A SIMULATION APPROACH FOR THE TRANSSHIPMENT OPERATIONS AT MARITIME CONTAINER TERMINALS

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ABSTRACT

Maritime container terminals must deal with multiple problems when serving the incoming container vessels. Simulation techniques can fill the gap between mathematically robust optimisation algorithms and the practical application of the solutions of these algorithms to real-world scenarios, where uncertainty may lead decision makers to rule out a number of the best analytical solutions. In this context, the main goal of this paper is to introduce a general scheme based on the combination of optimisation and simulation techniques to provide a set of feasible schedules of the container transshipment operations of an incoming container vessel at a maritime container terminal.

Keywords: simulation, optimisation, decision support system, port

1. INTRODUCTION

Serving the incoming container vessels is the main goal of maritime container terminals due to its economic impact. This means to unload a subset of the containers included into the stowage plan of each vessel arrived to the terminal, termed *import containers*. These containers must be temporarily stored on the yard of the terminal until their later retrieval by another transportation mean. At the same time, other containers, termed *export containers*, must be loaded into the vessels to be carried to subsequent terminals along a predefined shipping route (Gunter and Kim, 2006).

The transshipment operations (*i.e.*, loading and unloading containers) in the seaside of a maritime terminal are performed through a pre-established set of quay cranes (Legato, Trunfio, and Meisel, 2012). However, an appropriate schedule of the transshipment operations associated with the containers included into the stowage plan of each incoming vessel must be determined to provide an accurate estimation of the service quality to shipping companies and, thus, becoming attractive infrastructures for them. The potential number of operations that a quay crane can perform determines its working performance. In most cases, the quay cranes perform up to 25-30 moves per hour due to their technical characteristics (Chao and Lin, 2011). In spite of the latest technological advances, the practical performance of the quay cranes is highly influenced by many factors. These factors include the skills of the crane driver, the availability of internal delivery vehicles, and the interferences between quay cranes in the same berth, among others. However, in this case, it is assumed that the crane cycle corresponds to the time to unload/load a container from/to the incoming vessel. In the end, the interaction of the former factors leads to a scenario characterised by uncertainty, where the duration of the operations is not deterministic but stochastic.

Simulation techniques can fill the gap between mathematically robust optimisation algorithms, and the practical application of the analytical solutions reported by these algorithms to real scenarios, where uncertainty may lead the decision makers to rule out a number of the best analytical solutions. In this context, the main goal of this paper is to introduce a general scheme to provide a set of feasible schedules of the transshipment operations of an incoming container vessel in a maritime container terminal.

2. QUAY CRANE SCHEDULING PROBLEM

Determining an appropriate completion of the transshipment operations associated with an incoming container vessel in a maritime container terminal is formalised as an optimisation problem termed Quay Crane Scheduling Problem, in short QCSP.

Input data of the QCSP is composed of a set of n tasks, denoted as $\Omega = \{t_1, t_2, ..., t_n\}$, and a set of m quay cranes, denoted as $QC = \{qc_1, qc_2, ..., qc_m\}$. It is here assumed that the quay cranes have similar technical characteristics and differences between crane drivers in terms of skill and practice are not present. This means that quay cranes are able to perform the transhipment operations with the same working performance. Also, the movement time of the quay cranes is not negligible. Thus, a travel time is required to move a quay crane between two adjacent bays of the container vessel. In addition, each quay crane $q \in$

QC can operate after its earliest ready time r^q and is initially located on the bay l_0^q. Each task t ∈ Ω represents the loading or unloading operation of a set of containers located in a known bay of the vessel. Task t requires certain processing time, denoted as p_t, which derives mainly from the characteristics of the quay crane that performs it and the skills of its crane driver.

Unlike other classic scheduling problems (*e.g.*, job shop scheduling problem), the QCSP introduces a set of complex constraints that restrict the feasibility of the schedules and constitutes a challenge from the algorithmic standpoint. Firstly, the quay cranes are rail-mounted, in such a way that they cannot cross to each other. No impact on the individual working performance arisen from the interferences between quay cranes is considered in this work. In addition, they have to keep a certain safety distance between them to prevent potential collisions. This implies that some tasks cannot be performed simultaneously if they are located at a distance of less than the safety distance between pairs of quay cranes. Moreover, the transshipment operations require the support of a set of internal delivery vehicles aimed at moving the containers between the quay and the yard. Each internal delivery vehicle can be associated with any transshipment operation over the planning horizon, in such a way that a completely free vehicle-crane assignment policy is assumed. The time required to store/retrieve a container on/from the yard depends on the characteristics of the container and its freights, the vehicle, and the source/target location on the yard, among others.

It is worth mentioning that feasible solutions of the QCSP are schedules that determine the starting and finishing times of all the n tasks associated with the incoming container vessel while fulfilling the previous constraints of the optimisation problem. Also, movements and waiting times of the quay cranes are specified in each feasible solution. Lastly, it is assumed that the optimisation criterion of the QCSP seeks to minimise the service time of the container vessel in the remainder of this work.

The QCSP has been addressed in the scientific literature by several authors, especially over the last few years. In general terms, the proposals published so far can be mainly classified according to several criteria: container aggregation, technical characteristics of the quay cranes, level of potential interferences, and performance measure. The former makes reference to how the containers included into the stowage plan can be handled by the quay cranes. Tasks at the highest level of aggregation usually comprise all the containers located into a given bay. For example, this is the case of the work by Boysen, Emde, and Fliedner, 2012. At the lowest level of aggregation, tasks comprise individual containers of the stowage plan. This is the approach by Than, Zhao, and Liu, 2012, and that assumed in the present work. Also, the technical characteristics of the quay cranes have produced a wide range of relevant works. Some authors have studied the impact of the temporal availability of the cranes on the overall performance of the transshipment operations (Unsal O., Oguz C., 2013) whereas a few works consider the movement of the quay cranes as non-negligible (Lu, Han, Xi, and Erera, 2012). Furthermore, one of the distinguishing factors of the problem under analysis is the presence of potential interferences between adjacent quay cranes when performing the transshipment operations. In this regard, some authors include a safety distance in their proposals with the aim of avoiding risk situations. This is the case of the work by Chung and Chan, 2013. Lastly, the performance measure has given rise to the widest range of approaches to solve the QCSP. In this regard, some of the most relevant optimisation criteria are aimed at providing a fast service of the vessels (Lee and Chen, 2010), maximising the crane utilisation rate (Vis and Anholt, 2010). Finally, the interested reader is referred to the work by Bierwirth and Meisel, 2015 to obtain a comprehensive literature review of the QCSP and its related fields.

3. DESIGN OF THE DECISION SUPPORT SYSTEM

The present paper proposes a decision support system aimed providing high-quality solutions of the QCSP, while handling the inherent uncertainty of the environment. Figure 1 depicts the general structure of the proposed decision support system. As shown in the figure, this structure relies on two main components: an optimisation technique and a simulation model. The optimisation technique is an efficient implementation of an Estimation of Distribution Algorithm designed to solve the QCSP (Expósito-Izquierdo, González-Velarde, Melián-Batista, and Moreno-Vega, 2013). Furthermore, the simulation model of the decision support system is implemented using a process-oriented Java-based discrete-event simulation library (PSIGHOS), developed by the Simulation Group at the Universidad de La Laguna (Castilla, García, and Aguilar, 2009).

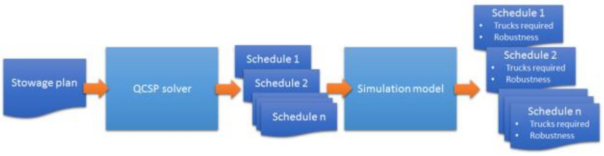

Figure 1. Basic schema of the decision support system

3.1. Optimisation technique

As indicated in the introduction of the paper, the QCSP has received a great deal of attention of the scientific community. In particular, one of the most competitive optimisation techniques to solve the QCSP so far is the Estimation of Distribution Algorithm proposed by Expósito-Izquierdo, González-Velarde, Melián-Batista, and Moreno-Vega, 2013. Broadly speaking, it is a meta-heuristic technique based on the principles of probability theory. In the case of the QCSP, this technique uses a probabilistic learning model to record statistical information about the search space, in such a way that the probability of performing a given task by means of a quay crane depends on the quality of the previous solutions in which this assignment has appeared.

Unfortunately, up to now the QCSP has been only addressed in the literature from a deterministic point of view, where no uncertainty of the environment is considered. In practice, a wide range of uncertainty sources affects the transshipment operations. Some of these are the individual productivity of the crane drivers, the changing arrival of the container vessels, and the availability of internal delivery vehicles, among others. In fact, one of the main unrealistic assumptions considered by previous authors relates to the full availability of internal delivery vehicles. Specifically, the works in the literature consider that there are always enough internal delivery vehicles to support the needs of the quay cranes assigned to the incoming container vessel. Therefore, each quay crane obtains a steady flow of containers.

3.2. Simulation model

Discrete-event simulation (DES) is a widespread simulation paradigm, especially common in the engineering field. DES is based on identifying the most relevant "milestones" that make the system state to change, i.e., the events. The most basic DES engine simply handles a time-ordered list of events by going through each event, updating a global simulation clock, and executing the actions associated to the event (which may include the creation or cancellation of future events) (Pidd, 2004). Although the "event worldview" is a flexible and mathematically robust conceptual framework, many problem statements benefit from a higher-level approach, such as that based on modelling the behaviour of the system as a set of interacting processes (Balci, 1988).

PSIGHOS (Castilla, García, and Aguilar, 2009) adheres to this process-oriented worldview, and allow a modeller to structure a real system in terms of "processes" and its atomic steps ("activities"). This approach makes easier the management of simulated resources (either human or material).

The designed discrete-event simulation model focuses on the quay cranes as the main entities of the system. Each quay crane starts at a specific position and has an associated process, comprising movements among adjacent bays and transshipment operations. The process is built from the schedule reported by the optimisation technique previously described when solving a QCSP instance.

The simulation model requires some additional adjustments and time parameters with respect to the QCSP solver. First, *tasks*, as defined by the QCSP solver must be divided into single transshipment operations, since every one requires a delivery operation to be completed. Each transshipment operation is assumed to last one time unit. Travel time, *i.e.*, the time that a quay crane spends moving from one bay to an adjacent one, is assumed to be equal to the operation time. Finally, delivery time, *i.e.*, the time that an internal delivery vehicle spends bearing the container to the yard and coming back to the incoming vessel, is assumed to be proportional to the operation time and can be set to any value K = {1, 2, 3, …}.

The simulation model includes some of the factors that affect crane performance:

- Interferences among quay cranes are included by explicitly modelling the physical position of the cranes. Each position represents a bay of the vessel, and is treated as a resource to avoid collisions among quay cranes. A crane can only move from one bay to an adjacent one as a single step of the workflow.
- Internal delivery vehicles are also treated as resources. In order to start a transshipment operation, the quay crane must be placed at the correct bay and seise an available delivery vehicle. Once the operation has finished, the vehicle moves to the yard and, after storing/retrieving the incumbent container, returns to the vessel and becomes available again.

We assessed the validity of the simulation model by checking that it was able to accurately reproduce the schedule of the optimisation technique, thus obtaining the same result.

The simulation model serves two different purposes. Firstly, it allows the decision-maker to estimate the minimum amount of internal delivery vehicles *dv* required to achieve the theoretical performance of the schedule reported by the optimisation technique. It is worth recalling that this estimation assumes deterministic duration of the tasks. The second purpose is to estimate the robustness of the solutions with respect to the variability of the estimated duration of tasks. We assigned a uniform error *e* to each time parameter *pt* (*i.e.*, transshipment operation, travel time, and delivery time). For each pair <stowage plan, number of delivery vehicles>, we replicated *k* times the simulation and collected the percentage of solutions below (or equal to) the deterministic result.

4. RESULTS

We analysed the decision support system for the instance represented in Figure 2. This instance defines a 21-bay container vessel requiring to perform 533 transshipment tasks. There are three quay cranes available to perform these tasks.

First, we run the QCSP solver, which obtained a set of feasible solutions. We took the best of those solutions to continue with the simulation analysis (Figure 3). Although the solution incorporates some potential interferences among cranes, they are distant enough in the time schedule so to result almost negligible. Hence, we would only expect delays in the schedule due to the unavailability of internal delivery vehicles.

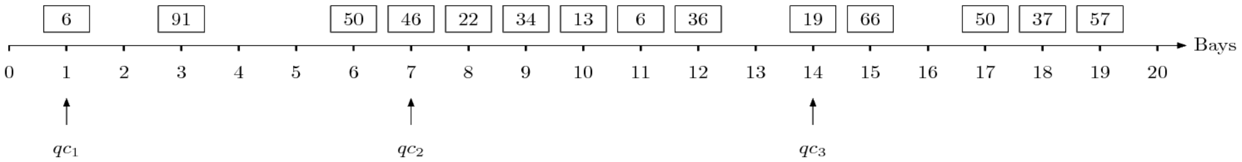

Figure 2. Tasks in the vessel. Each box represents a set of # load/unload tasks to be performed in this bay

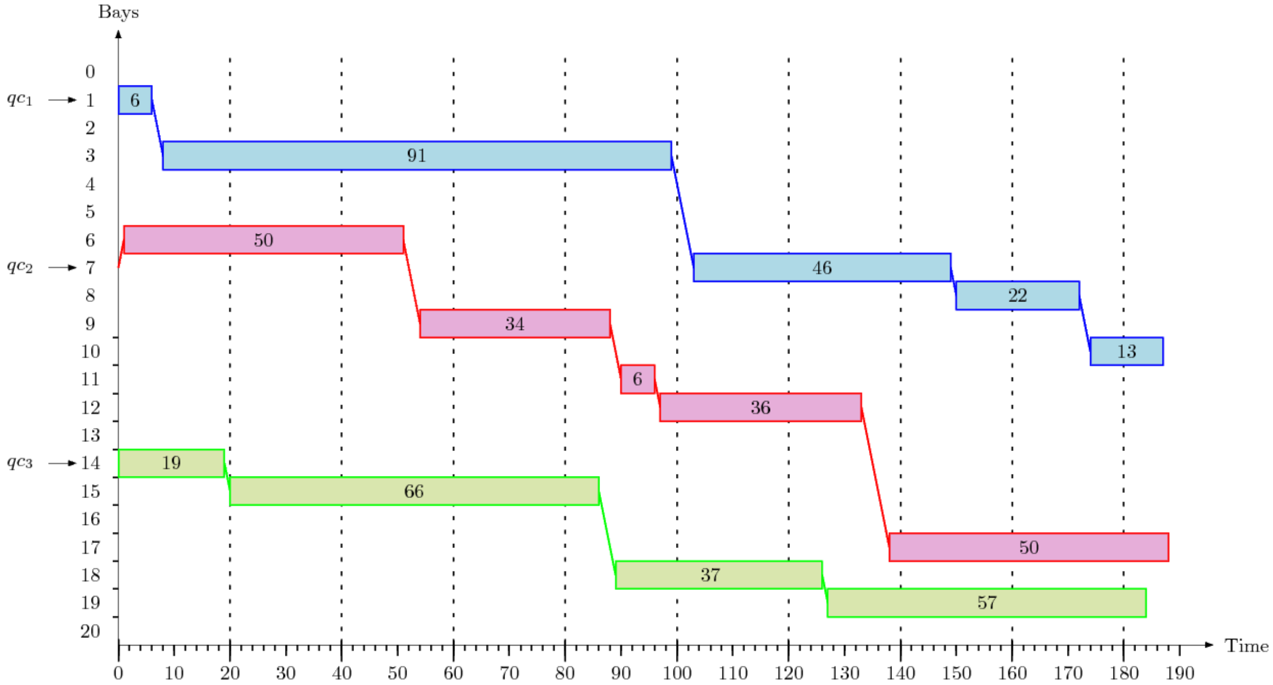

Figure 3. Best schedule reported by the QCSP Solver

Figure 4 shows a simplified schema of the simulation model obtained for the schedule of the first crane in the solution from the QCSP solver. Actually, the simulator splits “Transshipment Task 6” and “Transshipment Task 91” into a set of individual transhipment operations, each one lasting one time unit, and every one requiring a delivery vehicle.

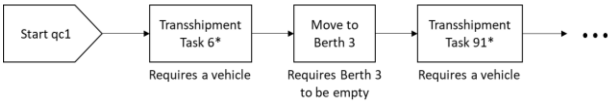

Figure 4. Simplified simulated process for quay crane 1

Table 1 summarises the main parameters set in the simulation analysis. We assumed the delivery time to be three times the operation time. Consequently, the whole load/unload operation takes 4 TUs.

In order to estimate the optimum amount of internal delivery vehicles, we run the simulation model for *dv = 1 to 16*. As seen in Figure 5, the case study requires at least 12 delivery vehicles to achieve the best solution posed by the QCSP solver (the dashed line). As it is expected, adding more vehicles does not provide any further reduction in the objective time.

Table 1: Main parameters of the simulation experiments

Parameter	Value
# Quay cranes	3
# Transshipment operations	533
# Bays	21
Operation time	1 TU
Delivery time	3 TUs
Travel time	1 TU
Percentage error for probabilistic analysis	25%
Replications per simulation experiment	500

TU: Time Unit

We observed the robustness of the solutions after adding a 25% uncertainty. Table 2 presents both the objective time and the average busy time of the quay cranes. The latest is an estimation of how balanced is the workload among cranes.

Table 2: Results of the Probabilistic Simulations

	Objective time			% average busy time of quay cranes	
# Delivery vehicles	Deterministic	Probabilistic (average [CI 95%])	Robustness	Deterministic	Probabilistic (average [CI 95%])
1	2129	2120.41 [2098.40, 2141.97]	80.60%	8.79%	8.75% [8.63, 8.85]
2	1065	1059.78 [1048.99, 1070.85]	83.40%	17.58%	17.51% [17.25, 17.73]
3	709	706.59 [699.28, 713.87]	76.40%	26.33%	26.26% [25.91, 26.60]
4	533	530.75 [525.26, 536.33]	81.40%	35.11%	35.04% [34.53, 35.49]
5	426	425.84 [421.27, 429.98]	54.00%	43.91%	43.70% [43.08, 44.25]
6	355	356.33 [352.50, 359.84]	24.40%	52.74%	52.24% [51.49, 52.94]
7	305	307.58 [304.07, 311.08]	8.00%	61.29%	60.64% [59.70, 61.43]
8	267	271.66 [268.53, 275.40]	0.00%	69.96%	68.77% [67.80, 69.67]
9	240	244.29 [241.18, 247.53]	0.00%	78.18%	76.53% [75.41, 77.48]
10	218	223.56 [220.04, 227.30]	0.00%	86.40%	83.66% [82.67, 84.64]
11	202	208.15 [205.08, 211.48]	0.00%	93.80%	89.99% [88.97, 91.02]
12	188	196.79 [194.00, 200.25]	0.00%	100.00%	95.18% [94.34, 95.98]
13	188	190.19 [187.02, 193.65]	9.60%	100.00%	98.50% [97.95, 99.02]
14	188	187.67 [184.67, 191.11]	63.00%	100.00%	99.80% [99.62, 99.95]
15	188	187.30 [184.09, 190.78]	69.80%	100.00%	99.99% [99.96, 100.00]
16	188	187.29 [184.09, 190.78]	70.00%	100.00%	100.00% [100.00, 100.00]

Det,: Deterministic

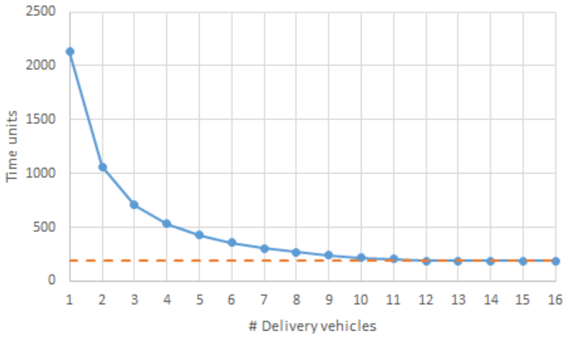

Figure 5. Results of the deterministic simulations

When a reduced number of vehicles is used, the objective time is high but it presents a remarkable robustness. These are configurations where there is a considerable room to improve the deterministic solution.

For solutions with a number of vehicles slightly lower or equal to (|QC| * 4), we find a robustness of 0%. The rationale behind this behaviour relies on two main aspects:

1. There is less room to improve the deterministic solution, since quay cranes are busier and objective value is closer to the optimum.
2. Any small discrepancy between the deterministic length of a task and its probabilistic value leads to a desynchronising pace. If a task lasts for more time than expected, there will be delays that will affect the whole schedule. Even more, if a task lasts for less time than expected, a crane will be preempting a delivery vehicle over another crane that is finishing its own tasks. Because we have less delivery vehicles than those expected to achieve the optimum (dv ≤ (|QC| * 4), this pre-emption prevents the simulated system to achieve the deterministic result.

When we assign more delivery vehicles than those stated in the deterministic analysis, the robustness improves until all the cranes are completely busy.

5. CONCLUSIONS AND FURTHER RESEARCH

The present paper introduces a decision support system that integrates an approximate optimisation technique and a simulation model to address the Quay Crane Scheduling Problem. This hybrid approach allows the decision-maker to estimate the minimum amount of internal delivery vehicles required to achieve the theoretical performance of schedules of the transshipment operations and to estimate the robustness of these solutions with respect to the variability of the estimated duration of tasks.

We have presented an example of the use of this system with a single QCSP solution. Dealing with multiple solutions is straightforward.

Although we have presented a synthetic case study, both the optimisation and simulation approaches are very flexible, and would allow a much more detailed specification of the optimisation problem. Indeed, the simulation model might include different specifications for quay cranes and internal delivery vehicles;

unexpected perturbations (*i.e.*, accidents, adverse meteorological conditions…); different strategies for the assignment of internal delivery vehicles to tasks, among others.

The simulation model described in this paper can handle non-null safety distances when reproducing the deterministic case. However, it is worth mentioning that when adding a probabilistic error, unexpected interferences among cranes might produce deadlocks in some realistic scenarios. Handling these deadlocks require providing the simulator with a number of decision rules. The application of these rules would result in a rescheduling, what is out of the scope of this work, but it is an interesting line to explore in further research.

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