Chapter 4
Related Work on Seaside Operations Planning

Due to the variety of technical equipments and terminal layouts, research has produced a multitude of optimization models for seaside operations planning in container terminals. This chapter provides literature surveys for the operations planning problems being in the focus of the thesis. Section 4.1 provides a classification scheme and a literature survey for BAP and QCAP formulations. Section 4.2 provides a classification scheme and a literature survey for QCSP formulations. Section 4.3 describes relationships of the seaside planning problems and well known Operations Research problems.

4.1 Related Work on the BAP and the QCAP

4.1.1 Classification Scheme

To show similarities and differences in the existing models for berth allocation, a classification scheme is developed in the following. Studies that concentrate on quay crane assignment either presuppose a particular type of BAP or integrate quay crane assignment decisions in the berth planning process. For this reason, QCAP approaches are captured by the classification scheme as well. Problems are classified according to four attributes. The *spatial attribute* concerns the berth layout and water depth restrictions. The *temporal attribute* describes the temporal constraints for the service process of vessels. The *handling time attribute* determines the way vessel handling times are considered in the problem. The fourth attribute defines a *performance measure* for evaluating possible solutions to a problem. Each attribute can take different values. They are listed in Table 4.1.

Spatial, temporal, and handling time attributes have been described in Sect. 3.2.1. The performance measures listed in Table 4.1 reflect different service quality criteria. Minimizing the waiting time or the handling time of a vessel aims at providing a competitive service to vessel operators. If both objectives are pursued (i.e., *wait* and

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Table 4.1 A classification scheme for BAP formulations

Value	Description
1. Spatial attribute	
disc	The quay is partitioned in *disc*rete berths
cont	The quay is assumed to be a *cont*inuous line
hybr	The *hybr*id quay mixes up properties of discrete and continuous berths
draft	Vessels with a *draft* exceeding a minimum water depth cannot be berthed arbitrarily
2. Temporal attribute	
stat	In *stat*ic problems there are no restrictions on the berthing times
dyn	In *dyn*amic problems arrival times restrict the earliest berthing times
due	*Due* dates restrict the latest allowed departure times of vessels
3. Handling time attribute	
fix	The handling time of a vessel is considered *fix*ed
pos	The handling time of a vessel depends on its berthing *pos*ition
QCAP	The handling time of a vessel depends on the assignment of QCs
QCSP	The handling time of a vessel depends on a QC operation schedule
4. Performance measure	
wait	*Wait*ing time of a vessel
hand	*Hand*ling time of a vessel
compl	*Compl*etion time of a vessel
speed	*Speed*up of a vessel to reach the terminal before the expected arrival time
tard	*Tard*iness of a vessel against the given due date
order	Deviation between the arrival *order* of vessels and the service order
rej	*Rej*ection of a vessel
res	*Res*ource utilization effected by the service of a vessel
pos	Berthing of a vessel apart from its desired berthing *pos*ition
misc	*Misc*ellaneous

hand are set), the port stay time of vessels is minimized. Minimizing the completion times of vessels (*compl*) aims at earliest possible departures. In the presence of soft arrival times or soft due dates either the speedup of vessels (*speed*) or the tardiness of vessels (*tard*) has to be minimized. The *order* measure strives at a reduction of the deviation between the arrival order of vessels and the planned service order. It is assessed by the number of vessels not served in First-come First-served manner. If it is foreseeable that a vessel cannot be served within the desired time window, it may be rejected at the terminal (and possibly reassigned to another terminal of the port). Hence, the minimization of vessel rejections (*rej*) is considered as a goal in some models. If labor or other resources are scarce at a terminal, the resource utilization (*res*) is optimized. The minimization of deviations between chosen berthing positions and desired positions (*pos*) aims at reducing the travel distances for the horizontal transport vehicles. If none of the above performance measures is used in a BAP formulation, the value *misc* (miscellaneous) is set in the classification.

The above listed measures address criteria to be minimized. Either the minimization of the total measure for all vessels or the minimization of the measure for the worst performing vessel can serve as an objective function in a BAP. A total measure is denoted in the classification scheme by a $\sum()$ function and a worst performing measure, i.e., a min–max objective, is denoted by a $\max()$ function. Vessel specific weights are indicated by the denotation w. Moreover, if weights appear with an index, i.e., w_1 to w_4, they address weights of combined performance measures.

Using the introduced classification scheme, a certain type of BAP is described by a selection of values for each of the four attributes. As an example, consider a problem where the quay is partitioned into discrete berths serving the vessels exclusively (*disc*). The arrival times restrict the earliest berthing of vessels (*dyn*) and handling times are known and fixed (*fix*). The objective is to minimize the total cost arising for tardiness of vessels (*tard*) and for berthing vessels apart from desired berthing positions (*pos*). Different cost rates (w_1, w_2) apply to these performance measures. According to the proposed scheme, this problem is classified by $disc \mid dyn \mid fix \mid \sum(w_1\ tard + w_2\ pos)$. In case that the maximum tardiness of vessels has to be minimized, the problem is classified by $disc \mid dyn \mid fix \mid max(tard)$.

4.1.2 Problem Classification

Table 4.2 gives a comprehensive survey of berth allocation and quay crane assignment formulations from the literature. Some authors outline approaches more or less informally while others provide precise optimization models. If a unique classification of a paper is not possible according to the given information, the best fit of classifying attributes is taken. The classification exclusively covers research dealing with the operational decisions regarding the BAP and QCAP. Not covered are studies employing analytical models, simulation, and queuing theory as is used for the evaluation of investment decisions and berthing policies, and for the determination of terminal throughput and system dynamics of CTs (see Edmond and Maggs, 1978; Schonfeld and Frank, 1984; Lai and Shih, 1992; Legato and Mazza, 2001; Henesey et al., 2004; Dragovic et al., 2005, 2006). Papers containing ideas and results published elsewhere, for example Kim (2005) and Crainic and Kim (2007), are also excluded.

As shown in Table 4.2, discrete and continuous problems are almost in balance, while dynamic problem formulations clearly prevail against static ones. The handling times of vessels are assumed to depend on the berthing positions in almost every discrete BAP formulation, because they are easily assessable in discrete models. However, only two continuous formulations and one half of the hybrid BAP formulations care for position based handling times. The QC resource is considered only in a few BAP formulations. Most models aim at the minimization of the port stay time of vessels. Frequently addressed are also the minimization of tardy vessel departures and berthing positions different from desired berthing positions.

Table 4.2 Overview of BAP formulations

Problem classification	Reference
$disc \mid stat \mid pos \mid \sum(wait + hand)$	Imai et al. (2001) Hansen and Oğuz (2003)
$disc \mid stat \mid pos \mid \sum(wait + hand + w_1\ order)$	Imai et al. (1997)
$disc \mid stat, due \mid pos \mid \sum w\ rej$	Imai et al. (2008b)
$disc \mid stat \mid pos, QCSP \mid \sum(wait + hand)$	Lee et al. (2006)
$disc \mid dyn \mid pos \mid \sum(wait + hand)$	Imai et al. (2001) Hansen and Oğuz (2003) Monaco and Sammarra (2007)
$disc \mid dyn \mid pos \mid \sum w(wait + hand)$	Imai et al. (2003) Theofanis et al. (2007a)
$disc \mid dyn \mid pos \mid \sum(w_1\ wait + w_2\ tard + w_3\ pos)$	Hansen et al. (2008)
$disc \mid dyn \mid pos \mid \sum w\ tard$	Golias et al. (2006)
$disc \mid dyn \mid pos \mid \sum w\ tard, \sum(wait + hand)$	Imai et al. (2007b)
$disc \mid dyn \mid pos \mid misc$	Golias et al. (2007)
$disc \mid dyn, due \mid pos \mid \sum w(wait + hand)$	Cordeau et al. (2005) Mauri et al. (2008)
$disc \mid dyn, due \mid pos \mid \sum w\ rej$	Imai et al. (2008b)
$disc, draft \mid dyn \mid pos \mid \sum(wait + hand)$	Han et al. (2006)
$disc, draft \mid dyn, due \mid pos \mid \sum wait$	Zhou et al. (2006)
$disc \mid dyn \mid pos, QCAP \mid \sum(wait + hand)$	Imai et al. (2008a)
$disc \mid dyn \mid QCAP \mid \sum(wait + hand + tard)$	Liang et al. (2009)
$disc \mid dyn, due \mid QCAP \mid -\sum(w_1 res - w_2 pos)$	Giallombardo et al. (2008)
$cont \mid stat \mid fix \mid max(compl)$	Li et al. (1998)
$cont \mid stat \mid fix \mid \sum w\ compl$	Guan et al. (2002)
$cont \mid stat \mid QCAP \mid \sum(w_1\ wait + w_2\ speed + w_3\ tard + w_4\ pos)$	Park and Kim (2003) Rashidi (2006)
$cont \mid stat \mid QCAP \mid max(compl)$	Oğuz et al. (2004)
$cont \mid dyn \mid fix \mid \sum w(wait + hand)$	Guan and Cheung (2004)
$cont \mid dyn \mid fix \mid \sum(w_1\ wait + w_2\ pos + w_3\ rej)$	Wang and Lim (2007)
$cont \mid dyn \mid fix \mid \sum(w_1\ tard + w_2\ pos)$	Moon (2000), Park and Kim (2002) Kim and Moon (2003) Briano et al. (2005)
$cont \mid dyn \mid fix \mid max(res)$	Lim (1998)
$cont, draft \mid dyn \mid fix \mid max(res)$	Lim (1999), Tong et al. (1999) Goh and Lim (2000)
$cont \mid dyn \mid pos \mid \sum(wait + hand)$	Imai et al. (2005)
$cont \mid dyn \mid QCAP \mid \sum res$	Meisel and Bierwirth (2006)
$cont \mid dyn \mid QCAP \mid \sum w\ res$	Theofanis et al. (2007b)
$cont \mid dyn \mid QCAP, QCSP \mid max(tard)$	Liu et al. (2006)
$cont \mid dyn \mid QCAP, QCSP \mid max(compl), \sum(wait + hand)$	Meier and Schumann (2007)
$cont \mid dyn \mid QCAP, QCSP \mid \sum(wait + hand + w_1\ tard)$	Ak and Erera (2006)
$cont \mid dyn, due \mid QCAP \mid max(res)$	Hendriks et al. (2008)
$cont \mid dyn, due \mid QCAP \mid \sum hand + w_1\ res$	Legato et al. (2008)
$hybr \mid dyn \mid fix \mid \sum(w_1\ wait + w_2\ pos)$	Moorthy and Teo (2006) Dai et al. (2008)
$hybr \mid dyn, due \mid fix \mid \sum w\ pos$	Chen and Hsieh (1999)
$hybr \mid dyn \mid pos \mid \sum(wait + hand)$	Imai et al. (2007a)
$hybr \mid dyn, due \mid pos \mid \sum w(wait + hand)$	Cordeau et al. (2005)
$hybr, draft \mid dyn \mid pos \mid \sum(wait + hand)$	Nishimura et al. (2001)
$hybr, draft \mid dyn \mid pos \mid max(compl), \sum wait, \sum order$	Cheong et al. (2007)
$hybr, draft \mid dyn \mid pos \mid \sum pos$	Hoffarth and Voß (1994)
$hybr \mid dyn \mid pos, QCAP \mid \sum wait, \sum tard$	Lokuge and Alahakoon (2007)

In the following, the relevant papers are briefly reviewed according the grouping into discrete, continuous, and hybrid problems. Formulations with handling time characteristics fix or pos are merely summarized, whereas formulations that consider the crane resource within berth planning are presented in more detail.

4.1.2.1 Discrete Problems

The discrete BAP has been studied in the static and in the dynamic variant by Imai et al. (2001). In both problem variants the assignment and sequencing of vessels to berths is searched with respect to minimum waiting and handling times of the vessels. A Lagrangean relaxation based heuristic is presented to solve the problem. Hansen and Oğuz (2003) and Monaco and Sammarra (2007) provide more compact MIP formulations for the same problem. In the discrete static BAP considered by Imai et al. (1997) not only waiting and handling times of the vessels are minimized but also the deviation between the arrival order of vessels and the service order. The problem is reduced to a classical assignment problem, which is solved by the Hungarian method. In a recent paper of Imai et al. (2008b) the minimization of the weighted number of vessel rejections is handed over to a Genetic Algorithm (GA). A vessel is rejected at a terminal if it cannot be served without overshooting a due date, represented by a maximum acceptable waiting time.

Dynamic variants of the discrete BAP are considered by Imai et al. (2003) and Theofanis et al. (2007a) in the context of weighted port stay times for the vessels. In the problem considered by Hansen et al. (2008) not only handling times but also service costs of vessels depend on the berth they are assigned to. Pursued is a tardiness objective which accounts for departure time related costs including penalties for tardiness as well as benefits for early departures. A Variable Neighborhood Search, used to solve the problem, turns out to be superior to the GA of Nishimura et al. (2001). Further departure time related objectives for the discrete dynamic BAP are proposed by Golias et al. (2006) and Imai et al. (2007b). In the model of Golias et al. (2007) arrival times and handling times of vessels are considered as stochastic variables. Since no specific performance measure is supposed for the problem, it is classified miscellaneous. A discrete dynamic BAP with due dates is formulated by Cordeau et al. (2005). A Tabu Search method is presented that outperforms the First-come First-served rule and also CPLEX. Mauri et al. (2008) design a Column Generation approach for the problem of Cordeau et al. (2005) which delivers better solutions in shorter runtime than Tabu Search. In the models of Han et al. (2006) and Zhou et al. (2006) the draft of vessels restricts the berth assignment decisions. In both papers, a GA is proposed to solve the problem. Moreover, Zhou et al. (2006) consider stochastic arrival and handling times of vessels and a waiting time restriction that is classified as a due date.

The crane resource is considered within a discrete BAP by Lee et al. (2006), Imai et al. (2008a), Liang et al. (2009), and Giallombardo et al. (2008). Lee et al. (2006) develop a GA to obtain berth plans that are evaluated by generating a feasible work plan for a given number of cranes at each berth. The evaluation bases on a modification of the QCSP model of Kim and Park (2004), which is not solved in the paper. Instead, a small-sized instance is provided as example. In the paper of Imai et al. (2008a) it is supposed that a certain number of QCs has to be assigned to each vessel. The model of Liang et al. (2009) decides on the assignment of cranes to berths as well as on the berthing times and the positions of the vessels. In Giallombardo et al. (2008), cranes, berthing times, and berthing positions are assigned to vessels, such that the crane utilization (*res*) is maximized and the berthing position dependent container flow between pairs of vessels (*pos*) is minimized.

4.1.2.2 Continuous Problems

The continuous static BAP with fixed vessel handling times has been introduced by Li et al. (1998). The problem is formulated as a "multiple-job-on-one-processor" scheduling problem. This allows to adapt the First-Fit-Decreasing heuristic, well-known from Bin Packing, for minimizing the maximum completion time among the vessels. Guan et al. (2002) propose to minimize the total weighted completion time of vessels for this type of problem and provide a priority rule based heuristic.

The continuous dynamic BAP with fixed handling times has been investigated in a number of studies. Guan and Cheung (2004) develop a tree search procedure to minimize the total weighted port stay time of vessels. In the problem of Wang and Lim (2007) the minimization of penalty cost for rejected vessels and apart berthing positions are the pursued objectives. A stochastic beam search algorithm is presented that is capable to solve instances with up to 400 vessels. A further objective, namely the minimization of tardiness of vessels, is treated by Moon (2000), Park and Kim (2002), Kim and Moon (2003), and Briano et al. (2005). Several solution methods are proposed for this problem, including a sub-gradient method (Park and Kim, 2002) and a Simulated Annealing approach (Kim and Moon, 2003). Lim (1998) formulates a problem, where the berthing times of vessels are already set by the arrival times. Instead, suitable berthing positions need to be determined and the goal is to minimize the maximum quay length required to serve vessels in accordance with the schedule. In this formulation of the problem, the goal is classified as a resource objective. The approach of Lim (1998) has been continued by Lim (1999), Tong et al. (1999), and Goh and Lim (2000).

The continuous BAP with handling times depending on berthing positions is studied by Imai et al. (2005). The authors suggest a heuristic solution method, which solves a discrete BAP first and then improves the obtained solution by shifting vessels along the quay as allowed in the continuous BAP.

The continuous BAP in combination with crane assignment issues has been introduced by Park and Kim (2003). In this pioneering model it is simultaneously decided on berthing times, berthing positions, and the assignment of QCs to vessels at first. Here, the idea is to assign single QC-hours to the vessels such that variable-in-time QC-to-Vessel assignments are possible. Next, it is decided on the specific cranes that serve a vessel. A Lagrangean relaxation based heuristic is used at the first decision level and dynamic programming is applied at the second level. A combined model for both decision levels is presented by Rashidi (2006).

The continuous static BAP with crane assignment issues is also studied by Oğuz et al. (2004). The pursued objective is to minimize the maximum completion time among the vessels. In contrast to Park and Kim (2003), Oğuz et al. (2004) merely consider time-invariant QC-to-Vessel assignments. However, crane productivity losses, which are frequently observed in practice, are anticipated in the made assignments. Unfortunately, the power of both approaches is not yet compared in the literature.

An approach aiming at the improvement of crane utilization is provided by Meisel and Bierwirth (2006). Here, a set of promising QC-to-Vessel assignment patterns is generated for each vessel at first and then a priority rule is used to fix the berthing time, the berthing position, and the particular crane assignment pattern for every vessel. The minimization of cost for manning QCs is pursued. On this basis, several real-world berth plans are considerably improved without deteriorating the service quality substantially. Also Theofanis et al. (2007b) aim at an effective use of cranes by penalizing crane assignments that do not meet a targeted productivity rate. As a common solution method, a GA is proposed for the problem, which does not deliver satisfying results yet.

In a couple of papers, crane assignment and crane scheduling are involved to estimate vessel handling times for the berth planning. Liu et al. (2006) propose to derive vessel handling times from QCSP schedules which are generated in a preprocessing. Berthing times and QC-to-Vessel assignments are subsequently determined for the vessels with respect to given berthing positions and the projected handling times. The minimization of the maximum relative tardiness of vessel departures is considered as objective. Meier and Schumann (2007) generate a berth plan using the approach of Guan and Cheung (2004). Next, QC schedules are build for all vessels basing on the QCSP model of Zhu and Lim (2006). The gained handling times are used to revise the prior berth plan iteratively, which is controlled by a Multi-Agent System (MAS). However, the conducted computations indicate that this coordination is not yet effective in minimizing service objectives. A monolithic model for continuous dynamic berth allocation, crane assignment, and crane scheduling is presented by Ak and Erera (2006). The captured subproblems are considered on a highly aggregated level, which enables applying Tabu Search for the minimization of the port stay time and the avoidance of penalty cost for tardy departures of the vessels.

Further approaches include due dates of vessels into a dynamic BAP, which restricts the service of vessels to time windows. Hendriks et al. (2008) consider berth allocation at a tactical level, where service time windows, quay space, and crane capacity are reserved for a set of periodically arriving vessels. The objective is to minimize the maximum crane capacity reserved for a period. Legato et al. (2008) propose to take berthing positions, berthing times, and due dates from a berth plan that is generated using the model of Park and Kim (2003). The task remaining is to assign the available cranes to vessels such that the total handling time of vessels and the number of utilized cranes are minimized. A heuristic procedure is sketched for this problem and demonstrated at an example.

4.1.2.3 Hybrid Problems

The hybrid BAP with fixed handling times is investigated by Moorthy and Teo (2006), Dai et al. (2008), and Chen and Hsieh (1999). In Moorthy and Teo (2006) berthing areas of vessels are determined at a tactical level. The goal is to achieve robust berth plans with respect to stochastic perturbations of vessel arrivals. To identify the impact of vessel delays, the service processes of vessels are considered as activities and represented in a precedence graph which is analyzed using the Project Evaluation Review Technique. Dai et al. (2008) transfer the gained results to the operational level, where precise positions are searched within the projected berthing areas. For this problem a Simulated Annealing algorithm is proposed which minimizes vessel waiting time and the berthing position dependent container flow between pairs of vessels. In an early paper of Chen and Hsieh (1999), a MIP formulation is given for a same problem which also incorporates vessel due dates.

Hybrid BAP formulations with position dependent vessel handling times are studied from different perspectives in several papers. Imai et al. (2007a) investigate a hybrid BAP for indented berths whereas Cordeau et al. (2005) derive a hybrid problem from a discrete BAP where the quay is dynamically repartitioned. Additionally, the models of Nishimura et al. (2001), Cheong et al. (2007), and Hoffarth and Voß (1994) incorporate the draft of vessels. Although crane assignment issues are approached in Hoffarth and Voß (1994), a heuristic is proposed that does not involve crane assignments in the berth allocation planning. Crane assignment decisions are explicitly included in a hybrid BAP by Lokuge and Alahakoon (2007) and accompanying papers, see Lokuge and Alahakoon (2004, 2005) and Lokuge et al. (2004). In this problem, multiple vessels can be served at one berth at a time. A set of cranes, shared by simultaneously served vessels, is assigned to each berth. A MAS is designed where all decisions to be made are distributed among specialized software agents. The system performance is compared with an existing terminal operating system (Jaya Container Terminal, Sri Lanka), achieving considerable reductions regarding vessel waiting times and tardiness.

Concluding the classification of BAP formulations, it can be seen that incorporating decision dependent handling times of vessels is one of the most active streams of current research in berth allocation planning. The impact of berthing positions on handling times is well-established in discrete and hybrid BAP formulations, but it is hardly considered in the continuous case. This is surprising because a deviation between a vessel's berthing position and the storage position of export containers in the yard certainly impacts the handling time in the continuous case as well. The consideration of the QC resource for the determination of handling times is a driving force of current research. Papers published on this issue reveal the growing interest in the interdependencies between seaside planning problems.

4.2 Related Work on the QCSP

4.2.1 Classification Scheme

As for berth planning problems, there is no classification scheme existing for QC scheduling problems so far. The proposed scheme classifies problems according to four attributes. The *task attribute* concerns the definition of tasks that represent the workload of the considered vessel. The *crane attribute* describes the availability of QCs at the vessel and the consideration of the crane movement speed. The *interference attribute* addresses the spatial constraints that are defined in a problem. These attributes have been described in detail in Sect. 3.2.3. A fourth attribute defines the *performance measure* for evaluating solutions to a problem. Each of the four attributes can take different values. They are listed in Table 4.3.

Most of the performance measures for crane schedules aim at short vessel handling times to allow for earliest possible departures. Minimizing the completion time of tasks (*compl*) serves the purpose of a short vessel handling time. The makespan of a schedule, i.e., the maximum completion time among all tasks, is of particular interest, because it determines the departure time for a vessel. An effective utilization of cranes leads also to short vessel handling times. Related performance measures are

Table 4.3 A classification scheme for QCSP formulations

Value	Description
1. Task attribute	
Area	Tasks refer to *area*s of bays
Bay	Tasks refer to single *bay*s
Stack	Tasks refer to container *stack*s within a bay
Group	Tasks refer to *group*s of containers
Container	Tasks refer to single *container*s
prmp	Preemption of tasks is allowed
prec	Precedence relations among tasks are given
2. Crane attribute	
ready	Individual *ready* times of QCs are given
TW	Cranes are available at the vessel within hard time windows
pos	Initial (and final) *pos*itions of QCs are prescribed
move	Travel time for crane *move*ment is respected
3. Interference attribute	
cross	Non-*cross*ing of QCs is respected
save	*Safe*ty margins between QCs are respected
4. Performance measure	
compl	*Compl*etion time of a task
finish	*Finish*ing time of a QC
util	*Util*ization rate of a QC
through	*Through*put of a QC
move	*Move*ment of a QC

the finishing time of cranes (*finish*), the utilization rate of cranes (*util*), the throughput of cranes (*through*), and the time spent for moving cranes to other quay positions (*move*).

Like in the classification of berth allocation problems, a $\sum()$ function indicates a total performance measurement of either tasks or QCs, and a max() function indicates a worst performance measurement. Objective functions with weighted tasks or cranes are indicated by a weight w, whereas weights w_1, w_2, etc., address a multi-objective function. As an example for the classification scheme consider a problem where the tasks consist of all loading and unloading operations of containers in bays. Assume further that initial positions and a moving speed are given for the cranes and non-crossing as well as safety margins must be respected. If the objective is to minimize the completion of the latest finished task, the problem is referred to as $Bay \mid pos, move \mid cross, save \mid max(compl)$ in the classification.

4.2.2 Problem Classification

Table 4.4 gives a comprehensive survey of QCSP formulations from the literature. The classification comprises optimization models and verbally introduced problem descriptions by a best fit. The survey shows that most approaches define tasks on the basis of single bays or container groups. Non-crossing constraints are involved in the majority of research, whereas safety margins have much less been considered. Crane attributes are neglected in diverse studies, i.e., there are no ready times or time windows and also no movement speed given for the cranes. Most of the published QCSP formulations are dealing with the makespan criterion. The following survey takes up the distinction of models by the task attribute. Crane scheduling problems for complete bays and for container groups are considered next. The remaining approaches are presented together in a third subsection.

4.2.2.1 Scheduling of Complete Bays

In the QCSP with complete bays it is searched for a crane schedule where each bay is exclusively served (usually without preemption) by one QC. For a realistic consideration of this problem, the incorporation of the non-crossing condition is more or less inevitable. Basically, non-crossing of cranes is quite easy to assure by generating schedules, where all QCs have an identical moving direction along the vessel which is not changed during the service. Such schedules are referred to as unidirectional schedules in the following.

Under the premise of unidirectional crane schedules, some results on approximation algorithms are presented for the QCSP in Lim et al. (2004c). Moreover, a reformulation of the considered QCSP as a constraint programming model is provided in Lim et al. (2004d). The authors show that every unidirectional schedule can be obtained from a certain assignment of tasks to QCs. Hence, the problem

Table 4.4 Overview of QCSP formulations

Problem classification	Reference
$Area \mid - \mid cross \mid max(util)$	Winter (1999) Steenken et al. (2001)
$Area \mid - \mid cross, save \mid -\sum w\, through$	Lim et al. (2002, 2004b)
$Bay \mid - \mid cross \mid max(compl)$	Lim et al. (2004c,d, 2007) Zhu and Lim (2006) Lee et al. (2007, 2008a)
$Bay \mid - \mid cross \mid \sum w\, compl$	Lee et al. (2008b)
$Bay \mid move \mid cross \mid \sum move$	Ak and Erera (2006)
$Bay \mid pos, move \mid cross, save \mid max(compl)$	Liu et al. (2006)
$Bay, prmp \mid - \mid - \mid \sum w\, compl$	Daganzo (1989) Peterkofsky and Daganzo (1990)
$Bay, prmp \mid pos, move \mid cross, save \mid max(compl)$	Liu et al. (2006)
$Stack, prec \mid - \mid - \mid max(compl)$	Goodchild and Daganzo (2004) Zhang and Kim (2009)
$Group, prec \mid ready, pos, move \mid cross, save \mid w_1\, max(compl) + w_2 \sum finish$	Kim and Park (2004) Moccia et al. (2006) Sammarra et al. (2007)
$Group, prec \mid ready, pos, move \mid cross, save \mid \sum w\, finish + \sum w\, tard$	Tavakkoli-Moghaddam et al. (2009)
$Group, prec \mid move \mid cross \mid max(compl)$	Ng and Mak (2006)
$Group, prec \mid TW \mid cross, save \mid max(compl)$	Jung et al. (2006)
$Container, prec \mid - \mid - \mid max(compl)$	Meisel and Wichmann (2008)

can be solved by exploring the space of task-to-QC assignments for which a constraint propagation method and a Simulated Annealing algorithm are presented. Recently, Lim et al. (2007) have shown for the QCSP with complete bays that there is always an optimal schedule among the unidirectional ones. This seminal result demonstrates that searching the space of unidirectional schedules is not a heuristic reduction of the problem. An exact method for the unidirectional problem delivers the optimal solution even if the premise of unidirectional crane schedules is dropped.

Liu et al. (2006) propose a MIP model for the QCSP which includes initial crane positions, moving speed, and interference conditions for the cranes. The structure of unidirectional schedules is anchored in this model, which allows to formulate the non-crossing condition and safety margins in a straight-forward manner. Furthermore, with the focus put on unidirectional schedules, the search space is significantly reduced which allows to solve non-trivial instances by a standard solver.

In a couple of papers, schedule unidirectionality is neither assumed in models nor in algorithms. A Branch-and-Bound method with limited capability and a better performing Simulated Annealing algorithm are presented for the QCSP with complete bays by Zhu and Lim (2006). A GA and a greedy algorithm are developed by Lee et al. (2007, 2008a) for the same problem. The approach is augmented in Lee et al. (2008b) by replacing the makespan criterion with the total weighted completion time of tasks. Ak and Erera (2006) treat the QCSP for a set of vessels that are served simultaneously at the quay. The assignment problem of cranes to the bays of the vessels is modeled as a min-cost flow problem, with the QC travel time between vessels to be minimized.

Scheduling of QCs with preemption allowed has been investigated by Daganzo (1989). The idea is to assign cranes to bays for certain time slots, such that the overall workload is well balanced for the cranes. As a consequence, a bay might be served consecutively by different QCs. Note that this early work does not take crane interference into consideration. The goal is to minimize the total weighted completion times of vessels. The considered scheduling problem is solved by rules of thumb and by a Branch-and-Bound method later proposed by Peterkofsky and Daganzo (1990). Preemptive schedules are also allowed in another version of the above mentioned model of Liu et al. (2006). The authors use this model to prove by experiment that the sharing of bays among cranes can significantly improve the makespan of a QCSP instance.

4.2.2.2 Scheduling of Container Groups

Enabling the cranes to share the workload of bays is the most typical feature of the QCSP with container groups. For this reason the need to avoid crane crossing is even more stressed in this problem than in the QCSP with complete bays. The QCSP with tasks defined on the basis of container groups has been introduced by Kim and Park (2004). Their model considers QC operations in detail by taking precedence relations among tasks, crane attributes, and crane interference into account. In this model, safety margins between QCs are enforced by a non-simultaneity constraint between tasks located in adjacent bays. The pursued objective is the minimization of the weighted sum of makespan and QC finishing times. The authors propose a Branch-and-Bound method and a Greedy Randomized Adaptive Search Procedure (GRASP). The Branch-and-Bound method outperforms GRASP in terms of solution quality but fails for larger test problems.

The model of Kim and Park (2004) has been refined by Moccia et al. (2006), leading to a more stringent problem formulation. They develop a Branch-and-Cut algorithm which significantly improves solutions for the benchmark suite provided in Kim and Park (2004). Sammarra et al. (2007) present a Tabu Search algorithm for the same problem where a neighborhood is defined by resequencing the tasks of a crane and by swapping tasks between cranes. Compared to the Branch-and-Cut of Moccia et al. (2006), Tabu Search cuts down the computation time significantly for the larger instances of the benchmark suite at the expense of a slightly weaker solution quality. Tavakkoli-Moghaddam et al. (2009) extend the model of Kim and Park (2004) towards scheduling cranes for a set of vessels in parallel. A GA is presented for the minimization of the total weighted finishing time of QCs and the total weighted tardiness of vessels (as known from berth planning). Unfortunately, the GA's performance is not compared with other algorithms proposed in this stream.

Ng and Mak (2006) obtain a QCSP with container groups by including the import containers and the export containers of a bay into two separate groups. A precedence relation is inserted between the two tasks of each bay. The problem is solved by partitioning the set of bays into areas such that sharing of workload by cranes is only possible at the border of two areas. Jung et al. (2006) discuss using time windows for the service of cranes but do not outline this feature in detail.

4.2.2.3 Further Problems

Taking a look at Table 4.4, it can be seen that defining tasks on the basis of bay areas, container stacks, or single containers is rather seldom dealt with in the scientific literature. Winter (1999) and Steenken et al. (2001) assign bay areas to QCs such that the maximum difference regarding the utilization of any two cranes is minimized. The authors show that crane scheduling on the basis of bay areas leads to a partitioning problem that can easily be solved optimal for instances of practical size. Lim et al. (2002) and Lim et al. (2004b) assign bay areas to QCs assuming individual throughput rates for the cranes. They aim at the maximization of the total throughput and propose several heuristics, where a Squeaky Wheel Optimization method combined with a local search performs best. Note that none of the mentioned approaches takes detailed crane schedules into consideration.

A stack-based QCSP model has been introduced by Goodchild and Daganzo (2004) and is further studied in a number of papers by Goodchild and Daganzo (2005a,b, 2006, 2007) and Goodchild (2006). The basic idea is to consider one crane processing the container stacks of one bay. Two precedence-related tasks are defined for each container stack, one for unloading the stack and one for loading the stack. Note that the loading and unloading of different stacks can be parallelized in the crane schedule, which is referred to as double cycling. The problem is to find a sequence for processing the stacks, which minimizes the makespan. The authors reformulate this problem as a two-machine flow shop scheduling problem which is solved to optimality using the rule of Johnson (1954). The approach is continued by Zhang and Kim (2009) who modify Johnson's rule in order to handle hatches that cover adjacent stacks. Double cycling is also addressed by Meisel and Wichmann (2008), who deal with crane scheduling on the basis of single containers. Contrasting the approach of Goodchild and Daganzo, reshuffle containers can be repositioned in the bay instead of temporarily unloading them, which accelerates the service process. A GRASP heuristic is used to solve the resulting scheduling problem.

QC scheduling is also considered within other operations planning problems concentrating, e.g., on stowage planning, horizontal transport operations, and yard crane scheduling, cf. Gambardella et al. (2001), Bish (2003), Kim et al. (2004a), Lee et al. (2005), Imai et al. (2006), Chen et al. (2007), and Canonaco et al. (2008). Since the primary focus of this research is not on the determination of crane schedules, these approaches are not explicitly addressed in the classification.

Concluding this review, major streams of QC scheduling research define tasks by complete bays or by container groups. Crane scheduling on the basis of container stacks or single containers, as investigated in the studies of Goodchild and Daganzo, Zhang and Kim (2009), and Meisel and Wichmann (2008), considers merely a single QC. This problem reduction eliminates important issues such as the assignment of tasks to cranes and the consideration of crane interference. Models that incorporate crane interference issues mainly address the non-crossing requirement. Safety margins and crane attributes like ready times, crane movement, etc., are often ignored. While one of these characteristics may influence the handling time of a vessel only moderately, their joint impact on vessel handling times is expected to be significant. Therefore, formulating rich QCSP models is crucial for deriving reliable QC schedules and vessel handling times.

4.3 Related OR Problems

Several well known problems from the field of Operations Research (OR) are closely related to the BAP, the QCAP, and the QCSP. In this section relations to machine scheduling, two-dimensional packing, project scheduling, and vehicle routing are briefly described. Reformulating the terminal specific problems to one of the standard problems enables existing solution methods to be applied. The potentials and limitations of such reformulations are briefly discussed.

In *machine scheduling* a set of jobs is considered which has to be processed by a set of machines. Job operations have to be sequenced on machines and feasible starting times for the job operations need to be found. A wide range of machine scheduling problems has been formulated in the literature, differing, for example, in the number and type of machines and in the particular machine routings required for the jobs. Usually a machine can process only one job at a time and job processing is assumed to be non-preemptive. Additionally, release times and due dates of jobs can be stated. Among others, makespan minimization is a typical objective. For an overview on this field of research the reader is referred to Pinedo (2002).

Machine scheduling approaches are of interest because berth allocation problems can be viewed as such, where the quay takes the role of a processor and the vessels take the role of the jobs. In the study of Li et al. (1998) a single processor (the whole quay) is able to handle several jobs in parallel. In the study of Guan et al. (2002) the quay is represented by a set of processors (quay segments) where a job is handled by a subset of processors simultaneously. Both studies address the continuous static BAP with fixed handling times. Release times of jobs have to be introduced to obtain a dynamic variant of this problem. The discrete BAP is treated as a scheduling problem for unrelated parallel machines with additional constraints by Imai et al. (1997) and Monaco and Sammarra (2007). In these approaches each berth is represented by one machine that processes the assigned jobs sequentially. Oğuz et al. (2004) view the QCs as a set of processors to incorporate the QCAP within the BAP. This allows for application of a parallel processor scheduling algorithm which strives for a makespan minimization.

Goodchild and Daganzo (2005b) formulate a stack-based QCSP as a two-machine flow shop problem. Each job (representing a container stack within a bay) consists of an unloading and a loading operation. One machine processes all unloading operations and the other machine processes all loading operations. Johnson's rule is applicable because the jobs have to pass the machines in identical order. Peterkofsky and Daganzo (1990) and Lim et al. (2007) discuss relations between bay-based QCSPs and the scheduling problem with parallel machines. While machines are basically unrelated in parallel machine scheduling, Lim et al. (2007) argue that quay cranes are related because the non-crossing requirement must be respected.

Two-dimensional packing deals with the arrangement of a set of rectangles with fixed size within an open-ended rectangular bin, see Baker et al. (1980). In a feasible solution no rectangles overlap. The objective is the minimization of the height of the packing within the bin.

The continuous static BAP with fixed vessel handling times shows close relations to two-dimensional packing problems. This becomes obvious by the space–time representation of berth plans. For berth planning only orthogonal packings need to be considered, i.e., each rectangle is positioned such that the edge representing the length of the vessel is in parallel to the axis representing the quay. Lim (1998) formulates the continuous BAP as a packing problem. In this model the berthing times of vessels are set according to the arrival times, and it is assumed that the quay is of infinite length. Berthing positions have to be determined such that the maximum quay length occupied at any time, i.e., the height of the packing, is minimized. This objective, however, is of little practical relevance because the length of a CT's quay is constant and berthing of vessels must be postponed whenever the quay space does not allow for a simultaneous service. The continuous dynamic BAP is modeled as a rectangle packing problem by Dai et al. (2008). In contrast to standard formulations of packing problems, the authors have to introduce additional constraints to respect arrival times of vessels.

Among the diverse project scheduling formulations, the *Resource Constrained Project Scheduling Problem* (RCPSP) is of predominant interest. Here, a set of activities has to be scheduled, each of them requiring a certain amount of one or more resources for their execution, see, e.g., Kolisch (1995). The available quantity of a resource is divided among activities executed simultaneously. Precedence constraints are typically involved in the RCPSP to express the relative order in which activities must be executed. The objective is the minimization of the project makespan.

A project scheduling approach is proposed by Moorthy and Teo (2006) to determine suitable berthing positions of vessels on a tactical level. They first generate berth plans and then state precedence relations between vessels occupying the same quay space while being served one after the other. Afterwards, the Project Evaluation Review Technique is used to determine the expected delays of vessels in a stochastic environment. In Meisel and Bierwirth (2006) the QC resource is considered within the BAP. Vessels, which are considered as activities in this approach, can be served in different modes, each one representing a different resource consumption pattern (QC-to-Vessel assignment). A precedence related dummy activity is introduced for each vessel activity in order to ensure that no vessel is served before its arrival time. A priority rule based method is used to schedule the activities while minimizing the QC resource utilization of the berth plan.

The *Vehicle Routing Problem* (VRP) deals with the assignment of delivery customer orders to a set of vehicles and with the determination of a route for each vehicle, starting at a depot, visiting the assigned customers, and returning to the depot. The capacity constraint of each vehicle is not allowed to be violated by the transport volume of its assigned orders. Contrasting other standard problems described above, which mostly pursue a min–max objective like makespan minimization, the VRP aims at minimizing a total measure, namely the overall route length of vehicles.

As demonstrated by Cordeau et al. (2005), the discrete BAP can be formulated as a multi-depot VRP with time windows. In this model each vessel is represented by a customer order and each berth is represented by a depot. A single vehicle is dedicated to each depot. A time window for the delivery of an order results from the expected arrival and departure time of the corresponding vessel. The objective of total route length minimization is replaced by the CT objective of vessel waiting time and handling time minimization.

Like the BAP, also the QCSP can be formulated as a variant of the VRP. Moccia et al. (2006) apply solution techniques for the Precedence Constrained Traveling Salesman Problem to crane scheduling. Sammarra et al. (2007) treat the QCSP as a VRP where adaptations are required to respect precedence constraints between QC tasks as well as crane interference issues. In both studies the VRP objective is replaced by a QCSP objective, namely the minimization of the makespan.

Summarizing, standard OR problems often nest inside seaside operations planning problems, but a one-to-one reformulation is not possible in most of the cases. Operations planning in CTs typically involves additional constraints and pursues different objectives. E.g., the minimization of the makespan, as typically pursued in machine scheduling, is not appropriate for berth planning, because it does not differentiate the individual service quality provided to vessels. Suitable formulations of the BAP, the QCAP, and the QCSP may be inspired by formulations of standard problems, but adaptations are still required. For this reason, standard solution methods cannot be applied in a straightforward manner.