DISCRETE-EVENT SIMULATION OF A COMPLEX INTERMODAL CONTAINER TERMINAL

A Case-Study of Standard Unloading/Loading Processes of Vessel Ships

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Abstract: This paper analyzes the performance of a complex maritime intermodal container terminal. The aim is to propose changes in the system resources or in handling procedures that guarantee better performance in perturbed conditions. A discrete-event system simulation study shows that, in future conditions of increased traffic volumes and reduced available stacking space, more internal transport vehicles, or appropriate scheduling and routing policies, or an increased degree of automation would improve the performance.

1 INTRODUCTION

In an intermodal container terminal (CT) freight is organized, stacked, handled and transported in standard units of a typical container, which is called TEU (Twenty Equivalent Unit) and which fits to ships, trains and trucks that are built and work for it.

A maritime CT is usually managed to offer three main services: a railway/road ‘export cycle’, when TEUs arrive by trains/trucks and depart on vessel ships; a railway/road ‘import cycle’, when TEUs arrive on vessel ships and depart by trains/trucks; a ‘transshipment cycle’, when TEUs arrive on vessel (feeder) ships and depart on feeder (vessel) ships. The hub in Taranto is managed by a private company (Taranto Container Terminal or TCT), whose primary business is for transhipment, because of the low quality of railway and road networks connecting the hub to Italy and the rest of Europe.

The terminal receives ships to a quay and uses yard blocks to stack full or empty TEUs. Imported TEUs are unloaded, exported TEUs are loaded, while in transshipped TEUs both processes occur. Full TEUs may be imported, exported or transshipped. Empty TEUs are unloaded from feeder ships or arrive on trains or trucks; then they are loaded on vessel ships. So, they are transhipped or exported.

The typical activities executed by humans and resources in a transshipment cycle are the following:

- Unloading TEUs from ship by quay cranes;
- Picking-up and transferring TEUs to a yard block by trailers;
- Picking-up and stacking TEUs in a yard block by yard cranes;
- Redistributing TEUs in yard blocks by yard cranes and trailers;
- Picking-up and transferring TEUs to ship by yard cranes and trailers;
- Loading on ship by quay cranes.

Managing these activities requires an optimized use of equipment and human operators. Human supervision is often required to control processes concurring and competing for the limited number of available resources. Moreover, efficiency is needed for services in reduced time without excessive costs: both the TCT needs to profitably use resources, and ship companies aim at saving the berthing time/cost.

TCT is expecting a growth in freight volumes and has recently expanded the yard. But no investment was made on local land infrastructures. Not much research was carried out on use of information and communication technologies or new control policies to improve efficiency, to the best of the author knowledge. Improvements can be achieved for TCT, which is very sensitive to disturbances and parameter variations (sudden or big increase of traffic volumes, reduction or reorganization of yard, changes in berthing spaces, different routing of trailers, faults and malfunctions).

Then, an intelligent control may guarantee robustness and a quick reaction to parameter variations. The aim here is to prove that current organization and control of the main unloading and loading processes could be not efficient in future operating conditions. Changing management of operations is necessary to guarantee good performance in perturbed conditions.

2 LITERATURE OVERVIEW

Managing a maritime CT is a complex task. Several analytical models have been proposed as tool for the simulation of terminals useful to an optimal design and layout, organization, management and control.

Modelling CTs requires the simulation of many operations that need coordination to minimize time and costs. Determining the best management and control policies is also important (Mastrolilli *et al.*, 1998). The main problems are: berth allocation; loading and unloading of ships (crane assignment, stowage planning); transfer of TEUs from ships to yard and back; stacking operations; transfer to/from other transport modes; workforce scheduling.

A thorough literature review on modelling approaches is given in (Steenken *et al.*, 2004). Two main classes of modelling approaches can be highlighted: microscopic and macroscopic methods (Cantarella *et al.*, 2006). Microscopic models are generally based on discrete-event system simulation that may include Petri Nets (Fischer and Kemper, 2000, Liu and Ioannou, 2002), object-oriented (Bielli *et al.*, 2006) and queuing networks theory approaches (Legato and Mazza, 2001). Even if high computational effort may be required, microscopic simulation explicitly models all activities as well as the whole system by considering the single TEUs as entities. Then, it estimates performance as consequence of different designs and/or management scenarios.

Macroscopic modelling (de Luca *et al.*, 2005) is suitable for supporting strategic decisions, system design and layout, investments on handling equipment. A network-based approach is presented in (Kozan, 2000) for optimising efficiency by using a linear programming method.

3 DEVS MODELLING

A Discrete EVent System (DEVS) specification technique (Zeigler *et al.,* 2000) completely and unambiguously represents and controls the terminal processes.

Atomic dynamic DEVSs model both TEUs flowing in the system and resources (cranes, trailers, trucks) used to handle them. DEVSs interact by transmitting outputs and receiving inputs, which are all instantaneous events. Timed processes are defined by a start-event and a stop-event.

For each DEVS, internal events are triggered by internal mechanisms, external input events are determined by other DEVSs, and external output events are generated and directed to other entities.

A DEVS state is changed by an input or when the time specified before an internal event elapses. In the first case, an external transition function determines the state next to the received input; in the second case, an internal transition function gives the state next to the internal event. The total state is $\mathbf{q} = (\mathbf{s}, e)$, where $\mathbf{s}$ is the sequential state and e is the time elapsed since the last transition.

To summarize, each DEVS is represented as:

$$\boldsymbol{DEVS} = < \mathbf{X}, \mathbf{Y}, \mathbf{S}, \delta_{int}, \delta_{ext}, \lambda, ta > \quad (1)$$

where $\mathbf{X}$ is the set of inputs, $\mathbf{Y}$ is the set of outputs, $\mathbf{S}$ is the set of sequential states, δ_{int}:$\mathbf{S}\rightarrow\mathbf{S}$ is the internal transition function, δ_{ext}:$\mathbf{Q}\times\mathbf{X}\rightarrow\mathbf{S}$ is the external transition function, $\mathbf{Q}=\{\mathbf{q}=(\mathbf{s},e)|\mathbf{s}\in \mathbf{S},0\leq e\leq ta(\mathbf{s})\}$, λ:$\mathbf{S}\rightarrow\mathbf{Y}$ is the output function, ta:$\mathbf{S}\rightarrow\mathfrak{R}_0^+$ is the time advance function, with $\mathfrak{R}_0^+$ set of positive real numbers with 0 included.

The network of DEVS atomic models is used as a platform for simulating the TCT dynamics. Details are omitted here for sake of space.

4 SIMULATION ANALYSIS

A simulation study is presented to analyse the contemporaneous processes of unloading and loading TEUs from and to a vessel ship.

The simulation model is based on the real TCT equipment and operation times, which were statistically observed during steady-state conditions.

The model was developed in a discrete-event environment by using Arena® (Kelton *et al.*, 1998).

4.1 Experimental Setup

The data used to set up the simulation experiments refer to the observations recorded during year 2004, when TCT achieved the maximum productivity (Table 1). About 14% of TEUs flew through railway/road transport modes. The numbers of full/empty TEUs are divided as in Table 2.

Table 1: Loaded/unloaded TEUs in TCT (2004).

Loaded TEUs		Unloaded TEUs	
Full	273224	Full	285488
Empty	108172	Empty	96434
Total TL	381396	Total TD	381922
Total T = TL+TD = 763318			
TEUs on railway 44486 ≅ 5.8% of T			
TEUs on road 64648 ≅ 8.5% of T			

Table 2: Flows of containers in TCT (2004).

Containers (Cycle)	No.
Full, from vessel to feeder	x
Full, from feeder to vessel	y
Full, from vessel to train/truck	t
Full, from train/truck to vessel	z
Empty, from feeder to blocks	r
Empty, from train/truck to blocks	h
Empty, from blocks to vessel	q

Then, we may establish the following relations:

$$x + y + z = 273224 \tag{2}$$

$$q = 108172 \tag{3}$$

$$x + y + t = 285488 \tag{4}$$

$$r = 96434 \tag{5}$$

$$t + z + h = 113134 \tag{6}$$

$$r + h = q \tag{7}$$

where (7) is due to the assumption that no empty TEU is accumulated and left in the yard blocks.

Then, it is easy to find: $x+y = 228658$, $t = 56830$, $z = 44566$, $r = 96434$, $h = 11738$, $q = 108172$. The TEUs separately handled by vessel and feeder ships were estimated in the ranges in Table 3, because x and y were assumed between 0 and 228658. Then, the average number of TEUs handled by vessel (*avs*) or feeder ships (*afs*) was determined by assuming traffic volumes of 346 vessel and 570 feeder ships in year 2004. These assumptions were based on the traffic data available for year 2003 and on the 15.9% increase in traffic (then in number of ships) in 2004.

Table 3: Containers handled by ships.

Vessels	TEUs	Est. Range	*avs*
Unload.	$x+t$	[56830,285488]	[164,825]
Loaded	$y+z+q$	[152738,381396]	[441,1102]
Total	$x+t+y+z+q$	438226	1266
Feeders	TEUs	Est. Range	*afs*
Unload.	$y+r$	[96434,325092]	[169,570]
Loaded	x	[0,228658]	[0,401]
Total	$y+r+x$	325092	570

If $x = y = 114329$, then the flows indicated by Tables 4 and 5 are obtained, which were used to set-up the simulation tests. Flows of TEUs from vessel ships to land are in a ratio 8 to 6 between road and railway modes, as observed in 2004. Unloaded and loaded TEUs are 39% and 61% of the total for vessel ships, 65% and 35% for feeder ships.

Table 4: Containers unloaded (U) and loaded (L) by vessel ships (F = feeder ships, TA = trains, TU = trucks, E = blocks for empty TEUs).

U	No. (%)	L	No. (%)
To F	114329 (66.80)	From F	114329 (42.81)
To TA	24356 (14.23)	From E	108172 (40.50)
To TU	32474 (18.97)	From TA	19100 (7.15)
Total	171159 (100)	From TU	25466 (9.54)
		Total	267067 (100)

Table 5: Containers unloaded (U) and loaded (L) by feeder ships (V = vessel ships, E = blocks for empty TEUs).

U	No. (%)	L	No.
To V	114329 (54.24)	From V	114329
To E	96434 (45.76)	Total	114329
Total	210763 (100)		

4.2 Simulation Assumptions

Simulation is based on the following assumptions:

- Only 1 vessel ship is berthed, full TEUs are unloaded, full and empty TEUs are loaded; 1300 TEUs are handled; 508 (39%) are unloaded, 792 (61%) are loaded, according to the percentage partitions shown in Table 4;
- The average values of handled TEUs in Table 3 is used, because information about daily movement or ship size was not available;
- Simulation is limited by the time necessary to end the unloading and loading processes;
- Transfers from/to the railway connection or the truck gate, are not considered;
- Operations length and distances travelled are measured in minutes and meters, respectively.

The model considers four quay cranes: QC1 and QC2 are for unloading, QC3 and QC4 for loading. Then, unloaded TEUs are stowed in ship sections different from those reserved for loaded TEUs, so that the processes are parallel. Sometimes cranes sequentially unload and load TEUs, depending on the stowage plan and on the destinations of TEUs.

A quay crane unloads/loads two TEUs on/from a trailer in eight steps (Table 6): S1) picking the first TEU from ship/trailer; S2) moving the crane with first TEU towards the trailer/ship; S3) releasing the first TEU on the trailer/ship; S4) moving the crane back to the ship/trailer; S5) picking the second TEU from ship/trailer; S6) moving the crane with second

TEU to the trailer/ship; S7) releasing the second TEU; S8) moving the crane back to the ship/trailer.

Table 6: Operation cycle of quay cranes.

Step	Duration
S1	Tria(0.4375,0.5,0.75)
S2	0.333
S3	Tria(0.4375,0.5,0.75)
S4	0.667
S5	Tria(0.4375,0.5,0.75)
S6	0.333
S7	Tria(0.4375,0.5,0.75)
S8	0.667

The triangular distribution is used because only the estimates of the minimum, most likely and maximum values (shown in this order) of the processing times are known. Simple translational return steps last longer (twice) than transfer steps because the crane is more unstable without TEUs.

Five trailers serve each quay crane. Each set of five trailers is indicated with a unique symbol: TR1, TR2, TR3, TR4 are associated to QC1, QC2, QC3, QC4, respectively. Each trailer always transports two TEUs, with a speed of 300 m/minutes (400 m/minutes when travelling unloaded). The closest trailer is selected for a task between ship and yard.

Before being loaded, exported and transshipped TEUs are stacked in blocks close to the quay area, while imported TEUs are stacked in blocks close to the land connections. Only one yard crane works on each block for unloaded TEUs from ships: YC1 serves transhipped TEUs; YC2/YC3 serves exported TEUs. Two yard cranes (YC4 and YC5 or YC6 and YC7) work for each block for TEUs to be loaded: YC4 serves empty TEUs, YC5 serves full TEUs; YC6 and YC7 serve full TEUs. YC7 has priority with respect to YC6 because it is closer to the quay. TEUs picked by YC4 and YC5 are loaded by QC3, those picked by YC6 and YC7 are loaded by QC4.

A yard crane unloads/loads two TEUs in/from a yard block from/to a trailer in eight steps (Table 7).

Table 7: Operation cycle of yard cranes.

Step	Duration
S1	Tria(0.125,0.375,0.625)
S2	0.25
S3	Tria(0.125,0.375,0.625)
S4	0.5
S5	Tria(0.125,0.375,0.625)
S6	0.25
S7	Tria(0.125,0.375,0.625)
S8	0.5

A typical and important performance index is the *Ship Turn-around Time* (STT), the average time spent by a berthed ship to unload and load TEUs. STT is measured between ship arrival and departure. Minimizing STT is the main objective of every terminal management. An empiric relation to calculate the minimum STT value is:

$$\mathrm{STT}_{\min} = nc \,/\, (ct \times nqc) \tag{8}$$

where *nc* is the number of unloaded/loaded TEUs, *ct* is the *cycle time* (the number of moves/hour of a quay crane), and *nqc* is the number of quay cranes.

Equation (8) gives a reference for the terminal productivity. Namely, it does not consider the dependence of *ct* on *nqc*, due to the interaction between *nqc* and the handling capacity in the limited quay space, and the effects of internal transfers. Figure 1 gives the STT when $nc = 3400$ and $ct = 42$ hours^{-1}. Equation (8) can also be used to estimate the necessary *nqc* to achieve a desired STT.

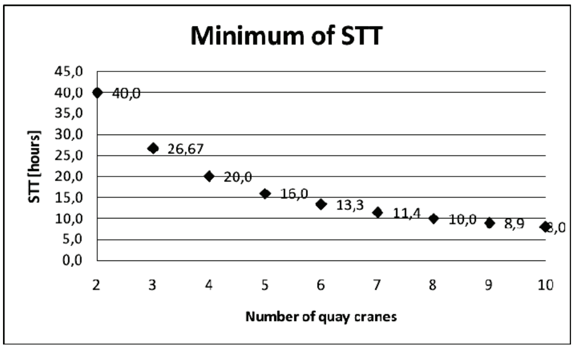

Figure 1: STT as function of *nqc*.

Assuming the most likely value $ct = 30$ hours^{-1}, if $nc_u = 508$ and $nc_l = 792$ are the unloaded and loaded TEUs, and if $nqc_u = nqc_l = 2$ are the cranes used for the two processes, then a reference limit for STT is:

$$\begin{aligned} \mathrm{STT}_{\min} &= \max\{\, nc_u/(ct \times nqc_u);\ nc_l/(ct \times nqc_l)\} \\ &= \max\{8.5;\ 13.2\} = 13.2 \text{ hours.} \end{aligned} \tag{9}$$

Finally, note that performance is affected by the partial automation of processes, the humans' cooperation, the non-optimal ship distribution of TEUs and weather conditions.

4.3 Simulation Results

Ten simulation runs were executed, using different seeds for generating random variables, in order to obtain sufficient results for a statistical evaluation. Each run was terminated after 1300 unloaded and loaded TEUs. The system state was initialized at the beginning of each run, to start from the same condition. Statistics were also initialized to have results independent on the data obtained from precedent runs. Initializations guarantee statistically independent and identically distributed replications of the terminating simulation.

STT was measured at the end of each run (Figure 2). The minimum, maximum, and average values were 891, 902, and 898, i.e. about 15 hours.

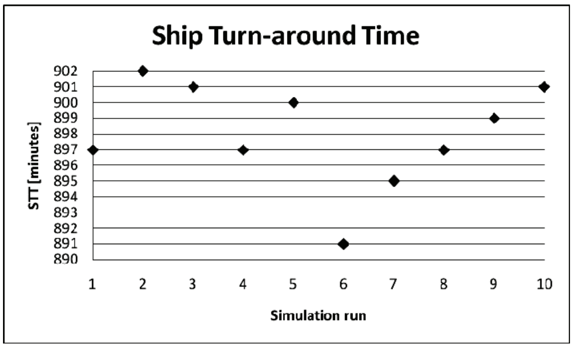

Figure 2: Measured STT in 10 simulation runs.

These results validate the model because:

- They are below the real TCT performance, because only 1 ship/day is served in standard real operating conditions;
- The measured values of STT are greater than the lower theoretical limit established by (9).

STT can be also measured for ships of different capacity or with a distribution of TEUs different from that in Table 4. If we let 1300 TEUs equally distributed between the four quay cranes, we obtain the results in Figure 3. The minimum, maximum and average values of STT were, respectively, 714, 723, and 718, that correspond to about 12 hours.

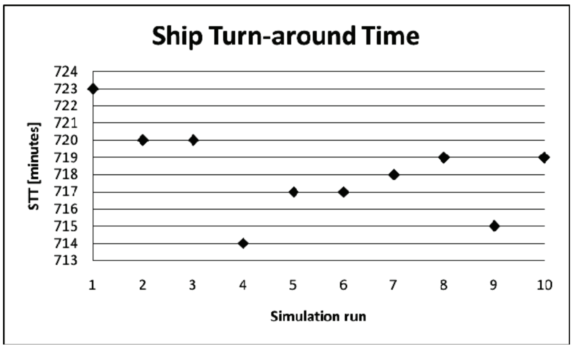

Figure 3: Measured STT in 10 simulation runs (TEUs equally distributed between quay cranes).

Performance indices were measured for critical resources like trailers and cranes: waiting times in queue; number of entities in queue; resource utilization. The associated statistics were: the average value in 10 runs; the minimum average value in a single run; the maximum average value in a single run; the maximum value.

Table 8 shows the waiting times. For unloading processes, TEUs may wait for the following busy resources: a) TR1 or TR2, when being on QC1 or QC2; b) YC1, YC2, YC3, when being on TR1 or TR2. For loading processes, TEUs may wait for: a) TR3, when being on YC4 used for empty TEUs; b) TR3, when being on YC5 used for full TEUs (busy resource TR3*); c) TR4, when being on YC6 used for full TEUs; d) TR4, when being on YC7 used for full TEUs (busy resource TR4*); e) QC3 or QC4, when being on trailers TR3 or TR4.

Table 8: Waiting times in queue of busy resources.

Busy Res.	Average	Min. Aver.	Max. Aver.	Max. Value
TR1	0.0788	0.00	0.1393	5.0002
TR2	0.0807	0.00	0.1613	4.7440
YC1	3.5193	2.5625	4.6946	17.7338
YC2	0.0612	0.00	0.1264	1.9246
YC3	0.0989	0.00	0.1965	2.0696
TR3	1.0662	1.0013	1.1135	6.8421
TR3*	28.4835	28.2937	28.6313	770.4400
TR4	5.1725	5.1165	5.2450	418.2100
TR4*	1.2628	1.21478	1.3079	7.8171
QC3	7.2326	7.0881	7.3267	10.5871
QC4	5.9521	5.8538	6.0713	10.2105

The average waiting times of TR1 and TR2 are below 5 seconds, and then delays in unloading TEUs due to the waiting of trailers below the quay cranes can be neglected. So, more trailers are not necessary for unloading in the simulated conditions. On the contrary, the results for TR3, TR3*, TR4, TR4* show that the loading process waits for long time when yard cranes are used. Thus, at least one more trailer should be used.

The large values for TR3* and TR4 were obtained because of the priority given to empty with respect to full TEUs, and because of the priority of selecting the closest yard crane YC7 instead of YC6.

If we consider the interactions of trailers with yard cranes during the unloading process, high waiting times are observed for YC1 only, because most of the unloaded TEUs were stacked in the block served by YC1. More yard cranes would speed-up the stacking process, but they are not necessary since the number and speed of trailers is sufficient to guarantee fast and almost continuous unloading operations by the quay cranes.

Long times are recorded for trailers when waiting for quay cranes to load TEUs (more than 7 minutes for QC3 and about 6 minutes for QC4). Then, one more trailer could help operations in the yard area, because the maximum number of queued trailers below a quay crane is three (see Table 9), such that the other two are available for yard cranes.

Table 9 shows the results for the number of entities in queue (the minimum value is always 0).

Table 10 shows the utilization of resources, i.e. the percentage number of busy units or the percentage busy time for single-unit resources (the minimum is always 0, the maximum is always 1).

Table 9: Number of entities in queue of busy resources.

Busy Res.	Average	Min. Aver.	Max. Aver.	Max. Value
TR1	0.0111	0.00	0.0199	1.0000
TR2	0.0114	0.00	0.0230	1.0000
YC1	0.6708	0.4637	0.9167	6.0000
YC2	0.0026	0.00	0.0062	1.0000
YC3	0.0056	0.00	0.0109	1.0000
TR3	0.2018	0.1911	0.2100	1.0000
TR3*	0.8882	0.8837	0.8906	1.0000
TR4	0.5703	0.5653	0.5770	1.0000
TR4*	0.1392	0.1339	0.1446	1.0000
QC3	1.5947	1.5753	1.6095	3.0000
QC4	1.3124	1.2990	1.3337	3.0000

Table 10: Utilization of resources.

Resource	Average	Min. Aver.	Max. Aver.
QC1	0.6104	0.6019	0.6218
QC2	0.6122	0.6036	0.6265
QC3	0.9919	0.9913	0.9926
QC4	0.9378	0.9324	0.9439
TR1	0.4818	0.4614	0.5013
TR2	0.4828	0.4660	0.5049
TR3	0.9897	0.9890	0.9899
TR4	0.9360	0.9307	0.9425
YC1	0.5712	0.5302	0.5970
YC2	0.1150	0.0892	0.1692
YC3	0.1617	0.1055	0.1812
YC4	0.8642	0.8612	0.8724
YC5	0.9825	0.9818	0.9831

Results for quay cranes indicate that unloading with QC1 and QC2 terminates before loading with QC3 and QC4. QC3 is used more than QC4 because of the high number of empty TEUs. Considerations about yard cranes are similar. Trailers TR1 and TR2 complete their tasks much earlier than TR3 and TR4, which are practically always busy. Then, the transport processes could benefit from more trailers.

5 CONCLUSIONS

This paper presents simulates a maritime terminal container (TCT) in standard operating conditions. Results prove the benefit from new control strategies different from those currently used. A new control approach could reduce terminal operating cycles in standard and, above all, in perturbed operating conditions.

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