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Invited Review

A follow-up survey of berth allocation and quay crane scheduling problems in container terminals

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ABSTRACT

This paper surveys recent publications on berth allocation, quay crane assignment, and quay crane scheduling problems in seaport container terminals. It continues the survey of Bierwirth and Meisel (2010) that covered the research up to 2009. Since then, there was a strong increase of activity observed in this research field resulting in more than 120 new publications. In this paper, we classify this new literature according to the features of models considered for berth allocation, quay crane scheduling and integrated approaches by using the classification schemes proposed in the preceding survey. Moreover, we identify trends in the field, we take a look at the methods that have been developed for solving new models, we discuss ways for evaluating models and algorithms, and, finally, we light up potential directions for future research.

1. Introduction

This contribution presents an update of our article 'A survey of berth allocation and quay crane scheduling problems in container terminals' which has been published in Bierwirth and Meisel (2010). The literature dealing with seaside operations planning in container terminals was connectedly reviewed in that paper for the first time, delivering an overview and classification of existing optimization models and solution methods. With the paper at hand, we carry on this project in order to reflect the bulk of new research published in the field throughout the last five years.

The rapid improvement of management techniques for the seaside operations in container terminals does definitely not stand alone. Important developments are also observed in related areas of port logistics and maritime transportation. A broad overview of port-related research including topics like port policies, port competition, and port development is provided by Woo, Pettit, Beresford, and Kwak (2012). An overview of the various operational planning issues faced by the management of container ports is provided by Goodchild, Zhao, and Wygonik (2010) and Rashidi and Tsang (2013). In a series of survey papers Carlo, Vis, and Roodbergen (2013, 2014a, 2014b) review the literature on seaside operations, transport operations and storage yard operations in container terminals. They also describe current trends driven by technological advancements as well as possible avenues for future research. An overview of modern equipment and performance figures of numerous container terminals in the world is given by Wiese, Kliewer, and Suhl (2009). Another overview of Lehnfeld and Knust (2014) considers the problem of loading and unloading container stacks as is faced in yard operations and stowage planning. Simulation studies that investigate the impact of management decisions on the performance of container terminals are reviewed by Angeloudis and Bell (2011) and Rashidi and Tsang (2013). Recent surveys on the design of liner shipping networks and the tactical management of a fleet of container vessels are given by Christiansen, Fagerholt, Nygreen, and Ronen (2013), Pantuso, Fagerholt, and Hvattum (2014), and Tran and Haasis (2013). Also some recent special issues of scientific journals like *Flexible Services and Manufacturing Journal* 23(4), 24(3), 25(4), *European Journal of Operational Research* 235(2), and *Transportation Science* (in press) provide good insight into the broad scope of topics currently considered in the area of maritime logistics.

Seaside operations planning in container terminals basically comprises the *berth allocation problem* (BAP), the *quay crane assignment problem* (QCAP), and the *quay crane scheduling problem* (QCSP). The decisions made when solving these problems are highly interrelated. Together they determine the port stay times of container vessels, which basically reflect the service quality promised to shipping companies and thus the competitiveness of a terminal as a whole. Consequently, the optimization problems involved in seaside operations planning are paid increasing attention in the operations research and transportation research literature. We have reviewed the reached state of this literature up to 2009 in Bierwirth and Meisel (2010). The paper

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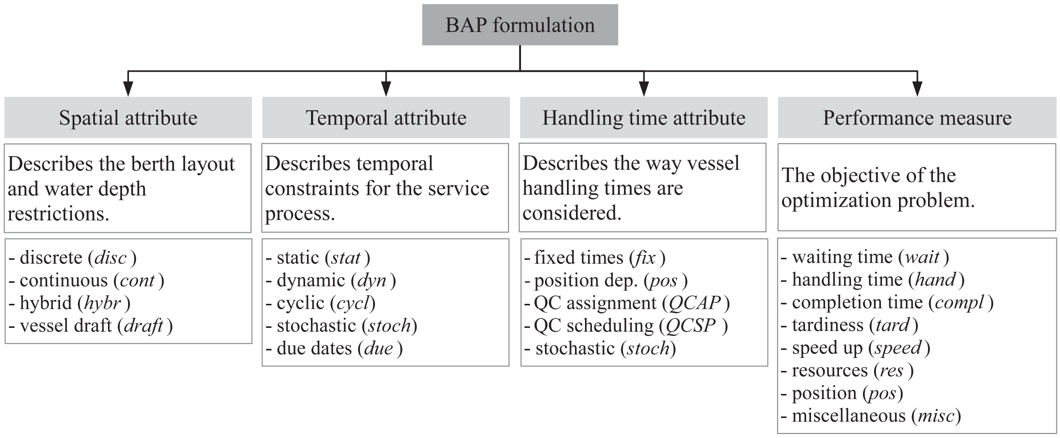

Fig. 1. BAP classification scheme.

provides classification schemes for BAP models and QCSP models. The QCAP hardly receives attention by its own, which is why there is no classification scheme for this problem. Nevertheless, integrated models connecting BAP and QCAP, QCAP and QCSP, or all three problems together are classified in Bierwirth and Meisel (2010) as well.

In the preparation of this follow-up paper, we followed some guidelines. First, in order to reduce redundancy with the preceding survey, only the relevant new literature published after 2009 is taken into consideration. Second, our problem classification schemes are taken up from the preceding survey and just slightly adapted to capture newly treated problem features. Third, the main outline of the previous survey paper is kept, structuring it into three sections that deal with the BAP, the QCSP and integrated approaches thereof. In the section on integrated planning we also review recent approaches of further integrating seaside operations planning with liner scheduling and with yard operations planning. An integration with liner scheduling aims for aligning the sailing times of vessels with the berthing times at the visited ports. Such integration promises reduced vessel waiting times at congested terminals. The integration with yard planning is motivated by the observation that fast seaside operations not just require efficient berth plans and quay crane operations but also an efficient usage of other resources like yard trucks, yard cranes, and storage locations. Therefore, recent studies strive for a combined solution of seaside problems and yardside problems in order to minimize yard congestions as well as the travel effort of transport vehicles while planning berth and quay crane operations.

In order to identify and collect all new relevant publications on berth allocation and crane operations planning, we have conducted a comprehensive literature search. At first we have scanned online search engines for papers that contain the key words ‘Berth allocation’, ‘Berth scheduling’, ‘Berth assignment’ or ‘Quay Crane’. The searched media include the online-resources of the publishers *Elsevier, Informs, Interscience, Palgrave, Springer, Taylor&Francis*, and the scientific search engine *Google Scholar*. At second we have used the citation indices of *ISI Web of Knowledge* and *Scopus* to identify further journal papers citing one of the previous surveys of Stahlbock and Voß (2008), Steenken, Voß, and Stahlbock (2004), Vis and de Koster (2003), and Bierwirth and Meisel (2010). The literature references of these papers were searched for further relevant publications. In this follow-up survey, we collect all papers that appeared in reviewed international journals or compilations and are not already surveyed in Bierwirth and Meisel (2010). With the exception of nine papers, all papers included in this survey appeared in 2010 or later. Papers that are published in proceedings, collections, extended abstracts, and technical reports are only taken up in this survey if the modeling approach or methodology is original and not published elsewhere. Altogether, this survey collects and classifies 131 new approaches for the BAP and the QCSP, described in more than 120 papers, of which 111 have been published in international scientific journals and 20 elsewhere.

The outline of the paper is as follows. In Sections 2 and 3, we classify the collected papers on berth allocation and quay crane scheduling, respectively. In both fields, we discuss recent developments to highlight promising topics for future research. In Section 4, we review those studies that investigate integrated approaches for seaside operations planning. Section 5 concludes the survey by highlighting topics that we consider particularly important in future research.

2. Berth allocation problems

2.1. Scope and classification scheme

In berth allocation problems, we are given a berth layout together with a set of vessels that have to be served within a planning horizon. The vessels must be moored within the boundaries of the quay and cannot occupy the same quay space at a time. In the basic optimization problem, berthing positions and berthing times have to be assigned to all vessels, such that a given objective function is optimized. A variety of optimization models for berth allocation have been proposed in the literature to capture real features of practical problems. In Bierwirth and Meisel (2010), we have proposed a scheme for classifying such models according to four attributes, namely a *spatial attribute*, a *temporal attribute*, a *handling time attribute*, and the *performance measure* addressed in the optimization. The values each attribute can take are listed in Fig. 1.

2.1.1. Spatial attribute

This attribute concerns the berth layout, which is either a discrete layout (*disc*), a continuous layout (*cont*), or a hybrid layout (*hybr*). In case of *disc*, the quay is partitioned into berths and only one vessel can be served at each single berth at a time. In case of *cont*, vessels can berth at arbitrary positions within the boundaries of the quay. Finally, in case *hybr*, the quay is partitioned into berths, but vessels may share a berth or one vessel may occupy more than one berth. A particular form of a hybrid berth is an indented berth where large vessels can be served from two oppositely located berths. The spatial attribute is extended by item *draft*, if the BAP-approach additionally considers a vessel's draft when deciding on its berthing position.

2.1.2. Temporal attribute

This attribute describes the arrival process of vessels. The attribute reflects static arrivals (*stat*), dynamic arrivals (*dyn*), cyclic arrivals (*cycl*), and stochastic arrival times (*stoch*). In case of *stat*, we assume that all vessels have arrived at the port and wait for being served. In contrast, in case of *dyn*, the vessels arrive at individual but deterministic arrival times imposing a constraint for the berth allocation.

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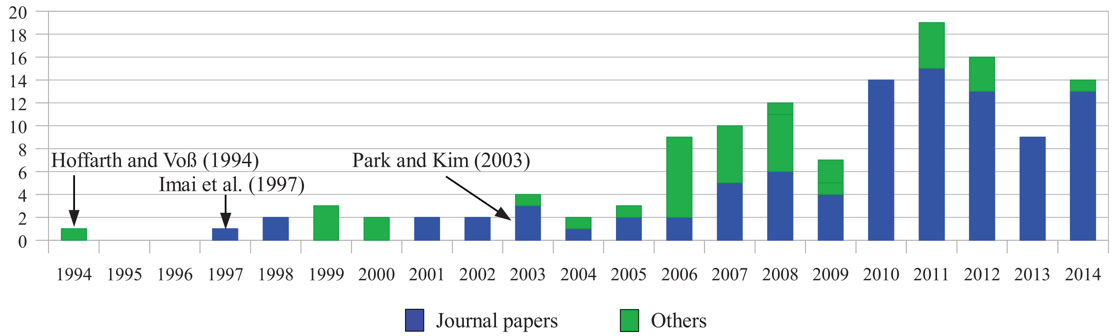

Fig. 2. Number of classified BAP models by year of publication.

In case *cycl*, the vessels call at terminals repeatedly in fixed time intervals according to their liner schedules. In case *stoch*, the arrival times of vessels are stochastic parameters either defined by continuous random distributions or by scenarios with discrete probability of occurrence. Cyclic and stochastic arrival times are considered in a number of recent publications and, therefore, we have extended the original classification scheme with regard to these cases. The temporal attribute is completed by value *due*, if a due date is preset for the departure of a vessel or if a maximum waiting time is preset for a vessel before the service has to start.

2.1.3. Handling time attribute

This attribute describes the way how handling times of vessels are given as an input to the problem. It takes value *fix*, if the handling times of vessels are known and considered unchangeable. Value *pos* indicates that handling times depend on the berthing positions of vessels and value *QCAP* indicates that handling times are determined by including QC assignment decisions into the BAP. In case of value *QCSP*, the handling times are determined by incorporating the QC scheduling within the BAP. In order to classify the recent literature properly, we have inserted case *stoch* as a new attribute for the scheme. Again, handling times can be subject to either discrete or continuous random distributions. A similar extension of our scheme is also suggested by Carlo et al. (2013), who also open it to further sources of influence on vessel handling times, like operations of transfer vehicles and yard cranes. However, as we hardly find instantiations of these cases in the literature, we refrain from extending the scheme in further directions.

2.1.4. Performance measure

This attribute considers the performance measures of a berth allocation model. Most models consider to minimize the port stay time of vessels. This is reached by different objective functions, e.g. when minimizing waiting times before berthing (*wait*), minimizing handling times of vessels (*hand*), minimizing service completion times (*compl*), or minimizing tardy vessel departures (*tard*). If soft arrival times are given, also a possible speedup of vessels (*speed*) is taken into consideration at the expense of additional bunker cost. Other models aim at reducing the variable operation cost of a terminal by optimizing the utilization of resources (*res*) like cranes, vehicles, berth space, and manpower. An often considered feature is to save horizontal transport capacity by finding berthing positions for vessels close to the yard, which is why we include this goal by its own value *pos*. Rarely met performance measures are summarized by value *misc* (miscellaneous). The introduced measures are either summed up for all vessels in the objective function, which is denoted by $\sum()$ in the classification scheme. Alternatively, if the minimization of the measure for the worst performing vessel is pursued, i.e. a min–max objective is faced, we denote this by *max*(). Vessel-specific priorities or cost rates are shown by weights. Different weights w_1 to w_4 address combined performance measures.

2.2. Literature overview

In the relevant literature, we have found and classified 79 new models for berth allocation, most of them published after 2009. Fig. 2 shows the BAP models developed by researchers since 1994 by year of their publication, including also those approaches reviewed in Bierwirth and Meisel (2010). The figure shows that the interest in berth allocation started with the early papers of Hoffarth and Voß (1994) and Imai, Nagaiwa, and Tat (1997). However, the growth of publications followed the pioneering paper of Park and Kim (2003), who combined berth allocation and QC assignment for the first time, and the early survey on container terminal operations by Steenken et al. (2004). In particular, journal publications scaled up to ten and more per year after 2010. To the mid of 2014, already 13 new journal papers have been published or accepted for publication. The continuous effort spend on research in berth allocation confirms it as a well established field today, which still shows potential for future research.

Table 1 lists the new papers collected in this survey. They are sorted lexicographically according to the attributes used to classify the models. Hence, papers proposing more than one model appear in this table multiple times. In most of the approaches discrete or continuous layouts are considered, while hybrid layouts possess a minor share. Only few models concentrate on static vessel arrival times, hence, dynamic arrival times form a quasi-standard in the recent research. In the discrete layout models, handling times are specified by the assigned berthing position in the vast majority of approaches. To the contrary, in models for continuous layouts, the focus prevails on resources where vessel handling times are frequently determined through integrating the QCAP into the berth allocation. The most often pursued objectives comprise service measures by minimizing the total waiting and handling times of vessels. However, a widespread mixture of other often quite specific objectives is studied as well.

With Table 1, we also provide an overview of the methods that are used for solving the BAP models. Note that only the most successful method presented in a paper appears in the table. It is not surprising that heuristic approaches dominate as the BAP is known to be $\mathcal{NP}$-hard in both, the discrete and the continuous case, see e.g. Lim (1998) and Hansen and Oğuz (2003). Exact methods are applied in only one fourth of the approaches, ranging from MILP formulations combined with standard solvers to highly sophisticated branching-based algorithms. Among the heuristic approaches, Genetic Algorithms and Evolutionary Algorithms take the by far largest share with 40 percent, see Fig. 3 (left). The rest of the methods comprise other meta-heuristics like Tabu Search and Simulated Annealing as well as problem specific heuristics like local search techniques and greedy rules. The richness of BAP models favors meta-heuristic approaches as they allow handling various problem features flexibly. On the other hand, a systematic evaluation of algorithms is hindered by the strong heterogeneity of BAP models. Although comparing models is definitely necessary for assessing the suitability of methods, the comparison of alternative models formulated by different research groups is just emerging

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Table 1
Overview of BAP formulations.

Problem classification	Reference	Method[a]
$disc \mid stat \mid fix \mid \sum wpos$	Safaei, Bazzazi, and Assadi (2010)	MILP
$disc \mid stat \mid pos \mid max(compl)$	Emde, Boysen, and Briskorn (2014)	B&B
$disc \mid stat \mid pos, QCSP \mid \sum(wait + hand)$	Song, Cherrett, and Guan (2012)	GA
$disc \mid dyn \mid pos \mid \sum(wait + hand)$	Arango, Cortés, Muñuzuri, and Onieva (2011)	GA
$disc \mid dyn \mid pos \mid \sum(wait + hand)$	Golias, Boilé, and Theofanis (2009)	GA
$disc \mid dyn \mid pos \mid \sum(wait + hand)$	Golias, Boilé, Theofanis, and Taboada (2010)	NRPM
$disc \mid dyn \mid pos \mid \sum(wait + hand)$	Golias, Portal, Konur, Kaisar, and Kolomvos (2014)	GA
$disc \mid dyn \mid pos \mid \sum(wait + hand)$	Golias and Haralambides (2011)	GA
$disc \mid dyn \mid pos \mid \sum(wait + hand)$	Saharidis, Golias, Boilé, Theofanis, and Ierapetritou (2010)	GA
$disc \mid dyn \mid pos \mid \sum(wait + hand)$	Ting, Wu, and Chou (2014)	PSO
$disc \mid dyn \mid pos \mid \sum w(wait + hand)$	Buhrkal, Zuglian, Ropke, Larsen, and Lusby (2011)	GSPM
$disc \mid dyn \mid pos \mid \sum w(wait + hand)$	Golias, Boilé, and Theofanis (2010)	GA
$disc \mid dyn \mid pos \mid \sum w(wait + hand)$	Lalla-Ruiz, Melián-Batista, and Moreno-Vega (2012)	TS
$disc \mid dyn \mid pos \mid \sum w(wait + hand)$	Lin and Ting (2014)	SA
$disc \mid dyn \mid pos \mid \sum w(wait + hand) + res$	Silva, Novaes, and Coelho (2011)	GA
$disc \mid dyn \mid pos \mid \sum(w\ wait + tard)$	Golias, Saharidis, Boilé, Theofanis, and Ierapetritou (2009)	GA
$disc \mid dyn \mid pos, stoch \mid \sum(wait + hand), misc$	Golias (2010)	GA
$disc \mid dyn \mid pos, stoch \mid \sum(wait + hand), misc$	Golias (2011)	GA
$disc \mid dyn \mid pos, stoch \mid \sum(wait + hand), misc$	Karafa, Golias, Ivey, Saharidis, and Leonardos (2013)	EA
$disc \mid dyn \mid pos, QCSP \mid max(compl)$	Lee and Wang (2010b)	GA
$disc \mid dyn \mid QCAP \mid \sum(wait + hand + tard), res$	Liang, Lin, and Jo (2009)	GA
$disc \mid dyn \mid QCAP \mid \sum(wait + hand + tard), res$	Liang, Guo, and Yang (2011)	GA
$disc \mid dyn \mid QCAP \mid \sum(wait + hand + tard + misc)$	Liang, Hwang, and Gen (2012)	GA
$disc \mid dyn \mid QCAP \mid -\sum(w_1\ res + w_2\ pos)$	Giallombardo, Moccia, Salani, and Vacca (2010)	TS
$disc \mid dyn \mid QCAP \mid -\sum(w_1\ res + w_2\ pos)$	Lalla-Ruiz, González-Velarde, Melián-Batista, and Moreno-Vega (2014)	GA
$disc \mid dyn, due \mid fix \mid \sum wpos + res$	Lee and Jin (2013)	GA
$disc \mid dyn, due \mid pos \mid \sum w(wait + hand)$	de Oliveira, Mauri, and Lorena (2012a)	SA
$disc \mid dyn, due \mid pos \mid \sum w(wait + hand) + misc$	Li and Pang (2011)	MILP
$disc \mid dyn, due \mid QCAP \mid \sum whand, \sum wres$	Ursavas (2014)	B&C
$disc \mid dyn, due \mid QCAP \mid \sum(w_1\ wait + w_2\ pos)$	Vacca, Salani, and Bierlaire (2013)	B&P
$disc \mid cycl \mid fix \mid \sum(wait + w_1\ res + w_2\ misc)$	Imai, Yamakawa, and Huang (2014)	LR
$disc, draft \mid stat \mid fix \mid \sum w(wait + hand)$	Xu, Li, and Leung (2012)	RULE
$disc, draft \mid dyn \mid fix \mid \sum w(wait + hand)$	Xu et al. (2012)	RULE
$disc, draft \mid stoch \mid pos, stoch \mid \sum wwait$	Guldogan, Bulut, and Tasgetiren (2012)	GA
$disc, draft \mid stoch \mid QCAP, stoch \mid \sum(wait + hand + wtard)$	Han, Lu, and Xi (2010)	GA
$disc, draft \mid stoch, due \mid QCAP, stoch \mid \sum wait$	Zhou and Kang (2008)	GA
$cont \mid stat \mid QCAP \mid max(compl)$	Blazewicz, Cheng, Machowiak, and Oguz (2011)	RULE
$cont \mid stat \mid QCAP \mid \sum(w_1\ wait + w_2\ speed + w_3\ tard + w_4\ pos)$	Rashidi and Tsang (2013)	–
$cont \mid stat \mid stoch \mid misc$	Guan and Yang (2010)	RULE
$cont \mid dyn \mid fix \mid \sum w(wait + hand)$	Lee, Chen, and Cao (2010)	GRASP
$cont \mid dyn \mid fix \mid \sum(w_1\ wait + w_2\ pos), misc$	Zhen and Chang (2012)	RULE
$cont \mid dyn \mid fix \mid w \sum tard + misc$	Xu, Chen, and Quan (2012)	SA
$cont \mid dyn \mid fix \mid \sum tard, misc$	Du, Chen, Quan, Long, and Fung (2011)	MILP
$cont \mid dyn \mid pos \mid \sum(wait + hand)$	Ganji, Babazadeh, and Arabshahi (2010)	GA
$cont \mid dyn \mid pos, QCAP \mid \sum(wait + hand)$	Na and Zhihong (2009)	RULE
$cont \mid dyn \mid pos, QCAP \mid \sum(w_1\ speed + w_2\ tard + w_3\ res)$	Meisel and Bierwirth (2013)	SWO
$cont \mid dyn \mid QCAP \mid \sum wwait$	Salido, Rodriguez-Molins, and Barber (2012)	GRASP
$cont \mid dyn \mid QCAP \mid \sum wwait, \sum wtard$	Salido, Rodriguez-Molins, and Barber (2011)	GRASP
$cont \mid dyn \mid QCAP \mid \sum w(wait + hand)$	Rodriguez-Molins, Barber, Sierra, Puente, and Salido (2012)	GA
$cont \mid dyn \mid QCAP \mid \sum(wait + hand)$	Yang, Wang, and Li (2012)	GA
$cont \mid dyn \mid QCAP \mid \sum(w_1\ wait + w_2\ tard), \sum pos, \sum res$	Chang, Jiang, Yan, and He (2010)	GA
$cont \mid dyn \mid QCAP \mid \sum(w_1\ wait + w_2\ tard), \sum pos, \sum res$	He, Mi, Chang, and Yan (2009)	GA
$cont \mid dyn \mid QCAP \mid \sum(w_1\ pos + w_2\ tard + w_3\ res)$	Zeng, Hu, Wang, and Fang (2011)	TS
$cont \mid dyn \mid QCAP \mid \sum(w_1\ pos + w_2\ tard + w_3\ res)$	Zeng, Yang, and Hu (2011)	TS
$cont \mid dyn \mid QCAP \mid \sum(w_1\ pos + w_2\ wait + w_3\ tard)$	Aras, Türkoğulları, Taşkın, and Altınel (2014)	MILP
$cont \mid dyn \mid QCAP \mid \sum(w_1\ pos + w_2\ wait + w_3\ tard)$	Zhang, Zheng, Zhang, Shi, and Armstrong (2010)	LR
$cont \mid dyn \mid QCAP \mid \sum(w_1\ pos + w_2\ wait + w_3\ tard), misc$	Hu, Hu, and Du (2014)	MILP
$cont \mid dyn \mid QCAP \mid w_1 \sum(wait + hand) + w_2\ misc$	Rodriguez-Molins et al. (2014)	GA
$cont \mid dyn \mid QCAP \mid max(tard)$	Chen, Lee, and Cao (2012)	BCA
$cont \mid dyn \mid QCAP, QCSP \mid \sum wwait$	Rodriguez-Molins, Salido, and Barber (2014)	GRASP
$cont \mid dyn \mid QCAP, QCSP \mid \sum(wait + hand)$	Lu, Han, and Xi (2011)	GA
$cont \mid dyn, due \mid pos \mid \sum w(wait + hand)$	de Oliveira, Mauri, and Lorena (2012b)	SA
$cont \mid dyn, due \mid QCAP \mid \sum(w_1\ hand + w_2\ pos + w_3\ res)$	Raa, Dullaert, and Schaeren (2011)	MILP
$cont \mid cycl \mid fix \mid \sum wpos$	Hendriks, Lefeber, and Udding (2013)	MILP
$cont \mid cycl \mid QCAP \mid max(res)$	Hendriks, Laumanns, Lefeber, and Udding (2010)	MILP
$cont \mid cycl, due \mid QCAP \mid \sum(w_1\ speed + w_2\ tard + w_3\ pos)$	Zhen, Chew, and Lee (2011)	SWO
$cont \mid stoch \mid stoch \mid \sum(w_1\ wait + w_2\ pos) + misc$	Zhen, Lee, and Chew (2011)	SA
$cont, draft \mid dyn \mid pos, QCAP \mid \sum(w_1\ speed + w_2\ tard + w_3\ res)$	Elwany, Ali, and Abouelseoud (2013)	SA
$hybr \mid dyn \mid pos \mid \sum(wait + hand)$	Imai, Nishimura, and Papadimitriou (2013)	GA
$hybr \mid dyn \mid pos \mid \sum(wait + hand + wtard)$	Mauri, de Andrade, and Lorena (2011)	MA
$hybr \mid dyn \mid pos \mid \sum w(wait + hand)$	Lin and Ting (2014)	SA
$hybr \mid dyn \mid pos \mid \sum misc$	Lee, Jin, and Chen (2012)	TS
$hybr \mid dyn \mid QCAP \mid \sum(w_1\ pos + w_2\ wait + w_3\ tard)$	Türkoğulları, Taşkın, Aras, and Altınel (2014)	B&C

(Continued on next page)

Table 1
(Continued)

Problem classification	Reference	Method[a]
$hybr \mid cycl \mid QCAP \mid \sum(w_1\ misc + w_2\ res)$	Hendriks, Armbruster, Laumanns, Lefeber, and Udding (2012)	MILP
$hybr, draft \mid dyn \mid pos \mid \sum(wait + hand)$	Robenek, Umang, Bierlaire, and Ropke (2014)	B&P
$hybr, draft \mid dyn \mid pos \mid \sum(wait + hand)$	Umang, Bierlaire, and Vacca (2011)	MILP
$hybr, draft \mid dyn \mid pos \mid \sum(wait + hand)$	Umang, Bierlaire, and Vacca (2013)	GSPM
$hybr, draft \mid dyn \mid pos \mid \sum(wait + hand), \sum tard$	Cheong and Tan (2008)	ACO
$hybr, draft \mid dyn \mid pos \mid max(compl), \sum wait, \sum order$	Cheong, Tan, Liu, and Lin (2010)	EA

[a] Abbreviations used in last column: ACO—ant colony optimization, B&B—Branch-and-Bound, B&C—Branch-and-Cut, B&P—Branch-and-Price, BCA—Bender's cuts algorithm, EA—Evolutionary Algorithm, GA—Genetic Algorithm, GRASP—greedy randomized adaptive search, GSPM—generalized set-partitioning model, LR—Lagrangian relaxation (sub-gradient optimization), MA—Memetic algorithm, MILP—standard solver (CPLEX, Lindo, etc.), NRPM—non-numerical ranking preferences method, PSO—particle swarm optimization, RULE—rule based heuristics (greedy, insertion, etc.), SA—simulated annealing, SIM—simulation, SWO—Squeaky Wheel Optimization method, TS—Tabu Search.

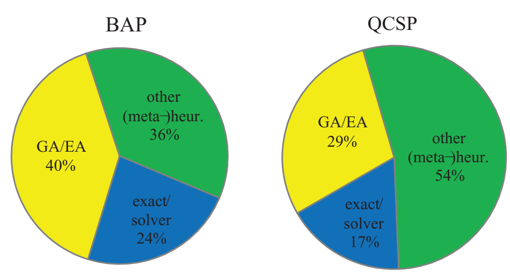

Fig. 3. Methods for solving BAP and QCSP.

Table 2
New issues in berth allocation planning.

Feature	Reference
Fuel consumption and emissions	Du et al. (2011), Golias et al. (2009), Hu et al. (2014)
Tidal access	Xu et al. (2012)
Cyclic arrivals	Hendriks et al. (2012, 2010, 2013), Imai et al. (2014), Zhen et al. (2011)
Direct transshipments	Liang et al. (2012)
Crane operation ranges	Ursavas (2014), Zhang et al. (2010)
Mobile cranes	Ursavas (2014)
Mobile quay walls	Emde et al. (2014)
Indented berths	Imai et al. (2013)
Service center	Guan and Yang (2010)

slowly, see Buhrkal et al. (2011), Umang et al. (2013), and Imai et al. (2013). To make this process sustainable, commonly accepted BAP benchmark instances are needed to provide authors with the opportunity to evaluate their work. However, the current benchmarks are either not general enough to fulfill this aim or they are merely used in small substreams of the entire research field. Defining benchmark problems for general berth allocation problems that fulfill the principles of comparability, unbiasedness, and reproducibility remains an open topic for future research.

In the following, we abstain from reviewing all papers listed in Table 1 individually. Instead, the next subsection discusses those papers in more detail that contain novel features of which we think they might receive particular attention in the future.

2.3. New developments

New technological developments that impact the berth allocation problem include the construction of mega vessels and deep sea ports, the change to fully automated terminals, and the arise of indented berths and mobile ports. Also operational challenges arising from tide-dependent accessibility of ports, increasing security issues, and environmental considerations have been taken up into BAP research recently. Still, papers considering such topics are rather scarce in the literature. Below, 15 papers are reviewed in no particular order that deal with such kind of innovation. Table 2 gives an overview of the novel features appearing in the consideration of berth allocation problems.

In order to control the fuel consumption of a vessel on its way to a port, Golias et al. (2009) and Du et al. (2011) consider the arrival time as a decision variable in berth allocation planning. More precisely, the authors assume that the arrival time can be varied within a certain range, in correspondence to the sailing speed of the vessel and the fuel consumption. The approach can be used for trading off the fuel consumed for going to and waiting at a terminal with the service objective of meeting a given due date. Du et al. (2011) furthermore propose an emission estimation model that converts fuel consumption into greenhouse gas emissions. Experiments with artificial test instances indicate that substantial savings can be gained from such an integration. To achieve an even better tradeoff of fuel consumption, emissions, and service times, Hu et al. (2014) combine berth allocation with quay crane assignment. Again, arrival times are considered as a decision variable used to determine the optimal sailing speed. Next to this, the assignment of cranes to vessels is used for adjusting the handling time, which in turn impacts the arrival time needed for ensuring a timely departure of a vessel from the port.

Xu et al. (2012) include tidal restrictions into a BAP model, expressing that vessels can only access a berth within certain time windows when the tide provides a sufficient water depth. The research is motivated by a terminal in the Pearl River Delta in China. The discrete BAP is modeled as a parallel machine scheduling problem for the static and the dynamic case. The problem is solved by heuristic priority rules.

Hendriks et al. (2012, 2010, 2013) and Zhen et al. (2011) consider cyclic arrivals of vessels. These papers attempt to find a template for a berth plan of fixed length (like one week) that is then used by a terminal repeatedly over a long time as blueprint for the weekly operational BAP. The corresponding models respect that the services of those vessels that are scheduled toward the end of the planning horizon extend into the subsequent planning period. For this purpose, the berth template problem is considered as a packing problem on a cylinder. Hendriks et al. (2010) treat such a problem in combination with quay crane allocation in order to meet service agreements contracted between ports and vessel operators at minimum crane capacity requirements. Hendriks et al. (2012) and Hendriks et al. (2013) further extend the berth template problem toward multi-terminal ports and toward an integration with yard storage allocation. Also Zhen et al. (2011) combine the template design with yard storage allocation for which they develop powerful meta-heuristics. Imai et al. (2014) consider a berth template problem for a single terminal incorporating strategic decisions on accepting or rejecting the service of calling vessels. The authors propose a Lagrangian relaxation-based heuristic for minimizing waiting times of vessels, idle times of berths, and penalties for those vessels that are rejected because of insufficient berthing capacity. Being allowed to reject vessels, the heuristic produces feasible templates for problems where up to 100 ships call at a highly congested terminal. Also Giallombardo et al. (2010) and Vacca et al. (2013) deal with berth allocation on a strategic-tactical level but they do not consider cyclic arrivals explicitly. Therefore, although closely related, we have not classified these papers as cyclic approaches.

Liang et al. (2012) consider direct container transshipments between vessels within a BAP. Direct transshipments can save storage space in the yard, reduce travel effort of horizontal transport means, and speed up the service of vessels. However, they raise additional requirements for the berthing positions of the involved vessels and the operations of the QCs. Accordingly, the authors present a model to plan overlapping handling time periods for vessels with direct transshipment and to decide on the number of cranes provided at a berth. A Genetic Algorithm is proposed and the solution of an example instance confirms that direct transshipments can actually speed up the service process.

Ursavas (2014) takes a more detailed look at the integration of berth allocation and quay crane assignment. The author considers different types of cranes, rail mounted gantry cranes (RMGCs) and rubber tired gantry cranes (RTGCs), whose deployment is integrated into a discrete BAP. The RMGCs are subject to a non-crossing constraint, which needs to be taken into account when assigning cranes to vessels. Furthermore, they can be deployed just within certain operation ranges covering only a subset of the terminal's berths. This is because cranes receive energy supply via cables which are restricted in length. RTGCs are more flexible as they can move to any berth, but they show a lower handling rate compared with RMGCs. Ursavas (2014) uses a Branch-and-Cut algorithm to solve a problem observed at the Port of Izmir in Turkey. It is shown that this approach improves service time and costs by 10 percent to 25 percent compared with the solution developed by the practitioners at that port.

Zhang et al. (2010) incorporate crane coverage ranges into a continuous berth allocation problem. They solve the problem by Lagrangian relaxation and sub-gradient optimization. The approach is evaluated in a case study for Tianjin Five Continents International Container Terminal, China. For instances with 20–25 vessels, solutions with an average gap of 6.5 percent are produced within a few minutes.

Emde et al. (2014) consider the use of mobile quay walls (MQWs) at a single berth. An MQW is a floating platform that can be attached to a vessel once that the ship moored at the quay wall. The platform provides additional cranes for serving the enclosed vessel from two opposite sides. It further provides the opportunity to berth another vessel at the seaside of the MQW. The technology might help reducing the service time of vessels at terminals with scarce quay space. A Branch-and-Bound method is developed to sequence the vessels at the berth. It can optimally solve instances with up to 18 vessels within less than 15 minutes.

Imai et al. (2013) investigate berth allocation for indented berths that can either accommodate one large or several small vessels. If small vessels are served at an indented berth, precedence constraints have to be respected. This is because the access to the berth is blocked by vessels that are already moored close to the exit. This drawback is circumvented in so-called channel berths that can be entered from two sides. The authors show by experiment that the channel berth layout outperforms the indented berth and also the classical continuous berth layout as it allows serving large ships from opposing sides without restricting the accessibility of the berth.

Guan and Yang (2010) consider the role of an inspection center within the operational processes of a terminal. The inspection center checks whether containers hold illegal cargo. Due to increasing safety requirements in international trade, inspection centers receive growing importance for port management. Since the inspection center is a central operating unit responsible for checking containers of different vessels, it easily becomes a bottleneck if several vessels are served in parallel. The handling time of a vessel thus depends on the service rate of the QCs but also on the service rate of the inspection center, which makes it a stochastic variable. The authors propose priority rules for solving this problem. Experiments show that the Largest Processing Time rule performs best for the considered test instance.

3. Quay crane scheduling

3.1. Scope and classification scheme

In quay crane scheduling problems, we consider a set of containers to be unloaded and loaded at a single vessel and a set of assigned QCs. Containers can be clustered by groups, bays, or bay areas to reduce the number of tasks to be scheduled and the complexity of the scheduling problem. It is assumed that every task must be processed once by a QC while a QC can process at most one task at a time. A solution to the problem, called a QC schedule, defines a starting time for every task on a crane. Usually, the minimization of the vessel handling time is pursued, which is defined by the latest completion time among all crane tasks (the so-called makespan). In Bierwirth and Meisel (2010), a scheme for classifying QCSP models according to four attributes, namely a *task attribute*, a *crane attribute*, an *interference attribute*, and the *performance measure* addressed in the optimization, is proposed, see Fig. 4.

3.1.1. Task attribute

This attribute describes the aggregation of a vessel's containers into crane tasks. At the highest level of aggregation, a task comprises all containers to load and unload within a certain area of vessel bays (*area*). Using a lower level of aggregation in the QCSP, the workload of a vessel can often be shared better among the cranes. For instance, a task can be defined comprising all containers to be unloaded and loaded at a bay of a vessel (*bay*). A still lower aggregation level is achieved by considering single container groups of a bay (*group*) or container stacks of a bay (*stack*) as tasks to be scheduled. A completely disaggregated QCSP defines crane tasks by single container movements (*container*). Further restrictions regarding the execution of tasks complete this attribute. Precedence relations (*prec*) indicate, e.g., that an unloading task must precede a loading task within a bay. Under preemption (*prmp*) the interruption of executing a task is allowed, which is sometimes favorable to divide a task among multiple cranes.

3.1.2. Crane attribute

This attribute captures the properties of the crane resource. For instance, individual ready times (*ready*) and/or initial positions (*pos*) can be announced for cranes. If the availability of QCs is restricted to given time windows, the crane attribute takes value *TW*. Furthermore, if the time for moving cranes alongside the vessel is not negligible, value *move* is set in the classification.

3.1.3. Interference attribute

This attribute indicates restrictions for the movements of cranes. For instance, if QCs are rail-mounted, they cannot pass each other, which is modeled by a non-crossing constraint (*cross*) in the QCSP. For rubber-tired cranes such constraints are obsolete. Furthermore, QCs might have to keep a safety distance among each other during operation (*safe*).

3.1.4. Performance measure

This attribute defines the performance measures for QCSP models. The schedule performance can depend on the completion times of tasks (*compl*) or on the finishing times of cranes (*finish*), both striving for a fast service of vessels. In case of scarce crane resource, a relevant performance measure is the crane utilization rate (*util*), defined by the ratio of a crane's productive time and the total vessel handling time. Another such measure is the throughput of cranes (*through*) defined by the number of container moves per hour. Sometimes, even the time

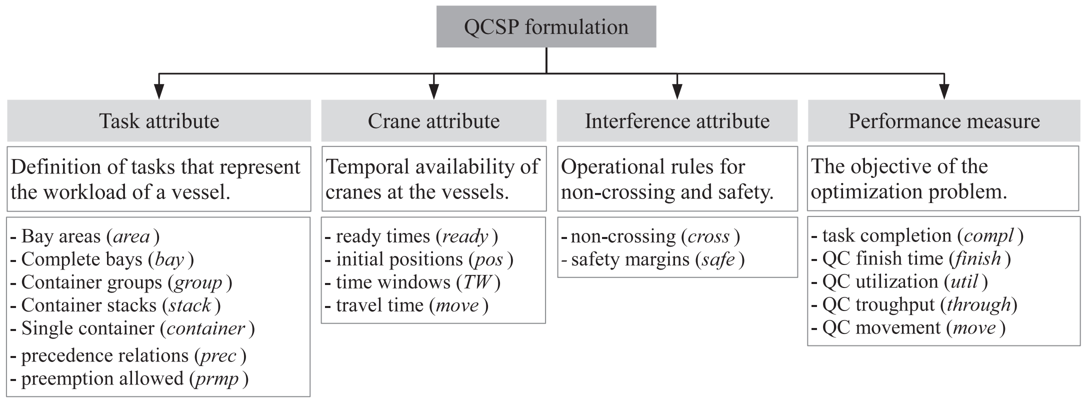

Fig. 4. QCSP classification scheme.

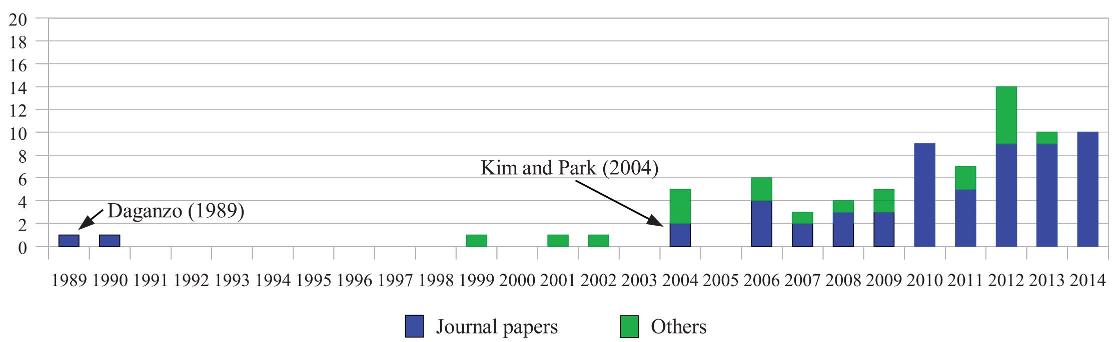

Fig. 5. Number of classified QCSP models by year of publication.

spent for moving cranes along the quay (*move*) is subject to minimization. Like in the BAP-scheme, the measures can be summed up ($\sum$) for all tasks or cranes, or the maximum value (*max*) can be considered in an objective function. For example, minimizing the makespan of a crane schedule is expressed by *max*(*compl*).

3.2. Literature overview

In the recent literature, we have found and classified 52 QCSP models. Fig. 5 shows all QCSP models developed so far by year of their publication, including also those approaches reviewed in Bierwirth and Meisel (2010). The figure shows that the recognition of the problem dates back to the early paper of Daganzo (1989). However, the scientific interest in QC scheduling really began to grow after the publication of the pioneering paper of Kim and Park (2004). In this paper, a detailed model of crane scheduling considering container groups, non-crossing restrictions, and safety distances has been presented for the first time. Furthermore, computational results are reported for a set of benchmark problems later used also by other researchers. Like in the berth allocation research, the number of publications per year grew considerably within the last decade. To the mid of 2014, already ten journal papers have been published or accepted for publication.

Table 3 lists the papers collected for this survey, with the vast majority published after 2009. Almost one half of these approaches consider the task aggregation level of container groups, which enables to specify rich models including numerous features of practical relevance. This stream is related to research in machine scheduling where quite similar technological and organizational requirements are met. Also bay-oriented approaches still receive a lot of attention as already the QCSP with bays is $\mathcal{NP}$-hard in the presence of a non-crossing constraint, see Zhu and Lim (2006). When disaggregating tasks to stacks or containers, the increasing number of tasks drastically raises complexity, leading to intractable problems at current time. Therefore, these papers often consider the operations of just a single crane, where non-crossing or safety distances are out of scope. Table 3 further verifies that the minimization of the vessel handling times, denoted as *max*(*compl*), is the predominant objective in QC scheduling research.

Table 3 also provides an overview of the methods proposed for solving the various QCSP models. Like for berth allocation problems, we identify three main classes of methods, namely exact methods, genetic and evolutionary methods, and other heuristic and meta-heuristic approaches. The percentage of each of these three classes is shown in Fig. 3 (right). More than one half of the algorithms are (meta-)heuristic methods. In particular, we observe a considerable number of approximation algorithms taking up ideas developed in machine scheduling. Next to meta-heuristics like Tabu Search, Simulated Annealing, and Variable Neighborhood Search also the Branch-and-Bound algorithm UDS, which works on a heuristic reduction of the solution space, belongs to this class.

Different to the BAP, research on the QCSP often concentrates on comparing the outcome of alternative algorithms. One reason is that the widely accepted benchmark set of Kim and Park (2004) is available since long. It contains instances for the QCSP with container groups ranging from 10 to 50 tasks and 2 to 6 cranes. Analyzing this benchmark set shows that the average number of tasks per bay is consistently 1 in all instances. Therefore, Meisel and Bierwirth (2011) have created a systematic process for generating new test instances under a controllable task-per-bay ratio. They also provide a benchmark set of 400 instances ranging from 10 to 100 tasks and 2 to 6 cranes. The benchmark generator furthermore reflects many other practical features like the loading capacity of bays, variable safety margins of cranes, and heterogeneous container distributions within a vessel. The recent literature shows that these new benchmarks obtain acceptance in the community, see e.g. Kaveshgar et al. (2012a), Legato et al. (2012), Unsal and Oguz (2013), Chen et al. (2014), Yi et al. (2012), and Lu et al. (2012).

Table 3
Overview of QCSP formulations.

Problem classification	Reference	Method[a]
area, *prmp* | *move* | *cross* | *max*(*compl*)	Lu et al. (2011)	RULE
area, *prmp* | *move* | *cross*, *save* | *max*(*compl*)	Lu, Han, Xi, and Erera (2012)	PTH
bay | – | *cross* | *max*(*compl*)	Boysen, Emde, and Fliedner (2012)	DP
bay | – | *cross* | *max*(*compl*)	Lee and Chen (2010)	AA
bay | – | *cross* | *max*(*compl*)	Lee and Wang (2010b)	AA
bay | – | *cross* | *max*(*compl*)	Liu, Zheng, and Li (2014)	AA
bay | – | *cross* | *max*(*compl*)	Wang, Chen, and Wang (2009)	GA
bay | – | *cross* | *max*(*compl*)	Zhang, Khammuang, and Wirth (2008)	AA
bay | – | *cross* | $\sum$ *wcompl*	Lee and Wang (2010a)	AA
bay | – | *cross*, *save* | *max*(*compl*)	Hakam, Solvang, and Hammervoll (2012)	GA
bay | – | *cross*, *save* | *max*(*compl*)	Lee, Chen, and Cao (2011)	TS
bay | *move* | *cross*, *save* | *max*(*compl*)	Rodriguez-Molins et al. (2014)	RULE
bay | *pos*, *move* | – | w_1 *max*(*compl*) + w_2 $\sum$ *move*	Wang, Zheng, Zheng, Guo, and Liu (2012)	PSO
bay | *pos*, *move* | *cross* | *max*(*compl*)	Guan, Yang, and Zhou (2013)	DPH
bay | *pos*, *move* | *cross* | *max*(*compl*)	Yang (2012)	DPH
bay | *pos*, *move* | *cross*, *save* | $\sum$ *finish*, $\sum$ *util*, $\sum$ *through*	Vis and Anholt (2010)	SIM
bay, *prmp* | – | *cross* | *max*(*compl*)	Diabat and Theodorou (2014)	GA
bay, *prmp* | – | *cross* | $\sum$ *w max*(*compl*)	Fu, Diabat, and Tsai (2014)	GA
group, *prec* | *move* | *safe* | $\sum$ *max*(*compl*)	Nam and Lee (2013)	GA
group, *prec* | *move* | *cross*, *save* | *max*(*compl*)	Lu et al. (2012)	PTH
group, *prec* | *move* | *cross*, *save* | *max*(*compl*)	Unsal and Oguz (2013)	CP
group, *prec* | *move* | *cross*, *save* | *max*(*compl*)	Yi, GuoLong, and ChengJi (2012)	RULE
group, *prec* | *pos*, *move* | *cross* | $\sum$(w_1 *max*(*compl*) + w_2 *finish*)	Song et al. (2012)	MILP
group, *prec* | *pos*, *move* | *cross*, *save* | *max*(*compl*)	Chen, Lee, and Cao (2011)	TS
group, *prec* | *pos*, *move* | *cross*, *save* | *max*(*compl*)	Chung and Chan (2013)	GA
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Expósito-Izquierdo, Melián-Batista, and Moreno-Vega (2011b)	VNS
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Expósito-Izquierdo, Velarde, Melián-Batista, and Moreno-Vega (2012)	EDA
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Expósito-Izquierdo, González-Velarde, Melián-Batista, and Moreno-Vega (2013)	EDA
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Guo, Cheng, and Wang (2014)	GEO
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Legato and Trunfio (2014)	LOB
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Nguyen, Zhang, Johnston, and Chen Tan (2013)	GA
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | *max*(*compl*) + *w* $\sum$ *tard*	Monaco and Sammarra (2011)	TS
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | w_1 *max*(*compl*) + w_2 $\sum$ *finish*	Chung and Choy (2012)	GA
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | w_1 *max*(*compl*) + w_2 $\sum$ *finish*	Expósito-Izquierdo, Melián-Batista, and Moreno-Vega (2011a)	EDA
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | w_1 *max*(*compl*) + w_2 $\sum$ *finish*	Kaveshgar, Huynh, and Rahimian (2012a)	GA
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | w_1 *max*(*compl*) + w_2 $\sum$ *finish*	Kaveshgar, Huynh, and Rahimian (2012b)	GA
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | w_1 *max*(*compl*) + w_2 $\sum$ *finish*	Legato, Mazza, and Trunfio (2010)	SA
group, *prec* | *ready*, *pos*, *move* | *cross*, *save* | w_1 *max*(*compl*) + w_2 $\sum$ *finish* + w_3 $\sum$ *move* + *misc*	Wang and Kim (2011)	GRASP
group, *prec* | *TW*, *move* | *cross*, *save* | *max*(*compl*)	Unsal and Oguz (2013)	CP
group, *prec* | *TW*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Chen, Lee, and Goh (2014)	MILP
group, *prec* | *TW*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Legato, Trunfio, and Meisel (2012)	UDS
group, *prec* | *TW*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Meisel (2011)	UDS
group, *prec* | *TW*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Meisel and Bierwirth (2013)	UDS
stack, *prec* | – | – | *max*(*compl*)	Pap, Bojanić, Bojanić, and Georgijević (2013)	DP
stack, *prec* | – | – | *max*(*compl*)	Lee, Liu, and Chu (2014)	PTE
stack, *prec* | – | *cross* | *max*(*compl*)	Ku and Arthanari (2014)	LS
container | – | *cross* | *max*(*compl*)	Tang, Zhao, and Liu (2014)	PSO
container | – | *cross*, *save* | *max*(*compl*)	Choo, Klabjan, and Simchi-Levi (2010)	B&P
container | *move* | – | *max*(*compl*)	Cao, Shi, and Lee (2010)	GA
container, *prec* | – | – | *max*(*compl*)	Meisel and Wichmann (2010)	GRASP
container, *prec* | *pos*, *move* | – | *max*(*compl*)	Shin and Lee (2013)	GA
container, *prec* | *ready*, *pos*, *move* | *cross*, *save* | *max*(*compl*)	Choo et al. (2010)	B&P

[a] Abbreviations used in last column: AA—Approximation Algorithm, B&P—Branch-and-Price, CP—constraint programming, DP—dynamic programming, DPH—dynamic programming heuristic, EDA—estimation of distribution algorithm, GA—Genetic Algorithm, GEO—generalized extremal optimization, GRASP—greedy randomized adaptive search, LS—local search, LOB—local branching method, MILP—standard solver (CPLEX, Lindo, etc.), PSO—particle swarm optimization, PTH—polynomial time heuristic, PTE—polynomial time exact algorithm, RULE—rule based heuristics (greedy, insertion, etc.), SA—Simulated annealing, SIM—simulation, TS—Tabu Search, UDS—unidirectional search, VNS—Variable Neighborhood Search.

Not just the quality of algorithms but also the capabilities of QCSP models are computationally comparable by using benchmark instances under a scalable aggregation level. Instances for the QCSP with container groups can be transformed into corresponding instances for the QCSP with bays and the QCSP with bay areas by aggregating tasks belonging to the same bay or bay area, respectively. Such across-model evaluations are reported by Meisel and Bierwirth (2011) on the basis of 50 QCSP instances each containing 50 container groups in a vessel with 15 bays served by 4 QCs. The computations show that the average vessel handling time obtained from the group-model is 4.8 percent below the handling time obtained from the bay-model and even 9.5 percent below the handling time obtained from the area-model. It is also verified for this case that using more or less than 4 cranes reduces the benefit of using a detailed model. Hence, a prospect of future research might be to identify the conditions where disaggregated models really deliver improved solutions.

3.3. New developments

New technological developments that directly impact the quay crane scheduling include the invention of new spreader-technologies allowing QCs to handle two or three containers at the same time and to synchronize cranes with horizontal transport means as is required for performing double-cycling operations. Also the rise of indented berths and mobile crane platforms calls for innovative QC scheduling

Table 4
New issues in quay crane scheduling.

Feature	Reference
Indented berths and passing QCs	Boysen et al. (2012), Chen et al. (2011), Lee et al. (2011), Vis and Anholt (2010)
Mobile crane platforms	Nam and Lee (2013); Shin and Lee (2013)
Crane ranges	Monaco and Sammarra (2011)
Yard congestion	Choo et al. (2010)
Double cycling	Lee et al. (2014), Ku and Arthanari (2014)

methods. Below we review ten selected original papers that deal with innovations in the field of QCSP, see Table 4.

Boysen et al. (2012), Chen et al. (2011), and Lee et al. (2011) propose QCSP models for an indented berth where a large vessel can be served by QCs that are located at two opposite berths. While cranes located at a same side are subject to the non-crossing constraint, cranes located at opposite berths can pass each other when the spreader arm has been lifted. This creates additional flexibility in the crane operations although lifting the crane arm consumes precious time. While Chen et al. (2011) investigate a group-model for the QCSP, Lee et al. (2011) and Boysen et al. (2012) concentrate on bay-models. The research groups of Chen et al. (2011) and Lee et al. (2011) propose Tabu Search algorithms producing solutions with optimality gaps of a few percent for instances with 4–5 cranes and 40–50 tasks within a few minutes. Boysen et al. (2012) propose an exact pseudopolynomial-time Dynamic Programming procedure and a heuristic based on Beam Search. While Dynamic Programming can solve some instances with up to 100 tasks and 5 cranes, the Beam Search produces near optimal solutions with gaps below 1 percent for all instances of the benchmark suite. Vis and Anholt (2010) conduct a simulation study in order to compare the performance of QCs at a classical berth, where the vessel is served from one side, with an indented berth. The experiments show that the indented berth can reduce the handling time of vessels by up to 30 percent.

Nam and Lee (2013) investigate a QCSP where the QCs are mounted on floating platforms. This allows to position the cranes at both sides of an anchoring vessel. The platforms can pass each other and even switch the side at which they serve a vessel. The authors present an optimization model together with a rule-based algorithm and a Genetic Algorithm. The latter solves instances with up to 18 container groups and 3 mobile platforms within 10 minutes to an average optimality gap of 11 percent. Shin and Lee (2013) concentrate on a single crane platform and solve the corresponding QCSP at the level of individual containers. The authors develop a GA and apply it to instances with up to 120 containers.

Monaco and Sammarra (2011) incorporate moving ranges for the cranes into a QCSP model. Such a range limits the subset of bays that a crane can actually move to. As already observed in the papers of Ursavas (2014) and Zhang et al. (2010), discussed in Section 2.3, such restrictions can be of high practical relevance and thus need to be taken into account in berth allocation and crane operations planning. Monaco and Sammarra (2011) develop a Tabu Search heuristic for this problem and apply it to real world instances from the Gioia Tauro Container Terminal, Italy. The instances contain up to 65 tasks and 4 QCs. They can be solved within less than a minute with a gap of 35 percent against the lower bound obtained from CPLEX.

Choo et al. (2010) include a yard congestion constraint into a QCSP model. The constraint forbids that too many QCs simultaneously handle containers that have to be stored at or retrieved from a same yard area. In this way, it prevents congestion of yard trucks and yard cranes that have to handle the containers in this area. Computational experiments reveal that the QCSP becomes harder if tight yard congestion constraints are part of the problem.

Ku and Arthanari (2014) investigate a stack-based QCSP where unloading moves of containers are combined with loading moves to avoid empty movements of the crane spreader. This concept of double-cycling, introduced by Goodchild and Daganzo (2006), is of importance for port practitioners. However, it received only little scientific attention, e.g. by Zhang and Kim (2009) who extended Goodchild and Daganzo's approach with respect to incorporating hatch covers. Very recently, it was shown by Lee et al. (2014) that the QC double-cycling problem with hatch covers is polynomially solvable. Ku and Arthanari (2014) present an optimization model that avoids infeasible crane cycles not detected in the model of Zhang and Kim (2009). The authors also discuss issues that might be subject of future research like, for example, the appropriate level of aggregating tasks in such a QCSP model.

4. Integrated planning

4.1. Scope and classification scheme

The handling times of vessels, which are a central input for berth allocation, are typically unknown at the time of planning as they depend on various factors. They might be estimated based on the number of containers to be unloaded and loaded, a crane number corresponding to the vessel size, and the average productivity rate of cranes. However, if the estimated handling time exceeds the actual handling time, berth and crane capacity is wasted. Otherwise, if the estimate is below the actual handling time, crane and berth capacity is utilized longer than expected, delaying the service operations of succeeding vessels. In practice, a rough estimation of the vessel handling time is often obtained through solving the berth allocation, the quay crane assignment, and the quay crane scheduling problems sequentially. Nevertheless, to obtain more reliable estimates, BAP, QCAP, and QCSP must be solved jointly, which is referred to as integrated seaside operations planning. In the scientific literature, different integration mechanisms are presented for solving two or all three of these problems jointly. A deep integration means to solve a monolithic model where the interdependencies of the involved problem-individual decisions are considered on the background of the merged set of constraints. Solving a monolithic model can deliver the best overall solution but is usually extremely difficult due to the huge complexity of the merged problem. To overcome this difficulty, a partial problem integration of two problems is often more practical. The idea of integration by preprocessing is to solve one of the problems under particular circumstances in order to precise the input data for the other problem. Another way of partial integration is to solve two problems alternately such that the outcome of one problem is fed back to the other problem restricting its decision space. In this way, decisions made for both problems are iteratively aligned. In Bierwirth and Meisel (2010), the following scheme has been proposed for denoting the three integration concepts: A deep integration of two problems A and B is expressed by $\boxed{\text{A, B}}$. If problem A is preprocessed to problem B, we denote this by A → B. If A and B are solved in a feedback loop, we express this by A ⇄ B.

4.2. Literature overview

In the category of integration studies, we have identified 33 approaches for integrating seaside operations planning published within the last five years. Fig. 6 illustrates the publication year of all integration approaches presented so far. As before, the papers of Daganzo (1989) and Park and Kim (2003) are highlighted, because they both provide pioneering integration approaches. Daganzo (1989) defines a monolithic model for crane assignment and crane scheduling, denoted by $\boxed{\text{QCAP, QCSP}}$. Park and Kim (2003) integrate berth allocation and crane assignment in two stages. At first, in a monolithic model, they jointly decide on the berthing position, the berthing

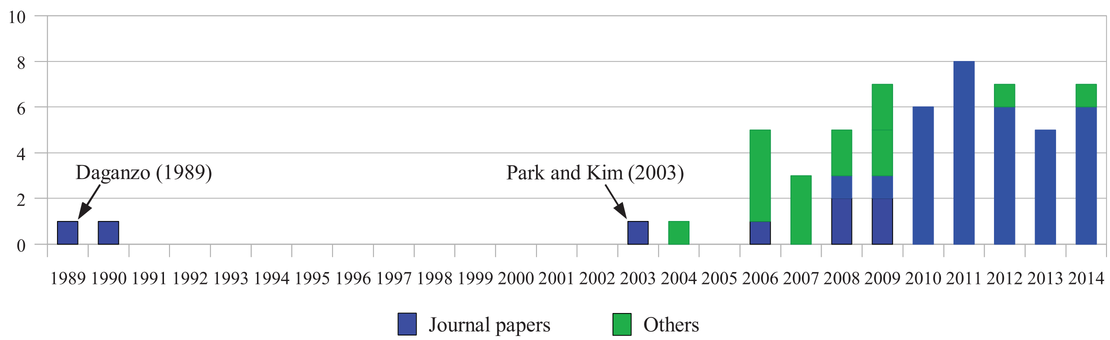

Fig. 6. Number of classified integration concepts by year of publication.

Table 5
Overview of integration studies for BAP, QCAP, and QCSP.

Integration concept	Reference
$\boxed{\text{BAP, QCAP(number)}}$	Blazewicz et al. (2011); Elwany et al. (2013); Giallombardo et al. (2010); Han et al. (2010); Hendriks et al. (2012, 2010); Hu et al. (2014); Lalla-Ruiz et al. (2014); Liang et al. (2011, 2012, 2009); Raa et al. (2011); Salido et al. (2011, 2012); Vacca et al. (2013); Zhen et al. (2011)
$\boxed{\text{BAP, QCAP}}$	Aras et al. (2014); Chang et al. (2010); Chen et al. (2012); He et al. (2009); Na and Zhihong (2009); Rashidi and Tsang (2013); Rodriguez-Molins et al. (2012, 2014); Ursavas (2014); Yang et al. (2012); Zhang et al. (2010); Zhou and Kang (2008)
$\boxed{\text{BAP, QCAP(number)}} \rightleftarrows$ QCAP(specific)	Türkoğullarıet al. (2014); Zeng et al. (2011, 2011)
BAP $\rightleftarrows$ QCSP	Lee and Wang (2010b); Song et al. (2012)
QCAP, QCSP	Unsal and Oguz (2013)
$\boxed{\text{BAP, QCAP, QCSP}}$	Lu et al. (2011); Rodriguez-Molins et al. (2014)
QCSP $\rightarrow$ $\boxed{\text{BAP, QCAP}} \rightleftarrows$ QCSP	Meisel and Bierwirth (2013)

time, and the number of cranes to assign to each vessel, which is denoted by $\boxed{\text{BAP, QCAP(number)}}$. At the second stage, they decide on the specific cranes to be used in the service of a vessel incorporating the outcome of the first stage. This leads to the overall denotation $\boxed{\text{BAP, QCAP(number)}} \rightarrow \boxed{\text{QCAP(specific)}}$. Fig. 6 shows also that observable, continuous activity in this field did not start before 2006. But about 5 journal papers appeared per year shortly after.

Table 5 lists those integration studies that appeared after the survey of Bierwirth and Meisel (2010) was published. The integration of BAP and QCAP is today the by far most often treated integration concept met in seaside operations planning. A large number of papers concentrates on finding a suitable berthing position and berthing time for a vessel combined with an appropriate number of cranes to be used in the service by a deep integration approach. Thereby, *time-invariant crane assignments* and *variable-in-time crane assignments* are often distinguished, see Bierwirth and Meisel (2010). The former means that a constant number of cranes is used for serving a vessel throughout the entire process (e.g. Han et al., 2010), while the latter means that the number of cranes can change dynamically during the service process (e.g. Vacca et al., 2013). Determining just the number of cranes simplifies the problem as it neglects the relative positioning of the rail-mounted cranes along the quay. Therefore, several authors consider a deep integration of BAP and QCAP including also the assignment of specific cranes to vessels.

In a few further approaches, berth allocation decisions are considered in combination with quay crane scheduling. A feedback loop based integration is proposed by Lee and Wang (2010b) and Song et al. (2012). They consider a discrete BAP with a fixed number of cranes available at each berth. Having determined a preliminary berth plan, a set of corresponding QCSPs for the cranes at a berth is solved and the calculated handling times are fed back to the berth planning stage. In this way, berthing and scheduling decisions are aligned. In contrast to discrete berths, the crane assignment turns out as a planning problem in case of continuous berths. Unsal and Oguz (2013) integrate the QCAP with the QCSP into a monolithic model that takes the berth allocation decisions as an input. A monolithic integration of all three seaside problems is investigated by Lu et al. (2011) and Rodriguez-Molins et al. (2014), which, however, captures the problems just roughly to limit the complexity of the resulting model. In order to be able to use existing solution algorithms for the BAP and the QCSP, Meisel and Bierwirth (2013) propose a three-stage integration framework using preprocessing and feedback mechanisms. Based on this framework, seaside planning problems for 40 vessels are solvable on a high level of detail within practical computation times.

4.3. New developments

This section concentrates on new developments regarding integrated problem solving in seaside operations planning. It is subdivided into a discussion of papers that aim at quantitative assessments of integration approaches and a short consideration of studies that integrate seaside planning with further problems of maritime logistics. In order to evaluate the advantage promised by integrated planning approaches, it is necessary to conduct computational experiments where solving a series of planning problems sequentially is compared with solving the same problems in an integrated manner. To the best of our knowledge merely two papers, Vacca et al. (2013) and Meisel and Bierwirth (2013), tread this path so far.

In Vacca et al. (2013), the authors consider the so-called Tactical Berth Allocation Problem, introduced by Giallombardo et al. (2010), and sequentially solve the contained subproblems BAP and QCAP to optimality. Two variants are considered for estimating vessel handling times in the BAP; a pessimistic variant, where the handling time is in turn overestimated, and an optimistic variant, where shortest possible handling times are assumed for large vessels. The outcome of both sequential approaches is compared with solutions of the monolithic model that are obtained from a Branch-and-Price algorithm. For problem instances with 10 vessels and 3 berths, the improvement

Table 6
Integration of BAP and QCSP with related decisions fields.

Seaside problem	Integrated problem	Reference
BAP	Yard storage allocation	Hendriks et al. (2013); Lee and Jin (2013), Lee et al. (2012), Robenek et al. (2014); Safaei et al. (2010); Salido et al. (2011, 2012); Zhen et al. (2011)
	Inter-terminal transportation	Hendriks et al. (2012), Lee et al. (2012)
	Ship routing	Li and Pang (2011)
QCSP	Yard storage allocation	Wang and Kim (2011)
	Yard truck scheduling	Cao et al. (2010), Tang et al. (2014)

gained from integration against pessimistic sequential planning is a little above the improvement gained against optimistic sequential planning. Anyway, in both cases average improvement rates below 1 percent are observed.

In the framework of Meisel and Bierwirth (2013), all three subproblems of seaside operations planning are incorporated. First, vessel handling times for the BAP are computed by solving QCSPs for a set of time-invariant crane assignments using the UDS heuristic of Meisel (2011). Second, a monolithic BAP and QCAP model is solved using the Squeaky Wheel Optimization method of Meisel and Bierwirth (2009). Third, feasible QC schedules are sought for the variable-in-time crane assignments derived from the berth plan. If at least one QC schedule is infeasible, the invalid part of the berth plan is fed back to the former stage, otherwise the framework ends up with an overall solution to the BAP, QCAP, and QCSP. This integrated approach is compared with sequential planning on a set of instances containing 40 vessels and 10 QCs belonging to a single continuous berth. The service cost obtained under an integrated planning cuts the cost of sequential planning by 34 percent. This result indicates that integration is able to generate benefit if problems are getting larger and if planning obeys to a higher level of detail and scope.

Recently, berth allocation problems are investigated in the context of other management problems faced in the storage yard of a container terminal as well as in the maritime transportation sector, see Table 6. Recall that Table 1 shows that approximately one third of BAP models come along with the handling time attribute *pos*. Value *pos* means that the handling time of a vessel depends on its berthing position meaning that the time needed to transport containers from the yard to the quay or vice versa substantially impacts the vessel handling time. The idea of integrating the BAP with yard planning is to connect berth allocation decisions with assigning yard storage locations to vessels and their containers and, thus, precising the impact of container transport distances. Often these distances are associated with cost incurred by using transport means like AGVs or straddle carriers. For instance, Hendriks et al. (2013) and Lee and Jin (2013) propose monolithic models and heuristics for minimizing the total distance to go by straddle carriers or yard trucks between the vessels' positions and the assigned storage location areas in the yard. In the paper of Robenek et al. (2014), a multi-commodity bulk port is considered, where handling and storage equipment is installed at fixed locations along the quay imposing hard constraints for the berth allocation decisions. A monolithic model for BAP and yard storage allocation is presented and solved by an exact Branch-and-Price algorithm. A two-stage approach is presented by Safaei et al. (2010), which brings together the BAP and a storage allocation problem for import containers in the yard. A feedback loop approach for this combination of problems is proposed by Zhen et al. (2011). Preprocessing and feedback loop approaches are also used to connect the stacking of individual containers in a yard with berth allocation decisions, see Salido et al. (2011, 2012). For large seaports, which possess several container terminals each owning a number of berths, Hendriks et al. (2012) integrate the berth planning for all terminals with the management of inter-terminal container transport flows. Here, the goal is to balance the handling effort at the terminals and to minimize the transport effort for moving containers between the terminals of the port. Also Lee et al. (2012) consider a multi-terminal port. In their problem, both, yard storage allocation and inter-terminal transportation are combined with berth allocation in order to minimize the total transportation cost of containers. Also ship routing problems have been considered in the context of berth allocation. Li and Pang (2011) investigate the routing of vessels between different terminals/ports in tramp shipping under limited berthing capacities at the terminals. Given sets of container transport requests, terminals with discrete berths, and vessels of varying capacity, the goal is to find routes for the vessels such that the sum of the total sailing time and the waiting time at the terminals is minimized.

Also quay crane scheduling problems are increasingly combined with yard management. In Wang and Kim (2011), a group-model for the QCSP is extended by decisions for assigning storage yard space to the unloaded containers. The objective of this problem is not just to handle a vessel as fast as possible but also to uniformly distribute the workload among the yard blocks and to avoid that containers of a group are spread over too many blocks in the yard. The proposed monolithic model is solved by a GRASP meta-heuristic. The container-models of Cao et al. (2010) and Tang et al. (2014) additionally include scheduling decisions for the yard trucks that transport containers between the quay and the yard. The goal is to avoid that QCs starve while loading and unloading containers by a close coupling of crane and truck operations. Cao et al. (2010) propose a model and a Genetic Algorithm for sequencing the container jobs of a single QC and for distributing the corresponding transport tasks among the yard trucks such that the makespan of the QC operations is minimized. The method solves instances with up to 15 containers and up to 4 yard trucks to an average optimality gap of 6 percent within less than a second. A monolithic model for jointly planning the operations of multiple QCs and yard trucks is presented in Tang et al. (2014). The problem is tackled by Particle Swarm Optimization, producing solutions with an optimality gap of 4 percent for large-sized instances with 500 containers, 4 QCs, and 14 yard trucks.

5. Summary and future research directions

This paper surveys the progress, observed in the literature since 2009, in the area of operations research techniques for seaside operations planning at container terminals. Despite a strong increase of research activity, there are still many topics that have to be addressed by future research. The innovative approaches described in Sections 2.3, 3.3 and 4.3 are one source of inspiration for future research. Below, we mention further research gaps that we consider worth an investigation in order to bring forward the research on terminal operations planning.

5.1. General research directions

The following research directions apply to all three research fields considered in this paper, namely berth allocation, quay crane scheduling, and integrated planning.

- Only a very few papers conduct across model evaluations in order to reveal the conditions for a particular berth allocation model, quay crane scheduling model, or integration concept to produce results superior to those of an alternative approach. With an increasing number of models being proposed for the considered problems, the comparison of these models with each other becomes more and more relevant. Such across model evaluations are needed to identify those formulations that are the most suitable starting points for future developments.
- Regarding the use of methods, we observe a dominance of Genetic and Evolutionary Algorithms proposed in the literature for the problems considered in this survey. Problem specific local search algorithms, meta-heuristics and especially mathematically driven heuristics and exact methods are clearly underrepresented so far. A reason for this might be that a general problem solver like a GA is relatively easy to implement and to be applied to an optimization problem that incorporates real world constraints. However, such approaches are often rough and limited with regard to solution quality. Meanwhile BAPs and QCSPs are much better understood so that research can get away from easy to use methods at the advantage of profound optimization techniques.
- Various new features like innovative layouts (e.g., indented berths), operating concepts (e.g., crane double cycling), and handling technologies (e.g., double spreader cranes) have been included into the considered problems. So far these features have been investigated isolatedly whereas their full improvement potential may require a concerted multi-dimensional innovation process at a terminal. Therefore, future research should consider combinations of these features to find out to what extend these advancements can actually increase the productivity of a container port.

5.2. Berth allocation planning

Berth allocation models and algorithms have well advanced in the recent years, capturing more and more practical requirements and coping with ever increasing problem sizes. Still, the approaches might be further developed into the following directions:

- We see a strong need to come up with benchmarks that cover different types of BAPs. While such benchmarks are now available for the QCSP, the BAP is still lacking a generally accepted benchmark set. This so far hinders an objective comparison of the available solution methods.
- The integration of liner schedules in the berth planning process is of high relevance for practice but not sufficiently dealt with in academia. Cyclic arrivals of vessels at a terminal have just been taken up by a very few papers. Other ideas of considering sporadic and regular calls of vessels together could lead to probabilistic BAP models which reserve capacity on an option basis aiming to increase flexibility of the vessel operators. Also investigation on berth planning processes taking place at dedicated terminals owned by vessel operators themselves might disclose further potentials into this direction.
- The handling of uncertain problem data and the corresponding development of planning methods receives increasing attention in the area of berth allocation. Still, this research is in its beginning in consideration of the fact that punctual arrivals at ports and timely services of vessels are often the exception rather than the rule at a terminal. Furthermore, we observe that most approaches dealing with uncertain data consider a discrete BAP. The reason might be that disturbances of a vessel's service process propagate just to the next vessel at this berth but not to multiple vessels as would be the case at a continuous quay. Therefore, uncertainty can be handled easier for discrete berths but the issue might be of even higher importance for terminals with a continuous quay.

5.3. Quay crane scheduling

The already rich field of quay crane scheduling models and algorithms may be developed into the following directions:

- In the area of crane operations planning, it strikes that stochastic approaches are still missing. This is surprising as the processing times of containers are not at all deterministic in reality. Therefore, in order to find more reliable crane schedules, it should be investigated how to deal with uncertain parameters like container cycle times or waiting times for transport vehicles as well as with stochastic events like breakdowns of handling equipment.
- Vessel stability is an open issue in the field of quay crane scheduling. The stability of a container vessel depends on the distribution of cargo among and within its bays. Stability constraints are typically considered in stowage planning such that a vessel is in safe condition after finishing all loading and unloading operations at a port. However, stability constraints might be violated also during the service process. Therefore, it needs to be investigated how crane schedules can be generated such that they ensure vessel stability throughout the whole service process.
- Ship-to-ship handling of transshipment containers, that is to unload a container from one vessel and to directly load it onto another vessel without storage in the yard, is a further innovation for the QCSP. Such a handling process requires a close coupling of the crane schedules of two or more vessels but it may substantially reduce horizontal transport effort, yard storage operations, and handling times of the involved vessels.

5.4. Integrated planning

We have noticed that integration of seaside operations planning is getting state-of-the-art and even integration of seaside operations with other areas of maritime logistics is yet in its beginning. Nevertheless, further work is needed to get a better understanding of the interaction of the various decisions made within such systems.

- The integration of seaside operations planning problems is eased by considering simplified models for the involved subproblems. However, the improvement potential offered by integrated planning might be underestimated or even gets lost if merely rough models or simple solution algorithms are applied for each of the involved decisions. Hence, the research on integration concepts should work on joining rich BAP, QCAP, and QCSP submodels such that features considered important for the individual problems are also contained in the integrated planning concepts.
- Integration of planning problems is typically considered as a mean of achieving short vessel handling times. It might also help to avoid bottlenecks in the yard and in horizontal transportation, for example, by combining berth allocation and yard storage allocation. However, terminal managers might consider further goals to be relevant. For example, in order to avoid high labor cost, it might be attempted to schedule handling operations preferably for day shifts rather than for night shifts. Therefore, it seems attractive to develop flexible integration concepts that can support various goals in port operations planning.
- Several interrelated problems are still waiting for an integrated planning approach. For example, the quality of a crane schedule clearly depends on the stowage plan of the vessel. Stowage planning therefore tries to anticipate the container loading and unloading process by minimizing overstowage of containers. Anyhow, even better results might be achieved if stowage planning is combined with the QCSP such that containers are distributed on a vessel in a way that guarantees productive crane operations. Further integration may take the hinterland operations of a terminal into account such that the entire process of handling a container at a terminal is considered from a holistic perspective.

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