The Port Reopening Scheduling Problem

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Abstract

When a port needs to be reopened after closure due to a natural disaster or terrorist event or domestic dispute, certain goods on incoming ships might be in short supply. This paper formulates the problem of scheduling the unloading of waiting ships to take into account the desired arrival times, quantities, and designated priorities of goods on those ships. Several objective functions are defined, special cases are discussed, and the relevant literature is surveyed.

1 Introduction

Global trade is critical to economic well-being. Over 90% of international trade is by sea. An efficient, effective, secure system of ports is crucial to international trade. Ports are also crucial to the national supply chain of critical products: fuel, food, medical supplies, etc. This paper is concerned with ports being shut down in part or entirely, by natural disasters like hurricanes or ice storms, terrorist attacks, strikes or other domestic disputes. How do we aid port operators and government officials to reschedule port operations in case of a shutdown? Shutting down ports due to hurricanes is not unusual and so provides insight into current methods for reopening them. Unfortunately, scheduling and prioritizing in reopening the port after a hurricane is typically done very informally. This paper seeks to formalize an approach to reopening a port in an efficient way that responds to a variety of priorities. If a port is damaged, we envision a number of vessels waiting to dock and be unloaded. In what order should the unloading take place? The decision of how to reopen a damaged port is rather complex. There are multiple goals, including minimizing economic and security impacts of delays in delivery of critical supplies. These problems can be subtle. For example, if an ice storm shuts down a port, perhaps the priority is to unload salt to de-ice. It wasn't a priority before. These subtleties call for the kind of formal approach that is outlined here.

2 Formalizing the Problem

Let us suppose that we are interested in a set G of n goods. We can think of G as consisting of items labeled $i = 1, 2, \ldots, n$. Each ship will have various quantities of these goods, usually packed in containers. For simplicity, let us disregard the fact that different goods are in different containers – that complication can be added later – and then think of a ship as corresponding to a vector $x = (x_1, x_2, \ldots, x_n)$, where x_i is the quantity of good i on the ship. Again for simplicity, we assume that x_i is an integer for each i. Real data describing the contents of all containers on a ship is on the ship's manifest and is collected by (in the US) Customs and Border Protection before the ship's arrival. Unfortunately, there is a large amount of such data, there is inconsistency in the units used to describe the contents (e.g., 1000 bottles of water vs. 1000 cases of bottles of water), the descriptions of contents are often imprecise or vague (e.g., "fruit" or "household goods"), and so it is not easy to get a vector like x.

Let us also assume that once a ship docks, we proceed to unload all of its cargo so it can leave the port and open a spot for another ship. For simplicity, the unloading time is assumed to be the same for each ship, though a realistic problem will consider unloading times. (In the literature, we distinguish between common and noncommon ***processing times***.) Thus, we can consider integer ***timeslots*** for unloading. We can think of a schedule Σ that assigns to each ship a timeslot, the first, second, third, etc., during which it will dock

[1]This paper is dedicated to Buck McMorris. Our collaborations over the years have been a source of pleasure and inspiration to me. Not only is he a colleague, but I am pleased to call him a friend. This work was supported by the US Department of Homeland Security under a grant to Rutgers University. Many of the ideas in this paper come from joint work with N.V.R. Mahadev and Aleksandar Pekeč, in joint papers [37, 38]. These ideas are modified here to apply to the port reopening scheduling problem.

and be unloaded. Thus, Σ can be thought of as a vector $(\sigma_1, \sigma_2, \ldots, \sigma_k)$ where σ_i gives the time slot during which ship i will be unloaded. Let us also assume that as we are aiming to reopen a port, we have enough berths for c ships at once. A schedule is ***capacity-acceptable*** if no timeslot gets more than c ships. Next, assume that ships are ready to dock and there is no delay after they are chosen. We just have to choose which ships to unload in which order, taking account of the capacity c of the port. The problem becomes more complicated (and more realistic) if we assume that some ships are not yet nearby and so each ship has a delay time before it could arrive and be unloaded.

Because some goods can rapidly become in short supply, we assume that there is a desired quantity d_i of good i (which we assume to be an integer) and that it is required no later than time t_i, i.e., the t_i^{th} unloading time slot. Let $d = (d_1, d_2, \ldots, d_n)$ and $t = (t_1, t_2, \ldots, t_n)$. The problem gets more realistic if we have vectors giving the desired quantity at time 1, the desired quantity at time 2, etc., but we shall disregard this complication here. Different goods also have different priorities p_i, with $p = (p_1, p_2, \ldots, p_n)$. For example, not having enough fuel or medicine or food may be much more critical than not having enough cookware, which is reflected in a higher p_i. We will have more to say about the priorities in Section 6.

In what follows, we will discuss a special case, namely where each d_i is 1. That allows us to concentrate on whether or not all the desired goods arrive in time, i.e., before desired arrival times. It also allows us to think of a schedule Σ for ship arrivals as corresponding to a schedule S that gives the arrival time S_i of the first item i for each i.

What makes one (capacity-acceptable) schedule better than another? We can assume that there is some objective function that takes into account demands for goods that are not met by the schedule either in terms of quantity or in terms of arrival time. Let $F(S, t, p)$ be the penalty assigned to schedule S given the desired arrival time and priority vectors t, p. (Recall that we are disregarding the vector d since we assume each component is 1. Also, the port capacity c is part of the problem, but not part of the penalty function.) Suppose we seek to minimize F. We shall discuss different potential penalty functions below.

The problem is similar to a number of problems that have been considered in the literature. For example, Mahadev, Pekeč, and Roberts [37, 38, 49] considered a problem posed by the Air Mobility Command (AMC) of the US Air Force. Suppose that we wish to move a number of items such as equipment or people by vehicles such as planes, trucks, etc. from an origin to a destination. Each item has a desired arrival time, we are penalized for missing the desired time, and penalty is applied not only to late (***tardy***) arrival but also early arrival. In our port problem, while the emphasis is on tardy arrivals, early arrivals of goods could be a problem if we add a complication of port capacity for storing goods until they are picked up. We will consider early arrival penalties, though we will not consider the details of port capacity for storing goods. In the AMC problem, it is assumed that each trip from origin to destination takes the same amount of time (though this assumption can be weakened) and there are only a limited number of spots for people or goods on the vehicles. The items have different priorities. For example, transporting a VIP may be more important than transporting an ordinary person and transporting fuel may be more important than transporting cookware. The penalty for tardy or early arrival depends on the priority.

Another similar problem arises in the workplace if we have a number of tasks to perform, a number of processesors on which to perform them, each task has a desired completion time and we are penalized for missing that time. We assume that once started, a task cannot be interrupted (***nonpreemption***) and that, for simplicity, each task takes the same amount of time. We have only a limited number of processors, so are only able to schedule a number of tasks each time period. Assume that the tasks can have different priorities. We seek to assign tasks to processors each time period so that the total penalty is minimized. This problem without the priorities is a well-studied problem in the machine scheduling literature. Some examples of papers on machine scheduling with earliness and tardiness penalties are [11, 15, 44, 8, 6, 3, 25, 26, 42, 4, 9, 39, 21, 16, 14, 55, 31]. Some survey papers on scheduling with objective functions are [2, 7, 29]. A general reference on scheduling, which includes a considerable amount of material on earliness/tardiness penalties, is [43]. Also, [22, 32, 58] are extensive surveys on scheduling with earliness and tardiness penalties.

3 Penalty Functions

We shall consider ***summable*** penalty functions, those where

$$F(S,t,p) = \sum_{i=1}^{n} g(S_i, t_i, p_i). \tag{1}$$

Simple cases of summable penalty functions are those that are ***separable*** in the sense that

$$g(S_i, t_i, p_i) = \begin{cases} h_T(p_i) f(S_i, t_i) & \text{if } S_i > t_i \\ h_E(p_i) f(S_i, t_i) & \text{if } S_i \leq t_i \end{cases} \tag{2}$$

where h_T and h_E are functions reflecting the tardiness and earliness contributions to the penalties of the priorities of the goods. A simple example of a summable, separable penalty function is given by

$$F(S,t,p) = \sum_{i=1}^{n} p_i |S_i - t_i|.$$

This penalty function arises in the literature of single machine scheduling with earliness and tardiness penalties and ***noncommon weights.*** (See [11, 15, 44, 8, 6, 3, 25, 26].) Here, $h_T(p_i) = h_E(p_i) = p_i$. If $f(S_i, t_i) = |S_i - t_i|$, it is sometimes convenient to rewrite the penalty function (1) resulting from (2) as follows. Let $T_i(S) = T_i = max\{0, S_i - t_i\}$, $E_i(S) = E_i = max\{0, t_i - S_i\}$. Then (1) is equivalent to

$$F(S,t,p) = F_{sumE/T}(S,t,p) = \sum_{i=1}^{n} h_T(p_i) T_i + \sum_{i=1}^{n} h_E(p_i) E_i. \tag{3}$$

If we replace $h_T(p_i)$ and $h_E(p_i)$ by constants α_i and β_i respectively, then we simply have a weighted sum of earliness and tardiness.

A variant of the function (3) arises if we change to $h_E(p_i) = 0$, so we only penalize tardiness, i.e.,

$$F(S,t,p) = \sum_{i=1}^{n} h_T(p_i) |S_i - t_i| \delta(S_i, t_i),$$

where

$$\delta(S_i, t_i) = \begin{cases} 1 & \text{if } S_i > t_i \\ 0 & \text{if } S_i \leq t_i \end{cases}$$

or, equivalently,

$$F(S,t,p) = F_{sumT}(S,t,p) = \sum_{i=1}^{n} h_T(p_i) T_i.$$

Another case that disregards the priorities or, alternatively, has constant but different h_T and h_E is:

$$F(S,t,p) = \sum_{i=1}^{n} \alpha |S_i - t_i| \delta(S_i, t_i) + \sum_{i=1}^{n} \beta |S_i - t_i| \gamma(S_i, t_i),$$

where

$$\gamma(S_i, t_i) = \begin{cases} 1 & \text{if } S_i \leq t_i \\ 0 & \text{if } S_i > t_i \end{cases}$$

In the case where we disregard priorities and the α and β correspond to different weighting factors for tardiness and earliness, respectively, this penalty function arises in single machine schedule with ***nonsymmetric*** earliness and tardiness penalties and ***common weights*** (see [42, 4, 15]. The case $\alpha = \beta$ is equivalent to the penalty function studied by [27, 54, 5, 23, 15, 57, 24].

The function $F_{sumE/T}(S,t,p)$ is considered for the case where all t_i are the same in [3, 11, 15, 44, 8, 6, 25, 26]. The more general function allowing differing t_i is considered in [12, 18, 19, 20, 10, 1, 40, 41].

Still other penalty functions are only concerned with minimizing the maximum deviation from desired arrival time, rather than a weighted sum of deviations. Of interest, for example, is the function

$$F(S,t,p) = F_{maxE/T}(S,t,p) = max\{h_T(p_1)T_1, h_T(p_2)T_2, \ldots, h_T(p_n)T_n, h_E(p_1)E_1, h_E(p_2)E_2, \ldots, h_E(p_n)E_n\}$$

where we maximize the weighted maximum deviation, including consideration of earliness deviations. If we are only interested in tardiness, we would consider instead

$$F(S,t,p) = F_{maxT}(S,t,p) = max\{h_T(p_1)T_1, h_T(p_2)T_2, \ldots, h_T(p_n)T_n\}.$$

The objective function $F_{maxE/T}(S,t,p)$ is considered in [52, 17], for example, while $F_{maxT}(S,t,p)$ is considered by many authors. Two survey papers describing work with these functions are [29, 2], with the former emphasizing constant weighted tardiness.

Since there are so many potential criteria for a good solution to the port reopening scheduling problem, it is surely useful to look at it as a multicriteria problem. For a survey from this point of view, see [58].

4 The Case of Common Desired Arrival Times

The most trivial case of the problem we have formulated is where all the desired arrival times t_i are the same time τ (this is sometimes called in the scheduling literature the case of ***common due dates***). Let us assume that the penalty function is summable and separable, that $f > 0$, that $h_E(p_i) = 0$ (there are no earliness penalties), and that $h_T(p_i)$ is an increasing function of p_i. Let us also assume that $c = 1$, i.e., we can only unload one ship at a time and, moreover, assume that there is only one kind of good on each ship. In this case, a simple greedy algorithm suffices to find a schedule that minimizes the penalty.

To explain this, suppose we rank the goods in order of decreasing priority, choosing arbitrarily in case of ties. The greedy algorithm proceeds as follows. Schedule the first good on the list at time 1, the next on the list at time 2, and so on until the last is scheduled at time n. To see that the resulting greedy schedule S_G minimizes the penalty, suppose that we have a schedule and the set of goods scheduled up to time τ is A and the set scheduled after time τ is B. Switching any two goods within A does not change the penalty. The order of elements in B that will minimize the penalty given the split of goods into A and B is clearly to put those of higher priority close to τ. Now consider the possibility of switching a good i in the set A_G associated with greedy schedule S_G with a good j in the set B_G associated with S_G, to obtain a schedule $S_G(i,j)$. Then if j is given timeslot $\tau + r$ in S_G, we have

$$F(S_G,t,p) - F(S_G(i,j),t,p) = h_T(p_j)f(S_{G_j},t_j) - h_T(p_i)f(S_{G(i,j)_i},t_i)$$

$$= h_T(p_j)f(\tau + r,\tau) - h_T(p_i)f(\tau + r,\tau)$$

$$= [h_T(p_j) - h_T(p_i)]f(\tau + r,\tau)$$

$$\leq 0,$$

since $p_j \leq p_i$, $h_T(u)$ is increasing, and $f > 0$. We conclude that a switch cannot decrease the penalty.

Things get more complicated if $c > 1$ or ships can have more than one good. Consider for example the case where we use the penalty function $F_{sumT}(S,t,p)$, we take $c = 1$, and there are two ships, ship 1 with goods vector $(1,0,0,1)$ and ship 2 with goods vector $(0,1,1,0)$, and assume that $p_1 > p_2 > p_3 > p_4$. What is a greedy algorithm? One natural idea here is to choose first the ship that has the item of highest priority and schedule that as close to desired arrival time as possible, and first if all t_i are the same as we are assuming in this section. Let us say the desired arrival times are given by $t = (1,1,1,1)$. Then we would schedule ship 1 first, at time 1, then ship 2 at time 2, obtaining a goods arrival schedule $S = (1,2,2,1)$ and penalty $F(S,t,p) = h_T(p_2) + h_T(p_3)$. However, if we schedule ship 2 first, we get a goods arrival schedule $S^* = (2,1,1,2)$ with penalty $F(S^*,t,p) = h_T(p_1) + h_T(p_4)$, which might be lower than $F(S,t,p)$, depending on the function h_T and the values of the p_i.

To show how complicated things get very quickly, consider another simple situation where we use the penalty function $F_{sumT}(S,t,p)$, we take $c = 1$, and there are three ships, ships 1, 2, 3 with goods vectors

(1,0,0,0), (0,1,0,0), and (0,0,1,1), respectively, with $t = (2,2,2,2), p_1 > p_2 > p_3 > p_4$. A natural greedy algorithm would say choose ship 1 first since it has the highest priority good, and put it at time 1, then ship 2 next since it has the second highest priority good, and put it at time 2, and finally ship 3 at time 3. This gives rise to a penalty of $h_T(p_3) + h_T(p_4)$. Scheduling ship 3 at time 2, ship 1 at time 1, ship 2 at time 3 gives a penalty of $h_T(p_2)$, which might be smaller. Thus, even with constant desired arrival times and only one ship per timeslot, finding an algorithm that would minimize penalty presents intriguing challenges.

5 Nonconstant Desired Arrival Times

It is interesting to observe that in the case of nonconstant arrival times, our intuition about the problem is not always very good. It seems reasonable to expect that if the priorities change, but the ratios of priorities p_i/p_j do not change, then an optimal schedule won't change. For example, consider the penalty function $F_{sumE/T}(S,t,p)$. One example of an increasing function h_T is given by $h_T(u) = 2^{u-1}$. Now consider the case where each ship has only one kind of good, $c = 1$, and we have $t = (1,2,2,2), p = (1,2,2,2)$. An optimal schedule is given by $S = (1,2,3,4)$. Yet, if we multiply each priority by 2, getting $p^* = (2,4,4,4)$, then the schedule S is no longer optimal, since it has a penalty of 24 while the schedule $S^* = (2,3,4,1)$ has penalty 22. (This example is taken from [37].)

6 Meaningful Conclusions

The truth or falsity of a conclusion about optimality of a schedule can sometimes depend on properties of the scales used to measure the variables. Discussions of this point in the literature of scheduling have concentrated on the scales used to measure the priority of a good. Mahadev, Pekeč, and Roberts [37, 38] point out that the conclusion that a particular schedule is optimal in one of the senses defined in Section 3 can be meaningless in a very precise sense of the theory of measurement. Thus, one needs to be very careful in drawing the conclusion of optimality of a schedule. To explain what this means, we note that in using scales of measurement, we often make arbitrary choices such as choosing a unit or a zero point. In measuring mass, for example, we can use, grams, kilograms, pounds, etc. In measuring temperature, we can use, for example, Fahrenheit or Centigrade. An ***admissible transformation*** of scale transforms one acceptable scale into another. For example, in changing from kilograms to pounds, it multiplies all values by 2.2, and in changing from degrees Centigrade to degrees Fahrenheit, it multiplies by 9/5 and then adds 32. In measurement theory, a statement involving scales is called ***meaningful*** if its truth or falsity is unchanged after applying admissible transformtions to all of the scales in question. For an introduction to the theory of measurement, see [30, 36, 56, 45]. For further information about the theory of meaningfulness, see [36, 45, 46, 48, 50, 51]. For applications of the concept of meaningfulness to combinatorial optimization, see [47, 48, 51, 13].

What properties does the priority scale have? Specifically, what transformations of the priority scale are reasonable to allow? Quaddus [44] thinks of the priorities as "costs" but suggests that techniques of preference and value theory as in the classic work of Keeney and Raiffa [28] might be relevant, suggesting that priorities are more like utility measures. In the literature of utility theory, various kinds of admissible transformations of utility values are considered, including those where we change just the unit and those where we change both unit and zero point. Let us first consider the case where the priorities p_i are unique up to choice of unit. In this case, we talk about a ***ratio scale*** and the admissible transformations are functions of the form $\phi(u) = \alpha u$. Consider the claim that schedule S is optimal under penalty function $F_{sumE/T}(S,t,p)$. This means that for any other schedule S^*,

$$F_{sumE/T}(S,t,p) \leq F_{sumE/T}(S^*,t,p). \quad (4)$$

Consider the case where $h_T(u) = u, h_E(v) = v$ for all u, v. Then we consider Equation (4) meaningful if its truth is unchanged if we replace any p_i by $\phi(p_i) = \alpha p_i$. Clearly (4) is meaningful in this sense. It is even meaningful with nonconstant functions h_T, h_E if these functions satisfy the equations $h_T(\alpha u) = \alpha h_T(u), h_E(\alpha v) = \alpha h_E(v)$. Thus, under these conditions, the statement (4) is meaningful in the sense of measurement theory. Similar conclusions hold if we replace the penalty function with $F_{sumT}(S,t,p), F_{maxE/T}(S,t,p)$, or $F_{maxT}(S,t,p)$.

However, consider the situation where priorities are only determined up to change of both unit and zero point. Here we say that priorities are measured on an ***interval scale*** and admissible transformations take the form $\phi(u) = \alpha u + \beta$. In this case, the truth of the statement (4) can depend on the choice of unit and zero point. Consider for example the case of $n = 4$ goods, with $t = (2, 2, 2, 1), p = (9, 9, 9, 1)$. Consider the penalty function $F_{sumE/T}(S, t, p)$ with $h_T(u) = u, h_E(v) = v$ for all u, v. It is easy to see that the schedule $S = (1, 2, 3, 4)$ is optimal. However, consider the admissible transformation $\phi(u) = \alpha u + \beta$, where $\alpha = 1/8$ and $\beta = 7/8$. After this admissible transformation, we change p to $p^* = (2, 2, 2, 1)$. Then $F(S, p^*, t) = 7$ while $F(S^*, p^*, t) = 6$ for $S^* = (4, 1, 2, 3)$. This shows that the conclusion that S is optimal in this case is meaningless. (This example is due to [37].)

An extensive analysis of the meaningfulness of conclusions for scheduling problems under a variety of penalty functions and a variety of assumptions about admissible transformations of priorities is given in [37, 38].

7 Closing Comments

This paper has set out the port reopening scheduling problem. We have seen that even a very simplified version leads to rather subtle issues. Among the special assumptions we have considered are:

- all desired amounts are one unit, i.e., $d_i = 1$ for all i;
- in reopening, the port has limited capacity of one ship at a time, i.e., $c = 1$;
- all goods have the same desired arrival time t_i;
- all goods have only one desired arrival time t_i, rather than specifying a minimum amount desired per time;
- all ships have the same unloading time;
- all ships are ready to dock without delay;
- there is no problem storing unloaded but undemanded goods at the port;
- each ship has only one kind of good.

Even making all or most of these special assumptions leaves a complex scheduling problem. Removing these special assumptions leads to a wide variety of challenging problems, as we noted when we removed the last one.

We have also considered a variety of penalty functions. Certainly there are others that should be considered. Moreover, we have not tried to formulate a multicriteria optimization problem that might also be appropriate.

We have also not discussed the problem of how one determines priorities and desired arrival times of the goods in question. We can envision a number of approaches to this, for example having each stakeholder (government, port operators, shippers) providing these priorities and times and then using some sort of consensus procedure. We could also create a bidding procedure for obtaining them[2]. The measurement-theoretic properties of the priorities (the kinds of scales they define or admissible transformations they allow) also need to be understood better.

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[2] Thanks to Paul Kantor for suggesting this idea; the details present another interesting research challenge.

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