Empirical Analysis and Simulation Modeling of a Canadian Seaport Transportation Network

David Gillen
University of British Columbia, Vancouver, British Columbia, Canada

Hamed Hasheminia*
San Francisco State University, San Francisco, California, USA

In this empirical paper, we use operational data from a west coast Canadian seaport and utilize a simulation model to measure the effect of changes in the seaport's intermodal system. We investigate the effect of changes on total dwell time – i.e. the time between when the vessels berth at port and the time the ongoing trains leave the port with the containers. We developed the simulation model considering all port operational resources including reach-stackers, cranes, tractor trailers, workforce schedules, train schedules, and current schedule of vessel arrivals. All models were calibrated using real data on operational parameters such as the number of resources available and the distribution of each resource. After calibration, we undertook a comprehensive sensitivity analysis and report on the operational parameters including the effect of increasing each resource on dwell times and the change in schedules of trains. Moreover, we use this simulation model to forecast the effect of an increase of vessel sizes on the dwell times and also the vulnerability of the seaport if it faces temporary increases in demand. Our major result suggests that the increase in vessel sizes – even if total demand remains the same – has significant adverse effects on the efficiency of the seaport. Also, we found that among all operational parameters, investments in increasing the frequency of train schedule is the best way to improve the efficiency of this port. We believe major results found in this paper can have policy implications for infrastructure investment; for example, how to invest private and public funds for best return in efficiency improvement, and what to expect from the ever growing trend of larger vessels. We also believe, practitioners can benefit significantly from the estimated results for the operational parameters that are reported in this paper.

* Corresponding Author. E-mail address: hamed@sfsu.edu

I. INTRODUCTION

Perhaps the most important revolution in the maritime industry in the past century has been containerization. The adoption of containerization allowed shipping lines to realize substantial economies of scale in ship size. The homogenizing of the cargo into standard TEUs reduced handling and storage costs. With containerization, larger vessels with higher TEU capacities and better fuel efficiency are being introduced to maritime industry. Containerization has also helped the intermodal transportation network; for example, a container can now be unloaded from a vessel and directly loaded on a train and shipped to destination via rail with minimal handling. The benefits of the economies of scale has resulted in shippers demanding and using larger vessels over time. Despite the benefits such a strategy has for shippers, seaports may face new challenges from congestion as these larger ships deposit more and more containers at each port visit. The economies of scale for ships and the diseconomies for landside facilties has resulted in a stream of research that focuses on the effect of an increase in one component of the intermodal supply chain, namely vessel sizes, on the Maritime industry.

Kidson et al (2015) reported that size of vessels visiting Australia has increased significantly in recent years. They describe the decrease in efficiency in larger ports and by reviewing the data of three major Australia ports - Melbourne, Sydney and Brisbane, they estimated the magnitude of the negative effect of this increase in vessel sizes on the efficiency of ports. Martin et al (2015) investigated the effects of a change in vessel size on the performance of Northern European Terminals. Van Hassel et al (2016) reported on the inevitability of the increase of vessel sizes and focused on Asia-U.S. and Asia-Europe maritime shipments and evaluated the economic effect of such an increase in size of vessels on the total cost of transportation networks. Ng and Kee (2008) investigated the optimal size of container vessels from ship operators' standpoint in Southeast Asia. Some other papers such as Imai and Rivera (2001) focused on the optimal size of fleet – the fleet size that results in the lowest total cost in a transportation network. One of the research goals of this paper is the empirical analysis of the effect of changes in vessel sizes on the efficiency of the Canadian seaport under study.

A positive impact of containerization on the Maritime Studies literature is that researchers can now focus on the flow of containers and use it to simulate operations in any seaport. Containers, irrespective of what they carry, can be counted as one entity – this standardization has helped researchers focus on only one entity to simulate the total flow in a seaport or on a greater scale an entire transportation network. As an example, a meta study (Notteboom et al 2013) reported that 40% of all port studies published in the Journal of Maritime Policy and Ports focus on containers.[1]

Many researchers have simulated seaport operations and these have been undertaken for several different countries and for a variety of purposes. For example, Merkuryev et al (1998) and Merkuryev et al (2000) simulated operations of a container terminal in Riga harbour in Latvia. They explored the impact of weather conditions on terminal operations. Hadjiconstantinou and Ma (2009) developed a discrete event simulation model and applied it to the port of Piraeus in Greece. The simulation results were used to develop a decision support system to optimize port operations. Dragović et al. (2014) proposed a simulation model for Boka Kotorska Bay (BKB) – a famous cruise ship destination and investigated different scenarios for quay extension. They used real data to validate the assumption of models. In another study Legato et al. (2001) used a simulation model for Gioia Tauro in Italy. They used a detailed flow chart of operations and defined interactions of terminal elements.

There are other aspects of seaports

[1] They also mentioned that this figure has risen to almost two-thirds in recent years.

that are being analyzed using simulation. A few seaport related topics that are being investigated using simulation are environmental aspects of ports (Moon and Woo 2014; Woo and Moon 2014 ; Parola and Sciomachen 2005), ports as part of a multi agent transportation network (Lee et al 2003), the effect of terminal leasing policy on performance (Turner 2000), reliability and variability of performance of ports (Gillen and Hasheminia 2016), and the vulnerability of ports and the effect of co-opetition among ports (Hsieh et al 2014). For more comprehensive review of the models used in container terminals, see Angeloudis and Bell (2011).

In the current paper, besides the earlier stated goal of investigating the effect of a change in fleet size on the seaport under study, we also will study the effect of an unanticipated increase in demand on port efficiency; such as an increase in ship arrivals due to labor or political disruption at another port. Moreover, one of the major goals of this research was to identify operational investment opportunities. For example, we directed the research to answer the following question: among all operational elements of a seaport from investing in number of cranes, investing in machinery such as tractor trailers or reach-stackers to expanding rail services and increasing train schedules at the port, which one is more effective.

In order to calibrate the simulation models, and get realistic models, we interviewed authorities of the port under study and used real values as reported by the Port Autorities for the distribution of the time it takes for each component in the network to move containers. We believe, these values for most of the ports should be more or less the same or certainly fall within our distribution. For instance, the distribution of the time it takes for a crane to unload a container or the time it takes for a reach-stacker to move containers inside a port with more or less the same size should be similar across ports similarly equipped. We believe the results of our parameter calibrations can be used by other practitioners in industry and other empirical research. To keep the real statistics confidential, we report rounded values – instead of actual values – for calibrated parameters. For example, if it takes a reach-stacker between 4 to 11 minutes to move containers, we are going to report is as 5 minutes to 10 minutes. Similarly, if the real ratio of 20ft containers out of all imported containers is 48.6%, we are going to report it as 50%. In other words, although the reported parameters are very close to what the port is experiencing, they are not exactly the same as observed value. We believe using this method we not only share important statistics that can be used by practitioners as industry standards but also does not fully disclose the actual values of these parameters at the port that was studied.

In section 2 we introduce all of the parameters, components, and assumptions used for the simulation model. In this section, proximities for each parameter's distribution and also proxy for the number of servers – i.e. available resources – are reported. In section 3, we provide the simulation results for the effect of an increase in demand on the performance of the port (measured as dwell time), the effect of an increase in vessel size on the performance of the port, and the results for an increasee in investments used to extend available port resources. Section 4, provides a summary and discusses the major results of this paper. We also share our thoughts regarding extension for similar work.

II. MAJOR ASSUMPTIONS IS SIMULATION MODEL

The port under study is located on the west coast of Canada. The port operations are typical of marine ports in that vessels arrive and unload their 20ft and 40ft containers by crane. Once the containers are unloaded they are handled several times before being loaded on the train. They are moved to the storage yard by tractor trailers and reach stackers unload the containers from tractor trailers on the yard. The containers typically remain at their drop position until they get loaded on trains. For train loading, reach stackers place containers on tractor trailers which move containers from the yard to rail where they are loaded on the train that depart according to a fixed schedule.[2] The port also loads empty containers onto vessels. In the following section, the assumptions used in developing the simulation models are described.

2.1 Vessel Arrivals and distribution of containers on each vessel

On average, a vessel arrives at port every 2.5 days. The inter-arrival time of vessels are simulated using a uniform distribution of minimum 1 day and maximum 4 days. Also, the number of containers needed to be unloaded from or loaded onto each vessel was approximately normally distributed with an average of 2000 containers and standard deviation of 500

.

2.2 Distribution of Containers

This port both unloads and loads containers; for this port, approximately 55% of containers were incoming and 45% ongoing. Also, to make simulations as accurate as possible, we used a distribution for both 20ft and 40ft containers. Irrespective of the size of containers, the number of resources that are going to be utilized is usually the same. For example, you need a crane to unload each container irrespective of its size. However, for loading containers on trains, size does matter. Two 20-ft containers can be stacked on a 40-ft containers. Therefore, we distinguished between these two types of containers; roughly 80% of containers are 40ft and 20% are 20ft.

2.3 Destination distribution of containers

Trains leaving this port are heading for 3 major destinations labeled as Destination A, B and C. Destination A is a domestic destination, destination B is a U.S. city and, Destination C is a series of cities served with one ongoing train. Roughly, 15% of imported containers are destined to A, 20% are destined to B and 65% are C type. Besides two types of empty containers – 20ft and 40ft - that are loaded on vessels, we have 6 types of containers – 20ft and 40ft combined with the three destinations. Each container is labeled according to its size and destination. In total, we have eight labels for containers. In addition to trains, a small percentage of containers is carried by truck. In this study, we mainly focused on rail. Therefore, we assume for containers transported to destination by truck, that trucks are always available, in effect, we assumed truck capacity was unlimited.

2.4 Cranes

After consulting with port operators, we assumed there is heterogneity among crane operators and assumed crane productivity is uniformly distributed from 15 to 40 moves per hour. In other words an unloading/loading process is uniformly distributed from 1.5 minutes to 4 minutes per container. We also assumed there are 4 cranes in the system.

[2] This schedule is generally fixed up to a year in advance and sets the number, timing and number of cars in a train.

2.5 Tractor Trailers

There are 27 tractor trailers in the system and on average they can move 10 containers per hour. Therefore, we assume that on average it will take tractor trailers 6 minutes to move containers to the storage yard. We assumed the process is uniformly distributed from 4 minutes to 8 minutes.

2.6 Reach Stackers

There were approximiately 20 Reach Stackers in the system. On average it takes them 4 minutes to load contaienrs from Yard to Tractor Trailers. We assumed this distribution is uniform with lower bound of 2 minutes and upper bound of 6 minutes.

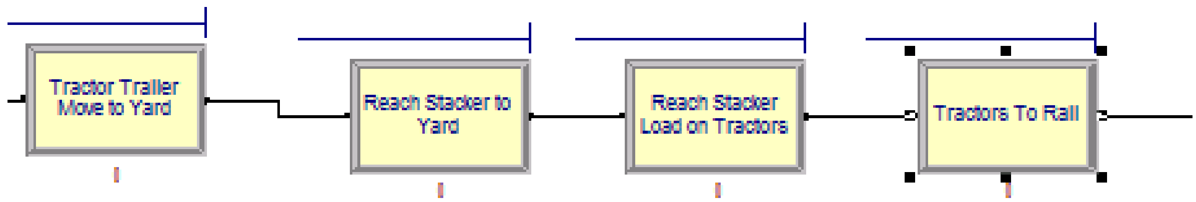


FIGURE 1. THE SEQUENCE OF MOVING COTNAINERS FROM PORTS TO YARD AND YARD TO RAIL

2.7 The sequence of movements of containers

In the above Figure 1, we depict the squence of container movements. Throughout these processes we assumed that the capacity of resources are shared among processes that need same resources. For example tractor-trailers are used both in the process of moving containers from port to Yard and for the process of moving containers from Yard to rail. We assumed no process recieves priority when resources are fully utilized so all jobs are being taken care of on first come first served basis.

2.8 Rail Car Capacity and Schedules of trains

One of the common practices at the port is putting two 20ft containers on top of a 40 ft container. We changed the rail-car-capacity definition to the number of 40ft containers that can be put on a train. As a result the maximum capacity of a train in warmer seasons is approximately 150 rail cars which is equivalent to 300 40ft containers. The average capacity of trains in all seasons – cold and warm is considered to be 270 40ft contianers.[1]

Everyday, on avarage 2 trains leave the port. Every 14 days, on average 2 train leave the port for Desitnation A and Destination B. The rest are leaving the port for Destination C.

2.9 Warm-up Period

It is essential that we let system run for a while before recording Statistics. This is done to make sure the system is in a stable state. Usually, in the beginning of a

[11] In ARENA, we used "Batch" to combine two 20ft containers together and treats them as a 40 ft containner after they are loaded on trains.

simulation the system is empty, therefore, jobs are processed quickly. As time elapses, the system will be closer and closer to a stable state. We allowed 90 days as a warm up and started recording statistics for 1 year following that warm up period. Also, for each of the specified values, we repeated the simulation 10 times and reported the averages of these 10 simulation runs. In simulation models, statistics change from 1 run to another and that is solely due to different sets of random numbers being used each time.

III. SIMULATION RESULTS AND SENSITIVITY ANALYSIS

The base data were used to calibrate the simulation model and to establish the current level of throughput and efficiency given the available resources and delivery schedule of TEUs. This starting position was an initial equilibrium that was subsequently 'shocked' by changes in one component of the system such as an increase in demand (more TEUs to be moved), a change in vessel size as measured by maximum TEU capacity, etc. Each change was modelled independently rather than concurrently.

The simulations focus only on the Port. They do not consider the ocean voyage that brought the TEUs to the Port, it does not consider rail or truck capacity beyond the Port. The simulations pertain only to what happens within the boundaries of the Port.

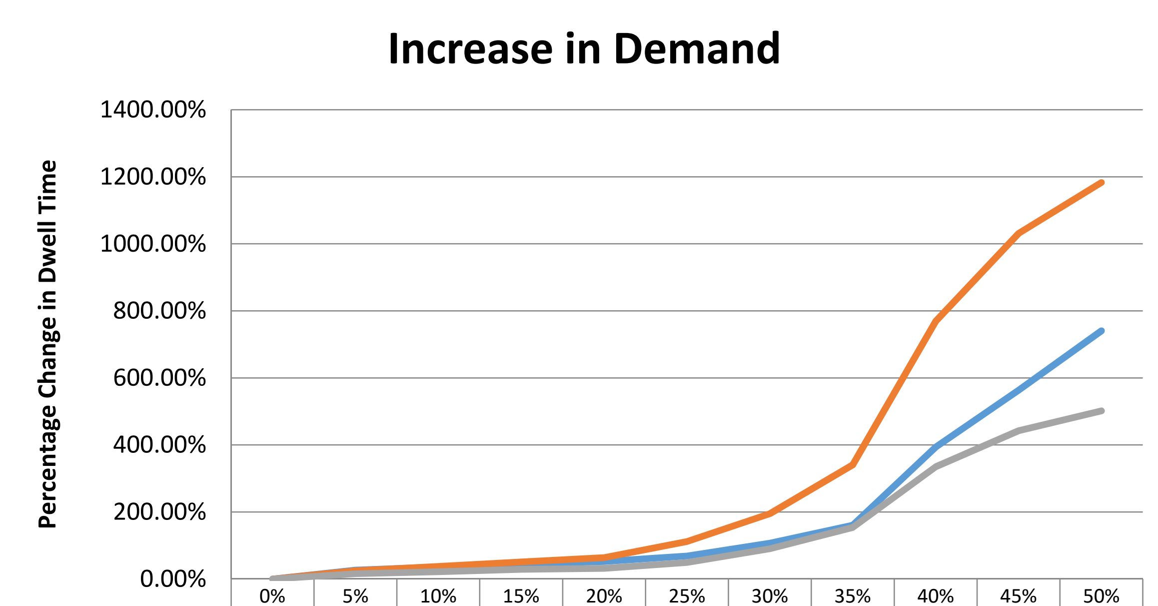
There were several different changes modelled and how they impacted the performance of the system were traced. The changes included an increase in demand by a specific amount - meaning the aggregate number of TEU entering the Port. For the aforementioned study, the distribution of TEU over the week, month or year was assumed to remain the same. Next, simulations of a change in vessel size were performed. Third, we examine the impact of changes to each of the number of cranes, reach stackers and tractor trailers on TEU dwell times in the Port. Lastly we looked at changes to the train schedule by increasing the capacity of trains by either adding more cars per train or an increase in the frequency of trains departing the Port.

The impacts were separated by destination (A, B, and C) and the changes that were simulated varied from 5% to 50%. The performance metric was the change in total time or additional days a container would remain within the Port or an increase in dwell time between TEU unloading and TEU exiting the Port.

3.1 Increases in Demand

The results of an increase in demand of differing amounts is illustrated in Figure 2. In Figure 2 the initial state is a 0% change. The increase in demand is distributed among the destinations in the same proportions as the initial distribution. We can see that up to a 20% increase in demand has almost no effect on the number of days a container dwells in the Port. It appears there is sufficient capacity in the Port to handle such a moderate increase in demand with no or limited degradation in service quality (measured by dwell time). However, once the increase in demand moves beyond 20%, there are significant impacts on dwell time with B destined TEUs affected the most initially and the other two simulated destinations subsequently. Destination A appears to be affected relatively little until demand increases beyond 35%.

As Figure 2 illustrates, at a 25% increase in demand of Destination B suffers a 100% increase in dwell time. At a 30% increase, Destination B gets worse and the other two destinations have a 100% increase in dwell time. After a 35% increase the entire system seems to break down as dwell times increase dramatically with Destination B always the worst followed by Destination A and Destination C suffering the least service quality degradation.



	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
Destination A	0.00%	26.92%	36.15%	45.00%	52.31%	68.85%	107.31%	160.77%	393.85%	563.46%	740.77%
Destination B	0.00%	25.19%	37.33%	50.74%	63.70%	112.22%	195.19%	340.74%	769.63%	1031.11	1182.96
Destination C	0.00%	15.86%	21.90%	28.97%	31.90%	49.31%	90.69%	154.14%	335.17%	442.41%	502.07%

FIGURE 2. PERCENTAGE CHANGE IN DWELL TIMES VS PERCENTAGE CHANGE IN DEMAND

3.2 Increases in Vessel Size

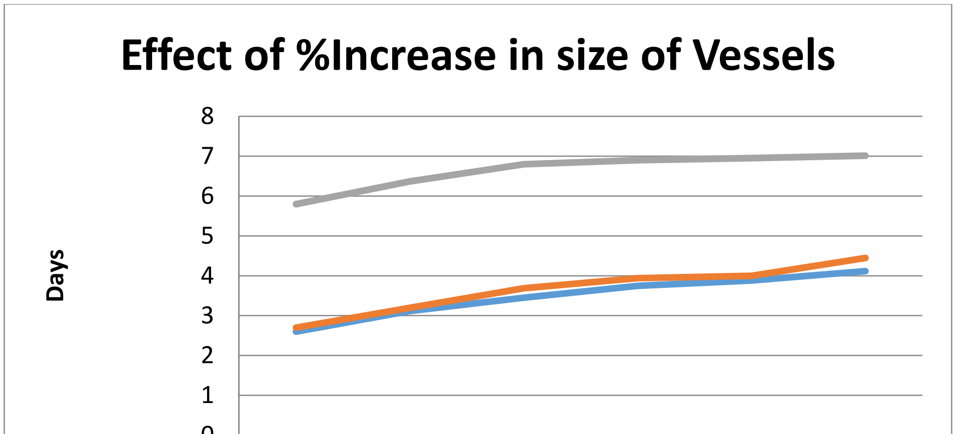
The simulation results in this case were examining the consequences of introducing variability in the vessel size with no change in the total number of TEUs arriving at the Port in a given time period. As an example, suppose presently there are 4 vessels arriving per week and they offload 400 TEU each, so total Port throughput in that week is 1600 TEU. Now consider a doubling in vessel size with the result that there are 2 vessel arrivals per week with each vessel discharging 800 TEU, so still 1600 TEU in total. The only thing that has changed is the variance of arrivals. We expect an increase in vessel sizes should have a negative effect of the performance of the port.

The negative impact of a variation in vessel size results from the increased queue length in the system. Although average resource utilization will be the same, the variation will increase, so some resources will be working full time at some times and less than full time at others.

Consider a situation of 50% utilization. In the case where 4 ships arrived per week with 400 TEU each all labour would be working a half day. However, in the second case with 2 ships per week and 800 TEU each, all labour work for 3 days in a row and do not work for 3 days. The result is the

TEU will wait in long queues since in the first 3 days all resources are fully utilized because of the peak and underutilized in the off-peak.[1] The simulation results show that averages are important but so is variability.

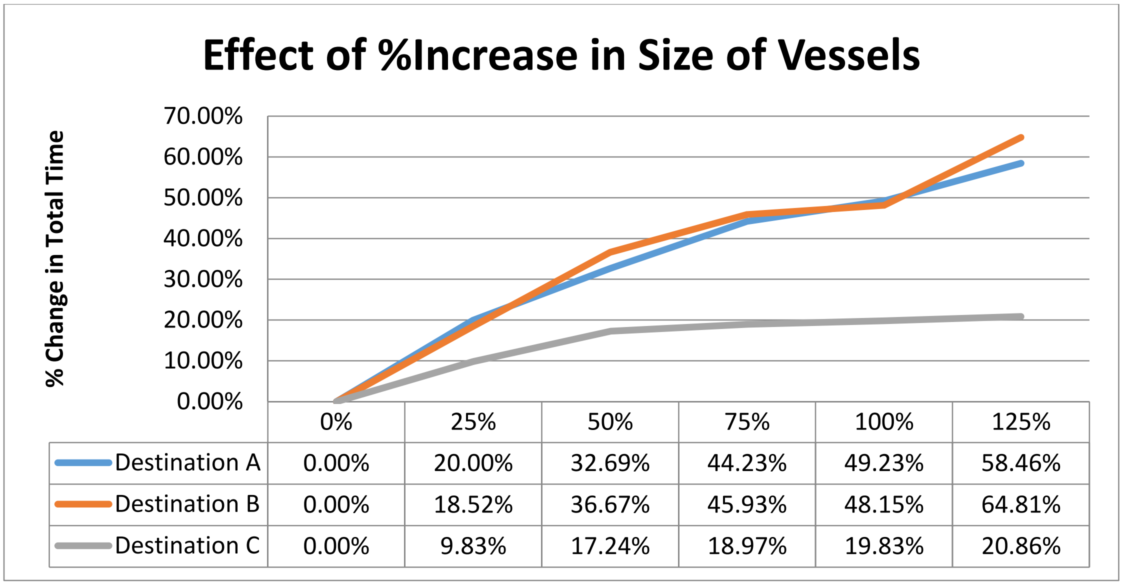
The results of the simulation of increases in the size of vessels are illustrated in Figure 3 and Figure 4; the first figure illustrates changes in days while the second shows percentage changes. We can see that the impact on each destination is somewhat similar; Destination C has a longer dwell time to begin with and the increase in variation does have a disproportionate impact on Destinations A and B. Initially Destinations A and B had low dwell times of 2.5 days while Destination C had a dwell time of near 6 days. Introducing variation with vessel size leads to a similar impact in days but a substantial difference in relative performance. The percentage increase in total dwell time is much higher for Destination A and B than for Destination C.



	0%	25%	50%	75%	100%	125%
Destination A	2.6	3.12	3.45	3.75	3.88	4.12
Destination B	2.7	3.2	3.69	3.94	4	4.45
Destination C	5.8	6.37	6.8	6.9	6.95	7.01

FIGURE 3. CHANGE IN DWELL TIMES VS PERCENTAGE CHANGE IN SIZE OF VESSELS

[1] Note this outcome is the same as we observe on roadways at morning and evening rush hour. A metric of # vehicles/capacity will show on average capacity is sufficient for satisfying demand but when we look at heterogeneity in demand we know in shorter time periods demand will exceed capacity.



	0%	25%	50%	75%	100%	125%
Destination A	0.00%	20.00%	32.69%	44.23%	49.23%	58.46%
Destination B	0.00%	18.52%	36.67%	45.93%	48.15%	64.81%
Destination C	0.00%	9.83%	17.24%	18.97%	19.83%	20.86%

FIGURE 4. PERCENTAGE CHANGE IN DWELL TIMES VS PERCENTAGE CHANGE IN SIZE OF VESSELS

3.3 Increases in the Number of Cranes

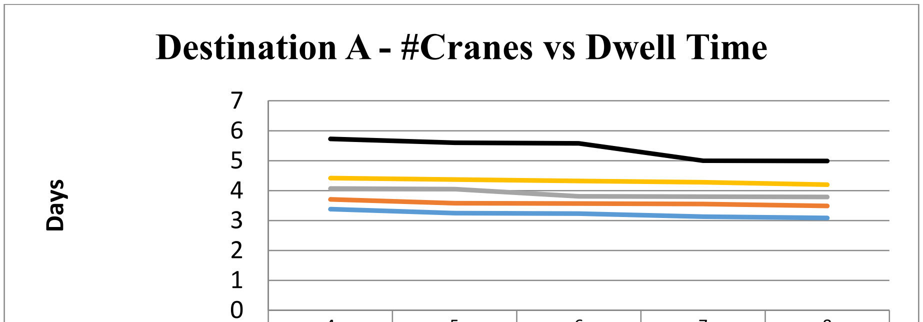
The next simulation examined the impact of an increase in the number of cranes on dwell time for each of the three destinations. The results are illustrated in Figure 5, Figure 6, and Figure 7. In each figure the number of cranes is contained on the horizontal axis and we move from 4 through 8 added cranes in 1 crane additions. The vertical axis is days and the impact of an increase in demand. The simulation scenario was to increase demand by a percentage and also increase the number of cranes in increments of 1 from 4 to a total of 8.

The results reveal some interesting features of the nature of the underlying production structure of offloading TEUs at the Port. First, the impacts differ across destinations, again because Destination C already has a high dwell time relative to the two other destinations. Yet, as demand increases by 5% dwell time goes down from 6.7 to 6.4 days with a doubling of cranes. The same result occurs with 10% through 25% increase in demand; dwell time goes down marginally. However, the dwell time shifts up in marginally larger increments until the 25% increase in demand leads to somewhat larger vertical increment in dwell days for each crane investment level.

Looking at Destination A, we see with 4 cranes, an increase in demand from 5% through 25% leads to an increase in dwell time from 3.4 days to 5.7 days. The pattern is the same until we hit 6 cranes at which point an investment in a 7^{th} crane reduces dwell time for the 25% increase in demand but not for smaller increases in demand.

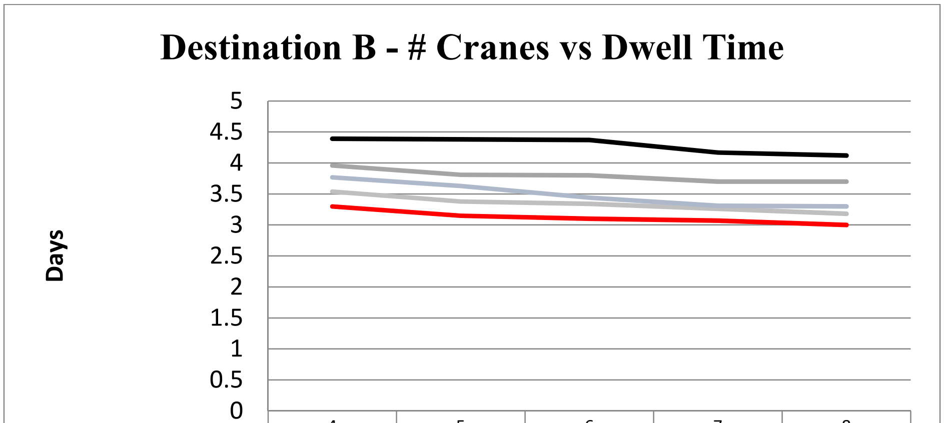
We saw earlier that increases in demand alone resulted in substantial increases in dwell times for each destination. Here we see that investments in crane capacity with increases in demand can result in keeping dwell time near constant provided sufficient crane capacity is available. For example, with Destination C, a shift from 5% to 25% increase in demand increases dwell time, holding cranes constant at 4, from 6.7 days to 8.6 days. With 25% more demand and adding more cranes from 4 to 8, results in dwell days falling from 8.6 to 8.5, a very small change. However, with Destination A, a shift in demand from 5% to 25% with 4 cranes moves dwell time from 3.4 days to 5.7 days, and maintaining a 25% increase in demand and increasing cranes from 4 to 8 reduces dwell days by 0.1 (from 8.6 to 8.5), again a small change with such an investment in cranes. Finally looking at Destination B we observe the same pattern.

To sum-up, investing in more crane capacity as demand increases allows the Port to maintain its service level but not improve it.



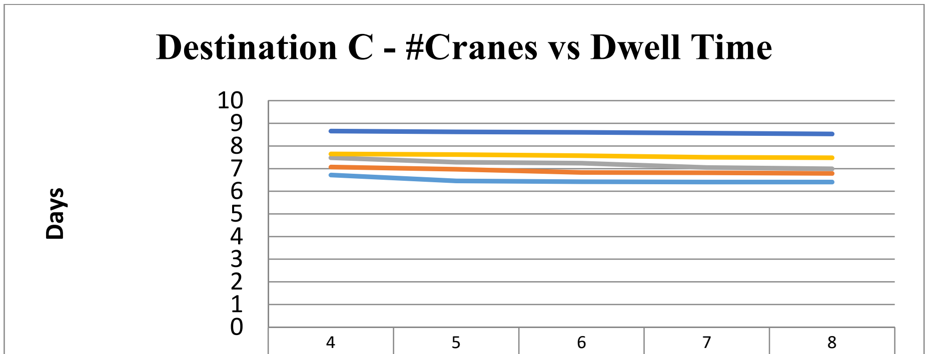
	4	5	6	7	8
5% More Demand	3.38	3.25	3.23	3.13	3.09
10% More Demand	3.708	3.58	3.57	3.55	3.49
15% More Demand	4.07	4.05	3.81	3.8	3.79
20% More Demand	4.42	4.37	4.32	4.28	4.2
25% More Demand	5.73	5.6	5.58	5	4.99

FIGURE 5. CHANGE IN DWELL TIMES IN DESTINATION A VS CHANGE IN NUMBER OF CRANES



	4	5	6	7	8
5% More Demand	3.3	3.15	3.1	3.07	3
10% More Demand	3.54	3.38	3.34	3.26	3.18
15% More Demand	3.77	3.63	3.44	3.31	3.3
20% More Demand	3.96	3.81	3.8	3.7	3.7
25% More Demand	4.39	4.38	4.37	4.17	4.12

FIGURE 6. CHANGE IN DWELL TIMES IN DESTINATION B VS CHANGE IN NUMBER OF CRANES



	4	5	6	7	8
5% More Demand	6.72	6.46	6.42	6.41	6.41
10% More Demand	7.07	6.97	6.83	6.82	6.79
15% More Demand	7.48	7.28	7.24	7.05	6.99
20% More Demand	7.65	7.62	7.57	7.5	7.48
25% More Demand	8.66	8.62	8.6	8.57	8.53

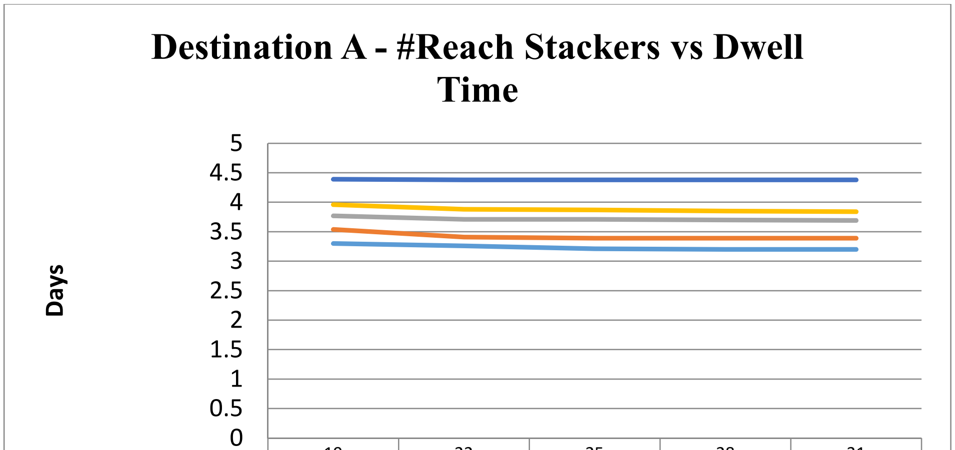
FIGURE 7. CHANGE IN DWELL TIMES IN DESTINATION C VS CHANGE IN NUMBER OF CRANES

3.4 Increases in Reach Stackers

We simulated the change in dwell days with changes in the number of reach stackers from 19 through 31 in increments of 3 with different levels of demand increases ranging from 5% through 25%. The results of the simulations are reported in Figure 8 through Figure 10. The results for each destination are quite similar to the results we obtained for the simulation for increases in the number of cranes.

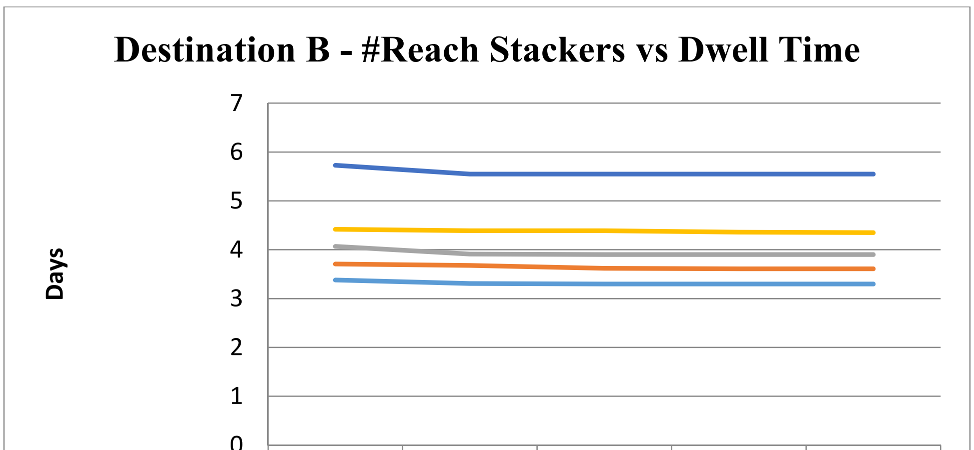
Adding more reach stackers as demand is increasing allows the Port to control the increase in dwell time as demand increases. As an example, for Other destinations with a 5% increase in demand dwell time is 6.7 days, and if we invest in 3 more reach stackers dwell time falls marginally to 6.6 days, 3 more reach stackers and dwell time falls to 6.5 days. A very small return from investments in reach stackers.

If demand increases by 25%, dwell time increases from 6.7 to 8.5 days and continual investment in reach stackers reduces dwell time from 8.6 to 8.5 days even with 12 more reach stackers. If we examine the results for Destination A and for Destination B we see the same result that holding reach stackers constant with demand increasing will increase dwell time and that 5 – 10% increases in demand have a small impact on dwell time. However, larger demand increases have a substantial impact and investing in reach stackers is not a solution to preserve service quality as measured by dwell time. This result holds across each destination. For Destination A which has low dwell time the outcomes are not substantively different than it is for Destination C which has a relatively high dwell time.



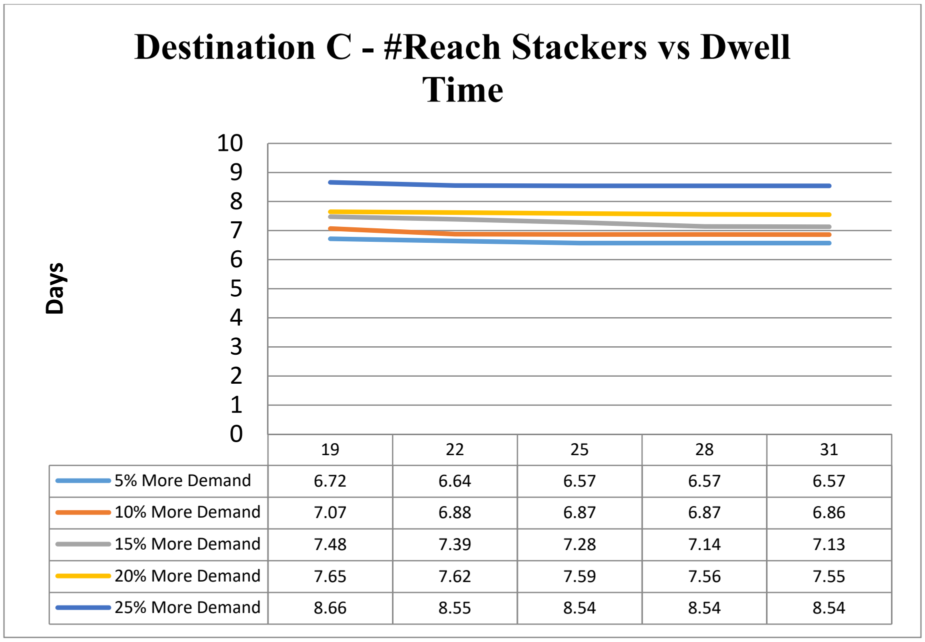
	19	22	25	28	31
5% More Demand	3.3	3.26	3.21	3.2	3.2
10% More Demand	3.54	3.41	3.39	3.39	3.39
15% More Demand	3.77	3.71	3.71	3.7	3.69
20% More Demand	3.96	3.88	3.87	3.85	3.84
25% More Demand	4.39	4.38	4.38	4.38	4.38

FIGURE 8. CHANGE IN DWELL TIMES IN DESTINATION A VS CHANGE IN NUMBER OF REACH-STACKERS



	19	22	25	28	31
5% More Demand	3.38	3.31	3.3	3.3	3.3
10% More Demand	3.708	3.68	3.62	3.61	3.61
15% More Demand	4.07	3.91	3.9	3.9	3.9
20% More Demand	4.42	4.39	4.39	4.36	4.35
25% More Demand	5.73	5.55	5.55	5.55	5.55

FIGURE 9. CHANGE IN DWELL TIMES IN DESTINATION B VS CHANGE IN NUMBER OF REACH-STACKERS



	19	22	25	28	31
5% More Demand	6.72	6.64	6.57	6.57	6.57
10% More Demand	7.07	6.88	6.87	6.87	6.86
15% More Demand	7.48	7.39	7.28	7.14	7.13
20% More Demand	7.65	7.62	7.59	7.56	7.55
25% More Demand	8.66	8.55	8.54	8.54	8.54

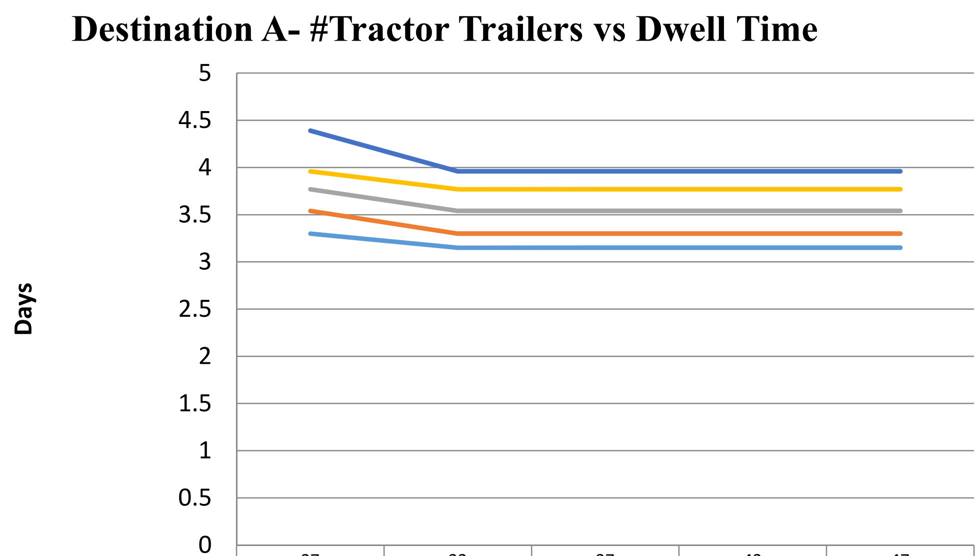
FIGURE 10. CHANGE IN DWELL TIMES IN DESTINATION C VS CHANGE IN NUMBER OF REACH-STACKERS

3.5 Increases in Tractor Trailers

The number of tractor trailers (TTs) used in the Port was simulated for increases from 27 to 47 TTs with investments in increments of 5. The results are contained in Figure 11 through Figure 13.

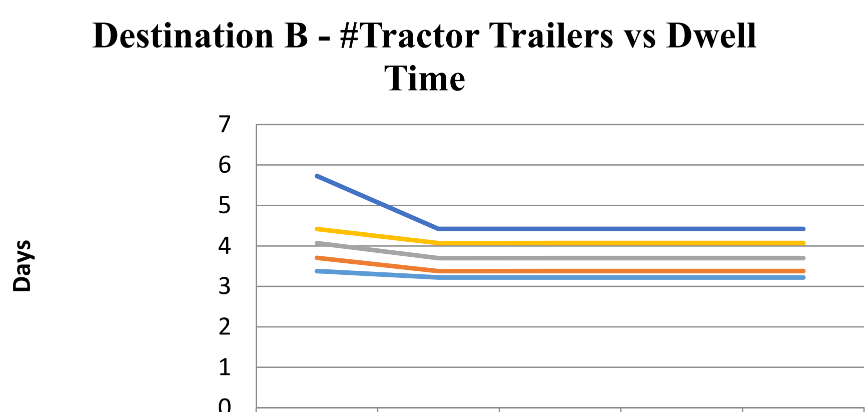
Investing in TTs to reduce dwell time for a small increase in demand yields a small return. For example, at a 5% demand growth moving from 27 to 47 TTs reduces dwell time at Other destinations by .3 or 4%. With a demand growth of 10% this return is 5% and at 20% demand growth this return is only 2%. As the rate of demand growth increases investing in TTs to sustain service levels yields small returns. Although the initial investment from 27 to 32 TTs does have a relatively high return subsequent investments yield relatively little in terms of maintaining or reducing dwell times..

As demand growth increases from 5% through to 25% dwell times increase considerably; holding TTs at 27, for example, dwell time increases from 6.7 to 8.6 for Other destinations, and 3.3 to 4.9 at Destination A and 3.4 to 5.7 at Destination B. An investment from 27 to 32 TTs for demand increases from 5% to 25% sees a growth in dwell time of 14% and without the investment in TTs the dwell time would have increased by 28%. After this the investment in TTs yields a smaller and constant return as we move from 32 to 47 TTs.



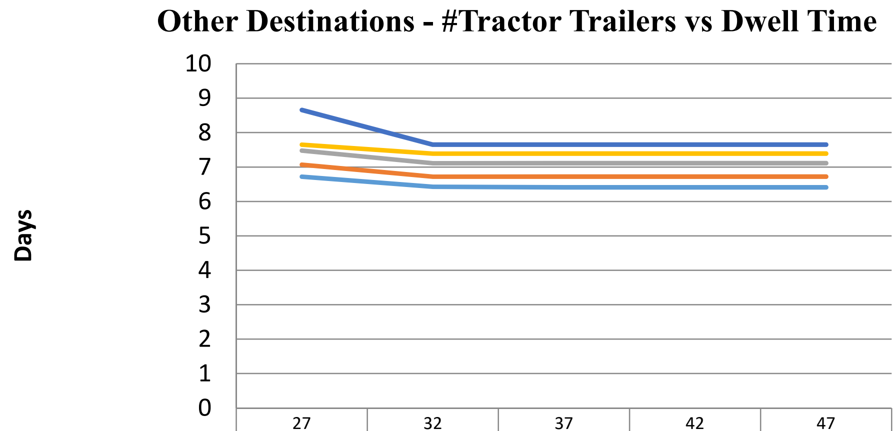
	27	32	37	42	47
5% More Demand	3.3	3.15	3.15	3.15	3.15
10% More Demand	3.54	3.3	3.3	3.3	3.3
15% More Demand	3.77	3.54	3.54	3.54	3.54
20% More Demand	3.96	3.77	3.77	3.77	3.77
25% More Demand	4.39	3.96	3.96	3.96	3.96

FIGURE 11. CHANGE IN DWELL TIMES IN DESTINATION A VS CHANGE IN NUMBER OF TRACTOR TRAILERS



	27	32	37	42	47
5% More Demand	3.38	3.22	3.22	3.22	3.22
10% More Demand	3.708	3.38	3.38	3.38	3.38
15% More Demand	4.07	3.7	3.7	3.7	3.7
20% More Demand	4.42	4.07	4.07	4.07	4.07
25% More Demand	5.73	4.42	4.42	4.42	4.42

FIGURE 12. CHANGE IN DWELL TIMES IN DESTINATION B VS CHANGE IN NUMBER OF TRACTOR TRAILERS



	27	32	37	42	47
5% More Demand	6.72	6.43	6.41	6.41	6.41
10% More Demand	7.07	6.72	6.72	6.72	6.72
15% More Demand	7.48	7.11	7.11	7.11	7.11
20% More Demand	7.65	7.39	7.39	7.39	7.39
25% More Demand	8.66	7.65	7.65	7.65	7.65

FIGURE 13. CHANGE IN DWELL TIMES IN DESTINATION B VS CHANGE IN NUMBER OF TRACTOR TRAILERS

3.6 Increases in Train Schedules

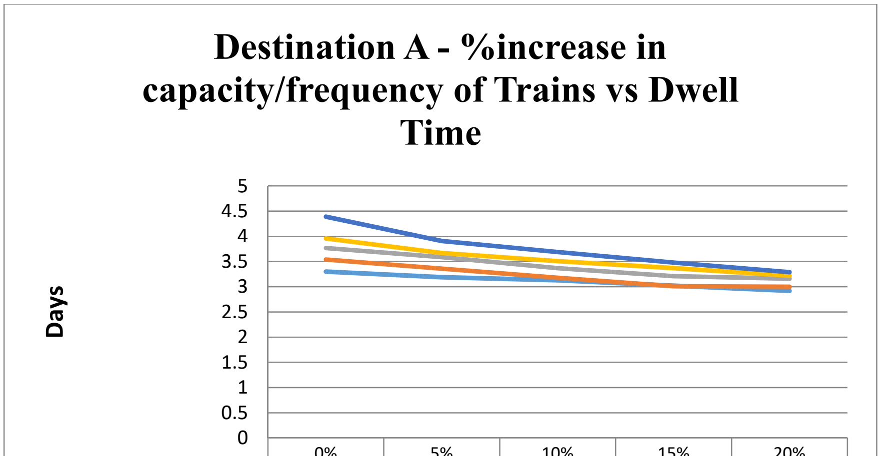
The final sets of simulations reported are for an increase in capacity/frequency of trains for the set of increases in demand from 5% through 25%. We simulated train capacity increases of 5 through 20%. There was no distinction made between increasing the number of trains or increasing the capacity of existing trains. The results are reported in Figure 14 through Figure 16.

Unlike the previous investments in cranes, reach stackers and TTs, investing in additional train capacity does have a significant impact on dwell time. Also, as we have seen throughout this set of simulations if your destination dwell time is already high, increases in demand have a relatively smaller impact on making you worse off but if your dwell times are short, increases in demand have a larger impact on degrading service quality.

First, with Destination A, a growth in demand to 25% increases dwell time from 3.3 days to 4.39 days, or 33%. If demand grows at 5% and train capacity grows at 5%, dwell time decreases by 3%, if capacity grows through to 20%, dwell time is reduced to 2.97 days a 11% reduction. If demand grows to 25% and train capacity grows to 20%, dwell time moves from 3.3 to 3.29 days, effectively no impact; a 20% train capacity growth offsets 25% demand growth.

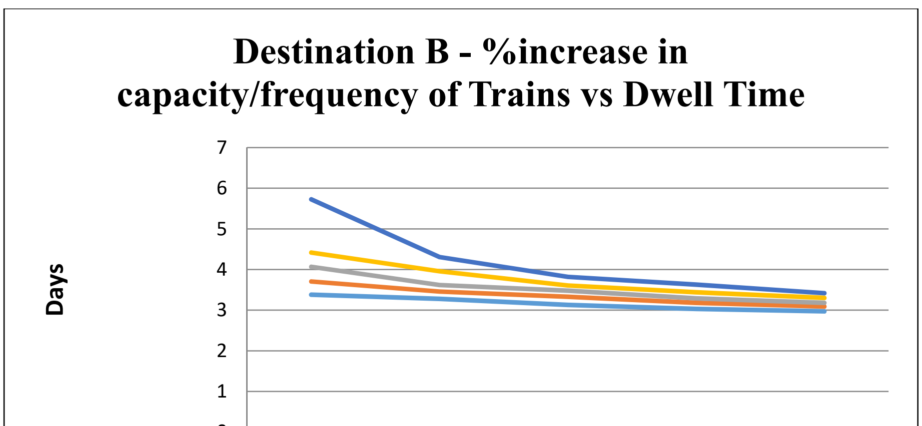
Looking at Destination B which has the second best dwell times, holding train capacity constant and allowing demand to grow from 5% through to 25% results in dwell times increasing from 3.38 to 5.73 days, a sizable 70% increase. However, if train capacity increases by 20% even with a 25% increase in demand dwell time increases only from 3.38 days to 3.42 days, a mere 1%.

Finally, inspecting the impact of additional train capacity on destination C we see a growth in demand with no additional investment in train capacity increases dwell times from 6.7 days to 8.6 days, a 28% increase. If we invest in train capacity as demand grows through to 25% we see that adding 20% more train capacity even with a 25% increase in demand leaves dwell times effectively unchanged; from 6.72 to 6.69.



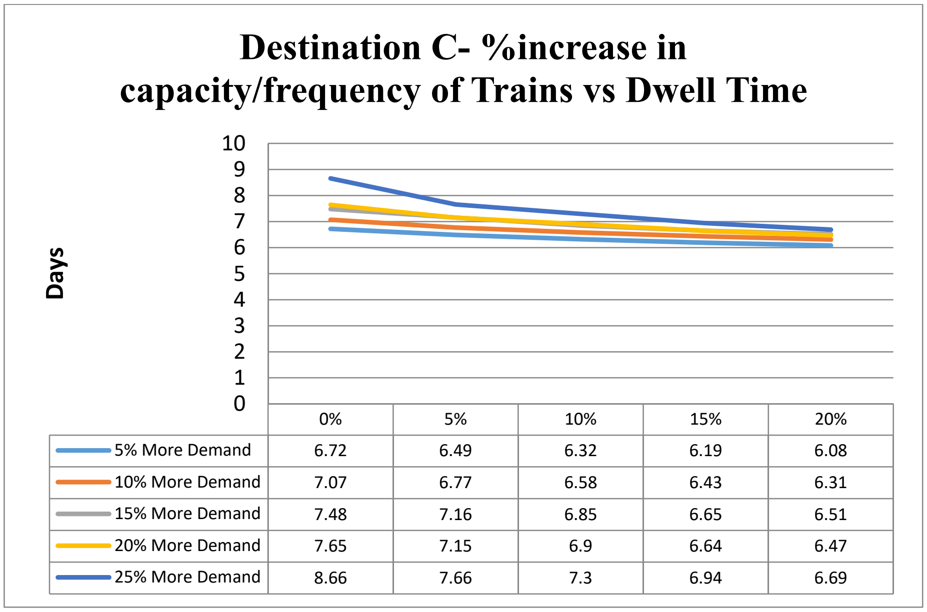
	0%	5%	10%	15%	20%
5% More Demand	3.3	3.19	3.13	3.02	2.92
10% More Demand	3.54	3.36	3.18	3.01	3
15% More Demand	3.77	3.59	3.37	3.21	3.16
20% More Demand	3.96	3.67	3.51	3.37	3.22
25% More Demand	4.39	3.91	3.69	3.48	3.29

FIGURE 14. CHANGE IN DWELL TIMES IN DESTINATION A VS PERCENTAGE CHANGE IN FREQUENCY OF TRAINS



	0%	5%	10%	15%	20%
5% More Demand	3.38	3.28	3.13	3.03	2.97
10% More Demand	3.708	3.46	3.33	3.18	3.09
15% More Demand	4.07	3.62	3.48	3.29	3.18
20% More Demand	4.42	3.96	3.61	3.44	3.3
25% More Demand	5.73	4.31	3.82	3.63	3.42

FIGURE 15. CHANGE IN DWELL TIMES IN DESTINATION B VS PERCENTAGE CHANGE IN FREQUENCY OF TRAINS



	0%	5%	10%	15%	20%
5% More Demand	6.72	6.49	6.32	6.19	6.08
10% More Demand	7.07	6.77	6.58	6.43	6.31
15% More Demand	7.48	7.16	6.85	6.65	6.51
20% More Demand	7.65	7.15	6.9	6.64	6.47
25% More Demand	8.66	7.66	7.3	6.94	6.69

FIGURE 16. CHANGE IN DWELL TIMES IN DESTINATION C VS PERCENTAGE CHANGE IN FREQUENCY OF TRAINS

IV. SUMMARY AND DISCUSSIONS

In this paper we used detailed operational level data and simulated a multi-mode – marine-port rail - transportation network in North America. Using detail data, we were able to calibrate our simulation model and we were able to test different scenarios. We shared our statistics about the port's operational details and believe other practitioners and scholars can benefit from these statistics when they study other ports.

Perhaps, one the most important findings of the paper concerns the effect of a gradual increase in vessel sizes on the port performance. To our knowledge this work was the first to test the effect of increase in vessel sizes on opeartions of a Canadian port on the westcoast. The results show that even when the total throughput – i.e. total number of containers that are imported annually remains the same, an increase in vessel size will have dramatic negative effects on port efficiency and performance; such increases in vessel sizes will be an externality on the ports. Our general findings about the effect of increase of vessel sizes were in line with other theoretical and empirical studies cited in the introduction section of this paper. Perhaps, what distinguishes this paper from other studies, is the numerical details of our predicted results.

Additionally, we performed sensitivity analysis and tested the effect of increasing operational resources of the port under study on the efficiency of the port. Specifically, we considered the effect of increasing number of Cranes, Reach-Stackers and Tractor Trailers on total dwell times. To our surprise, we did not find any substantial change in operational statistics of the port due to improvements in such resources. Under the scenario of a 25% increase in demand, among the three resources mentioned, it seemed like only increasing the number of tractor trailers can help with the performance of the port.

Lastly, we simulated the effect of increasing the frequency of trains scheduled on total dwell times. The addition of rail capacity to move TEUs out of the Port had a significant impact on maintaining service levels. An investment in capacity holding demand constant returned a small reduction in dwell time, this decreased as the demand growth increased. As demand increased and train capacity grew there was relatively little impact on dwell time, so the additional capacity was able to handle the additional demand growth, unlike the situation with investments in cranes, reach stackers and tractor trailers. It seems clear that investments in reducing variability and increased train capacity pay high dividends for the Port.

This research has not explored different permutations and combinations of investments in port resources. This could certainly be done in future studies to understand whether there is a trade off in adding both more cranes and reach stackers and how this trade off will change with investment levels.

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