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Ursavas, Evrim

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Original Article

Crane allocation with stability considerations

Evrim Ursavas

University of Groningen, Nettelbosje 2, Groningen 9747 AE, The Netherlands.
E-mail: e.ursavas@rug.nl

Abstract Crane planning in a container terminal is a major concern for terminal operators. Crane scheduling has an enormous impact on port efficiency and profitability, and these activities have, therefore, received high priority from terminal managers and researchers. Owing to the complex structure of the problem with numerous constraints and practical issues, terminal managers have been calling for a decision support tool which provides efficient and functional solutions. However, no main solution has yet emerged for the problem. This article proposes a decision support system (DSS) for solving complex crane scheduling problems in a container terminal, offering solutions that consider contextual issues such as crane crossing restrictions and dynamic crane assignment policy, and further addresses an additional consideration during vessel unloading: vessel stability. To show the practical application of the DSS, we conducted a case study using real ship data at the Izmir container terminal in Turkey. The effect of stability on the outcomes has been shown through additional experiments. Our findings reveal that the theoretical makespan can be reduced by 20 per cent during real life operations because of stability limitations.

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Keywords: quayside operations; crane scheduling; container terminal operations; decision support systems; stability

Introduction

Container terminals play a vital role as essential hubs in the overall transportation network. Developing solutions that respond to the most crucial port management problems will enable this network to benefit from faster vessel service times and increased container handling capacity, thereby stimulating international trade. The time a ship spends at a terminal is the main factor in port competitiveness. Within terminal operations, crane scheduling is a key process for maritime shipping companies, as it is related to the amount of time their ships spend at port. Including fixed costs, variable costs and product value losses, a 4-hour delay could cost as much as €40 000 and in Italy, for instance, the labour cost of one gang shift alone is approximately €850 (Dunya, 2007; Vernimmen *et al*, 2007; Trunfio and Legato, 2010; Daily Maersk, 2011). This economic impact further underlines the importance of using effective decision support tools for container terminals. We further note that within the container terminals quay cranes are the most expensive single unit of handling equipment. Empirical results show that vessel turnaround time is highly correlated with crane allocation (Kasypi and Muhammad, 2006, Loke *et al*, 2014). Thus, it is important to fully utilize the quay cranes and maximize the number of containers handled per unit time (Moccia *et al*, 2006). As crane activities are a common bottleneck in port activities, a decision support system (DSS) that provides efficient solutions to this major problem can considerably improve the network performance, with less need for investment in expensive new equipment (Steenken *et al*, 2004; Crainic and Kim, 2006; Goodchild and Daganzo, 2006; Lee *et al*, 2008; Stahlbock and Voß, 2008; Vacca *et al*, 2010; Legato *et al*, 2012).

Port management involves a complex system of interrelationships. When a ship arrives at port, it is moored at a berth and import containers are taken off the vessel, and placed on transfer vehicles by the quay cranes. The containers are then transferred by these transfer vehicles to the storage area, where a gantry crane takes the container off the vehicle and stores it in a stack. Later, a gantry crane will pick each container up from wherever it was stored and place it on an external truck, which then exits the port through the gate. Loading export containers onto a ship simply means carrying this process out in reverse.

After the vessel is berthed, the container handling process begins. In practice, information about the containers to be handled at the terminal is provided before the vessel's arrival. An unloading plan shows that containers on the bay are to be unloaded and the loading plan specifies which containers have to be loaded onto the vessel, in what order and at which bay they should be stacked (Kemme, 2013). The containers which need to be unloaded at the port are usually stacked in groups in different bays. Using the unloading plan, the stevedores select the containers to unload from the ship. The discharging time for containers is highly dependent on the stevedore's skills and his planning and scheduling abilities. If weight considerations are not fully met, the crew may need to pump water into ballast tanks while the ship is being unloaded, to keep the ship balanced, which could otherwise lead to severe damage and injuries. Not all vessels are equipped mechanically to maintain balance while being unloaded. These safety measures can also require interruptions to the unloading process (Karaminas *et al*, 2000; IACS, 2008; IMO, 2009; Berntzen, 2010; BIMCO, 2014; David and Gollasch, 2014). Moreover, ballasting in ports and coastal areas is expected to be kept to a minimum for environmental considerations (Helmepa, 2011). For example, such practices have caused undesirable effects within the waters of Hong Kong which have led to intoxications and threatened the local fish cage industry (To *et al*, 2002). As a result discharge times are generally highly variable. After a vessel has finished unloading, loading starts. There is little flexibility in loading operations as the stevedores must adhere strictly to a pre-determined loading plan, in which the location and the loading sequence of containers is specified (Shields, 1984). These loading plans are provided by shipping companies and take into account container size, balance and stability restrictions and the different terminals the vessel will visit along its route. Once the quay cranes have completed loading operations, the vessel is unmoored and it continues to the next port.

The terminals are faced with increasing pressure to shorten the time vessels spend at a port. As a result, large investments in new crane equipment are being made and a great deal of attention needs to be paid to planning operations. Depending on their size and other technological specifications, the prices for quay cranes range from approximately €6 million to €12 million (*World Cargo News*, 2012).

On the basis of the above, this study's main aim is to draw the researchers' attention to the practical issues within terminals that have not yet been sufficiently addressed in existing research. This article also takes a step towards that goal and proposes a model that embraces a novel approach to the crane scheduling problem, expanding the literature by better representing a 'real world' implementation through the inclusion of additional facts on crane and vessel specifications. The model incorporated within the DSS is capable of handling different types of cranes with crane crossing restrictions and container handling rates. Further, by using the DSS, container terminals are able to implement a dynamic crane assignment policy where crane assignments may vary during a vessel's service time. In other words, instead of assuming a fixed handling time for vessels, this study suggests an optimizing method which considers handling time as a function of crane allocation in each time segment. An essential feature of the proposed model is the reflection of stability limitations. Although a great deal of research has been devoted to the crane scheduling problem, most existing approaches aim to minimize the service time of all containers without considering the restrictions that must be obeyed with respect to weight distribution when the vessel is being unloaded. Imbalance in the weight distribution of containers on a ship can lead to the vessel capsizing, resulting in serious damage to the vessel and port facilities, and injury and loss of life (IACS, 2008; Krata *et al*, 2012; Sorensen, 2012; BIMCO, 2014; UNCTAD, 2014; Krata, 2015). As pointed out by

Eurans Logistics (2015): ‘Careful monitoring of the ships stability during loading operations is required or else the ship might capsize’. One example is the capsizing of the 101 m German-owned container ship MV Deneb at the Port of Algeciras during the handling of Maersk containers (EMSA, 2011). Two people were injured in the incident along with the economic losses encountered. Another example is the case of the MSC Napoli in 2007, where the vessel’s hull was damaged because of inappropriate loading in the cargo area. These underline the importance of vessel stability considerations (MAIB, 2008). The objective of this study is to develop a DSS that will provide solutions for the crane scheduling problem and which can ultimately be applied by terminal managers in real life unloading operations.

The following section discusses the relevant literature. The concept of container vessel stability is explained next. The subsequent sections explain the structure of the DSS and report the computational experiments in a case study. The last section presents concluding remarks and indications for future work.

Related Studies

Given the obvious need for effective decision-making strategies for managing container terminal operations, many researchers have worked on the subject (Vis and de Koster, 2003; Steenken *et al*, 2004; Stahlbock and Voß, 2008). This review will summarize studies concentrating on the crane scheduling problem.

A recent survey of research into quay crane scheduling is provided by Carlo *et al* (2013). The most recent studies on the subject aim at models which better reflect real world implementation issues (Bierwirth and Meisel, 2010). A crane scheduling problem aimed at minimizing vessel waiting times, originally solved using heuristics by Daganzo (1989), was later solved using the B&B method in a subsequent study by Peterkofsky and Daganzo (1990). Bierwirth and Meisel (2010) presented a classification scheme for quay crane scheduling problems based on the job-level definition. The levels defined for this are vessel bays, bay sections, container stacks and container groups defined by container characteristics, and individual containers. In this study we define a job as areas within a bay section with containers grouped on the basis of different weight characteristics. With respect to studies defining a job as container groups, Kim and Park (2004) proposed a B&B method to minimize a ship’s turnaround time and a heuristic search algorithm, called the greedy randomized adaptive search procedure (GRASP), to overcome the computational difficulty of the B&B method. GRASP’s performance was compared with that of the B&B method. Sammarra *et al* (2007) proposed tabu search heuristics and a disjunctive graph-based method for calculating the makespan for the formulation developed by Kim and Park. Bierwirth and Meisel (2009) and Moccia *et al* (2006) both pointed out some inaccuracies within the Kim and Park formulation related to crane interference and safety distance features. Kaveshgar *et al* (2012) proposed a genetic algorithm for the quay crane scheduling problem and compared its performance to that of Kim and Park (2004), Moccia *et al* (2006) and Sammarra *et al* (2007). Chung and Chan (2013) also proposed a genetic algorithm to deal with the quay crane scheduling problem, aiming to balance the workload of quay cranes. Kaveshgar and Huynh (2014) again used genetic algorithms, which considered the time availability of quay cranes. Recently, Legato *et al* (2012) incorporated different quay crane processing times for the container groups, using unidirectional schedules which restricted the movement of quay cranes only to left-to-right or right-to-left. In practice, quay cranes can move back and forth along a vessel to perform different tasks. Unidirectional schedules were also applied by Lim *et al* (2007) and Bierwirth and Meisel (2009). Although this assumption reduces the number of candidate solutions to a great extent, such schedules can cause problems during the actual implementation of the proposed solutions. Relying solely on the use of pumps for weight balancing will incur additional cost, environmental impacts and safety issues (Helmepa, 2011). The fact that not all vessels are designed with such capabilities should also not be overlooked. Another 'ideal-world' measure that recommends simultaneous loading and unloading to maintain the balance of the vessel is not completely applicable in real life because of the complexities, congestion and limitations arising within the terminal.

Managing a container terminal is a complex activity and there is an obvious need for effective decision-making strategies for managing these operations. As a result, DSSs for container operations and planning have been developed by researchers in the field (Shen and Khoong, 1995; Murty *et al*, 2005; Ngai *et al*, 2007; Bandeira *et al*, 2009; Ngai *et al*, 2011; Gharehgozli *et al*, 2013; Li and Yip, 2013; Ursavas, 2014; Zhen, 2014). This study aims to fill a gap in the literature by further incorporating real life questions into the actual implementation of proposed solutions. It should be emphasized that stability issues can lead not only to damage to containers and vessels, but can also cause injury. Special attention is paid to stability in a vessel's design but managing stability problems during the handling of containers continues to rely on the expertise of personnel. Discussions with Metin Ozyilmaz, operations manager at the Port of Izmir and the regulations within Vocational Qualifications Authority, confirmed that the results of studies which neglect this crucial issue cannot be regarded as feasible and applicable and further adaptation is needed to ensure the safety of operational processes (Ursavas Guldogan, 2010; Interview with Metin Ozyilmaz, 2013; Interview with Murat Gocen, 2013; VQA, 2014). In summary, this study contributes to the literature on DSS through the following features and novel ideas:

- Cranes of different types working at individual productivity rates can be included in the model
- Safety margins for cranes working side by side can be respected
- Crane crossing restrictions and individual handling rates specific to the crane type used can be set
- Managers can implement a dynamic crane assignment policy using the proposed solutions, which prevents solutions based on misleading crane unavailability assumptions
- The solutions generated by the DSS reflect vessel stability restrictions which could otherwise lead to disasters, as occurred in the case of Deneb

These new features lead to a novel model for crane scheduling problems. The proposed model-driven DSS is evaluated using real world examples from data taken from actual vessel plans. The data set used in the case study consists of general container vessel stowage plans and specific container positions per bay. Shipping companies provide this information to the container terminal of the Port of Izmir. The data on stowage plans are from one of the world's largest shipping lines by container vessel capacity.

The following section will explain the stability concept within container vessels.

Container Vessels and Stability

Containerization has become the standard method of transporting cargo, and container vessels of different sizes and capacities have, therefore, been in use for decades. It is expected that the different types of container vessels such as feeders, Panamax or Ultra Large Container Vessels will continue to be in demand for various purposes depending on the distance to be travelled, terminal restrictions or structural limitations such as canals, icing and bridges.

Regardless of its type and size, a container vessel must maintain its stability both at sea or when berthed. This factor is well-recognized in a vessel's design. However, it is also crucial to consider a ship's balance during handling operations, as it could be impaired because of unbalanced weight distribution. Basically, weight should be distributed equally through a vessel within some tolerance limits. Having excess weight on one side of the vessel could cause a dangerous list. To avoid inclination from the vertical towards port or starboard (heeling) and ensure zero or minimum trim (the angle of the vessel fore to aft), weight distribution variations during handling should be kept at a minimum.

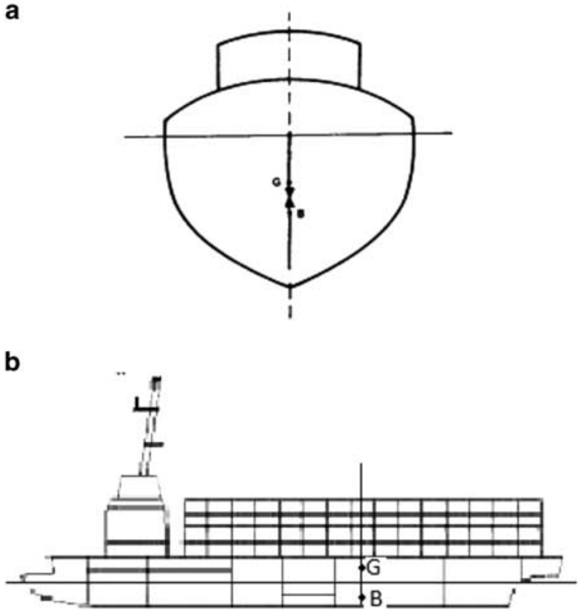


Figure 1: Transverse and longitudinal sections.
(**a**) Transverse section of a vessel.
(**b**) Longitudinal section of a vessel.

Otherwise, a vessel's structure could be weakened by the bending moment and the torsion exerted. Exceeding design thresholds could cause the vessel to capsize.

Stability controls are verified through various moment calculations. During unloading operations, transverse and longitudinal moments must be monitored.

Figure 1 illustrates the transverse and longitudinal segments of a vessel. B is the centre of the vessel's underwater volume. In Figure 1a, G is the longitudinal centre of gravity. Similarly, G in Figure 1b depicts the position of the transverse centre of gravity.

The moment balance between the bow and stern – the longitudinal moment – must be kept within certain thresholds. If l_i is the longitudinal coordinate of the centre of container i and W_i is the weight of container i, then:

$$\Omega_{ll} \leq \sum_i W_i l_i \leq \Omega_{ul}$$

must hold, where Ω_{ll} and Ω_{ul} are the lower and upper limits of the longitudinal moment of the ship. These limits can change according to the vessel type. Vessels respond differently to changes and moments occurring during handling operations.

This means that the moment caused by a single container will cause different ships to react differently to the same disturbance. Depending on a vessel's rigidity or sensitivity, a marginal disturbance could cause the ship to capsize or remain still. It is important to note that a vessel's centre of gravity point is bound to shift during handling operations, which means that it must be monitored for safety and security (Barrass and Derrett, 2012). According to Peregrine Storrs-Fox: 'Any one container can have a huge impact on lots of others in an 18 000 TEU ship. The potential for a massive incident is out there' (Storrs-Fox, 2014). Like the longitudinal moment, the moment balance between the right and the left must also be controlled. If s_i is the transverse coordinate of the centre of container i, then:

$$-\Omega_{tl} \leq \sum_i W_i s_i \leq \Omega_{tl}$$

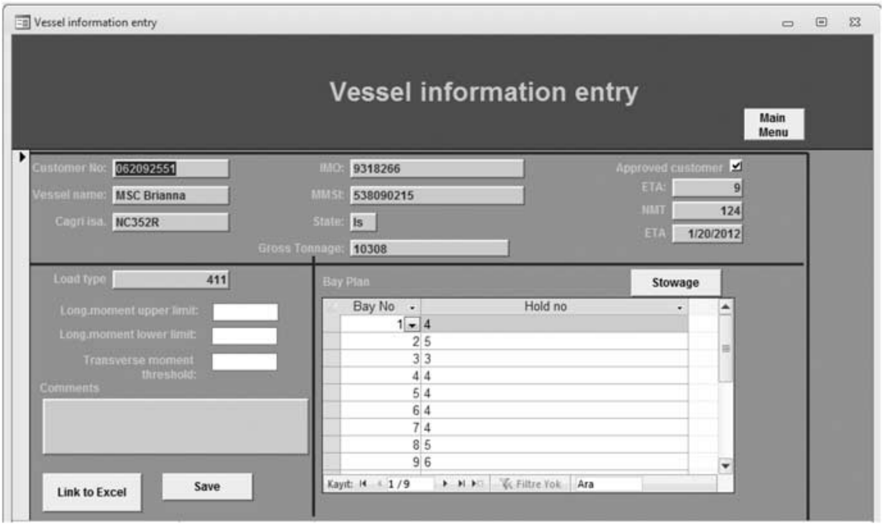
must hold, where Ω_{tl} is the threshold of the transverse moment of the ship.

The vertical equilibrium constraint which requires that the weight on each tier be greater or equal to the weight on the tier immediately above it can be reached during unloading operations, assuming that the vessel has arrived at port in a stable state.

The details of the DSS architecture addressing these stability issues are presented in the following section.

The Decision Support System (DSS)

The software programme developed is designed to run on a PC with Microsoft Windows. The model-driven DSS employs an architecture for generating solutions to user-mediated problem cases. The programme's main components are its user interface for inputting parameters, a report visualization tool, a database management system for storing the vessel and terminal data, and the core of the DSS itself – where the model is solved using the solution algorithm. Microsoft Access is used for the database; the other processes and the interaction with the optimization algorithm are developed by VBA. Gurobi solver is used to solve the optimization model. The specifications and the input parameters used for the model were developed in consultation with the port staff at Izmir (Ursavas Guldogan, 2010; Interview with Metin Ozyilmaz, 2013; Interview with Murat Gocen, 2013). During a meeting on 16 February 2011 held within the terminal automation system development project, Metin Ozyıilmaz has underlined the importance of close collaboration with practitioners during the development of new decision support tools. The mathematical model was subsequently developed in the course of the present research.



Customer No: 062092551
Vessel name: MSC Brianna
Cagri isa. NC352R
IMO: 9318266
MMSI: 538090215
State: Is
Gross Tonnage: 10308
Approved customer ☑
ETA: 9
NMT 124
ETA 1/20/2012
Load type 411
Long.moment upper limit:
Long.moment lower limit:
Transverse moment threshold:
Comments

Bay Plan

Bay No	Hold no
1	4
2	5
3	3
4	4
5	4
6	4
7	4
8	5
9	6

Figure 2: User interface for vessel information entry.

A high degree of flexibility with a good level of parameterization is provided to help decision makers analyse a situation. The DSS input consists of parameters representing the attributes of vessels, containers and cranes. This data is entered by the user through the user interface shown in Figure 2. Changes to one or more of these parameters impacts on the whole system and consequently on the results reported to the user.

- Vessel bay information: number of bays and their positions
- Number of holds within a bay
- Number of containers within a hold
- Container weights
- Longitudinal and transverse coordinates of holds
- Lower and upper limits of the longitudinal and transverse moments of the ship
- Crane specifications: numbers, handling rates and their initial positions

After entering these input data, the user executes the programme and the optimization module within the DSS is run to produce solutions to the unloading operations problem. The model is a newly formulated mixed integer programming model that expresses the practical issues of the crane scheduling problem in great detail. The module details are as follows:

Indices

i	$(1, \ldots, I)$ set of tasks (holds)
j	$(1, \ldots, J)$ set of cranes

k	$(1, \ldots, K)$ set of bays
t	$(1, \ldots, T)$ time periods

Parameters

N_{i0}	number of containers initially on task i
W_i	weight of containers on task i
H_k	set of tasks in bay k
B_i	bay id of task i
l_i	longitudinal coordinate of the centre of task i
s_i	transverse coordinate of the centre of task i
Ω_{ll}	lower limit of the longitudinal moment of the ship
Ω_{ul}	upper limit of the longitudinal moment of the ship
Ω_{tl}	threshold of the transverse moment of the ship
R_j	container handling rate of jth crane
E	agreed deadline for the vessel (in terms of time)
si_k	starting id of tasks assigned to bay k
ei_k	finishing id of tasks assigned to bay k
m	A small number between 0 and 1
$\omega_{1,2,3,4}$	importance factors for the objective function components $(\omega_1 + \omega_2 + \omega_3 + \omega_4 = 1)$

Decision Variables

y_{ijt}	1 if crane j allocated to task i at time t
N_{it}	number of containers at time t on task i
x_{jt}	travelling distance of crane j to start work at time t
C	makespan
P_{jt}	position of crane j at time t
FB_{it}	1 if task i still has containers to be handled at time t
F_i	completion time of task i

The problem is where to position the cranes in the decision space while obeying the restrictions and constraints and minimizing the total working time to complete each ship. The main aim of the problem is to minimize the total working time for the vessel. Crane consumption and crane movements should also be considered in achieving this objective. The function is obtained by minimizing the completion period of the latest job, total crane movements, total crane assignments and the number of containers left unloaded in a hold in each period. The decision-makers' aim is to use the least amount of resources while keeping the service time of the vessel short. It is important to note that a vessel has to pay a fee not only for each move (load or discharge operation), but also for the gang operating the cranes and the cost of the vehicles feeding the cranes. Therefore, it is also important to minimize the completion time of each task as, for example, a crane driver will be allocated to a crane during the start and completion of a job. It should also be noted that tasks assigned to the same quay crane can belong to different bays. This means that quay crane travel and setup times are also factors to be considered. Accordingly, factors other than the make-span cannot be neglected. We, therefore, formulated the following objective function where different weight factors could be assigned according to setting.

$$\min \quad \omega_1 C + \omega_2 \sum_j \sum_t x_{jt} + \omega_3 \sum_i \sum_j \sum_t y_{ijt} + \omega_4 \sum_i \sum_t tN_{it}$$

The problem constraints can be specified as follows:

A crane cannot work at more than one hold at a time. This is ensured by the following constraint set:

$$\sum_i y_{ijt} \leq 1 \qquad \forall j, t \tag{1}$$

For safety considerations, cranes are not allowed to work simultaneously within the same bay. A bay is defined according to safety regulations which typically define 40-foot bays. Constraint set (2) ensures that this safety measurement is met.

$$\sum_{i=si_k}^{ei_k} \sum_j y_{ijt} \leq 1 \qquad \forall t, k \tag{2}$$

The number of containers left unhandled should be adjusted as the cranes continue their operations. The number of containers unloaded depends on the crane handling rate of the specific crane assigned to the hold. Accordingly, in constraint set (3) the number of containers to be handled in each hold is decreased by its crane handling rate at each period.

$$N_{it} - \sum_j R_j . y_{ijt} \leq N_{i,t+1} \qquad \forall i,t, t \neq T \tag{3}$$

Crane passing restrictions should be handled next. First, in constraint set (4) the position of crane j at time t is determined by P_{jt}. Constraint set (5) then handles the crane passing constraints. If crane j is serving a vessel at bay k, then no other crane with a higher crane id can serve a vessel at any bay positioned to its right.

$$\sum_i B_i.y_{ijt} = P_{jt} \qquad \forall j, t, t \neq T \tag{4}$$

$$P_{jt} \leq P_{j+1t} \qquad \forall j, t, t \neq T \tag{5}$$

A track should be kept on cranes moving bays during the service time. Constraint sets (6) and (7) do this each time a crane leaves a bay. This is typically because of crane setup, attaching, detaching and movement.

$$P_{jt+1} - P_{jt} \leq x_{jt} \qquad \forall j, t, t \neq T \tag{6}$$

$$P_{jt} - P_{jt+1} \leq x_{jt} \qquad \forall j, t, t \neq T \tag{7}$$

Constraint sets (8) and (9) assign values for FB_{it}. This is assigned 1 if there are containers to be handled at time t in hold i. The completion time of each task and makespan is determined by constraint sets (10) and (11).

$$FB_{it} \leq N_{it} \qquad \forall i, t, t \neq T \tag{8}$$

$$mN_{it} \leq FB_{it} \qquad \forall i, t, t \neq T \tag{9}$$

$$F_i = \sum_t FB_{it} \qquad \forall i \tag{10}$$

$$F_i \leq C \qquad \forall i \tag{11}$$

The stability of the vessel as detailed in the preceding section is ensured by constraint sets (12) and (13). Container weights unloaded within a period from different parts of the vessel must be within threshold levels depending on their longitudinal and transverse coordinates.

$$\Omega_{ll} \leq \sum_i W_i(N_{it} - N_{it+1})l_i \leq \Omega_{ul} \qquad \forall t, t \neq T \tag{12}$$

$$-\Omega_{tl} \leq \sum_i W_i(N_{it} - N_{it+1})s_i \leq \Omega_{tl} \qquad \forall t, t \neq T \tag{13}$$

Finally, the following decision variables must be binary.

$$y_{ijt}, FB_{it} \in \{0, 1\} \qquad \forall i, j, t \tag{14}$$

Executing this module provides solution reports to the user through the user interface. Gurobi solver is invoked to solve the mixed integer programming model presented. Integer results are obtained through the B&B algorithm. The following section will demonstrate the use of the DSS in real world instances.

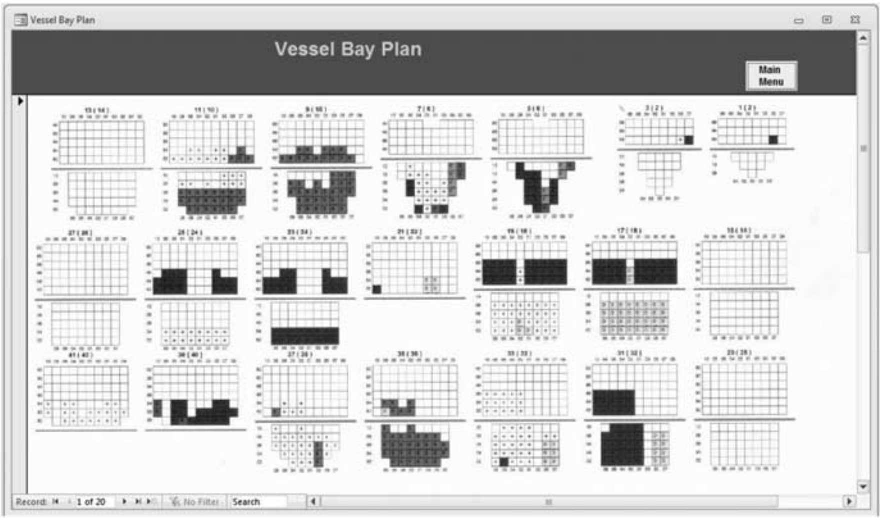


Figure 3: Vessel bay plan.

Case Study

We used real life ship unloading plans to demonstrate the applicability of the DSS. The aim of the case study is to demonstrate clearly the features and capabilities of the DSS and to illustrate its potential use by container terminals.

Figure 3 presents an actual unloading plan for a vessel sent to the container terminal in the Port of Izmir in Turkey.

The bay plan in the figure shows the container vessel split into compartments that we have termed ‘bays’. Set of containers handled within a task in a bay is denoted as hold. In principle, the numbering of the bays always starts at the front of the vessel and ends, depending on the length, with the highest number. For instance, bay 1 is at the very front (bow) and bay 41 is at the very end (stern) of the vessel. Odd numbered bays (1, 3, 5 and so on) are 20-foot stows and even numbered bays (2, 4, 6 and so on) are 40-foot stows.

For example, in Figure 3, the container with slot notation Bay 23 is a 20-foot container loaded in 20-foot bay number 23. The container with slot notation Bay 24 is a 40-foot container loaded in 40-foot bay number 24, which itself consists of two 20-foot bays numbered 23 and 25.

A container’s location across the width of the ship gives its row number. This starts at 1 in the centre and progresses outwards with odd numbers on the right and even numbers on the left. The level at which the container is placed is denoted by tier. Containers loaded below deck (below the hatch covers) and containers loaded on deck (above the hatch covers) are distinguished. The coding is in even numbers, with the tiers on deck coded from 80 onwards (BTB – Bureau Telematica Binnenvaart, 2007).

Different letters represent the different container terminals where the containers are to be unloaded. This vessel has six Ports of Destinations (POD). Ports before the Port of Izmir are excluded. The following PODs are present for this vessel route:

Alsancak – Port of Izmir, Turkey (A)
ITCAG – Port of Cagliari, Italy (B)
ITGOA – Port of Genoa, Italy (C)
ITLIV – Port of Livorno, Italy (D)
ITNAP – Port of Napoli, Italy (F)
ITSAL – Port of Salerno, Italy (G)

For instance, containers with letter A are to be unloaded in the Port of Izmir, in Turkey and containers with letter C will be discharged at the Port of Genoa, in Italy. Notations including a letter b such as ‘Ab’ mean that the container is empty.

Containers to be discharged at the Port of Izmir are distributed into five 40-foot bays and eight 20-foot bays numbered 2, 3, 17, 18, 19, 23, 24, 25, 31, 32, 33 and 40.

On the basis of the agreement with the shipping company, there are three quay cranes assigned to this vessel. The terminal has two main types of cranes, Type I and Type II, with average handling times of 3 and 4.5 min per container, respectively. These are rail-mounted cranes which must obey crane crossing restrictions.

The container weights provided by the shipping company are in the range of 2–30 tons. The table below provides the weight in tons of each container to be unloaded at the Port of Izmir next to their stow positions in the form of bay-row-tier notation (Table 1).

When the vessel arrives at the port it is assumed to be seaworthy, that is, balanced and able to travel safely. This assumption is on the basis that the vessel left its prior ports having implemented appropriately planned stowage plans. The problem is to determine the crane schedule guaranteeing the stability of the vessel during operations. The thresholds for this vessel are provided as -150, 150 and 150 for lower/upper longitudinal and transverse moments, respectively. Once the user has entered the above data through the user interface, our DSS provides reports including a crane schedule and makespan value.

The user can choose between different types of quay cranes. To demonstrate the capabilities of the DSS, results under different crane allocations are presented here. Users can compare these results to support resource allocation decisions.

Table 1: Container weights

03-07-84: 15t	17-07-82: 14t	17-05-82: 15t	17-03-82: 14t	17-01-82: 14t	17-04-82: 15t	17-06-82: 15t
02-05-84: 30t	17-07-84: 14t	17-05-84: 15t	17-03-84: 14t	17-01-84: 13t	17-04-84: 14t	17-06-84: 15t
17-09-82: 15t	17-07-86: 10t	17-05-86: 13t	17-03-86: 13t	17-01-86: 12t	17-04-86: 13t	17-06-86: 10t
17-09-84: 15t	19-07-82: 15t	19-05-82: 14t	19-03-82: 15t	19-01-82: 13t	19-04-82: 15t	19-06-82: 16t
17-09-86: 13t	19-07-84: 15t	19-05-84: 13t	19-03-84: 15t	19-01-84: 12t	19-04-84: 15t	19-06-84: 15t
19-09-82: 15t	19-07-86: 13t	19-05-86: 11t	19-03-86: 13t	19-01-86: 12t	19-04-86: 13t	19-06-86: 13t
19-09-84: 14t	23-07-82: 15t	23-05-82: 15t	23-04-82: 15t	23-06-82: 16t	23-08-82: 14t	23-10-82: 18t
19-09-86: 9t	23-07-84: 11t	23-05-84: 15t	23-04-84: 15t	23-06-84: 15t	23-08-84: 14t	23-10-84: 15t
21-10-82: 15t	25-07-82: 14t	23-05-86: 13t	23-04-86: 13t	23-06-86: 14t	25-08-82: 17t	25-10-82: 18t
23-09-82: 17t	25-07-84: 11t	25-05-82: 15t	25-04-82: 16t	25-06-82: 16t	25-08-84: 14t	25-10-84: 15t
23-09-84: 9t	24-05-02: 2t	25-05-84: 15t	25-04-84: 15t	25-06-84: 15t	25-08-86: 11t	24-06-02: 30t
25-09-82: 16t	24-05-04: 2t	25-05-86: 12t	25-04-86: 12t	25-06-86: 14t	24-04-02: 28t	24-06-04: 2t
25-09-84: 11t	32-04-82: 29t	24-03-02: 2t	24-01-02: 28t	24-02-02: 30t	24-04-04: 2t	17-08-82: 14t
24-07-02: 2t	32-04-84: 25t	24-03-04: 2t	24-01-04: 2t	24-02-04: 2t	24-08-02: 2t	17-08-84: 14t
24-07-04: 2t	32-04-86: 25t	32-06-82: 30t	32-08-82: 30t	32-10-82: 30t	24-08-04: 2t	17-08-86: 12t
32-02-82: 25t	32-02-02: 30	32-06-84: 27t	32-08-84: 29t	32-10-84: 30t	40-06-80: 29t	19-08-82: 17t
32-02-84: 25t	32-02-04: 29t	32-06-86: 27t	32-08-86: 27t	32-10-86: 29t	40-06-82 29t	19-08-84: 15t
32-02-86: 23t	32-02-06: 29t	32-04-02: 30t	32-06-04: 27t	32-08-02: 30t	40-06-84: 27t	19-08-86: 13t
32-01-02: 30t	32-02-08: 29t	32-04-04: 27t	32-06-06: 27t	32-08-04: 30t	40-09-82: 30t	17-10-82: 15t
32-01-04: 27t	32-02-10: 27t	32-04-06: 27t	32-06-08: 26t	32-08-06: 29t	40-05-84: 28t	17-10-84: 15t
32-01-06: 27t	33-06-02: 15t	32-04-08: 26t	32-06-10: 26t	32-08-08: 27t	40-02-80: 30t	17-10-86: 15t
32-01-08: 26t	40-07-80: 29t	32-04-10: 25t	40-03-80: 29t	40-01-80: 30t	19-10-84: 15t	19-10-82: 15t
32-01-10: 26t	40-07-82 29t	40-05-80: 30t	40-03-82 29t	40-01-82 29t	19-10-86: 11t	—
31-06-02: 15t	40-07-84: 26t	40-05-82 29t	—	—	—	—

First, the results for allocating two Type I cranes and one Type II are presented. The model has 17 550 constraints and 18 082 variables, of which 14 036 are discrete. The Gurobi solver took 0.089 CPU seconds to solve the model. The makespan of the solution is approximately 4 hours and 57 min. The crane plan is presented in Figure 4. The figure shows the movements for each crane across the vessel's bays. The initial starting positions of cranes 1, 2 and 3, set by the user, are at bays 1, 5 and 10, respectively. As can be seen from the solution report, crane 1 moves to bay 5, and then works at bays 1, 5, 6 and 1. Crane 2 starts at bay 5 and then works at bays 7, 9, 7 and 9. Crane 3 moves to bay 9 and then works at bays 11, 9 and 11. This solution adheres to crane crossing restrictions and preserves the stability of the vessel during service time.

The Gannt chart in Figure 5 provides a crane schedule for the solution presented. This report provides details of the working periods for each specific crane. The solution report confirms that crane crossing restrictions are complied with and, therefore, that at any time a crane is working at a bay, no other crane with a higher crane id is working a bay positioned to its right.

As explained in the previous section, one feature of the DSS is its ability to treat different crane types individually. To illustrate the use of this feature, another candidate solution was prepared using two Type II cranes and one Type I. As a result, the makespan increased to 5 hours and 6 min because of slower cranes being used. However, decision makers could still choose to implement

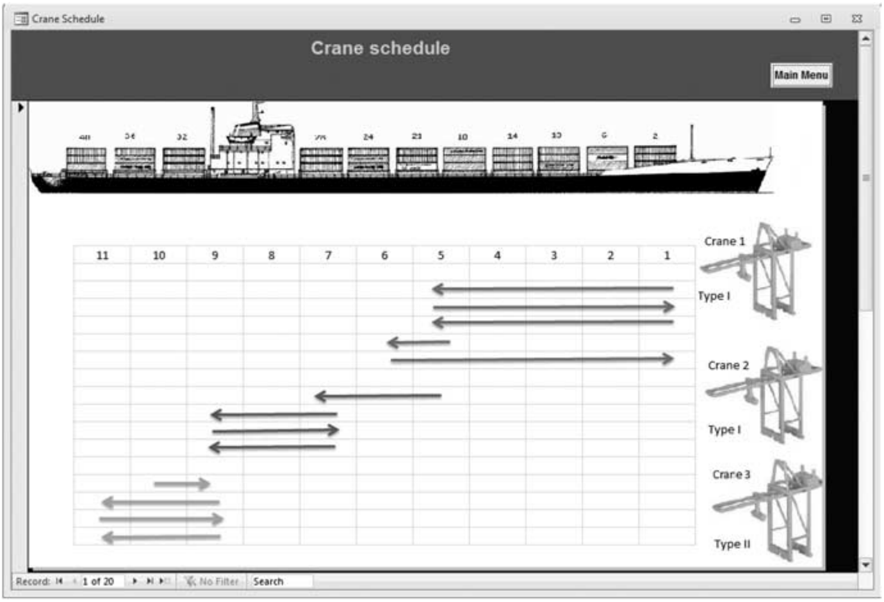


Figure 4: Crane move report solution I.

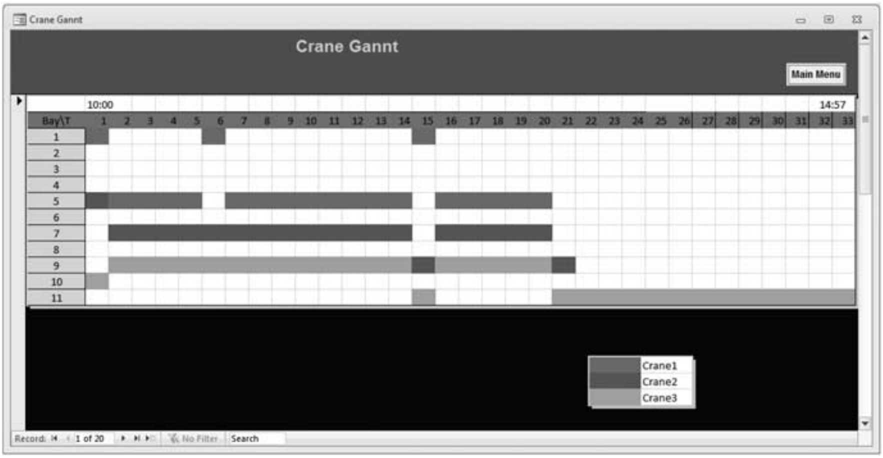


Figure 5: Crane schedule.

this solution, for example, if planning to reserve faster cranes for higher priority customers. Accordingly, the DSS provides a framework for comparing different solutions. Figure 6 presents the crane plan for this solution.

To observe the effect of stability restrictions on these solutions, further experiments were performed in which the stability constraints were removed

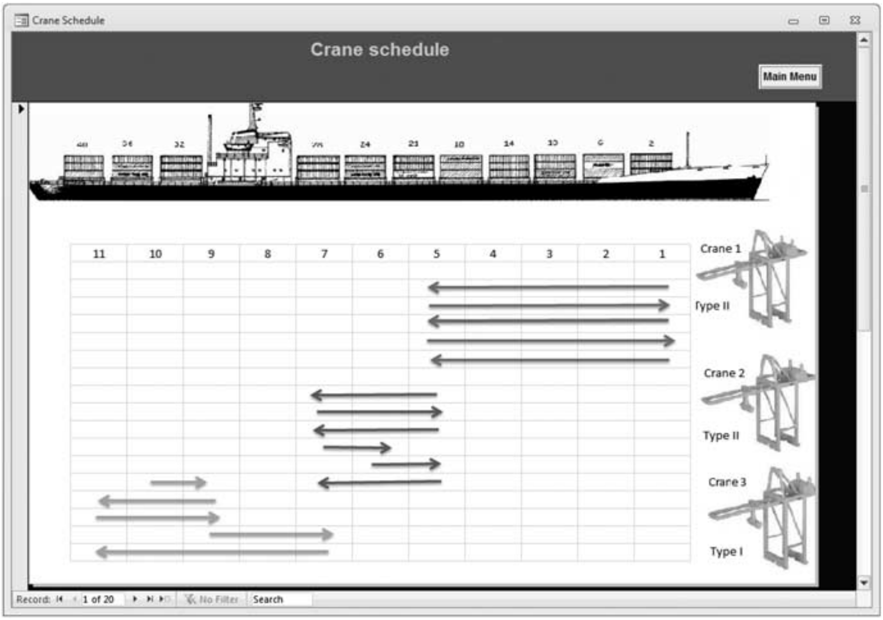


Figure 6: Crane move report solution II.

from the previously analysed cases. Figures 7 and 8 are solution reports for where two Type I and one Type II cranes are used. Figure 9 shows the results for two Type II and one Type I cranes.

Stability noticeably affects the outcomes. For instance, for the first crane allocation case the makespan is reduced to 3 hours 18 min from 4 hours 57 min. As can be seen in Figure 7, crane 1 works at bays 5, 7 and 6; crane 2 works at bays 5, 7, 9 and 7; and crane 3 at bays 9 and 11. The starting position for each crane was the same as the previous case.

For the second case, the makespan is reduced to 4 hours 3 min from 5 hours 6 min. The crane movements are shown in Figure 9. This difference in crane routes is because in these solutions the cranes do not have to control the vessel's weight distribution during their operations, resulting in fewer crane movements and a reduced makespan. However, such a solution might not be applicable in real life as it could cause the vessel to become unstable. Even if the vessel is equipped with ballast tanks to keep the ship balanced, this requires additional work and could lead to interruptions during the process. Accordingly, the proposed theoretical makespan provided by the solution will be increased during implementation.

The running times for the above cases were approximately 0.1 seconds. In practice, unloading plans are sent to the container terminal a week before the vessel's arrival. Minor updates can be sent a minimum of 1 day before arrival.

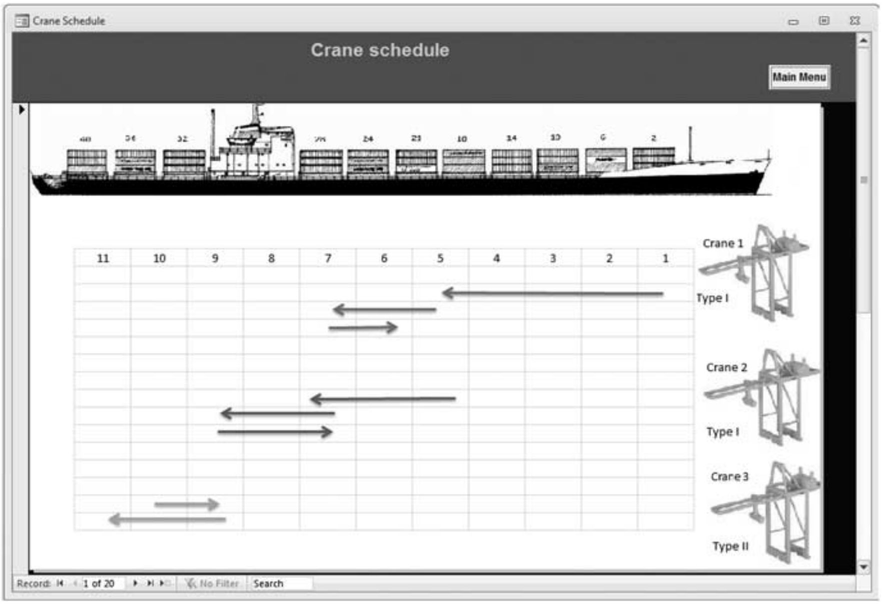


Figure 7: Crane move report I ignoring stability restrictions.

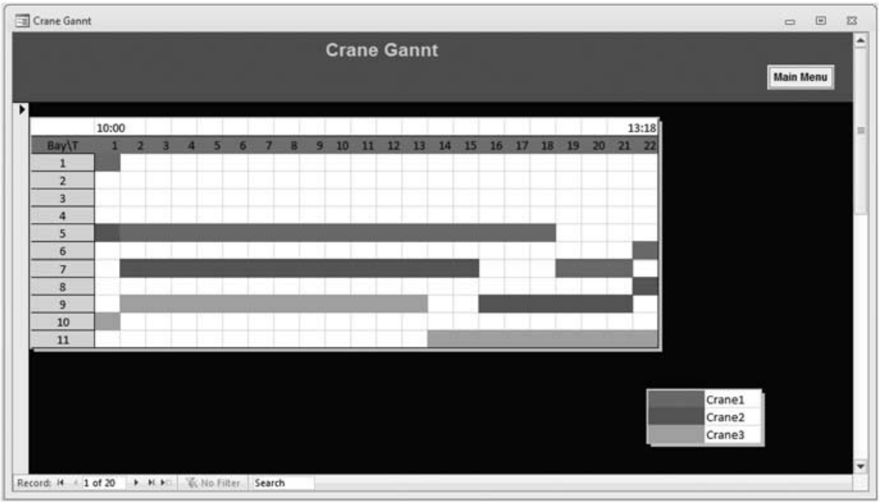


Figure 8: Crane schedule report I ignoring stability restrictions.

Accordingly, the DSS is designed for use as an offline planning tool. Nonetheless, additional experiments were conducted to observe the performance of the algorithm under increased container volumes. For testing purposes, the number

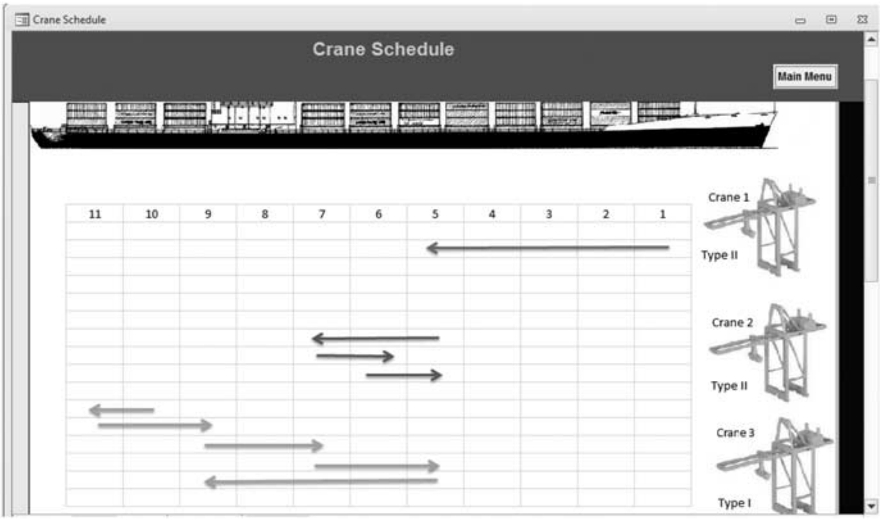


Figure 9: Crane move report II ignoring stability restrictions.

of containers to be unloaded within a single terminal was increased to 3000, that is, 6000 TEUs of 20-foot containers. Terminal managers informed us that unloading this number of containers within a single terminal would be considered a large job. Conforming to the terminal characteristics of larger terminals, the number of cranes allocated to the vessel was increased to 8. Container weights were assigned randomly, ranging from 2 tons to 30 tons each. The experiment was repeated 20 times to test settings with different weight and crane assignments. The model implemented has 31 118 constraints and 61 277 variables, 53 925 of which are discrete. The calculated makespan ranged from 21 to 25 hours within a 5 per cent relative gap at most, influenced by the stability restrictions because of different weight distributions. The algorithm execution time for each instance varied between 0.649 s and 1.253 CPU seconds.

This section explained the use of the DSS using actual unloading plans and presented the programme's performance under increased container volumes. The effect of stability on the outcomes was shown through additional experiments. The following section provides concluding remarks and future research opportunities.

Concluding Remarks

Containers are widely used in today's goods transportation. Ports are indispensible transit points for this trade and they will continue to play a vital role in providing the most efficient mode of transportation.

Within a container terminal, cranes are one of the most crucial and limited resources. Effective management of this limited resource for the handling of containers is of critical importance both for shipping companies and container terminals. Terminal operators need decision support tools to help them by solving this complex problem involving numerous restrictions. One critically important restriction during handling operations is preserving the stability of the vessel. However, this constraint has been inadequately reflected in previous studies. The stability problem is not only capable of damaging containers and vessels, causing economic loss, but can also result in injuries and loss of life. Accordingly, balance restrictions should be carefully considered to yield feasible and applicable schedules.

The main aim of this study is to draw researchers' attention to the restrictions and limitations of real life operations in container terminals. The study was realized in collaboration with container terminal operators Metin Ozyilmaz and Murat Gocen to gain a deeper understanding of the problem. In addition, a DSS was developed to fill an industrial need. The system was tested using actual unloading plans and its performance was evaluated under different settings. The model has been demonstrated as capable of guiding container terminal operators through the decision-making process.

We expect that more attention will be paid to developing feasible and applicable solutions for use in container terminals. This study will be continued by extending it to yard operations. The containers unloaded by quay cranes are moved to storage yards using transfer vehicles. Here, the synchronization of the quay cranes and transfer vehicles is important for the smooth flow of operations. Allocating efficient numbers of vehicles to the unloading operations and taking into account restrictions such as congestion within the yard and transport lanes will further support decision makers in solving complex real life problems.

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