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Chapter 1
Comparison of Fleet Size Determination Models for Horizontal Transportation of Shipping Containers using Automated Straddle Carriers

Bani Anvari, Apostolos Ziakopoulos, James Morley, Dimitris Pachakis, and Panayotis Angeloudis

Abstract
Planning of Horizontal Transport is a significant problem with material impact on the development budget and productivity of a container terminal. This paper uses Queuing Theory, Petri Networks and Discrete Event Simulation to address the fleet size determination problem for tactical planning. Considering the different information and modelling effort required for the three methods, it is recommended that Queuing Theory be applied in the preliminary planning stage as it is conservative, while Discrete Event Simulation which can yield significantly more cost-efficient results is applied for the detailed planning stage. Further development would be still required towards an easily applicable tool based on Petri Nets for practitioners to use in current planning problems, but the methodology itself can provide reasonable yet conservative results at a preliminary planning stage.

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1.1 Introduction

The maritime sector is responsible for the transportation of a significant share of the freight volumes generated as a result of increasing consumer demand and global supply chains. This was estimated in 2015 to account for over 80% of total world merchandise trade and between 55% and 67% percent in value terms (see UNCTAD (2016)). With the introduction of containerisation in the 1950s, freight movements became standardised, more efficient and less expensive (see Rodrigue et al (2017)). Annually, there are about 5,000 container vessels ferrying over 580 million *T*wenty-foot *E*quivalent *U*nits (TEU) of containers between ports in 200 countries worldwide (see AL (2018)). These container ships use dedicated areas in ports called container terminals to handle their cargo. Due to fierce regional and international competition, terminal operators seek ways to maximise throughput and productivity (seeSaanen and Valkengoed (2005)). The three groups of operations in a terminal which have the greatest influence on quayside productivity are: (un-)loading containers to/from the vessel (quay-side operations), storing/retrieving containers at/from the stacking yard-side (yard-side stacking operations), and transporting containers between the quay-side and the yard-side (horizontal transport operations), see Chen et al (2003); Park et al (2011). The stored containers are usually either loaded to another vessel (transhipment containers) or carried out by rail, truck or barge (domestic containers). The operational performance of container terminals has been studied and optimised at length by academic research that can be broadly categorised into three distinct areas for which recent literature surveys can be found: Quayside operations (see Carlo et al (2015); Meisel (2009), pp. 31-46), storage yard operations (see Carlo et al (2014a)), horizontal transport operations (see Carlo et al (2014b)).

Because of costs, area requirements and operational and staffing consequences, a thorough feasibility and fleet sizing analysis should be performed before choosing equipment for horizontal transport and container stacking activities. On the choice of horizontal transport, there are mainly three decisions at that have to be made (see Carlo et al (2014b)):

1) Which type of equipment or vehicle is the most appropriate,
2) how many are needed, and
3) how can we optimally deploy (assign, route and dispatch) this equipment?

With regards to the sizing decision (how many?), optimization methods (Integer Programming), Queuing Theory and Discrete Event Simulation are commonly used for tactical and strategic planning of container terminals (see Mrnjavac and Zenzerović (2000); Carteni and de Luca (2012); Cai et al (2013), Carlo et al (2014b); Zehendner et al (2013)). In practice, and based on one author's industrial experience, due to the time it takes to implement, test and commission new algorithms, fleet size determination for tactical purposes is performed by empirical ratios (see *e.g.* PIANC-135 (2014)) and verified by Discrete Event Simulation at the final design stage. Empirical ratios reflect a standard geometry, which although it has been implemented and studied before, would be hazardous to apply in radically different geometries.

Another developed graphical and mathematical modelling method is *P*etri *N*etworks (Petri Net or PN), see *e.g.* Murata (1989); Lenka and Das (2012); Li and Zhou (2009); Kumanan and Raja (2008), a modelling approach originally developed for the study of qualitative properties of systems exhibiting concurrency and synchronization. PNs have been used in the past to represent complex dynamic systems through the block-based representation of continuous and discrete processes into subsystems that host a series of sequential logical operations. PNs have been used in the past in manufacturing, transport networks, rail operations and communication systems to describe, analyse and verify systems characterised by precedence relations, concurrent activities asynchronous events and resource sharing conflicts. To our knowledge, there are few applications of PNs on container terminals and none on the fleet size determination problem for horizontal transport via *A*utomated *St*raddle *C*arriers (AStC). Liu and Ioannou (2002a) introduced a timed-place PN to model the lower level control systems of *A*utomated *G*uided *V*ehicles (AGV) (such as collision avoidance, intersection priority, and direction control) and yard and quay cranes (such as status, movement direction for crane and spreader, and hoisting/lowering control) in an automated container terminal. Perhaps the previous work closest to the problem at hand is Liu and Ioannou (2002b), where the same authors present a PN model for scheduling and fleet size determination of AGVs serving a sequence of machines in a manufacturing workshop. PNs, in this case, are used to schedule the minimum number of AGVs possible so that the machines have zero idle time. The fleet size is found as the minimum number of AGVs for which such a schedule can be found. More recently, Kim et al (2010) use a deterministic PNs for estimating the cycle time of an unloading vessel in a vessel-to-vessel transfer concept called *the Mobile Harbour*. Kezić et al (2007) use Discrete Dynamic Theory and Petri Nets for the design of a collision prevention supervisor between automated and non-automated vehicles in a mixed terminal.

The objective of this paper is to introduce and illustrate the application of PNs to the fleet size determination problem for tactical purposes and provide a comparative analysis of Queuing Theory, PNs and Discrete Event Simulation methods by applying them to the same problem. The proposed offshore terminal in Venice (Italy) is used for modelling the complex processes of horizontal transport in a container terminal and determining the optimal number of horizontal transport equipment required for efficient and cost-efficient operations at the quay- and yard-side. Through the comparative study presented herein, the different types of insights afforded by different methods can be appreciated.

The paper is organised as follows: Section 1.2 presents an introduction to AStC. In Section 1.3, the details of the deployment of AStCs in the proposed new offshore terminal in Venice (Italy) are described. Different Queuing Theory formulations, PNs and Discrete Event Simulation are used to determine the optimal fleet size of AStCs in a container terminal in Sections 1.4.1, 1.4.2, 1.4.3 and 1.4.4. The performance analysis using the three methods are compared in Section 1.5, while Section 1.6 summarises the general conclusions of this paper.

1.2 Automated Straddle Carrier Operations

Frequently used container handling equipment at the yard are *R*ubber-Tyred Gantry (RTG) cranes, *R*ail-*M*ounted *G*antry (RMG) cranes and *St*raddle *C*arriers (StC). Based on a survey by Wiese et al (2009) as well as Wiese et al (2011) of 114 container terminals, however, 63.2% of container terminals use RTG cranes, 6.1% use RMG cranes (mainly in Europe) and 20.2% use StCs as their main horizontal transport and stacking equipment. This makes StCs the second most used container handling equipment in storage yards despite the fact that the stacking density of the yard when using a gantry crane can be double that compared to a StC (see Saanen and Valkengoed (2005)). The reason for their popularity is the versatility of use since the same equipment can be picking containers up from the ground, transporting the containers horizontally to the storage area and stacking them nowadays up to one over 3-high (see *e.g.* Kalmar (2018b); Konecranes (2018c); Liebherr (2018)). Additionally, they can make significant differences in its productivity (see Cai et al (2013)), while keeping the operational and capital expenditures in a terminal low. The latter is because they do not require fixed infrastructure such as runways or crane rails.

AStCs (see Kalmar (2018b); Konecranes (2017)) have operational characteristics that closely correspond to those of conventional StCs with the added benefit of not requiring the presence of a driver. Hence the operating costs can be considerably reduced, while the operational flexibility is fully maintained. In contrast to other types of automated horizontal transport equipment, they can drop a container on the *S*hip-*T*o-*S*hore (STS) crane back reach, and they do not require a lifting equipment to be loaded or unloaded. Therefore, they enable the decoupling of the horizontal transport from the STS crane operations by the existence of a buffer zone at the quay apron. This increases the efficiency of STS cranes and vessel turnaround times. Their productivity is dependent on a number of geometric, mechanical or operational factors, including operating and lifting speeds, traveling distance, restacking strategies, assigned workloads and waiting times and the layout of buffer (interchange) zones under STS cranes, and between the yard and the gates, etc. (see Vis and Harika (2004)). For example, the size of buffer zones is critical since spill-overs caused by lack of space disrupt the coupled operations (such as STS crane loading and unloading and gate truck service).

Automated horizontal transport vehicles in container terminals can be classified into two categories:

- *AGVs* (see Konecranes (2018a); VDL (2018); Gaussin (2018)) including *Lift AGVs* (see Konecranes (2018b)), and
- *Automated Lifting V*ehicles (ALV), *i.e.*, unmanned vehicles for horizontal transport (see Kalmar (2018a); Konecranes (2017)) with own lifting abilities.

Accordingly, AStCs belong to the class of ALV that can independently lift and set down containers while AGVs require direct assistance by other yard cranes to load and unload containers on their platforms. An intermediate solution is the Lift AGV, which on the one hand gets loaded by the STS crane at the quay, but on the other can self-unload the container on a platform at the yard, offering partial decoupling. The advantage of the decoupling has been demonstrated in a number of studies, summarised in Carlo et al (2014b), where it is indicated that roughly twice as many single load AGVs than single-load ALVs would be required to perform the same transport operations at a similar service level. The large difference in the number of vehicles is related to the AGVs dependence (coupling) on an external crane for loading and unloading.

a) b)

Fig. 1.1 AStC at the Fisherman's Island Terminal in Brisbane: a) Operating at the yard-side and b) serving the hook under a STS crane (see Durrant-Whyte et al (2007))

The first implementation of AStCs, seen in Figure 1.1, allows the stacking of up to three containers high and enables operations in a completely automated fashion. In more recent implementations, such as the in Trapac Terminal in the Port of Los Angeles (see Di Meglio and Sisson (2013)), a shorter (one over one) and faster vehicle, called *AutoShuttle* (see Kalmar (2018a), or *A-Sprinter* (see Konecranes (2017)) is deployed for only horizontal transport between the quay and the (automated) stacking yard. The manned version of this equipment has different names under different manufacturers, such as *Shuttle Carrier* (see Kalmar (2018c)) or *Boxrunner* (see Konecranes (2018c)).

1.3 Case Study of AStCs for Venice Port

The Venice Onshore Offshore Port, a system of two container terminals linked with a seaway connection, was considered for the port of Venice by the Venice Port Authority (see Haskoning (2014) as well as Pachakis et al (2017)). The new system aims not only at serving mainland northern Italy but also several customers in central Europe such as Austria, Switzerland, south Germany, Hungary, Slovenia and Croatia.

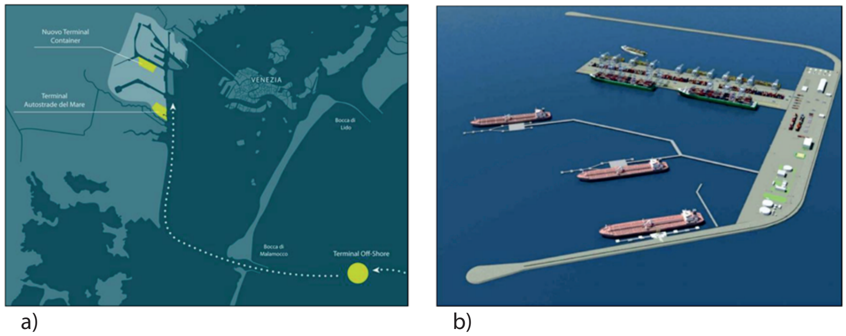

Fig. 1.2 The new port of Venice: a) The onshore and offshore terminal locations and b) the offshore container and liquid bulk terminal structure (rendering), see Pachakis et al (2017)

As shown in Figure 1.2a, the Venice Onshore Offshore Port consists of 3-parts: an offshore terminal for (un-)loading containers, a barge transfer system (see Figure 1.3) for feeding said containers to/from an onshore terminal (called *MonteSyndial*). The structure of the offshore terminal of the new port of Venice is shown in Figure 1.2b.

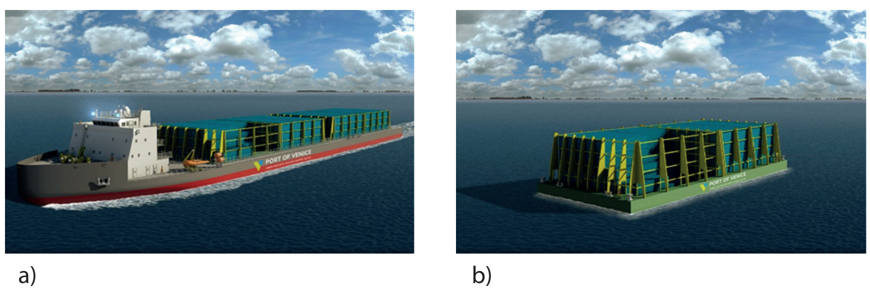

Fig. 1.3 Renderings of a) the semi-submersible barge transporter vessel and b) the container carrying barge. Concepts developed for the Port of Venice by BMT TITRON (see Causer (2014))

Given the available area and productivity demands, AStCs are proposed as the system for stacking and horizontal transport of the offshore terminal, after an evaluation of four different systems concerning capital and operating costs (see Pachakis et al (2017)). This paper considers the fleet sizing of AStCs for the horizontal transportation and stacking of containers at the offshore container terminal. As shown in Figure 1.4, eight STS cranes (maroon color) and ten barge cranes (blue color) are assigned for (un-)loading containers to/from the vessels on the deep-sea side and the barge side of this terminal. The areas colored orange in Figure 1.4 are for turning into and out of the stacking yard but can also be used for waiting of the AStCs. The stacking yard is divided into three stacks with travelling lanes between them.

1.4 Modelling the AStCs Movements

1.4.1 Operational Assumptions

For the comparative analysis of modelling techniques, the following target STS crane productivities are assumed: 34 moves/hour on the deep-sea side and (ambitiously) 30 moves/hour on the barge side.[1] The cycle times are thus 2.00 min and 1.76 min respectively.

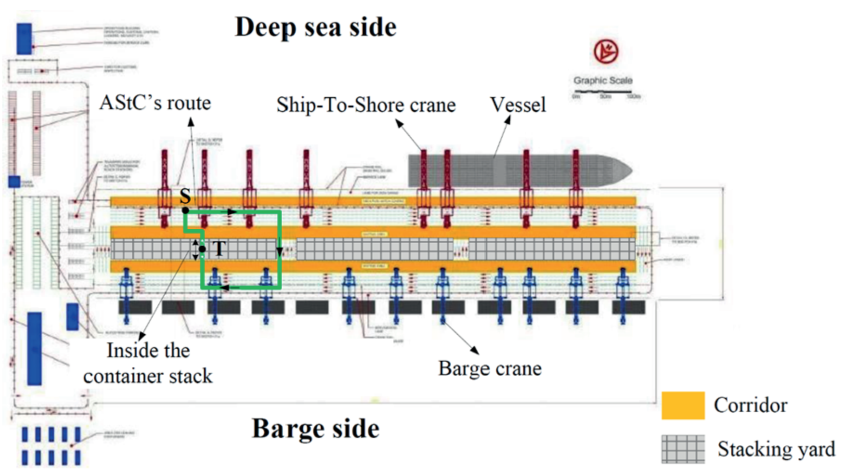

Fig. 1.4 The offshore container terminal layout of Venice's port at the planning stage (see Pachakis et al (2017)) and the route (green line) that each AStC travels to finish one cycle. The orange area near the stacking yard is the turning and waiting area for the AStCs. The out of gauge cargo loading area is under the STS cranes, also shown in orange.

To estimate the number of AStCs required to operate the offshore terminal at the target throughput, some of the technical and operational assumptions are summarised in Table 1. These assumptions are applied in the calculations of the average cycle time of the StC. These average cycle times are then used in the queuing model and the PN model. For Discrete Event Simulation modelling, the equipment travel is modelled on a certain path from random locations in the stack with the equipment speeds and the various times apply as deterministic delays. The software has a collision avoidance routing, so the corresponding delays are accounted.

The average travel route of the AStCs is marked green with indicators along its entire length in Figure 1.4, and with the starting point and destination location symbolised with "S" and "T", respectively. The average travelling length of the AStCs

[1] PIANC-135 (2014) reports the range of low, medium and high productivity per STS crane in large container terminals to be between 20-25 moves/hour, 25-30 moves/hour and 30-35 moves/hour respectively. For the case study the assumption is met that one crane move corresponds to one container move.

for the Queuing Theory and PN models applications is calculated from the centre of each stack (point "T") to the centre of the berth opposite to the stack (point "S"). This geometry is consistent with the container locations being uniformly distributed anywhere in the stack and uniformly anywhere along the berth corresponding to that stack. All AStCs have higher speeds on the travel lanes than inside the container stacks. To minimise the in-block travel time, the travel lane between stacks is used at least once in the route of the AStCs. The travel distances outside and inside the stack are 581m and 39m respectively. Considering the horizontal and vertical movements and including 25% delay allowance, the final AStC cycle time is about 600s for the route in Figure 1.4. Thus, each AStC can finish approximately 10 moves/hour in the stacking yard, which is close to observed productivities in the industry.

The maximum stacking height is set to up to 3 containers high. For the calculation of the lifting and lowering time, the working height considered is the maximum times the average utilisation factor of the stack. The housekeeping operations are accounted in the cycle time of an AStC by adding 10% of the vertical movement time to the cycle time. The acceleration (deceleration) time of an AStC (*i.e.* when turning or stopping) is accounted for in the cycle time by adding 40s to the horizontal movement time. Traffic and safety adjustments are also accounted for in the cycle time of AStC by adding 20s to the horizontal movement time. Miscellaneous manoeuvres (*i.e.* positioning by STS crane) are also covered by adding 20s to the horizontal cycle time. Delay is added as 25% of the sum of horizontal and vertical movement times, which is added to the total cycle time of an AStC.

Table 1.1 Operational assumptions for the AStC operation (see Kalmar (2018c)) and common industry assumptions

AStC Specification	Unit	Value
Average travel speed outside the block (85% of max. speed)	[m/s]	5.90
Average travel speed within the block	[m/s]	1.39
Time for 90 degrees turn	[s]	2
Housekeeping moves of total	[%]	10
Acceleration adjustments	[s]	40
Traffic and safety adjustments	[s]	20
Miscellaneous manoeuvring time	[s]	20
Maximum stacking height	[boxes]	3
Maximum lifting speed for unloading	[m/s]	0.33
Maximum lifting speed for loading	[m/s]	0.27
Maximum lowering speed for unloading	[m/s]	0.30
Maximum lowering speed for loading	[m/s]	0.25

1.4.2 Queuing Theory

Queuing Theory (see Gross et al (2017)) is commonly used by consultants in the preliminary stages of a project, during tactical planning, because of its solid theoretical basis, its ability to provide quick and indicative results. Queuing Theory also provides a sanity check to the results of other methods such as simulations, by comparing the corresponding long term (steady-state) averages. The standard notation established by Kendall (1953) for defining every queue in its most basic form is $A/B/c/K/m$, where A denotes the stochastic arrival time distribution, B represents the stochastic service time distribution, c is the number of operating servers in the system, K denotes the capacity of the queue, and m represents the maximum number of customers. A and B are commonly defined as a Poisson (or Exponential) distribution (M), a deterministic value (D) or a General distribution (G). K and m are infinite when they are not defined. For instance, in the $M/M/1$ queuing system, both arrival and service distributions are a Poisson distribution, and one server is operating in the system. Table 1.2 summarises the parameters used in the queuing systems based on the case study. In the models described herein, the customers are the containers that are (un-)loaded from a single STS crane at an *average arrival rate* λ of 34 moves/hour and 30 moves/hour on the deep-sea and barge cranes, respectively. The servers are the AStCs that are assigned to a single STS crane and operate at an *average service rate* μ of 10 moves/hour.

Table 1.2 Parameters used in the Queuing Theory models according to the case study

Parameter	Meaning	Deep-sea Side			Barge Side		
λ [moves/hour]	STS crane productivity	34	34	34	30	30	30
c [# ASC]	No. of AStCs in the system	4	5	6	4	5	6
μ [cycles/hour]	AStC service rate	10	10	10	10	10	10

There are several already solved queuing models in the literature, each with their advantages and limitations. None of the available models will capture exactly the STS-AStC operations. The objective of this section and the modelling exercise is to

(i) highlight how the existing models can be used to approximate as best as possible these operations,

(ii) indicate any insight that can be gained through applying them, such as a rough first estimate for the quantity of AStCs required for the terminal, and

(iii) explore how the readily available performance results can be used to support decisions about the fleet sizing of the AStCs.

Seven standard queuing models, $M/M/1$, $M/D/1$, $M/M/c$, $G/M/1$, the AllenCunneen [A-C] Approximation for $G/M/1$, $G/M/c$, and $M/M/c/K$ are explored in this chapter, as possible models for the STS-AStC queuing system. The single server models $M/M/1$, $M/D/1$, and $G/M/1$, were applied under the operating assumption that each AStC acts as a separate server with its queue, which is the traffic lane in the backreach or portal of the STS crane, who drops the containers randomly in each of the traffic lanes. The minimum amount of ALVs, c_{min}, required for a stable queue given the parameters λ and μ is calculated as 4 (vehicles). Hence the performance metrics for these systems are calculated for between 4 and 6 AStCs per crane. The multi-server models ($M/M/c$, $G/M/c$) can apply to the situation where the STS crane drops containers sequentially in the next empty position on the traffic lanes, and the AStCs pick the containers from any traffic lane as they come. This way there is one queue (the drop-off/pick-up positions under the crane) and multiple servers. It is noted that the *F*irst-*C*ome-*F*irst-*S*erve (FCFS) queue discipline cannot be applied in practice with these operations. Finally, the $M/M/c/K$ model represents the case where the STS crane drops the containers on a finite number of positions on the quay apron and if all these positions are full and no empty AStC is coming to the transfer area, the crane has to wait. The reason that the General interarrival distribution is desired as a model is to see the effect of reducing the variance of crane productivity (say by adding a secondary trolley) in demand for horizontal transport equipment. Here, a coefficient of variation of 5% was used in the $G/M/1$ formulations. The Allen-Cunneen [A-C] Approximation for $G/M/1$ is used because it provides a simple to implement the formula for spreadsheet calculations. An Exponential distribution for the service time is considered appropriate as the distances that the AStC travels from the apron to the stack (and vice versa) vary considerably.

Using the seven Queuing Theory formulations, the performance metrics (*average number of containers in the system*, *queue length* and *average waiting times*) of the system after assigning 4-6 AStCs per STS crane are calculated for different STS crane productivities (arrival rates). The results are sorted by the *average arrival rate* λ in Figure 1.5 and Figure 1.6. It is evident from the results that the examined performance metrics follow the same trends of performance improvement as the AStC number increases and the related arrival rate decreases, despite having different values from model to model.

As expected and can be seen in Figure 1.5a and 1.5b as well as in Figure 1.6b, the performance of the $M/M/c$ (green bars) model is clearly better than the $M/M/1$ (blue bars), with regard to the customers in system (see Figure 1.5a), as there are more containers in transit but fewer standing in queue (see Figure 1.5b) and waiting less time on average (see Figure 1.6b). Reduction in the variance of the service times (red bars), as expected improves the queuing performance, but it is deemed a less realistic model. The reduction in variance in the arrival distribution as modelled by the $G/M/1$ system (violet and cyan bars) is shown to result in a significant reduction in containers in the queue (see Figure 1.5b) and their *average waiting time* compared to the $M/M/1$ (see Figure 1.6b, blue bars). The explicit modelling of the *interarrival time* variability by introducing the General arrival distribution allows the quantification of this effect. In that sense, the $G/M/c$ model probably allows the

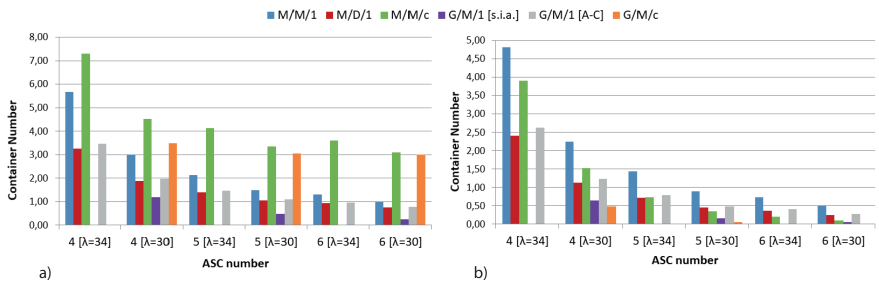

Fig. 1.5 a) Average number of containers in the system per STS crane, b) average number of containers in the queue per STS crane

best flexibility at the expense of some computational complexity. However, solution routines are readily available for its implementation (see Gross et al (2017)).

On the question of decision support, the above-mentioned performance measures provide some insight, but to the authors' knowledge, there is no rigid rule that defines what the minimum acceptable level of service for container terminals is. Obviously, the terminal operator wants to maximize the utilization of their equipment, and given the cost of AStCs, they would try to provide the minimum number that ensures the STS crane productivity is unaffected, which in turn is the level of service that the shipping lines measure and value. Therefore, judgement is necessary to decide the fleet size. Indeed one can see from Figure 1.5 and Figure 1.6 that the performance is marginally improved for 5 AStCs per quay crane or more.

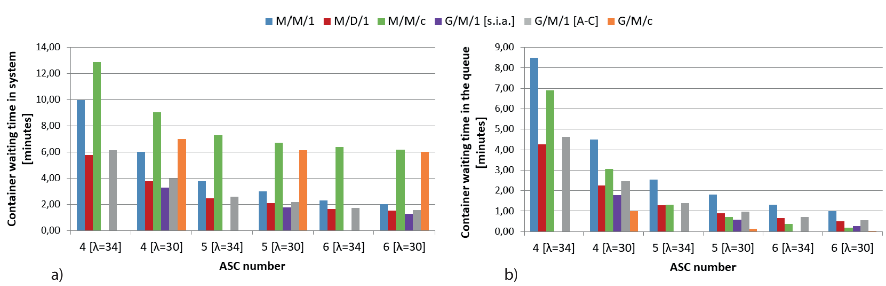

Fig. 1.6 a) Average container waiting time in the system per STS crane and b) average container waiting time in the queue per STS crane

Perhaps the model closest to the problem at hand is a multi-server queue with limited size ($M/M/c/K$), as it can approximate the situation of the limited number of transfer positions (buffer) under the STS crane and the multiple AStCs (servers) transferring the containers between the yard and the apron. A system size of K corresponds to the situation where every one of the c AStCs is carrying a container, and there is a container laid on each of the K-c transfer positions at the apron. An appropriate level-of-service criterion needs to be defined to evaluate the appropriate fleet size and the number of transfer points required. In this article, the criterion was blocking probability as this would mean that the STS crane would have to wait before laying a container on the apron. Because of the nature of this model (blocked clients have turned away), it is not possible to estimate the average delay on the STS crane, but only approximate the revised container arrival rate as $\lambda' = (1\text{-}P[full])\cdot\lambda$. The crane productivity rate of λ = 33 moves/hour (weighted average productivity between deep-sea and barge cranes) was considered here. If a minimum acceptable productivity is agreed as λ' = 30 moves/hour then the level of service criterion becomes [P[full]]max = 10%. The sizing problem then is a 2-step process:

(i) determine the min number of AStCs for which the utilisation is high and the blocking probability is acceptable,

(ii) conduct sensitivity on the number of transfer positions on the apron so that the blocking probability is acceptable.

As a starting value for the number of transfer positions (K-c) we can take the minimum number of traffic lanes required behind the STS crane. In the Venice example, assuming that 4 STS will be put on a deep-sea vessel, 4 traffic lanes and one bypass lane would be needed (see Figure 1.4). The 4 transfer positions (assumed one container high) are on each of the 4 traffic lanes.

The results of this queuing model indicated that with 4 AStCs assigned to an STS crane, the equipment is sufficiently busy (utilization is 77%) and the probability of blocking is 7% (with four transfer positions) as shown in Figure 1.7a. Having between three and four transfer points (*i.e.* traffic lanes at the deep-sea berth and the barge berth) will keep the blocking probability within an acceptable range (9%-7% respectively, see Figure 1.7b).

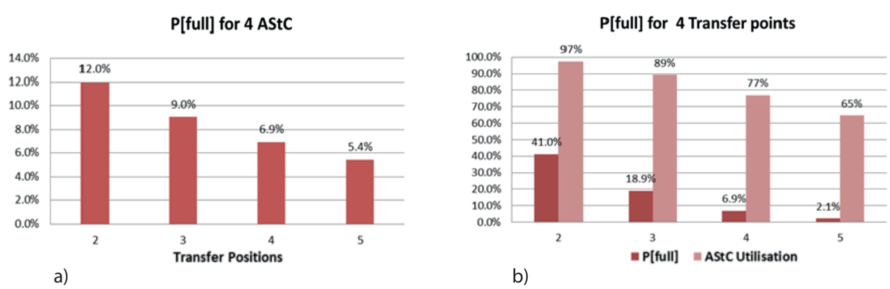

Fig. 1.7 Using the M/M/c/K queuing model, a) blocking probabilities and AStC utilisations 2-5 AStCs are assigned to an STS crane and b) blocking probabilities for 2-5 transfer positions for 4 AStCs to an STS crane.

1.4.3 Petri Nets

A PN is a conceptual and visual-graphical tool particularly suited to represent and analyse the properties of concurrent systems with discrete number functions. Its mathematical features enable systematic analysis and verification, while its modular composition enables the construction of complex systems characterised by precedence relations, concurrent activities, asynchronous events and resource sharing conflicts (see Liu and Ioannou (2002a)). Because of these qualities PNs have been used extensively to model manufacturing, communication and urban transport systems, as mentioned earlier.

It should be noted that overall, PNs are a means to formalise a model of flow operations, similar to Queuing Theory. For the solution of that model (and hence to get the metrics that help in the performance evaluation of the operations model), various mathematical methods are used, such as analytical techniques for solving (semi-)Markov Processes or Discrete Event Simulation (see Lenka and Das (2012)). The available tools for PN solutions have integrated some of these methods in an autonomous capacity. In this sense PNs are not dissimilar from Queuing Theory as the latter also uses concepts from stochastic process modelling (*e.g.* Birth-Death models, Markov and semi-Markov Chains), and Discrete Event Simulation to get the performance metrics (queue size, waiting times etc.). Therefore, it is the authors' belief that PNs can be considered a valid candidate for evaluating decision alternatives in container terminal horizontal transport. On one hand they borrow elements from both deterministic and stochastic processes while on the other they present a middle option regarding computational demands and modelling complexity.

Following the standard definitions (see Murata (1989)), PNs consist of four elements: Place, Transition, Arc and Token, which are summarised in Table 1.3. In PNs, an area, activity or state of the system can be modelled using a Place, and the number of instances of a Place can be represented with Tokens. Sequential processes are modelled with Tokens progressing through state machines. Arcs between resource Places and Transitions represent the acquisition (return) of some resources by a process. In the end, the process state machines can be merged into a model of the whole system by combining the common resource Places.

In mathematic terms, a PN represents a (bipartite) network graph and consists of five parts (see Murata (1989)):

$$PN = (P, T, F, W, M_0) \tag{1}$$

Where P is a finite set of Places, $P = p_1, p_2, \ldots, p_\mathrm{i}$. T is a finite set of Transitions, $T = t_1, t_2, \ldots, t_\mathrm{j}$. F is a finite set of Arcs (flow relation) that $F \subseteq (P \times T) \cup (T \times P)$. W is a weight function and M_0 is the initial marking. The essence of the mathematic representation of PNs is that a Transition cannot fire until a series of conditions have been fulfilled:

- The destination Place has the capacity for incoming tokens.
- There are enough Tokens available at the input places.

Table 1.3 Petri Net elements

Element	Function	Traditional Representation	Graphical Representation
Place	Area, activity or state of the system	Circle	○
Transition	Functions linking places	Rectangular bar	▬
Arc	Connect places to transitions and vice versa, enforce conditions	Vector (arrow or curved arc)	⟶
Token	Counting/controlling medium, the quantifying aspect of the net	Dot	●

- No other Transition fires simultaneously.
- Other conditions such as time or color restrictions may apply, depending on the Petri Net type.

One of the most important properties of PNs is that they are memoryless. This is a Markovian property which entails that any state in a PN is only dependent on the immediately previous one and not the ones before that. Commonly computed performance measures in PNs are the

(i) probability mass function of the number of Tokens at steady-state in a Place,
(ii) average number of Tokens in a Place and the
(iii) frequency of firing a Transition (throughput).

In this article, an indicative *Timed-Place Stochastic Colored Petri Net* is introduced to illustrate the modelling and analysis of horizontal transport movement in container terminals via PNs for fleet sizing. The definitions and transition rates for modelling a full AStC cycle are summarised in Table 4. It is “Timed” because a delay between transitions had been programmed to represent the AStC cycle and it is also “Place” because the Places can hold more than one Token (that are equal and indistinguishable apart from their colors).

Although the transition sequence and times for each AStC (token) (final duration in Table 1.4; net time calculated using the terminal and equipment geometry, and machine parameters in Table 1.1, adding a delay equal to 25% of the net time) are deterministic, the order with which Token transitions occur is random, hence introducing an element of stochastic behaviour. This stochasticity is due to the fact that a PN is required to depict simultaneous events, such as movements of different AStCs operating concurrently, in a realistic manner. In the model, this is achieved by randomizing the transitions between each PN stage. All eligible Transitions (those that are in a “ready to fire state”) are placed in a pool and a selection is conducted amongst them, usually via a random number generation process. Thus a semblance of time is created, much like "stop-motion" animation, for the PN and the movements of the entire AStC fleet (than are simultaneous in reality) can be simulated after a satisfactory amount of repetitions. For completeness it is mentioned that in certain PNs there is also the option of introducing logic in firing specific Transitions, a feature which is not used in the current analysis.

Moreover, the PN model used here can be characterised as ordinary, live, persistent, regular; all stages would be reachable and reversible, and 3-, 4-, 5- or 6-bounded depending on AStC configuration.[2] Here, colored Tokens represent the movements of AStCs; black Tokens for deep-sea side and red Tokens for barge side.

Table 1.4 AStC transition rates in PIPE (v4.3.0) for the deep-sea side PN segment, similar values were used for the barge side

Origin Place ($P_\#$)	**Transition ($T_\#$)**	**Destination Place ($P_\#$)**	**Movement Type**	**Net Time** [s]	**Delay Time** [s]	**Final Duration** [s]
P_1: STS Crane Queue	$T_{1,2}$: Safety Clearance	P_2: Crane Loading Spot	Horizontal	29.24	7.31	36.54
P_2: STS Crane Loading Spot	$T_{2,3}$: Start Loading	P_3: Loaded	Vertical	28.30	7.07	35.37
P_3: Loaded	$T_{3,4}$: Depart for Block	P_4: Reach Block Entrance	Horizontal	88.07	22.02	110.09
P_4: Reach Block Entrance	$T_{4,5}$: Slow Down	P_5: Block Destination	Horizontal	8.29	2.07	10.37
P_5: Block Destination	$T_{5,6}$: Start Loading	P_6: Unloading	Vertical	37.73	9.43	47.17
P_6: Unloading	$T_{6,7}$: Depart	P_7: Reach Block Exit	Horizontal	8.29	2.07	10.37
P_7: Reach Block Exit	$T_{7,1}$: Speed up	P_1: STS Crane Queue	Horizontal	88.07	22.02	110.09
			Total	**288**	**72**	**360**

Colored PNs (see Jensen et al (2007)) are utilized here to distinguish between AStCs of the two different sides, commonly operating in the block destination stage at any given moment. Colored PNs provide the capability of modelling the two sides simultaneously and still keep the option of separating them at a later stage for any reason (equipment incompatibility, geometric separation of the process, etc.). An indicative configuration of the PN model with five deep-sea side AStCs and 4 barge side AStCs at the initial stage and at a random later stage are shown in Figure 1.8a and Figure 1.9b. Although in the figures the Places before the cranes are indicated as *loading spot* and the Places outside the yard block as *unloading*, the status of the AStCs could be reversed, describing a discharging process, without any change in the model. This is because the loading and discharging time under the crane (final duration at Place $P2$ in Table 1.4) and the lifting and dropping times in the yard block (final duration at Place $P5$ in Table 1.4) is taken as equal. In other words,

[2] A PN is called "k-bounded" when all its places contain no more than k Tokens at any given time, including the initial stage.

what is modelled in the PN is the movement of the AStCs irrespective of the flow of containers (inbound or outbound).

For simplicity, the PN models the operations of one STS crane and one barge crane with the assorted AStCs, *i.e.* gang on each side. Although outside the scope of this illustrative example, the network of Places and Transitions can be expanded without loss of generality to consider all the cranes and all the AStC that serve a deep-sea vessel and set of barges, in a pooled resource set up, similar to Liu and Ioannou (2002b). In such a case, dispatching rules would also be necessary to decide which *STS c*rane queue (STSC queue) the AStCs would join.

The above AStC cycle time of 360 sec (rounded) leads to a productivity rate of 10 cycles per hour. To match the STS crane productivity requirements (30 moves/hour or 34 moves/hour for barge and deep-sea side, respectively), the experiments have a minimum of 3 Tokens. In contrast to Discrete Event Simulation, because of the way the PN is set, there is no link, such as a crane routine that pulls the Tokens from the Place *STSC queue* to the Place *loading spot* at a certain rate, other than the random selection of which Token moves next (Transition firing). In contrast to Queuing Theory, the times that the Tokens spend at the Places *loading* and *unloading* are deterministic. As such, there are no metrics for Tokens in a Place that are directly comparable with these two methods.

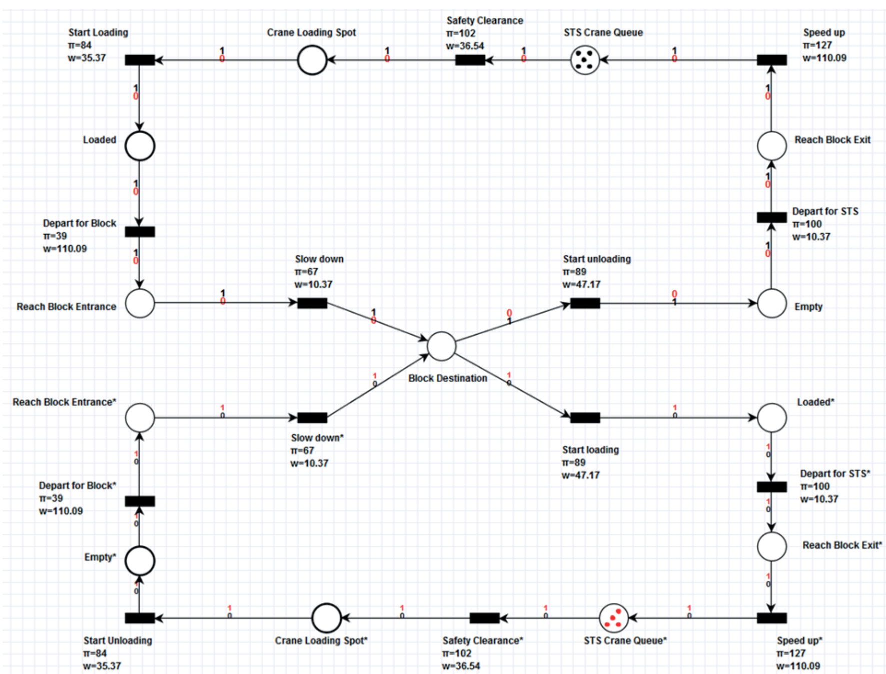

Fig. 1.8 PN model of the terminal with 5 deep-sea side AStCs and 4 barge side AStCs at the *initial stage* (barge side Places are shown with "*")

The Places *loading spot* and *loaded* are the only ones with capacity restrictions of 1 token (Places appear as bold circles) as it was assumed only one AStC can operate under the crane at a time, like in Queuing Theory. Arc weights, by definition, are integers that are assigned to each Arc. They determine how many Tokens are destroyed from the input Place as they pass towards the Transition and how many Tokens are created from the Transition to the output Place. In traditional PNs, Arc weights can generate or remove Tokens to simulate a production line environment (with parts being split or assembled, for instance). In this case however, due to the nature of the PN designed, no AStC Tokens are generated or lost since the number of AStCs is stable for each analysis. Therefore we used Arc weights of 1 to ensure this number remains stable each time the PN is created and loaded for analysis by the software, and when analysis is underway (each time the PN Transitions fire and a new state of the PN is created). In addition to the previous, Arcs include filters of the proper color to separate AStCs per barge or deep-sea side (so that no barge AStC can enter the deep-sea side of operations and vice versa). Hence, there are two types of Arc weights, utilized here, black and red with values 0 and 1 on each Arc. To simulate the need of at least one AStC to be on standby by the quay crane, so the latter keeps operating, the highest priority, π, has been assigned to the Place *STSC queue*, and others have gradually diminishing ones.

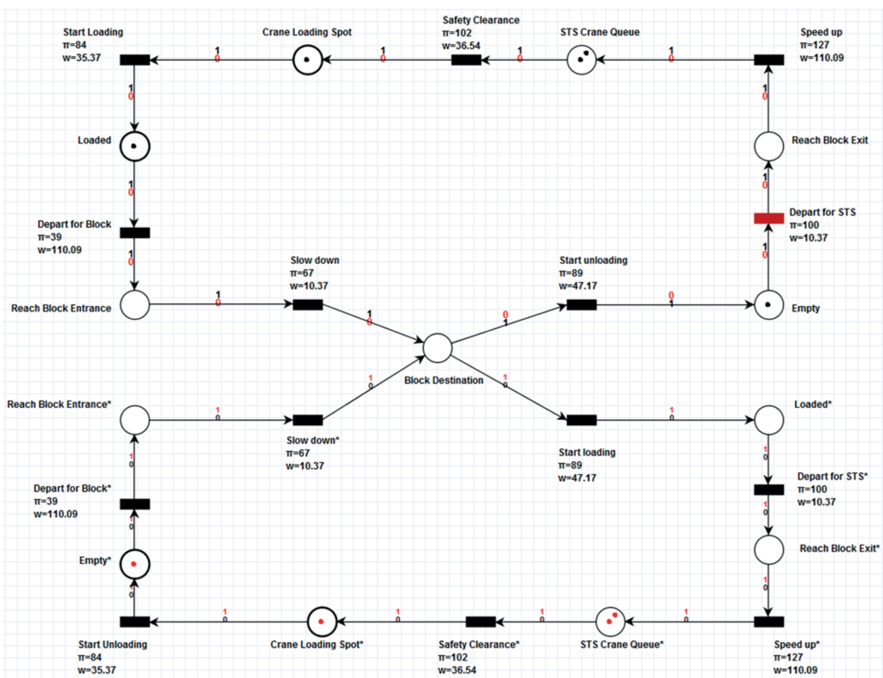

Fig. 1.9 PN model of the terminal with 5 deep-sea side AStCs and 4 barge side AStCs at a *random stage* (barge side places are shown with *)

The PIPE2 software (see Dingle et al (2009); Bonet et al (2007)), is a Java-based, platform-independent, open source tool for the construction and analysis of *G*eneralised *S*tochastic *P*etri *N*et (GSPN) and was used for simulating the PN and extracting results. For each experiment, the PN is loaded with an equal number of Tokens of each color, for each scenario (3, 4, 5 and six Tokens respectively), to conduct analysis comparable to the other methods. As previously described, the Token movements occur with a fixed sequence and transition times for any individual AStC, but in a random order between different AStCs. Because every firing Transition in PIPE2 is determined from the pool of all eligible ones randomly (via a Java random function), the number of Tokens at each Place at any time is a random variable. The random ordering of the individual Token movements simulating the simultaneous AStC movements introduces a stochasticity factor to the PN. The steady state average and confidence interval of the number of Tokens at each Place are calculated for every experiment, which is the selected performance metric here. Each firing is the process of conducting a discrete transition, thus changing the state of the PN. It was found that 2,000 firings are sufficient for the PN to reach a steady state beyond the initial conditions. It was also found that, after 30 replications, there was a satisfactory convergence of the PN analysis, with consolidation at the 4th decimal digit. The average number of Tokens (AStCs) at Place $P1$, *i.e.* in the *STSC queue*, for both terminal sides (deep-sea side and barge-side) and their 95% confidence interval values are shown in Table 1.5.

Table 1.5 Terminal PN simulation results for the average AStCs queue length at quay cranes

	Average Number of Tokens at STSC Queue Place			
#AStC / STSC	**Deep-sea Side**	**95% Confidence Interval**	**Barge Side**	**95% Confidence Interval**
3	0.72	± 0.025	0.72	± 0.025
4	1.73	±0.035	1.70	±0.035
5	2.73	±0.033	2.70	±0.033
6	3.73	±0.026	3.71	±0.026

The criterion for the optimal fleet size is the same as with the other methods, *i.e.*, the smallest size that does not lead to crane underutilization (as measured by the average number of Tokens on the Place *STSC queue* and not by some observed STS crane productivity, as this is not possible in the PN set up. The analysis shows that, given the geometry and cycle times, the best option for the AStC fleet size appears to be 4 vehicles ($1.0 <$ average tokens in queue < 2.0). If 3 vehicles are assigned, there will be some time periods without any AStC standing by the crane, which might lead waiting for the more expensive equipment (cranes). On the other hand, if 5 or more AStCs are assigned, it appears that they would form an unnecessarily large queue for operations, leading to underutilized equipment (reduced efficiency) for both the deep-sea side and the barge side.

The presented PN model has deterministic times in the different places as shown in Table 1.4. Consequently, from the performance measure results that are used in other equipment sizing methods, only the number of AStCs at Place $P1$ (*STSC queue*) is a comparable random variable. An indication for the vehicle queue length, *i.e.*, the AStCs available to service each quay crane can be given by the average number of Tokens at the Place $P1$, to be read in conjunction with the total number of AStCs operating. While in practice this usually means that one AStC can enter the crane portal at a time, the rest of the vehicles in the queue will be on close standby to fall into position when the crane begins the start of the next loading phase and ensure productivity is not disrupted.

1.4.4 Discrete Event Simulation

In using Discrete Event Simulation, the aim is to determine the number of AStCs needed to operate the offshore terminal at the target throughput and to achieve target quay crane productivities. As with the previous methods, the approach includes oversizing the fleet results to underutilized AStC (*i.e.* unnecessary costs), while under sizing the fleet results in reduced crane productivity. The criteria used to determine the optimal fleet size were a) the AStC utilisation and b) the quay crane productivities (see Table 1.6). Again, judgement is required to balance the requirements for AStC utilisation with the need for crane productivity. The authors believe that in the preliminary stages this approach is better than an optimization algorithm.

Table 1.6 AStCs utilization and quay crane productivities for two deployment strategies (*gangs* and *pooling*) with two scenarios (1: an average and 2: a contingency vessel schedule)

Scenario	**Strategy**	**AStC Utilization** [%]	**Deep-sea STS Crane Productivity** [moves/hour]	**Barge Crane Productivity** [moves/hour]
Scenario 1	Gang	38	27	20
	Pooling	43	31	24
Scenario 2	Gang	39	27	20
	Pooling	44	28	22

FlexSim (2018) is an advanced Discrete Event Simulation (see Law (2014)) platform that is designed for detailed simulation of container terminal operations. A specific model was built for the offshore terminal of Venice and can be seen in Figure 1.10. The software models both the geometrical attributes of the terminal (*e.g.* the dimensions of the stack and the lengths of the traffic lanes) and the container handling processes (*i.e.* the delays in the handling and various rules on quay crane and equipment assignment). The operating design of this terminal is unique in the sense that there are a high number of direct moves for import containers as they are taken directly between the deep-water berth and the barge berth. Considering the very limited storage space available, the barges are used as import storage and the terminal yard as export storage. Several initial validation models were set up to determine rules that apply to the barge and barge carrier system and the container transfer from the barge quay to the deep-sea quay and vice versa. The following rules have been identified through discussions with the project team and analysis of smaller validation runs.

- In the first instance, the loading of export containers to barges has to commence at the onshore terminal approximately 48 hours before a mainline vessel arrival, to allow time for transfers into the offshore terminal stacks.
- The barge delivering a main line vessels export containers is unloaded into the offshore terminal stacking area. Therefore, export container barges must be unloaded before a mainline vessels arrival.
- The empty barges are then used to take the import containers back to the onshore terminal.
- Up to 5 cranes are used per vessel on the deep-sea berth.
- Up to 6 cranes and six barges are used on the barge berth per main line vessel.
- The barge carrier (Figure 1.3a) is assumed to take any available barges to and from the offshore terminal on a regular repeating pattern. Taking single barges (Figure 1.3b) is avoided where possible to maximise efficiency.
- At the offshore terminal, the priority is to permit empty barges to load containers directly transferred from the deep-sea going vessel.
- At the onshore terminal, the priority is to load up barges for transfer to the offshore terminal promptly.
- Unlimited barge lay-up area available at the side of the offshore terminal berths
- Flexible berth allocations are allowed.
- Maintenance routines and breakdowns are not included in the assessment of equipment numbers. Instead, the numbers are assumed to be the number of regular equipment available for operations, and additional equipment (commonly 10%) will be allowed for planned maintenance and breakdowns.
- Housekeeping operations (customs and stack block optimisations) are carried out in AStC idle periods, *i.e.* outside the busy periods simulated herein.

The model was used to study the fleet sizing problem and test two different AStCs deployment strategies for the terminal, namely running in *gangs* and *pooling*. Simulation allows the planner to apply different operating strategies (such as *pooling*) and see the particular effects on operations, despite the fact that it is not possible to compare the results with the other methods (Petri Nets and Queuing Theory). Although the theoretical results regarding *pooling* are generally known, It was decided to study the effect of *pooling* in this sizing problem, because, it was not clear to the team a priori that *pooling* would yield the best result under all operating circumstances, and how big the difference would be in terms of fleet sizes and resulting quay crane productivities. So it was decided first to compare the two operating strategies and then study the sizing problem on the most efficient deployment strategy.

For the *gangs* strategy, specific AStCs are assigned to specific deep-sea berth STS cranes, ensuring that horizontal transport equipment is always available for berth operations regardless of vessel arrival times or patterns. For the *pooling* strategy, a central pool of AStCs serves all STS and barge cranes, each AStC assigned to different tasks based on a pre-assigned task prioritisation.

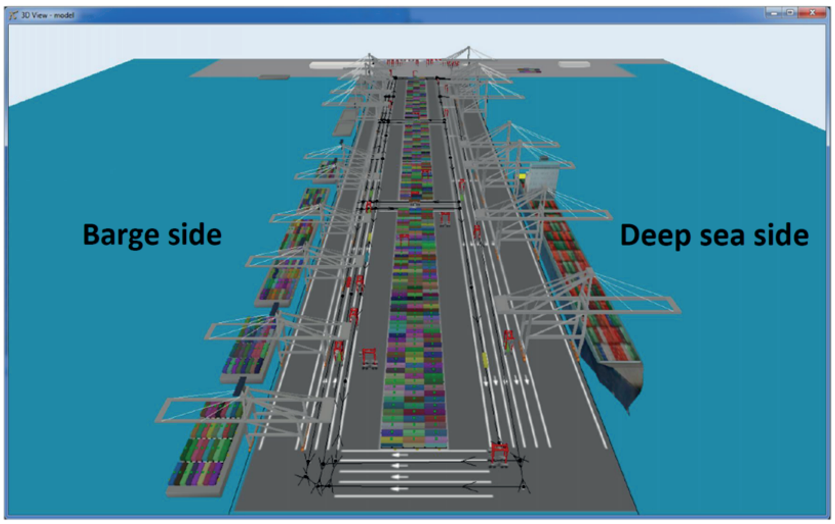

Fig. 1.10 Animation view of the FlexSim simulation model for the Venice offshore container terminal

To best represent the most critical operational cases, two scenarios have been investigated (see Table 1.6). In Scenario 1, a *typical vessel schedule* where vessels arrivals are scheduled and variations come from a Uniform distribution with up to 12 hours maximum variance before or after the estimated time of arrival. In Scenario 2, a *contingency vessel schedule*, where two vessels unload or load simultaneously, or one vessel unloads and one vessel loads simultaneously before the vessel schedule returns to a regular weekly pattern. Each model was run to simulate twelve weeks of terminal operations based upon pre-determined schedules for barge and mainline vessels arrivals generated from a setup with two barge carriers and 20 barges. The first ten weeks are run to make sure that the terminal is correctly populated with containers and to establish the steady state shipping patterns. The last two weeks are then monitored closely on the screen to identify any bottlenecks that may arise during operation and for statistics and data collection. For Scenario 2, because it represents severe events, they were manually simulated in shorter runs after the steady state is reached and then the time taken to recover normal operations (defined as yielding comparable service time results to scenario one runs) was recorded.

Prior analysis for the STS and barge crane fleet size indicated that 8 STS cranes and 11 barge cranes were required to meet the productivity demands of the operations. Four AStCs were initially assigned to each STS and barge crane (*i.e.* fleet size of 76 AStCs) to compare the deployment strategies. The two deployment strategies, *gangs* and *pooling*, were run with the average and contingency scenarios. The equipment utilisation results and the quay crane productivity rates are summarised in Table 1.6).

The initial comparison between the two operating strategiesconfirms that the *gang* strategy, as set up in the model, is less efficient than a *pooling* strategy. Both the utilization of AStCs and the resulting quay crane productivities while operating in *gangs* are lower compared to the central pool strategy, in both scenarios, despite the equal number of horizontal transport equipment. The improved productivity is primarily because AStCs can be assigned to berth cranes more flexibly with a higher AStC-to-berth crane ratio when additional StCs are available. These results confirm the well-known conclusion that *pooling* of equipment shares the workload more evenly and achieves more uniform equipment utilization. However, there are two observations that may not be obvious:

1 The *gang* strategy has a much more consistent performance. No change in crane productivity between the typical and the contingency scenarios was observed; whereas with *pooling* the productivity drops in the contingency scenario, and
2 The gains in crane productivity with the *pooling* strategy in the contingency scenario are marginal (additional 1-2 moves/hour).

Due to the efficiency gains of the *pooling* strategy during the typical schedule (Scenario 1), the central pool option was selected for further analysis. The initial low AStCs utilization (43%) indicates that there may be space for reducing the fleet size.

In the second step of the analysis, simulations were run with the AStCs pool size gradually reducing from 64 to 32, to compare the effect on their utilization, total cycle time (*i.e.* service and waiting time) and crane productivities (see Table 1.7). It can be seen from the increase in average AStC cycle time that increasing the fleet size beyond 48 (*i.e.* 2.52 AStCs per crane) will only result in congestion and queuing at the berth, without any increase in quay crane productivity. Therefore, a fleet size of 50 AStCs (48 operating and two spares) was selected as the optimal fleet size for the particular layout, operations and quay crane arrangement, yielding the maximum crane productivity at the smallest fleet size for both the regular and contingency scenarios.

Table 1.8 shows the simulated average quay crane productivities with an equipment pool of 48 AStCs in operation, compared to the target STS crane productivities for both the deep-seaside and the barge side. Table 8, also shows the average crane waiting times. It can be seen that although they are slightly lower than the target, they are within the industry benchmark range PIANC-158 (2014) of 30-35

Table 1.7 AStCs utilization and quay crane productivities for a *pooling* strategy with two scenarios (1: typical and 2: contingency vessel schedule)

Scenario	**AStC Pool Size**	**AStC Utilization** [%]	**AStC Average Cycle Time** [min]	**Deep-sea STS Crane Productivity** [moves/hour]	**Barge Crane Productivity** [moves/hour]
Scenario 1	32	77	7	29	23
	40	68	9	31	24
	48	63	9	31	24
	56	57	9	31	24
	64	52	9	31	24
Scenario 2	32	78	6	27	20
	40	70	7	27	20
	48	65	9	29	22
	56	58	9	29	22
	64	52	9	29	22

moves/hour for high STS crane productivity. Additionally, it is shown that the average quay crane waiting time is consistently low (particularly for the contingency scenario), below 5% of the total. These additional operational indicators provide confidence in the selected fleet size.

Table 1.8 Simulated quay crane productivities and waiting times (1: an average and 2: a contingency vessel schedule)

Scenario	**Berth Type**	**Target Crane Productivity** [moves/hour]	**Average Crane Productivity** [moves/hour]	**Difference** [%]	**Average Crane Waiting Time** [%]
Scenario 1	Deep-sea	34	31	-9	3
	Barge	30	29	-4	3
Scenario 2	Deep-sea	34	29	-15	5
	Barge	30	26	-12	3

Compared to the other fleet sizing methods, Discrete Event Simulation not only yielded a 37% more economical fleet sizing (2.5 AStCs to a quay crane versus 4 vehicles, or 48 total versus 76), it also highlighted different aspects of the operations that would not be possible otherwise. Of course, these results come at the cost of additional time, data and complexity requirements.

1.5 Comparison of AStC Sizing Models

This section summarises the advantages and disadvantages of each of the previously considered methods and attempts to provide a recommendation for when they should be used. Queuing Theory formulations and practical examples are widely available, rendering them particularly easy to implement. Most publicly available implementations are approximate and moderately conservative, which makes them good candidates for preliminary fleet sizing. Additionally, they provide intuition regarding the uncertainty of the operations to the practitioner that wants more than first order (average) results. On the other hand, there are many different solutions available, and judgement should be exercised as to which queuing model is most representative of each particular problem. There is a trade-off between the sophistication of arrival and service time probability distributions and the number of servers and buffer positions in the currently available models, *i.e.* there are single-server, infinite-queue models with complex distributions, or multi-server, finite size models for Exponential arrival and service distributions. All these solutions describe steady-state queuing systems with non-deterministic rules, so more complex operating strategies can be intractable in their solving. Perhaps the model closest to the problem of fleet sizing of AStCs is a multi-server queue with limited size ($M/M/c/K$), as it can approximate the situation of the limited number of transfer positions (buffer) under the quay crane and the multiple AStCs (servers) transferring the containers between the yard and the apron. The results of this queuing model indicate 4 AStCs assigned to an STS crane, and having between three and four transfer points will keep the blocking probability within an acceptable range.

Petri Nets are visual-graphical tools that can be formulated to represent any Markovian (memoryless) System with discrete number functions, simple or complex. Their implementation in this example and in other automated horizontal transport applications (see *e.g.* Kim et al (2010); Liu and Ioannou (2002b); Li and Zhou (2009); Kezić et al (2007); Liu and Ioannou (2002a)) promises some cost efficiency and has advantages, such as visualization tools similar to flowcharts, block diagrams and networks for easy verification of the system examined, with direct display of its parts. An important contrast with Queuing Theory is that while it traditionally uses stochasticity for the arrival, service and departure stages, certain types of PNs such as the one utilized here have deterministic transition (travel, delay and service) times but random execution order of the transitions that are then realised during a certain deterministic time margin. In certain cases, such as when highly non-linear relationships are involved in basic system components it appears that PNs may not the most appropriate tool to tackle planning problems. However, it should be noted that PNs are a conceptual modelling tool first and foremost, and they have value as such.

Overall, PNs appear remarkably flexible and able to describe operation procedures, such as concurrent activities, precedence, priority and scheduling rules in a simple and graphical manner, something that neither Queuing Theory nor Discrete Event Simulation can do without significant mathematical and programming effort. Hence, their implementation merits consideration as a “middle road” between quickness of results and computational and modelling complexity. Nonetheless, PNs are not as easily accessible and well-understood yet to practitioners as Queuing Theory formulas, while there is still some computational effort required to obtain useful results. Perhaps the biggest hindrance to the more widespread implementation of PNs since the early 2,000s is the requirement to adapt the model representation to a Petri Net graph, whereas modern Discrete Event Simulation environments such as FlexSim, with customized application modules, allow a more natural representation. From the results obtained from PNs, 4 AStCs per quay crane appears as the optimum solution for both deep-sea and barge side berths. The authors' recommendation is that further development would be still required in an easily applicable tool for practitioners to use in current planning problems, but the methodology itself as the simple illustration herein demonstrated can provide results at a preliminary planning stage. It also has the capability as shown elsewhere (see Liu and Ioannou (2002a); Liu and Ioannou (2002b)) to model system logic and control relationships. It is hoped that openly available PN platforms such as PIPE2 become easy enough for practitioners to use and with sufficient complexity implemented to readily apply in actual container terminal problems.

Discrete Event Simulation models allow realistic investigation of any process in a container terminal, and a full evaluation of the performance of the layout, equipment and deployment strategy. However, this comes at the cost of additional time, data definition and processing and programming complexity, to the point that in current recommended practice (see *e.g.* Salt (2008)) it is best to tailor simulation solutions to answer specific questions than model a system in full realistic detail. Nonetheless, the rapid growth in the simulation software platforms and bespoke modules for container terminal applications of the last ten years has led to significant reduction in the effort required to create, debug, run and post-process the results of a representative simulation model. Compared to the other fleet size determination methods, Discrete Event Simulation yielded a significantly more economical fleet sizing (2.5 AStCs to a quay crane) but was also able to test and validate the most efficient operating strategy that would result in this sizing (*pooling*). It is, therefore, the authors' recommendation that Discrete Event Simulation can be readily used during the detailed planning phase of the container terminal, when sufficient time, resources and information from the end user is available to create a sufficiently detailed and validated model that takes advantage of the capabilities of the method. With all methods, their application to the Venice offshore terminal horizontal transport fleet size determination problem showed that judgement is required in setting and evaluating the appropriate performance criteria. For the preliminary fleet size determination, it is recommended to look at different metrics, as provided by each method, to obtain a better insight into which fleet size offers the best trade-off between initial cost, utilisation, and crane productivity.

1.6 Conclusions

This paper presented and compared multiple practical methods for addressing the horizontal transport equipment fleet sizing problem in container terminals. An additional contribution of this paper is the application and evaluation for the first time of Petri Nets as a method for horizontal transport planning and fleet sizing. The applicability of methods and their results and insights were compared and demonstrated in the planned Venice offshore container terminal, using AStCs as means of horizontal transport. It is concluded that while Queuing Theory is a mature field that can be applied with some approximation to the preliminary sizing problem, it is rather conservative. Discrete Event Simulation is also a mature method that can yield significantly more cost-efficient results and recommended for detailed design due to its time and information requirements. Further development would be still required in an easily applicable tool based on Petri Nets for practitioners to use in current planning problems, but the methodology itself can provide reasonable yet conservative results at a preliminary planning stage.

1.6.1 Acknowledgements

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References

AL [Alphaliner (ed)] (2018) Alphaliner TOP 100. https://alphaliner.axsmarine.com/PublicTop100/, accessed: September 01, 2018

Bonet P, Lladó CM, Puigjaner R, Knottenbelt WJ (2007) PIPE v2.5: A Petri Net Tool for Performance Modeling. In: Proceedings of the XXXIII Latin American Conference on Informatics

Cai B, Huang S, Liu D, Yuan S, Dissanayake G, Lau H, Pagac D (2013) Multi-objective optimization for autonomous straddle carrier scheduling at automated container terminals. IEEE Transactions on Automation Science and Engineering 10(3):711–725

Carlo HJ, Vis IF, Roodbergen KJ (2014a) Storage yard operations in container terminals: literature overview. European Journal of Operational Research 235(2):412–430

Carlo HJ, Vis IF, Roodbergen KJ (2014b) Transport operations in container terminals: literature overview, trends, research directions and classification scheme. European Journal of Operational Research 236(1):1–13

Carlo HJ, Vis IF, Roodbergen KJ (2015) Seaside operations in container terminals: literature overview, trends, and research directions. Flexible Services and Manufacturing Journal 27(2-3):224–262

Carteni A, de Luca S (2012) Tactical and strategic planning for a container terminal: modelling issues within a discrete event simulation approach. Simulation Modelling Practice and Theory 21(1):123–145

Causer AM (2014) BMT TITRON designs 'Mama Vessels'. http://www.bmt.org/news/2014/12/bmt-titron-designs-mama-vessels/, accessed: September 01, 2018

Chen C, Hsu W, Huang S (2003) Simulation and Optimization of Container Yard Operations: A Survey. In: Proceedings of International Conference on Port and Maritime R and D and Technology, pp 23–29

Di Meglio LJ, Sisson M (2013) Planning for the TraPac Automated Container Terminal. In: Proceedings of the 13th Triannual International Conference on Ports 2013, American Society of Civil Engineers, Reston (USA), pp 1882–1890

Dingle NJ, Knottenbelt WJ, Suto T (2009) Pipe2: A tool for the performance evaluation of generalised stochastic petri nets. ACM SIGMETRICS Performance Evaluation Review 36(4):34–39

Durrant-Whyte H, Pagac D, Rogers B, Stevens M, Nelmes G (2007) An autonomous straddle carrier for movement of shipping containers. IEEE Robotics & Automation 14(3):14–23

FlexSim [FlexSim Software Products (ed)] (2018) FlexSim CT. https://www.flexsim.com/flexsim-ct/, accessed: September 01, 2018

Gaussin (ed) (2018) Self-Driving Automated Vehicles. http://www.gaussin.com/self-driving-automated-vehicles/?lang=en, accessed: September 01, 2018

Gross D, Shortle JF, Thompson JM, Harris CM (2017) Fundamentals of Queueing Theory. Wiley, Hoboken

Haskoning [Royal HaskoningDHV (ed)] (2014) Royal HaskoningDHV Master Plan Delivers Major Efficiencies for Port of Venice Extension. https://www.royalhaskoningdhv.com/en-gb/news-room/news/20141211pr-master-plan-major-efficiencies-port-of-venice-extension/3346, accessed: September 01, 2018

Jensen K, Kristensen LM, Wells L (2007) Coloured petri nets and cpn tools for modelling and validation of concurrent systems. International Journal on Software Tools for Technology Transfer 9(3-4):213–254

Kalmar (ed) (2018a) Kalmar AutoShuttle. https://www.kalmarglobal.com/equipment/shuttle-carriers/autoshuttle, accessed: September 01, 2018

Kalmar (ed) (2018b) Kalmar AutoStrad^{TM}. https://www.kalmarglobal.com/equipment/straddle-carriers/autostrad/, accessed: September 01, 2018

Kalmar (ed) (2018c) Kalmar Shuttle Carrier. Data Sheet, Cargotec, Helsinki (Finland)

Kendall DG (1953) Stochastic processes occurring in the theory of queues and their analysis by the method of the imbedded markov chain. The Annals of Mathematical Statistics 24(3):338–354

Kezić D, Vujović I, Gudelj A (2007) Petri net approach of collision prevention supervisor design in port transport system. Promet – Traffic & Transportation 19(5):269–275

Kim W, Kim J, Kim K, Kwon H, Morrison J (2010) Capacity and Queueing Evaluation of Port Systems with Offshore Container Unloading. In: LOGMS 2010: Proceedings of the 1th International Conference in Logistics and Maritime Systems, National Research Foundation of Korea, Daejeon (South Korea)

Konecranes (ed) (2018a) AGV – Automated Container Transport for Performance-Orientated Terminals. http://www.konecranes.com/equipment/container-handling-equipment/automated-guided-vehicles/agv, accessed: September 01, 2018

Konecranes (ed) (2018b) Lift AGV. http://www.konecranes.com/equipment/container-handling-equipment/automated-guided-vehicles/lift-agv, accessed: September 01, 2018

Konecranes (ed) (2018c) Straddle Carriers. http://www.konecranes.co.uk/equipment/container-handling-equipment/straddle-carriers, accessed: September 01, 2018

Konecranes [Konecranes Noell Straddle Carriers (ed)] (2017) The All-Rounders Straddle Carriers. Technical Equipment Description, Konecranes, Hyvinkää (Finland)

Kumanan S, Raja K (2008) Modeling and simulation of projects with petri nets. American Journal of Applied Sciences 5(12):1742–1749

Law AM (2014) Simulation Modeling and Analysis. McGraw-Hill Education, New York

Lenka A, Das C (2012) A review of petri net modeling of dynamical systems. Indian Journal of Computer Science and Engineering 3(4):605–622

Li ZW, Zhou MC (2009) Deadlock Resolution in Automated Manufacturing Systems. Springer, Berlin

Liebherr [Liebherr Container Cranes Ltd (ed)] (2018) Technical Description Straddle Carrier. Technical Equipment Description, Liebherr-International AG, Bulle (Swiss)

Liu CI, Ioannou P (2002a) Petri net modeling and analysis of automated container terminal using automated guided vehicle systems. Journal of the Transportation Research Board 1782(1):73–84

Liu CI, Ioannou PA (2002b) A petri net based approach for agv dispatch scheduling and fleet size determination. IFAC Proceedings Volumes 35(1):19–24

Meisel F (2009) Seaside Operations Planning in Container Terminals. Springer, Berlin

Mrnjavac E, Zenzerović Z (2000) Modelling of port container terminal using the queuing theory. European Transport VI(15):54–58

Murata T (1989) Petri nets: properties, analysis and applications. Proceedings of the IEEE 77(4):541–580

Pachakis D, Libardo A, Menegazzo P (2017) The venice offshore-onshore terminal concept. Case Studies on Transport Policy 5(2):367–379

Park T, Choe R, Kim YH, Ryu KR (2011) Dynamic adjustment of container stacking policy in an automated container terminal. International Journal of Production Economics 133(1):385–392

PIANC-135 [MarCom Working Group 135] (2014) Design Principles for Small and Medium Marine Container Terminals. Technical Report No. 14, Permanent International Association of Navigation Congresses (PIANC), Brussels

PIANC-158 [MarCom Working Group 158] (2014) Masterplans for the development of Existing Ports. Technical Report, Permanent International Association of Navigation Congresses (PIANC), Brussels

Rodrigue JP, Comtois C, Slack B (2017) The Geography of Transport Systems. Routledge, New York

Saanen YA, Valkengoed MV (2005) Comparison of Three Automated Stacking Alternatives by Means of Simulation. In: Proceedings of the 37th Conference on Winter Simulation, INFORMS, Catonsville (USA), pp 1567–1576

Salt J (2008) The seven habits of highly defective simulation projects. Journal of Simulation 2(3):155–161

UNCTAD [United Nations Conference on Trade and Development (ed)] (2016) Review of Maritime Transport. Technical Report, United Nations, New York

VDL [VDL Containersystemen (ed)] (2018) Automated Guided Vehicle. `http://www.vdlcontainersystemen.com/?page/4496632/AGV.aspx`, accessed: September 01, 2018

Vis I, Harika I (2004) Comparison of vehicle types at an automated container terminal. OR Spectrum 26(1):117–143

Wiese J, Kliewer N, Suhl L (2009) A Survey of Container Terminal Characteristics and Equipment Types. Working Paper 0901, DS & OR Lab, Paderborn

Wiese J, Suhl L, Kliewer N (2011) Planning Container Terminal Layouts Considering Equipment Types and Storage Block Design. In: Böse JW (ed) Handbook of Terminal Planning, Springer, New York, pp 219–245

Zehendner E, Rodriguez-Verjan G, Absi N, Dauzère-Pérès S, Feillet D (2013) Optimized allocation of straddle carriers to reduce overall delays at multimodal container terminals. Flexible Services and Manufacturing Journal 27(2-3):300–330