Chapter 2
Ship Stability Considerations in the Quay Crane Scheduling Problem

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Abstract The aim of this paper is to present the recent literature that has advanced in the field of maritime logistics, specifically with regards to the consideration of vessel stability during the process of unloading and/or loading containers onto vessels. This process is essentially known as the Quay Crane Scheduling Problem (QCSP) which determines the operational profile of each quay crane in terms of the container tasks and timing. The literature on this and other problems pertaining to quayside operational planning is presented, before introducing the works with a contribution in ship stability. The works are described with insights into their formulation and solution techniques, as well as their contribution to the literature. Most importantly, the results are discussed and directions are provided for future work in the area.

2.1 Research in Maritime Logistics

The field of maritime logistics involves a number of important operational problems which have attracted the interest of researchers in recent years, due to continuously increasing volumes of containerized cargo. Attention is largely focused on quayside operations, which refer to the sequence of activities taking place from the arrival of a ship within the seaside of the port to the handling of its container load to the yard-side. High costs of berthing and container handling incurred on vessel operators, as well as the high costs of operating container terminal equipment create the need for efficient processes, able to accommodate the high demand at minimum cost [25].

Container terminals comprise four main areas, namely the quay, the buffer, the yard and the gate. An overview of the container terminal layout is presented in Fig. 2.1. The quay and the buffer areas are considered seaside, while the yard and gate areas are considered landside as can be found in [7]. Once a vessel is berthed, a certain number of quay cranes (QC) are employed to discharge import and transshipment containers from the vessel to the quay and/or load export and transshipment

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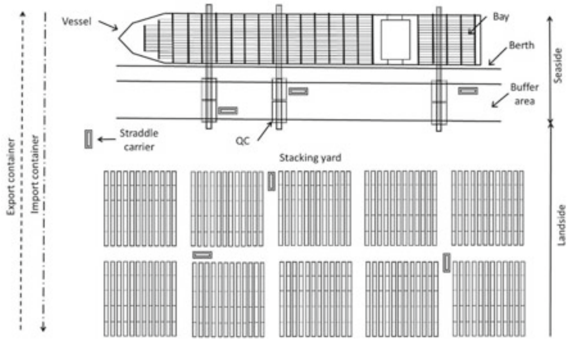

Fig. 2.1 Overview of container terminal layout

containers from the quay onto the vessel. The vessel is longitudinally divided into several bays and, each container is discharged from or loaded onto a given bay according to a stowage plan. Import, transshipment and export containers are temporarily stored in the container stacking yard. Import containers are transported from the quay to the stacking yard where they stay till being delivered to customers through the gate. Transshipment and export containers are stored in the stacking yard until the vessel that ships them to their next destination arrive. They are subsequently transported to the quay. Container transport from the quay to the stacking yard and vice versa is ensured by shuttle vehicles such as internal trucks, automated guided vehicles and straddle carriers [2]. For a more comprehensive overview on the layout of container terminals and, the handling and transport equipment, the reader can refer to [23] and **brinkman 2011**. Quayside problems include the Berth Allocation Problem (BAP) which determines the berths that incoming vessels are assigned to, the Quay Crane Assignment Problem (QCAP), whereby the required cranes are assigned to each ship, before scheduling of crane tasks can take place through the Quay Crane Scheduling Problem (QCSP).

The BAP is one of the well-studied problems in the literature of maritime logistics. It can be distinguished into the static BAP and dynamic BAP, depending on the assumed arrival profile of ships. The static case of the BAP is addressed by Simrin et al. [21], who develop a Lagrangian relaxation based approach for the problem, while the dynamic case is tackled by Arango et al. [7] and Schoonenberg et al. [19]. Other authors focus on service priority agreements between port and vessel operators [6, 11], and explicitly account for these in their formulations, as these are often very expensive agreements. Aside from containers terminals, the BAP has also been studied in the context of bulk ports [1], in which additional challenges arise with respect to the decision of a ship's berthing position, depending on the facilities and equipment required for the handling of various types of cargo.

The QCAP is frequently integrated with either the BAP or the QCSP, due to the strong interdependence with each of the aforementioned problems. An example of the integration of the BAP with the QCAP is the work of [15]. The QCSP is known to be the most complex among the three quayside operational problems, due to the fact that tasks must be scheduled while strict physical constraints are satisfied. Specifically, given that cranes travel on a single rail, non-crossing must be enforced at all times. In addition, cranes must be positioned at least certain bays apart to prevent interference. Therefore, the QCSP is inherently complex, leading the majority of researchers to develop heuristic techniques to tackle it.

The first notable work on the QCSP is that of [13], who develop a branch-and-bound and a Greedy Randomized Adaptive Search Procedure (GRASP) to solve the problem with the objective of minimizing the weighted sum of the makespan and QCs completion times. Their model was later refined by Moccia et al. [17] who account for safety margin constraints in a more stringent way and solve medium and large instances of the problem using branch-and-cut (B&C). Other heuristics used include Tabu Search (TS) [18], tree-search-based heuristics [16] and Genetic Algorithm (GA) [14], among others. As far as exact techniques are concerned, [12] develop a Branch-and-Price algorithm to solve the problem to optimality.

Due to the strong interdependency between all three problems pertaining to quay-side operations, and especially between the assignment and scheduling problem, researchers have investigated the integration of these two problems, rather than treating them only sequentially. The resulting problem is known as the integrated Quay Crane Assignment and Scheduling Problem (QCASP), for which researchers have presented novel approaches both in terms of problem formulation and solution techniques that aim to effectively and efficiently solve this inherently complex problem. Integration consistently leads to better results but it comes at the cost of increased computational intensity, which is an issue that many researchers attempt to address. Diabat and Theodorou [8, 22] try to overcome the complexity of the integrated problem by transforming crane scheduling into a crane-to-bay allocation problem and solve the problem using heuristics, namely a Genetic Algorithm (GA) and Lagrangian-relaxation based heuristic, respectively. The authors assume a uni-directional crane movement to model the problem. Bi-directional movement is adopted by Fu et al. [10] and Fu and Diabat [9] who also solve the integrated QCASP using a GA and Lagrangian relaxation-based heuristic, respectively. Other researchers, such as [19] approach the integrated QCASP from a cost perspective, aiming to indicate the impact of load time cost on vessel's prioritization. The authors allow for adjustable QC operational costs as well as adjustable working rates, as quay cranes are not necessarily identical.

The continuous advancement of research gives rise to more practical operational aspects which were not previously considered. One such aspect is the issue of vessel stability during the process of handling a container vessel, which is presented in more detail in the following section, both in terms of problem description and literature contribution.

2.2 Ship Stability Consideration

To provide a visual illustration of the significance of ship stability, Fig. 2.2 depicts the great imbalance that can be caused in the case of uneven container weight distribution across the vessel. The stability of the vessel is violated if the vessel's center of

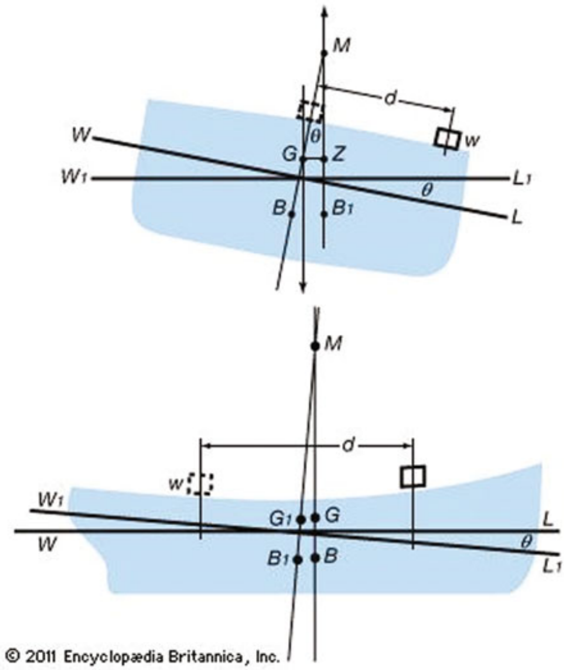

Fig. 2.2 Illustration of imbalance during container loading/unloading process

gravity shifts too much toward one side during the loading or unloading process. This shift results from workload distribution along the vessel and the sequence of operations. Henceforth the QCSP should consider vessel stability constraints to allow for obtaining QC schedules that can be used in practice.

In 2013, [24] produced the first paper that highlighted the importance of considering vessel stability in the QCSP. Wang et al. [24] incorporate vessel stability into a mixed integer program (MIP) and develop a Genetic Algorithm (GA) to solve the problem. The GA discards any QC schedule that violates the QCSP constraints, including those related to vessel stability.

Al-Dhaheri and Diabat [2] develop a Mixed Integer Program (MIP), in which they implicitly account for vessel stability by minimizing the differences between the container loads stacked over a number of bays and by maintaining a balanced load across all bays. Furthermore, this MIP accounts for important considerations such as the bidirectional movement of cranes and the ability to move between bays even before completion of all container tasks. The increased complexity of these additional considerations is offset by the simple objective, and overall the model is proved to successfully address the vessel stability issue and it is solvable for small- to medium-sized instances. While typically in the literature the objective of the QCSP is to minimize the "makespan" of the QC schedule, the contribution of the aforementioned paper is that it proves that this objective is equally served by ensuring sufficient balance of the workload distribution among the cranes.

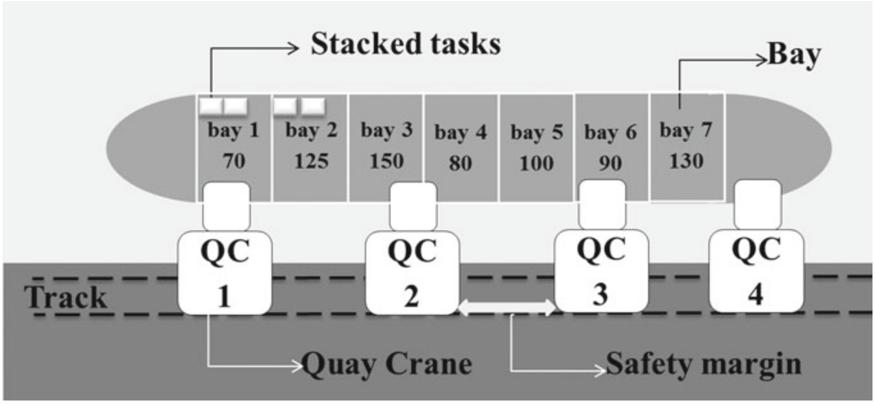

Fig. 2.3 Graphical illustration of the container weight distribution during the QCSP

Unlike the majority of models developed in the literature, the current model allows for QCs to travel between bays, even before the container tasks at that bay are completed. In fact, this is readily implemented in practice because this extra degree of freedom allows for better solutions. This leads to a model that better reflects real-life circumstances, as long as the non-crossing constraints are maintained at all times. Given the fact that the time required for cranes to travel between bays is negligible, compared to the handling times, it is not taken into consideration. However, the authors illustrate how this can be easily incorporated as an extension to the model. The authors also relax the restriction of unidirectional crane movement that is frequently adopted by researchers. Thus, the authors allow for fully taking advantage of the assumption that cranes can move between bays, even before the completion of all container handling at the currently assigned bay. Finally, identical service rates are assumed for all cranes, but once again the authors demonstrate that the formulation can be modified to account for variability in service rates.

Figure 2.3 provides a graphical illustration of the problem, depicting the sequential indexing along the quay for both bays and cranes, the rail upon which cranes are mounted, the safety margins between adjacent cranes, as well as the stacked containers on the first bay. When dividing the vessels into bay areas, the safety margin between two adjacent QCs can be implicitly taken into consideration; hence the safety margin has not been incorporated into this model.

The authors conduct a computational analysis through which several important insights are drawn: first of all, a lower number of cranes with higher efficiency is a preferred option compared to a higher number of cranes with lower efficiency. A second conclusion is that changing the distribution of container workload across bays has an impact on the total handling time required to serve the vessel; in fact, the greater the standard deviation of the container workload difference between bays, the greater the handling time required. Another interesting observation made by the authors' analysis is that reordering of container workload does not have an impact on the handling time, but it actually has a great impact on the CPU time. While this may not be significant for small problem instances, it does become the case when applied to real-life problem sizes. In addition, the authors examined the effect of increasing the number of bays, while maintaining the same workload and concluded that a larger number of bays do not lead to a lower handling time, as would be expected due to the fact that more bays allow for more flexible movement of QCs. As a final remark, the authors note that increasing the problem size leads to an exponential increase in CPU time, thus rendering the model more appropriate for small and medium rather than large sized problems.

In the work of [4] the authors aim to explicitly rather than implicitly consider vessel stability. Once again, a novel MIP is developed that is very flexible in handling various settings of the QCSP, such as those related to crane traveling time, task preemption, and the unidirectional quay crane operating mode. While the MIP formulation provides an optimal unidirectional schedule for all considered small-sized problem, in relatively reasonable time, it does not return the optimal solution for all these instances. Moreover, the experimentation of the MIP formulation on small-sized problems and the use of the proposed lower bound (LB), highlight the interest for adopting a search strategy focused on unidirectional schedules.

A Genetic Algorithm is also designed to solve the problem. The GA embraces the unidirectional search strategy. It provides optimal unidirectional schedules for all small-sized instances within significantly lower time than the one required by GAMS. Furthermore, for medium and large size instances, where GAMS fails to solve the problem, the GA returns a near-optimal solution within a reasonable computational time. This promotes the use of the proposed GA as a solution approach for the considered QCSP, especially for medium and large sized instances.

One aspect that remains to be addressed is the inherent uncertainty associated with the scheduling problem. This is addressed in the work of [4], who develop a formulation that incorporates the randomness related to the handling rates and idle times of quay cranes and stacking cranes. The objective is to minimize vessel handling time while considering the entire container handling process involving both seaside operations and container transfer operations, tasks that take place between the quay and the stacking yard. A stochastic mixed integer programming model is proposed and a simulation based Genetic Algorithm (GA) is applied to construct QC schedules that account for the dynamics and the uncertainty inherent to the container handling process. The proposed GA framework embeds a simulation model to evaluate the fitness of each chromosome. The proposed algorithm is tested under both stochastic and deterministic circumstances. The obtained solutions are furthermore evaluated more accurately using the simulation model with a larger sample size. Simulation results show that the algorithm provides better QC schedules when it is used under stochastic environment. However, the algorithm incurs much larger computational time when it is used under stochastic environment than when it is used under deterministic environment.

The authors point out that the intended QC performance in terms of utilization rate cannot be reached without employing a sufficient number of Straddle Carriers (SCs). Moreover, the results highlight the significance of using a simulation model to obtain more realistic and reliable performance of the QC schedules returned by the algorithm under deterministic environment. Computational experiments demonstrate satisfactory results of the proposed algorithm and stress the importance of simulation in obtaining more reliable estimates of QC schedule performance.

The final model presented in the current review is that of [3], which encompasses three major contributions: first, to develop a new and more tractable optimization model for the single-vessel QCSP with vessel stability constraints; secondly, to extend this model to the multiple-vessel QCSP; and thirdly, to design an efficient solution algorithm that is capable of solving real-sized instances of the problem. In order to achieve these research milestones, the QCSP is initially formulated for the single vessel case, with the objective of minimizing the makespan without considering stability constraints. After devising a new formulation for the single vessel case (whose performance is evaluated against benchmark formulations of the literature), the authors use its solution in another optimization problem that considers the stability constraints. Then they extend the model to the multiple vessel case, which is solved with the help of Lagrangian relaxation, whereby the problem is decomposed by vessel and each is solved efficiently as a single vessel case. The Lagrangian subproblems don't have the integrity property, and therefore the solution of the Lagrangian subproblems provides a lower bound, that is at least as good as the linear programming relaxation bound, on the optimal value of the original problem. The Lagrangian multipliers are updated using the cutting plane method and the solution of the Lagrangian master problem provides an upper bound on the optimal value of the Lagrangian lower bound. Upper bounds on the optimal value of the original problem objective function are obtained using a constructive heuristic, and through computational experiments we demonstrate the performance of the Lagrangian relaxation-based procedures.

First the authors present the single ship case: for a given ship, and a number of identical quay cranes (QCs) Q, the aim of the QCSP with ship stability considerations is to schedule the work of cranes in a way that all tasks are performed. A task is defined on the basis of the unloading or loading operation of a single container. Preemption is permitted, as a single bay can be assigned to multiple QCs for the handling of its containers. However, at any time, there can be at most one QC working on any bay. This is enforced through what are known as interference constraints. In addition, all QCs travel on a single rail along the quay, which implies that crossing is not allowed. We assume that the traveling time between two consecutive bays is constant, and identical for all QCs. A safety margin is also maintained which is measured by the minimum distance in bays between adjacent QCs.

The authors extend the formulation from the single ship to the multi ship case, assuming in this case that the berthing order is known for the ships to be handled, i.e. the static case of the problem is addressed. In addition, they assume that cranes can move between ships, which means it is not necessary for a crane to complete all operations at the current ship before moving on to the next.

2.3 Outlook and Future Work

As far as future research is concerned, there is great potential for expansion of the models presented addressing the issue of ship stability. There are several assumptions that can be easily included, such as a non-constant productivity rate for cranes and the consideration of the travel times required for cranes to travel between bays. In addition, non-identical container weights could be assumed, as is the case in practice, which would pose additional modeling challenges in terms of weight distribution. Another modeling contribution would be to assume both unloading and loading operations.

This work can be further enhanced by integrating the QCSP with stability constraints with the Berth Allocation Problem (BAP). Until now this has been a challenge in the field, due to the very high complexity of the integrated problem. However, extending the current formulation and implementing a similar solution approach could lead to an efficient solution of the problem. A future direction for the solution approach could be to apply Branch & Price (B&P) to solve the single ship problem with stability constraints in one stage rather than in a two stage approach involving a heuristic. Then, the multi-ship problem would be solved once again with Lagrangian relaxation and with the subproblems solved using B&P.

For a truly comprehensive formulation, other aspects of container terminal operations could be accounted for, such as yard congestion. This occurs when the yard storage areas are overly accessed by vehicles transporting containers to respective stacks. An interesting extension would be to consider lateral in addition to horizontal stability, which would require a three dimensional approach to the problem. Finally, the QCSP could be combined with the Container Relocation Problem (CRP), which involves placing container on other bays while containers deeper in the stack of the current bay are being accessed. Also, given that the QCs represent one of the major valuable resources at container terminals, it is worth further investigating the SCs to assign to each QC while taking into account more details regarding yard congestion and containers' stack location. Also, it could be useful to investigate other SCs deployment strategies such as pooling, where SCs are assigned to vessels rather than to QCs. Thus, within a pooling strategy, any SC can serve any QC assigned to the vessel.

As far as solution techniques are concerned, more heuristics can be developed and compared to the existing ones, in terms of performance and efficiency. Finally, conducting tests on real-life instances that have been used by other works and benchmarking them would be extremely beneficial in terms of comparatively evaluating the model and ultimately judging its appropriateness for use by container terminal operators.

References

1. Al Hammadi, J., Diabat, A.: An integrated berth allocation and yard assignment problem for bulk ports: formulation and case study. RAIRO Oper. Res. (2017) (in press)
2. Al-Dhaheri, N., Diabat, A.: The quay crane scheduling problem. J. Manuf. Syst. **36**, 87–94 (2015)
3. Al-Dhaheri, N., Diabat, A.: A Lagrangian-relaxation-based heuristic for the multiship quay crane scheduling problem with ship stability constraints. Ann. Oper. Res. (2016)
4. Al-Dhaheri, N., Jebali, A., Diabat, A.: A simulation based Genetic Algorithm approach for the quay crane scheduling under uncertainty. Simul. Model. Pract. Theory **66**, 122–138 (2016a)
5. Al-Dhaheri, N., Jebali, A., Diabat, A.: The quay crane scheduling problem with nonzero crane repositioning time and vessel stability constraints. Comput. Ind. Eng. **94**, 230–244 (2016b)
6. Alzaabi, S., Diabat, A.: On the berth allocation problem. RAIRO Oper. Res. **50**(3), 491–501 (2016)
7. Arango, C., Corts, P., Onieva, L., Escudero, A.: Simulation-optimization models for the dynamic berth allocation problem. Comput. Aided Civil Infrastruct. Eng. **28**(10), 769–779 (2013)
8. Diabat, A., Theodorou, E.: An integrated quay crane assignment and scheduling problem. Comput. Ind. Eng. **73**, 115–123 (2014)
9. Fu, YM., Diabat, A.: A Lagrangian relaxation approach for solving the integrated quay crane assignment and scheduling problem. Appl. Math. Model. **39**(3–4), 1194–1201 (2015)
10. Fu, YM., Diabat, A., Tsai, IT.: A multi-vessel quay crane assignment and scheduling problem: formulation and heuristic solution approach. Expert Syst. Appl. **41**(15), 6959–6965 (2014)
11. Imai, A., Nishimura, E., Papadimitriou, S.: Berth allocation with service priority. Transp. Res. Part B: Methodol. **37**(5), 437–457 (2003)
12. Kenan, N., Diabat, A.: A branch-and-price algorithm to solve a quay crane scheduling problem. Proc. Comput. Sci. **61**, 527–532 (2015)
13. Kim, K.H., Park, Y.M.: A crane scheduling method for port container terminals. Eur. J. Oper. Res. **156**(3), 752–768 (2004)
14. Liang, C., Huang, Y., Yang, Y.: A quay crane dynamic scheduling problem by hybrid evolutionary algorithm for berth allocation planning. Comput. Ind. Eng. **56**(3), 1021–1028 (2009)
15. Lu, Z., Han, X., Xi, L.: Simultaneous berth and quay crane allocation problem in container terminal. Adv. Sci. Lett. **4**(6–7), 2113–2118 (2011)
16. Meisel, F.: The quay crane scheduling problem with time windows. Naval Res. Logist. (NRL) **53**(1), 45–59
17. Moccia, L., Cordeau, JF., Gaudioso, M., Laporte, G.: A branch-and-cut algorithm for the quay crane scheduling problem in a container terminal. Naval Res. Logist. **53**(1), 45–59 (2006)
18. Sammarra, M., Cordeau, JF., Laporte, G., Monaco, MF.: A Tabu search heuristic for the quay crane scheduling problem. J. Sched. **10**(4–5), 327–336 (2007)
19. Schoonenberg, W., Hols, J., Diabat, A.: A cost based approach for a crane assignment and scheduling problem. In: International Conference on Industrial Engineering and Systems Management (IESM), 21–23 Oct 2015, Seville, Spain
20. Simrin, A., Diabat, A.: The dynamic berth allocation problem: a linearized formulation. RAIRO Oper. Res. **49**(3), 473–494 (2015)
21. Simrin, A.S., Alkawaleet, N.N., Diabat, A.H.: A Lagrangian relaxation based Heuristic for the static berth allocation problem using the cutting plane method. In: Proceedings of the 15th International Conference on Enterprise Information Systems, pp. 565–569 (2013)
22. Theodorou, E., Diabat, A.: A joint quay crane assignment and scheduling problem: Formulation, solution algorithm and computational results. Optim. Lett. **9**, 799–817 (2015)
23. Vo, S., Stahlbock, R., Steenken, D.: Container terminal operation and operations research—a classification and literature review. OR Spectrum **26**(1), 3–49 (2004)
24. Wang, J., Hu, H., Song, Y.: Optimization of quay crane scheduling constrained by stability of vessels. Transp. Res. Rec.: J. Transp. Res. Board **2330**(1), 47–54 (2013)
25. Zeng, Q., Diabat, A., Zhang, Q.: A simulation optimization approach for solving the dual-cycling problem in container terminals. Marit. Policy Manag. **42**(8), 87–94 (2015)

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