quay crane (server I)

The quay crane is modelled as a single server with deterministic service times. This server station is labelled I in Fig. 8. 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, drop the container onto a landside vehicle or the ground, and wait for the vehicle to depart and a vehicle with the next container to load to position itself below the crane. Notice that after a container for loading has been unloaded from a vehicle, the vehicle must wait for the crane to return with a container for unloading.

Service times are assumed to be $1/\lambda$ and $1/\lambda'$ minutes per customer for the single and double cycling cases, respectively ($\lambda' < \lambda$). In practical operations quay crane cycle times are very consistent, so we assume no variance in these service times.

4.2. Travel times between servers

We assume the travel time between the apron and the local import storage is a min. The travel time between the local export storage and the apron is b min, and the travel time between the local import and local export facilities is e min. We model these variables deterministically, since the main contribution to randomness comes from the local storage operation. Thus, the total travel time per vehicle in one single-cycle (the time between departing and arriving at the quay crane while single cycling), τ, is $\tau = 2a$ while unloading and $\tau = 2b$ while loading. The total travel time for one cycle while double cylcing is $\tau = a + b + e$.

4.3. The local storage (server II)

Service at the local storage is the placement of containers in the appropriate storage location or retrieval from the appropriate storage location. With single cycling, service is defined by the driver finding the storage location, and either attaching or detaching the chassis. If straddle carriers are used the driver must find the correct location and either drop or pick up the container. 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 straddle carriers are being used the driver must find the location of the import drop, drop the container, find the location of the export, and 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 is reasonable as in operation, the driver never has to wait for a service s/he performs, although service times will vary.

Although with double cycling the landside vehicles pick-up and drop-off containers at different instants in time, and at different locations, we can consider these two locations part of the same mathematical server. The service time is just the sum of the times in the unloading and loading stations. Call the service time at II with single cycling w (assumed to be the same for loading and unloading) and with double cycling, w'. With double cycling, the driver must drop-off and pick-up a container, so $E[w'] = 2E[w]$.

4.4. Required number of landside vehicles

Assume for the moment that the number of vehicles in the system (N) is so large that the queue at server I never dissipates. Then, since the crane operates at a regular rate ($r = \lambda$ or λ'), the number of containers in transit N_{I} will be $N_{\mathrm{I}} = r\tau$ (as per Little's formula), and the arrivals to server II will be steady and deterministic. Therefore, this storage area acts as a $D/G/\infty$ queueing system with arrival rate r and service time $\beta = w$ or w'. The mean and variance of the number of vehicles in the local storage area, N_{II}, is therefore given by the well-known $D/G/\infty$ formula (see e.g. Newell, 1987; Diez-Roux and Daganzo, 1995).

$$E[N_{\mathrm{II}}] = rE[\beta] \tag{9}$$
$$\mathrm{var}(N_{\mathrm{II}}) = \lambda[E[\beta] - E[\min(\beta_1, \beta_2)]] \tag{10}$$

where β_1 and β_2 are independent draws from β. Then, the number of vehicles under the crane or waiting for the crane is $N_{\mathrm{C}} = N - N_{\mathrm{I}} - N_{\mathrm{II}}$, with mean and variance:

$$E[N_{\mathrm{C}}] = N - r\tau - rE[\beta] \tag{11}$$
$$\mathrm{var}(N_{\mathrm{C}}) = \mathrm{var}(N_{\mathrm{II}}) \tag{12}$$

We now use Eqs. (9)–(12) to choose N. The goal is ensuring that $N_{\mathrm{C}} \geqslant 1$ with very high probability. If we assume for practical purposes that N_{C} rarely strays from its mean by more than two standard deviations, we conclude that N_{C} should satisfy $E[N_{\mathrm{C}}] = 2\sqrt{\mathrm{var}(N_{\mathrm{C}})} + 1$, and therefore $N = r(\tau + E[\beta]) + 1 + 2\sqrt{\lambda(E[\beta] - E[\min(\beta_1, \beta_2)])}$. This is the proposed recipe. Its expressions for single cycling (N) and double cycling (N') are given below. For the unloading phase with single cycling:

$$N = \lambda(2a) + 1 + \lambda E[\beta] + 2\sqrt{\lambda(E[\beta] - E[\min(\beta_1, \beta_2)])} \tag{13}$$

For the loading phase with single cycling:

$$N = \lambda(2b) + 1 + \lambda E[\beta] + 2\sqrt{\lambda(E[\beta] - E[\min(\beta_1, \beta_2)])} \tag{14}$$

And for both phases combined (since $\beta = w$):

$$N = \lambda(\max(2a, 2b)) + 1 + \lambda E[w] + 2\sqrt{\lambda(E[w] - E[\min(w_1, w_2)])} \tag{15}$$

Similarly, an estimate for the number of landside vehicles required per crane when double cycling is (since $\beta = w'$):

$$N' = \lambda'(a + b + e) + 1 + \lambda E[w'] + 2\sqrt{\lambda'(E[w'] - E[\min(w'_1, w'_2)])} \tag{16}$$

Note that it is possible for $N' > N$ but that this is not typical given typical travel times, and the differences in service rates (λ vs λ') and (w vs w'). For single cycling an average cycle time of 1 min and 45 s was recorded at the Efficient Marine Terminal Trial at the Port of Tacoma in 2003. The average double cycle took 2 min and 50 s TranSystems Corporation (2003). For this data, $\lambda = .57$ landside vehicles per minute and $\lambda' = .35$. Values

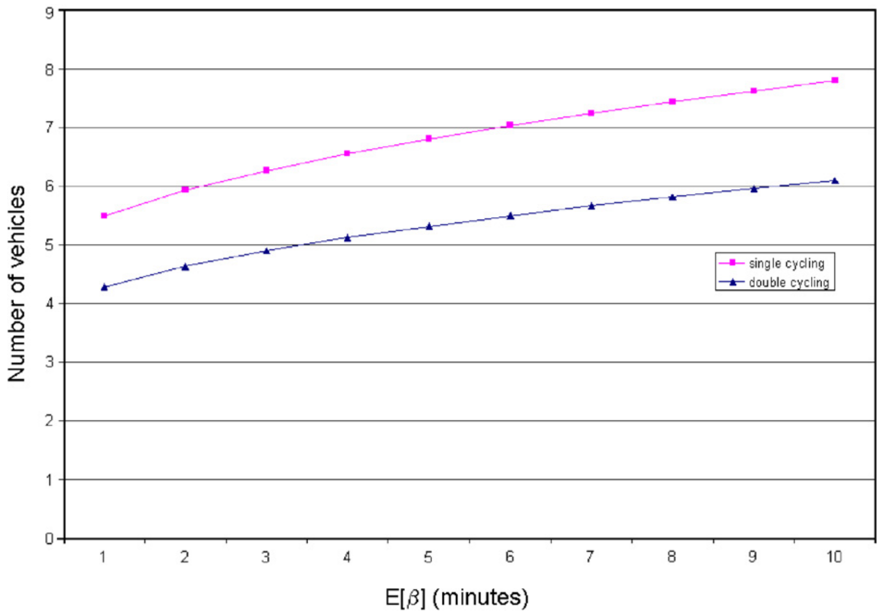

Fig. 9. Number of landside vehicle drivers required for single and double cycling, against expected wait time at II.

of $a = 2$ min, $b = 3$ min, and $e = 2$ min were estimated based on the current storage plan for, and the dimensions of, the Ben E. Nutter terminal at the Port of Oakland. Fig. 9 shows the number of drivers required with single and double cycling for different values of $E[\beta]$, assuming that β is exponentially distributed: $E[\min(\beta_1, \beta_2)] = E[\beta]/2$. If we take $E[w] = 3$ and $E[w'] = 6$ min we estimate 6.5 yard tractors required per crane with single cycling but only 5.5 required with double cycling. 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 one driver and tractor, a reduction of about 15%.

Eq. (16) only holds while there is a continuous series of double cycles. Therefore, if an extended period of single cycles is required (e.g. while unloading containers above deck, or when dealing with highly unbalanced ships) (13) and (14) should be used. If the single cycle episodes are short, they may be weathered by allowing small accumulations of containers on the apron, or sharing vehicles across vessels.

5. Discussion: Operational changes to support double cycling

Here we discuss the relationships between double cycling operations and other aspects of landside operations. We show that double cycling actually simplifies some of the operations, further reducing cost.

5.1. Loading plans

When developing a ship loading plan the following principles should be observed.

Principle 1: Smooth the difference between loads and unloads across the stacks. To reduce the unproductive delay, M_i, of the loading operations discussed in Section 3.2 we should spread the difference between the total number of loads and unloads as evenly as possible across all stacks. If we do this, the terms of (2) are constant $\{l_{ji} - u_{ji}\} \approx \{\Lambda_i - Y_i\}/C_i$, $M_i(c)$ is monotonic in c, and (3) yields $M_i \cong \max\{0, Y_i - \Lambda_i\}$, which is the least possible.

Principle 2: Put stacks destined for one port in as few rows as possible, and as close to one another as possible within each row. This will reduce the *time* required to unload and load the vessel by keeping the distance between stacks small. It will also reduce the number of times we pay the initial penalty for starting to operate on a row, thereby reducing total crane moves.

Principle 3: Segment space on the vessel by origin–destination pairs. This is a way to implement Principle 2. Assume vessel stops can be enumerated, as shown in Fig. 10. This can represent any tour with n stops including shuttle services ($n = 2$), as well as more typical routes with $n \geqslant 3$. The vessel of Fig. 10 has just called at port 4 and is sailing for port 1. The vessel is divided into six segments, one for each of the six 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

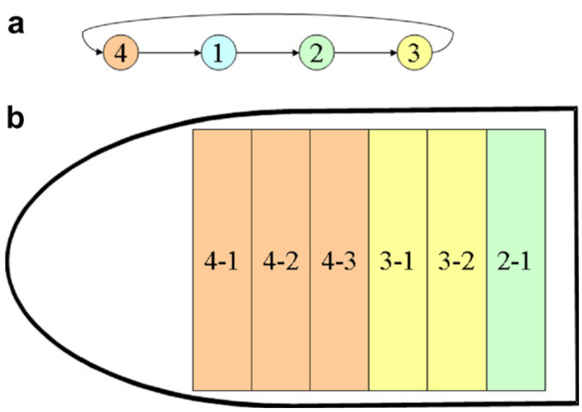

Fig. 10. (a) Vessel tour. The vessel has just left port 4, sailing for port 1. (b) Vessel storage segregated by origin–destination pairs (labelled O–D).

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, the number of OD pairs with containers on board the ship, P, is at most one-half of all OD pairs $\{P = \frac{n(n-1)}{2}\}$. Note that at any given time if the vessel is carrying containers from i to j it is not carrying containers from j to i. Thus, if loads are evenly balanced one can just reserve specific parts of the ship for specific two-way trades, $i \leftrightarrow j$.

Generally, O–D loads are not perfectly balanced, but when one accounts for the flow of empty containers imbalances are greatly reduced. Furthermore, since double-cycling is usually implemented only below deck, one should be able to partition this smaller space into sections that can be filled in both directions.

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, and 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. Figs. 11 and 12a show typical traffic flows for straddle carriers and yard tractors operating with single cycling. Figs. 11b and 12b show typical traffic flows for straddle carriers and yard tractors operating double cycling. These schematics are not meant to fully describe the traffic flows, but to provide a general description of the system. Before implementing double cycling, a port will need to reconsider traffic flow patterns based on the specifics of the port. Although it may initially seem traffic flows would be complicated by double cycling, these figures demonstrate that this is not the case.

5.3. Impact on storage equipment

We consider here 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). While wheeled operations are

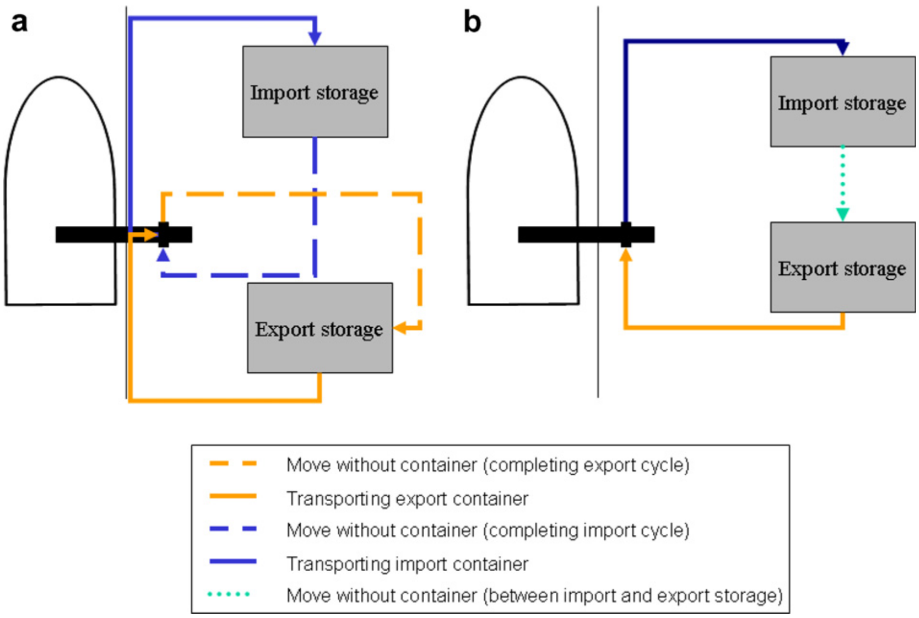

Fig. 11. (a) Traffic flows for straddle carriers when single cycling. (b) Double cycling.

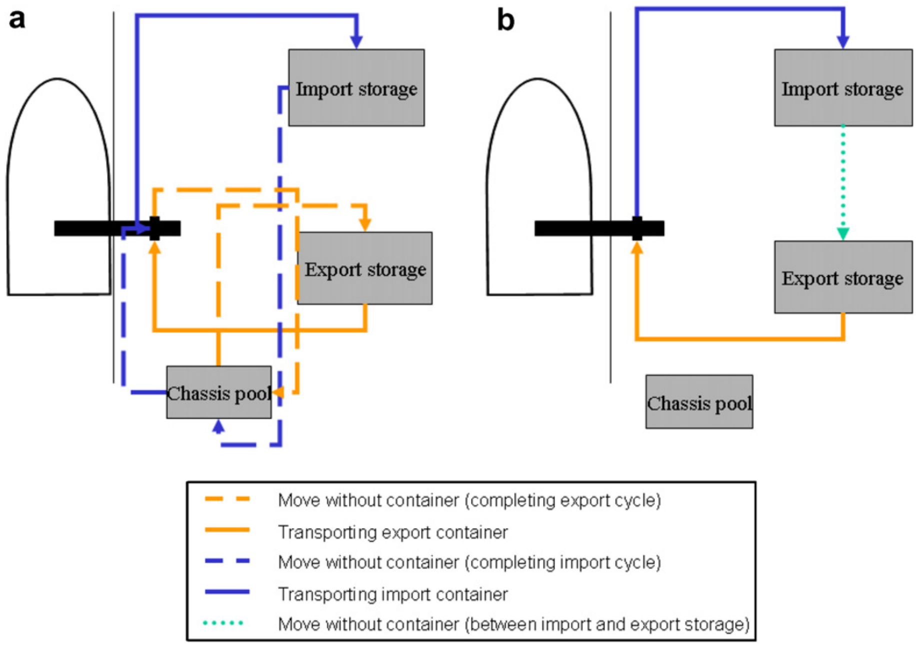

Fig. 12. (a) Traffic flow pattern for yard tractors single cycling. If imports are stored on-wheels it is necessary for the driver to stop at the empty chassis pool. (b) Landside traffic flow patterns for yard tractors when double cycling.

becoming less common due to the need for greater land utilization, many terminals still store a significant portion of their containers on chassis. With single cycling (and assuming that all containers are unloaded from the ship before any are loaded, as is current practice),[2] 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. So the number of chassis required is $\Lambda + Y$ where $\Lambda = \sum_{i=1}^{R} \Lambda_i$ and $Y = \sum_{i=1}^{R} Y_i$.

With double cycling, loads and unloads never sit in the terminal because almost as soon as one starts unloading the vessel, one starts loading it. In the worst case one would have all the containers of one row (i) on chassis, all the imports for rows $<i$ on chassis, and all the exports for rows $i > 1$ also on chassis, i.e. the required number of chassis when double cycling would be

$$\sum_{j=1}^{i} Y_j + \sum_{j=i}^{R} \Lambda_j \leqslant \max(\Lambda, Y) + \max_{i=1\ldots R}(C_i) \tag{17}$$

The estimate on the right side is independent of the ship loading pattern,[3] and for evenly loaded ships with many rows ($\Lambda \approx Y \gg C_i$) it is roughly one half of the number required for single cycling for the whole vessel ($\Lambda + Y$).

We note that if one were to single cycle, alternating loading and unloading, one row at a time, then the chassis requirements would be given by (17). The reduction in the number of chassis comes from alternating, rather than from double cycling. We also note that if ships have hatches that can support H containers, and one alternates loading and unloading one hatch at a time, then the required number of chassis would be $\max(\Lambda, Y) + H$. This is still considerably smaller than $\Lambda + Y$. In all these formulae one should use values for Λ, Y, C_i and H representative of the largest ship likely to call at the terminal.

[2] It is possible to operate in another way, where each stack is first unloaded and then loaded with single cycling, but that is not the method that is currently used, so it is not considered here.

[3] A tighter bound based on the distribution (mean and variance) of the export and import numbers for each stack is given in Goodchild (2005).

5.4. Yard storage locations

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 the amount of space that must be reserved for imports and exports is not affected by the operating strategy.

The same is not true, however, if space is shared by imports and exports (this is usually possible only when using a chassis storage system). When space is shared, one simply needs to provide room for all the chassis, and we have seen in Section 5.3 that alternating loading and unloading can greatly reduce the required number of chassis.

5.5. Longshoremen

Longshoremen 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 to double cycle. The same gang will be asked to monitor containers being placed on and retrieved from the vessel. When turn around time is reduced, we expect that ports will utilize this additional capacity by serving additional vessels, so requirements for labor will not be reduced, but port productivity (number of containers handled per time period) will increase.

5.6. Container handling equipment on the land side

With double cycling, containers are placed in short-term storage and retrieved from short-term storage, simultaneously. Thus, if these storage areas share handling equipment (such as top-picks or reach-stackers) the number of units required may be increased by double cycling since the units are needed simultaneously. This is not the case, however, if the import and export storage areas do not share equipment (e.g. as occurs when different storage technologies are used for exports and imports).

6. Conclusion

We have quantified the key operational 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 results of this paper provide port planners with insights into the impact of double cycling on requirements for port resources and their management.

Acknowledgments

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Appendix A. Derivation of Eq. (7)

Definition 4 (*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 Feller (1950) the formula for the probability density function of $T_i(z)$ evaluated at c is

$$f(c \mid z) = \frac{z}{\sqrt{2\pi Dc^3}} e^{\frac{-\{z-dc\}^2}{2Dc}} \tag{18}$$

The cumulative distribution function is therefore

$$Pr\{T_i(z) \leqslant c\} = F(c \mid z) = \int_0^c \frac{z\,\mathrm{d}y}{\sqrt{2\pi D y^3}} \mathrm{e}^{\frac{-\{z-dy\}^2}{2Dy}} \tag{19}$$

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

$$Pr\{T_i(z) \leqslant C_i\} \equiv Pr\{M_i \geqslant z\} \tag{20}$$

The expectation of a non-negative random variable is obtained by integrating the complementary cumulative distribution function. Hence, the expected maximal excursion, M_i, is the integral of (20); and using (19) to express the left hand side of (20) we find:

$$\begin{aligned}
E[M_i] &= \int_0^\infty \mathrm{d}z \int_0^{C_i} \mathrm{d}y \left\{ \frac{z}{\sqrt{2\pi D y^3}} \mathrm{e}^{\frac{-(z-dy)^2}{(2Dy)}} \right\} = \int_0^\infty \mathrm{d}z \int_0^{C_i} \left[\frac{z\,\mathrm{d}y}{\sqrt{2\pi D y^3}} \mathrm{e}^{-(z-dy)^2/2Dy} \right] \\
&= \int_0^{C_i} \mathrm{d}y \int_0^\infty \left[\frac{z\,\mathrm{d}z}{\sqrt{2\pi D y^3}} \mathrm{e}^{-(z-dy)^2/2Dy} \right] \quad \text{substitute} \quad w = \frac{(z-dy)}{\sqrt{Dy}} \\
&= \int_0^{C_i} \frac{\mathrm{d}y}{\sqrt{2\pi D y^3}} \int_{-d\sqrt{y}/\sqrt{D}}^\infty \left[\mathrm{d}w (wDy + d\sqrt{Dy^3}) \mathrm{e}^{-w^2/2} \right] \\
&= \int_0^{C_i} \frac{\mathrm{d}y}{\sqrt{2\pi D y}} \int_{-d\sqrt{y}/\sqrt{D}}^\infty \left[\mathrm{d}w (wD + d\sqrt{Dy}) \mathrm{e}^{-w^2/2} \right] \\
&= \int_0^{C_i} \frac{\mathrm{d}y}{\sqrt{2\pi D y}} \left[\int_{-d\sqrt{y}/\sqrt{D}}^\infty wD\mathrm{e}^{-w^2/2}\,\mathrm{d}w + \int_{-d\sqrt{y}/\sqrt{D}}^\infty d\sqrt{Dy}\mathrm{e}^{-w^2/2}\,\mathrm{d}w \right] \\
&= \int_0^{C_i} \frac{\mathrm{d}y}{\sqrt{2\pi D y}} \left[-D\mathrm{e}^{-w^2/2} \Big|_{-d\sqrt{y}/\sqrt{D}}^\infty + \int_{-d\sqrt{y}/\sqrt{D}}^\infty d\sqrt{Dy}\mathrm{e}^{-w^2/2}\,\mathrm{d}w \right] \\
&= \int_0^{C_i} \frac{\mathrm{d}y}{\sqrt{2\pi D y}} \left[D\mathrm{e}^{-d^2 y/2D} + d\sqrt{2\pi D y} \int_{-d\sqrt{y}/\sqrt{D}}^\infty \frac{\mathrm{e}^{-w^2/2}}{\sqrt{2\pi}}\,\mathrm{d}w \right] \\
&= \int_0^{C_i} \frac{\mathrm{d}y}{\sqrt{2\pi D y}} \left[D\mathrm{e}^{-d^2 y/2D} + d\sqrt{2\pi D y} \left(1 - \Phi\left(-\frac{d\sqrt{y}}{\sqrt{D}} \right) \right) \right] \\
&= \int_0^{C_i} \frac{\mathrm{d}y}{\sqrt{2\pi D y}} \left[D\mathrm{e}^{-d^2 y/2D} + d\sqrt{2\pi D y} \left(\Phi\left(\frac{d\sqrt{y}}{\sqrt{D}} \right) \right) \right] \\
&= \int_0^{C_i} \frac{\mathrm{d}y}{\sqrt{2\pi D y}} \left[D\mathrm{e}^{-d^2 y/2D} \right] + \int_0^{C_i} \frac{\mathrm{d}y}{\sqrt{2\pi D y}} \left[d\sqrt{2\pi D y} \left(\Phi\left(\frac{d\sqrt{y}}{\sqrt{D}} \right) \right) \right] \\
&= \int_0^{C_i} \frac{\sqrt{D}\mathrm{e}^{-d^2 y/2D}}{\sqrt{2\pi y}}\,\mathrm{d}y + \int_0^{C_i} d\left(\Phi\left(\frac{d\sqrt{y}}{\sqrt{D}} \right) \right) \mathrm{d}y \quad \text{substitute} \quad x = d\sqrt{y}/\sqrt{D} \\
&= \int_0^{d\sqrt{C_i}/\sqrt{D}} D\frac{\sqrt{2}\mathrm{e}^{-x^2/2}\,\mathrm{d}x}{d\sqrt{\pi}} + \int_0^{C_i} d\left(\Phi\left(\frac{d\sqrt{y}}{\sqrt{D}} \right) \right) \mathrm{d}y = \int_0^{d\sqrt{C_i}/\sqrt{D}} \frac{D\sqrt{2}}{d\sqrt{\pi}} \mathrm{e}^{-x^2/2}\,\mathrm{d}x + d\int_0^{C_i} \Phi\left(\frac{d\sqrt{y}}{\sqrt{D}} \right) \mathrm{d}y \\
&= \frac{2D}{d} \int_0^{d\sqrt{C_i}/\sqrt{D}} \mathrm{e}^{-x^2/2}\,\mathrm{d}x \Big/ \sqrt{2\pi} + d\int_0^{C_i} \Phi\left(\frac{d\sqrt{y}}{\sqrt{D}} \right) \mathrm{d}y \\
&= \frac{2D}{d} \left[\int_{-\infty}^{d\sqrt{C_i}/\sqrt{D}} \mathrm{e}^{-x^2/2}\,\mathrm{d}x \Big/ \sqrt{2\pi} - \frac{1}{2} \right] + d\int_0^{C_i} \Phi\left(\frac{d\sqrt{y}}{\sqrt{D}} \right) \mathrm{d}y \\
&= \frac{2D}{d} \left[\Phi\left(\frac{d\sqrt{C_i}}{\sqrt{D}} \right) - \frac{1}{2} \right] + \frac{2D}{d} \int_0^{d\sqrt{C_i}/\sqrt{D}} z\Phi(z)\,\mathrm{d}z \quad \text{where } \Phi(x) = \int_{-\infty}^x \frac{\mathrm{d}w}{\sqrt{2\pi}} \mathrm{e}^{\frac{-w^2}{2}}
\end{aligned}$$

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