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Functional integration approach for the berth allocation, quay crane assignment and specific quay crane assignment problems

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ABSTRACT

In container terminals, the integrated planning of berth allocation and quay crane assignment problems has attracted much attention in literature. These problems can be integrated either by functional integration or by deep integration approaches. In the functional integration approach, these problems are integrated by being divided into two sub-problems and a feedback loop is used to interconnect them. A presumed vessel handling time is used for each vessel at first to initiate the integration mechanism. The functional integration approach achieves the required performance of each problem and is less complicated compared with the deep integration in which the two problems are merged into a unified model. However, the sensitivity of the solution to the assumed vessel handling time and the non-convergence to a stable state are the weak points of the functional integration approach. This paper presents a new functional integration approach for the following problems: berth allocation, quay crane assignment and specific quay crane assignment. Numerical experiments are conducted to test the performance of the proposed approach. The results illustrate that the proposed approach shows no sensitivity to the presumed handling time and a significant improvement in the convergence to stable state. Compared to a unified model from literature, the effectiveness of the proposed approach is investigated. In addition, by using actual container terminal data, the applicability of the proposed approach is demonstrated.

1. Introduction

The development of containerized shipment provided cheap and fast transport of goods around the world. Therefore, containerized trade grew with an average annual rate of 6.5% from 1996 to 2013 (UNCTAD, 2014). Moreover, the share of containerized trade in the total volume of global trade increased from 22% in 1980 to 67% in 2012 (Chiang, 2013). This drastic growth and the competitive environment together put more pressure on container terminals to improve their performance. Therefore, the optimization of container terminal operations has been paid increasing attention in the scientific literature over the last few years.

Container terminal operations can be grouped into quay side, transfer, yard and gate operations (Voß, Stahlbock, & Steenken, 2004). In this paper, we concentrate on the integrated planning of quay side operations. Planning decision problems at the quay side include the Berth Allocation Problem (BAP), the Quay Crane Assignment Problem (QCAP), the Specific Quay Crane Assignment Problem (SQCAP) and the Quay Crane Scheduling Problem (QCSP). In the BAP, the berthing position, berthing time and departing time of each vessel are determined using estimates of the vessels' handling times and taking into account temporal and spatial constraints. In the QCAP, the vessel handling times are calculated based on a number of QCs assigned to each vessel, the number of containers to be handled and the average productivity of quay cranes (container moves/hour), taking into account the quay crane capacity of the terminal. The SQCAP follows the QCAP and determines the specific quay cranes to serve each vessel. The QCSP follows the quay crane assignment problem and determines the detailed schedules of the assigned quay cranes by providing the sequence of container unloading and loading operations on each vessel that a quay crane is supposed to perform. This paper specifically addresses the integration of the Berth Allocation Problem (BAP), the Quay Crane Assignment Problem (QCAP) and the Specific Quay Crane Assignment Problem (SQCAP). Fig. 1 shows the inputs and outputs of these three problems as well as their interrelations.

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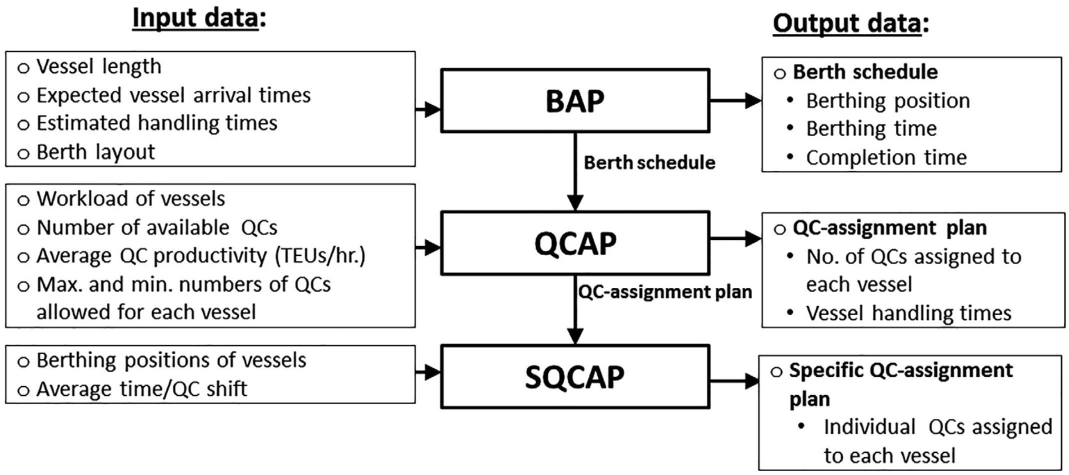

Fig. 1. Planning of berth allocation and quay crane assignment in container terminal.

These problems are typically solved independently as suggested by initial research. However, the planning decisions of berth allocation and quay crane assignment problems are tightly interrelated as the handling times of vessels, which are input to the BAP, can be determined by the QCAP. On the other hand, the berth schedules of vessels (berthing time, berthing position and departing time) which are input to the QCAP are determined by the BAP. For this reason, current research trends in container terminal management are focusing on the integrated planning of quay side operations. Efficient planning of quay side operations directly affects the vessel turnaround time which is the most important performance measure for rating container terminals.

In general, there are two main approaches for integrating sub-problems, namely the deep integration approach and the functional integration approach (Geoffrion, 1994). The deep integration approach involves merging the sub-problems into a unified model. For example, the BAP and the QCAP can be deeply integrated by unifying them into one problem of berth allocation and quay crane assignment. In the functional integration approach, the sub-problems are divided into a top level problem and a base level problem according to the hierarchical relation between them. To integrate the two levels, an integration mechanism is constructed between them. The integration mechanism includes a coupling variable, i.e. the shared variable between the sub-problems and a feedback loop. For example, the vessel handling time is used as a coupling variable to functionally integrate the BAP and the QCAP. To initiate the integration mechanism, the vessel handling times are presumed to solve the BAP which determines the berth schedule for the vessels. The berth schedule is then input to the base level problem (QCAP), in which the handling time for each vessel is determined. The results of the QCAP are returned again to the BAP by the feedback loop. The vessel handling times are updated in such way until this loop terminates once the iterative approach converges to the stable state at which the same berth schedule is obtained in successive iterations.

Compared with the deep integration approach, many merits of the functional integration approach are reported in literature (Yang, Wang, & Li, 2012). The most important merits are the reduced complexity, the flexibility to consider more practical issues and the consideration of the performance of each problem. However, the sensitivity of the solution to the assumed handling time as well as the non-convergence to a stable state, are still weak points in the existing approaches (Meier & Schumann, 2007; Yang et al., 2012).

In this paper, we introduce a new functional integration approach for the BAP, QCAP and SQCAP. There is only one functional integration approach for the BAP and the QCAP proposed by Yang et al. (2012). In the approach of Yang et al., practical aspects related to the quay crane assignments are ignored such as the time-variant QC assignments. The consideration of the time-variant QC assignments well improves the solutions as will be illustrated in Section 4.3. In addition, we include the SQCAP in the proposed approach. To investigate the performance and the applicability of the proposed approach, comparisons of the proposed approach with the optimal solutions of two different deep integration approaches proposed by Meisel and Bierwirth (2009) and Türkogulları, Taskın, Aras, and Altınel (2014) are conducted.

The remainder of this paper is organized as follows: Section 2 provides a review of related studies in recent years. Section 3 discusses the frame work of the proposed approach. Numerical experiments are introduced in Section 4. The conclusions and recommendations are in the last section.

2. Literature review

In this section, we review only studies related to the integration approaches of the quay side operations. The BAP is classified according to the berth layout and the arrival of vessels. According to Bierwirth and Meisel (2015), there are three cases for the berth layout, namely discrete, continuous and hybrid berth layout. In the discrete layout, the quay is divided into a finite set of sections, called berths, and only one vessel is allocated a single berth at time. Moreover, the lengths of the single berths are usually different. In the continuous case, the quay is divided into equally sized berthing sections and each vessel is allocated a number of berthing sections equal to the vessel length, a safety distance should be included among vessels when they are berthed adjacently. The continuous case provides better utilization of the quay as two vessels, if their length together is less than the length of a single berth, can be berthed simultaneously at it. The hybrid berth layout is similar to the discrete berth layout but a number of small vessels can be served at a single berth, while a large vessel can be served at a number of berths. Besides the berth layout, the BAP can be further classified according to the arrival time of vessels which can be static or dynamic. The static case assumes that all vessels are already in the port when the berth allocation is planned, whereas the dynamic case restricts the earliest berthing times of vessels such that vessels can't be berthed earlier than its arrival time.

Quay crane assignment is also classified into the time-invariant quay crane assignment and the time-variant quay crane assignment. In the time-invariant quay crane assignment, the number