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Scheduling for a Single-Terminal Intermodal System Recovery with Poisson Arrivals

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This paper studies the recovery of an intermodal freight system from a major disruption and develops a model for optimizing vehicle schedules under disrupted conditions. The proposed model optimizes the recovery of a single-terminal system with relatively short feeder routes on which vehicle roundtrip times are exponentially distributed and arrivals at the terminal are Poisson-distributed. Mathematical expectations are used to formulate the deterministic equivalent for the scheduling problem and a genetic algorithm is applied to optimize the schedules on main routes. The model developed in this paper can be applied to single-terminal transfer systems with any combination of transportation modes using discrete vehicles, as long as the feeder arrivals do not deviate much from the assumed Poisson distributions. Since its computational time is relatively insensitive to the numbers of vehicles on feeder routes, this model can be used to efficiently optimize intermodal systems with numerous vehicle arrivals.

Keywords: scheduling, disruption, intermodal, Poisson, genetic algorithm, transfer

0 INTRODUCTION

Efficient transfer coordination in an intermodal transportation network can reduce the dwell times of cargos at the transfer terminals where various routes interconnect, thereby also increasing the vehicle utilization rates, reducing the need for direct routes to connect many origins and destinations, reducing storage requirements at transfer terminals and improving total system efficiency. In this paper we analyze an intermodal freight system with a single transfer hub and develop a model that optimizes the schedule of vehicles on main routes while assuming Poisson arrivals on feeder routes. This model determines the departure times on main routes that minimize the supplier's overall system cost, including storage, vehicle, in-terminal operation and late delivery penalty cost.

The optimization problem addressed in this paper is related to some classical problems of operations research, such as machine scheduling, lot sizing and supply chains. Somewhat related machine scheduling problems can be found in [1] to [3]. [4] to [7] address the scheduling problem in transfer systems, but under different conditions from those considered here. For example, [4] and [5] analyze different transfer coordination policies and determine the thresholds in the intermodal systems with complex multi-stop routes and lower variance in travel durations, both typical for normal operations. In this paper we analyze the case with high variances in travel times which are typical of disrupted operations and model the arrivals as a Poisson process. [6] and [7] deal with scheduling takeoff times, a problem that will be studied in this paper. Both papers optimize departures on a single airline route and under different demand assumptions from those considered here (i.e. [6] assumes uniform demand, whereas [7] adopts time dependent demand). This paper is based on the same framework as [8] and develops a model which, unlike [8], is suitable for intermodal systems with numerous arrivals of vehicles on feeder routes. In [8], Marković and Schonfeld develop a scheduling model which assumes generally distributed vehicle roundtrip durations and vehicles operating on multiple feeder routes. Low computational efficiency of the stochastic program used in [8] enabled only the optimization of schedules in systems with relatively few arrivals on feeder routes. In this paper we provide a computationally less demanding model by assuming exponentially distributed vehicle roundtrips and fixed fleet size on feeder routes. These assumptions allow us to model the arrivals as a stationary Poisson process and derive expectations needed to formulate a scheduling problem which is optimized much more efficiently than the stochastic program in [8]. Thus, the model developed here can efficiently optimize large

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intermodal systems with numerous arrivals on feeder routes.

We analyze here the recovery of a system from a major disruption during which large amounts of freight have accumulated along the feeder routes, which are assumed here to be served by trucks. To dissipate the backlogs we let the trucks on feeder routes operate nonstop and deliver cargo to the terminal where the freight is transferred to main routes, which are assumed here to be aircraft routes. Thus our transfer terminal represents here an airport hub. We use pre-determined fleet sizes on feeder routes and seek to optimize the number of departures and specific departure schedules on main (air) routes. We consider one-directional flow going from origins along the feeders' routes towards destinations at main routes, as might be expected in emergency evacuations or recoveries from major disruptions.

In section 1 we describe the operations within the observed intermodal system and explain the tradeoff between different types of costs. The anticipated types of costs which are included in the objective function are formulated in section 2. Section 3 explains the constraints, while section 4 provides the model formulation which is further tested on numerical examples designed in section 5. Finally we draw conclusions and suggest possible extensions of this work.

1 PROBLEM

We consider an intermodal system with relatively short truck routes that feed cargo to the major airplane routes (Fig. 1), which has suffered a major disruption. In order to reduce the backlogs accumulated along the feeder routes while the system was inoperative, each truck operates nonstop and fully loaded between an origin and the hub, without pausing between such round trips while backlogs persist. The trucks collect freight from multiple origins along their feeder routes and deliver it at the airport hub. When the takeoff on route l is scheduled at time t_i^l, the airplane is filled to capacity with freight, as long as freight backlogs persist. If the airplane cannot carry all the freight waiting at the airport, the remaining freight has to wait for the next flight with available capacity. On the other hand, if prior to the takeoff there is little freight in the terminal's storage connecting to route l, the airplane's capacity is underused and an additional flight may be needed later. For simplicity, we assume that all trucks are similar and all operate at equal maximum capacity. Moreover, we assume that airplanes have similar capacities. Finally, we assume that the expected amount of cargo waiting for connections can never exceed a preset multiple (e.g. 0.8) of the terminal's storage capacity.

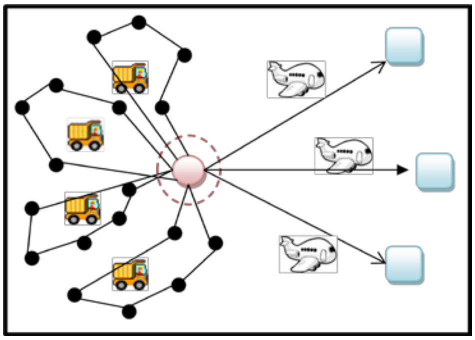

Fig. 1. *Intermodal freight system*

Our objective is to find the optimal (i) number of takeoffs on each air route and (ii) corresponding schedule, for the given probabilistic durations of roundtrips on truck routes. In computing total cost we consider the storage cost, in-terminal operation cost, penalty for late delivery and airline service cost. A tradeoff exists between the aforementioned types of costs. The earlier one schedules the takeoff, the lower are storage and penalty costs associated with the freight that successfully connects. However, the earlier the takeoff is scheduled, the greater are chances that an airplane's capacity will be underused due to insufficient level of stock. Operating less than full airplanes may require running additional flights, thereby increasing the airline service cost.

2 COSTS

In this section we introduce the notation used and explain how various types of costs are computed. We begin with the assumptions that allow us to model the arrivals on feeder routes as a Poisson process. We then compute the arrival intensities which are further used in the development of storage, in-terminal operation, penalty and airline cost.

Suppose that a single truck operates on a relatively short feeder route i whose starting and end point is the terminal where the truck-load connects to the airplane route l. Let's assume that duration of the truck's roundtrip is exponentially distributed with a mean denoted as $1/\lambda_i^l$. Moreover, it is reasonable to assume that observed transportation process has the following three properties:

1. The probability that a truck will accomplish more than one roundtrip within an infinitesimal time interval is negligible.
2. The duration of a roundtrip does not depend on the duration of the previously accomplished tour.
3. The probability that a roundtrip will end within the time interval t depends on the interval's length, rather than on epoch in which t was observed.

Having adopted the above assumptions, we can model the truck arrivals as a Poisson process with the mean arrival rate λ_i^l according to [9] and [10]. If we assign to feeder route i more than one truck, the arrival rate on route i is given in Eq. (1), in which n_i represents the number of trucks assigned to feeder route i.

$$r_i = n_i \lambda_i^l \quad . \tag{1}$$

Furthermore, if we define with I^l the set of feeder routes connecting to main route l, the arrival rate of truckloads connecting to route l is:

$$\lambda^l = \sum_{i \in I^l} n_i \lambda_i^l \quad . \tag{2}$$

If we denote the j^{th} takeoff time on route l as t_j^l, the expected number of truck-loads connecting to route l and arriving to terminal between two consecutive flights is:

$$E[TR^l (t_j^l - t_{j-1}^l)] = \lambda^l (t_j^l - t_{j-1}^l) \quad . \tag{3}$$

2.1 Storage Cost

To compute the storage cost, we need to keep track of the inventory level. Moreover, since multiple feeder routes are connecting to multiple main routes, we need to know the stock for each main route. Therefore we define the variable S_j^l which defines the inventory level of freight connecting to main route l, after the j^{th} takeoff. We also define A_j^l representing the amount of freight transported in the j^{th} flight on route l. Considering the inflow and outflow of freight into the terminal storage, Eq. (4) has to hold for all flights on all routes. Please note that S_0^l, t_0^l and A_0^l all equal 0. Moreover, we assume that all the freight arriving at the terminal before the last scheduled takeoff has to be flown. Thus we also set $S_{n^l}^l$ to equal 0.

$$S_{j-1}^l + \lambda^l (t_j^l - t_{j-1}^l) = A_j^l + S_j^l \qquad \forall j \in J^l \quad \forall l \in L \quad . \tag{4}$$

Moreover, since we do not know in advance if there will be enough freight in the terminal's storage to fill the airplane, we specify in Eq. (5) that the airplane will be loaded with all the connecting freight found in terminal that can fit within the airplane's capacity, denoted A_c.

$$A_j^l = \max\{A_c, S_{j-1}^l + \lambda^l (t_j^l - t_{j-1}^l)\} \quad . \tag{5}$$

Based on the previous derivations, in Eq. (6) we can compute the storage cost between two consecutive flights for freight connecting to route l. Please note that C_{DT} denotes the storage cost per truckload-hour.

$$\frac{1}{2}(S_{j-1}^l + S_j^l)(t_j^l - t_{j-1}^l) C_{DT} \quad . \tag{6}$$

We can further compute the total storage cost for freight connecting to route l by summing Eq. (6) over all the flights in J^l.

$$SC^l = \frac{1}{2} \sum_{j \in J^l} (S_j^l + S_{j-1}^l)(t_j^l - t_{j-1}^l) C_{DT} \quad . \tag{7}$$

Finally, we can compute the total storage cost by summing Eq. (7) over the set L which denotes main routes.

$$SC = \frac{1}{2} \sum_{l \in L} \sum_{j \in J^l} (S_j^l + S_{j-1}^l)(t_j^l - t_{j-1}^l) C_{DT} \quad . \tag{8}$$

2.2 In-terminal Operation Cost

Here we analyze the loading and unloading cost due to the cargo transfer from trucks to airplanes. We assume that in-terminal operation cost is lower when a truck arrives slightly before the takeoff and takes its truckload directly to the airplane, instead of unloading it in the terminal storage. Therefore, let's define parameter d, so that a truck arriving within the $(t_j^l - d, t_j^l)$ interval takes its truckload directly to the airplane. Now we can compute the expected number of truckloads that will be loaded directly on the airplane:

$$b_d = \sum_{l \in L} \sum_{j \in J^l} \lambda^l d \quad . \qquad (9)$$

Here we assume that d is smaller than the interval between two consecutive flights on the same route. Thus, the expected number of truckloads being loaded directly on the airplane depends on the number of takeoffs rather than on their schedule.

If we denote C_{td} the unit in-terminal operation cost for the case of direct transfer to the airplane, C_{ti} the unit cost for the case of indirect transfer to the airplane and G the total number of truckloads; the total in-terminal operation cost is:

$$IC = b_d C_{td} + (G - b_d) C_{ti} \quad . \qquad (10)$$

2.3 Penalty Cost

A penalty is imposed for late delivery, reflecting the lower value of freight that is delivered later. Here we assume that the time of the takeoff is relevant for computing the penalty cost. We define a penalty function f_p as the piecewise linear function of takeoff time starting from the beginning of the observed time period (the moment system starts recovering from a disruption), as shown in Fig. 2.

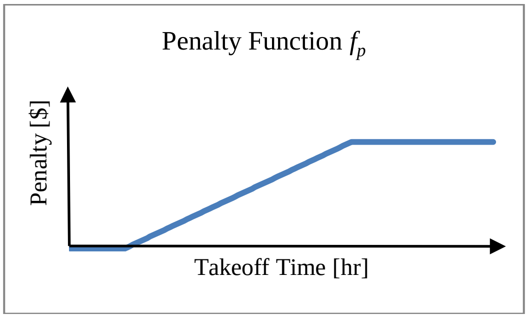

Fig. 2. *Penalty function*

Now we can compute the penalty cost by summing the penalty for all the flights on all the air routes, as shown in (11). Please note that we use again A_j^l defined in (5), which denotes the number of truckloads carried on the j^{th} takeoff on route l.

$$PC = \sum_{l \in L} \sum_{j \in J^l} A_j^l f_p(t_j^l) \quad . \qquad (11)$$

2.4 Airline Cost

The last type of cost considered is the airline service cost which covers the use of both airplanes and airport facilities. It is proportional to the number of the airplane roundtrips (takeoffs). We denote the number of takeoffs on route l as n^l. Moreover, we denote as C_A^l the cost of an airplane roundtrip on route l. Finally, the total airline service cost is:

$$AC = \sum_{l \in L} n^l C_A^l \quad . \qquad (12)$$

3 CONSTRAINTS

In this section we analyze several constraints needed in order for the mathematical model to fairly represent the real world. The first constraint that we consider is the time window constraint for takeoffs. Utilization of airport facilities is often restricted to certain time slots. Thus each takeoff must be scheduled within the prespecified time interval. Thus, the time window constraint is:

$$a_j^l < t_j^l < b_j^l \quad \forall j \in J^l \quad \forall l \in L \quad . \qquad (13)$$

Since limited airport capacity might require a minimum time interval between any two flights, we introduce the following constraint.

$$t_j^l - t_{j-1}^l \geq t_{\min} \quad \forall j \in J^l \quad \forall l \in L \ . \qquad (14)$$

The last constraint we consider is the terminal's storage capacity. We assume that the expected amount of freight at terminal should never exceed the multiple m_s of the storage capacity S_c. Since we previously explained how the expected inventory level for freight connecting to route l at takeoff time t_j^l is computed, we must now ensure that total expected inventory never exceeds the multiple of the storage capacity $m_s S_c$. Thus we define parameter p_t and control the total inventory level at time p_t. In order to do so we first need to find the inventory level of freight connecting to route l at time p_t. We introduce s^l which denotes the takeoff time on route l prior to p_t, and define k^l which equals takeoff's index j.

$$s^l = \max\left\{t_j^l : t_j^l \leq p_t\right\} \quad , \qquad (15)$$

$$k^l = index\ j : (t_j^l \leq p_t \wedge t_{j+1}^l \geq p_t) \ . \ (16)$$

Now we can compute the expected inventory of freight connecting to route l as:

$$S_{k^l}^l + \lambda^l (p_t - s^l) \quad . \qquad (17)$$

Finally we can define the storage capacity constraint by summing Eq. (17) over the set of main routes and setting the sum below the storage capacity S_c multiplied by m_s (a safety factor). Please note that constraint Eq. (18) should hold for any real value of time parameter p_t.

$$\sum_{l \in L} S_{k^l}^l + \lambda^l (p_t - s^l) \leq S_c m_s \quad \forall p_t \in R \ . \ (18)$$

4 MODEL

In the previous section the types of costs and constraints considered are explained. Now we can present the mathematical formulation of the model Eqs. (19) to (30), which represents a nonlinear program. Here we provide a compact formulation of the objective function using Eqs. (8), (10), (11) and (12). In Eqs. (20) to (30) we provide the constraints and other previously derived relations.

$$MinTC = SC + IC + PC + AC \ , \qquad (19)$$

subject to:

$$S_{j-1}^l + \lambda^l (t_j^l - t_{j-1}^l) = A_j^l + S_j^l \quad \forall j \in J^l \quad \forall l \in L \ , \qquad (20)$$

$$a_j^l < t_j^l < b_j^l \quad \forall j \in J^l \quad \forall l \in L \ , \qquad (21)$$

$$t_j^l - t_{j-1}^l \geq t_{\min} \quad \forall j \in J^l \quad \forall l \in L \ , \qquad (22)$$

$$\sum_{l \in L} S_{k^l}^l + \lambda^l (p_t - s^l) \leq S_c m_s \quad \forall p_t \in R \ , \ (23)$$

$$A_j^l = \max\left\{A_c, S_{j-1}^l + \lambda^l (t_j^l - t_{j-1}^l)\right\} , \qquad (24)$$

$$s^l = \max\left\{t_j^l : t_j^l \leq p_t\right\} \ , \qquad (25)$$

$$k^l = index\ j : (t_j^l \leq p_t \wedge t_{j+1}^l \geq p_t) \ , \qquad (26)$$

$$b_d = \sum_{l \in L} \sum_{j \in J^l} \lambda^l d \ , \qquad (27)$$

$$S_0^l = t_0^l = A_0^l = S_{n^l}^l = 0 \ , \qquad (28)$$

$$t_j^l \in R_+ \quad \forall j \in J^l \quad \forall l \in L \ , \qquad (29)$$

$$n^l \in Z_+ \quad \forall l \in L \ , \qquad (30)$$

The total cost function is a function of the number of takeoffs and takeoff times, as explained in the problem statement. The nonlinear model Eqs. (19) to (30) optimizes the schedule while considering the capacity of airplanes, airport and terminal storage, and time windows for takeoffs. In the following section we apply a genetic algorithm (GA) to optimize the schedule in two case studies. Interested readers may refer to [11] and [12] for more information about GA's.

5 APPLICATION

In order to test our model, we design two case studies. In the first case the schedule in an intermodal system with a single main route is optimized. In this simplified optimization problem we examine the anticipated tradeoff in types of costs through the sensitivity analysis. In the second case we analyze a complex system with multiple main routes and time windows.

5.1 Case Study with a Single Air Route

We analyze a system with ten feeder truck routes connecting to a single airplane main route. In Table 1 we provide the average roundtrip time on each feeder route, as well as the number of vehicles operating on each truck route. We seek to optimize the number of takeoffs and corresponding schedule assuming that all the freight arriving at the terminal before the last takeoff has to be transported. For this case, we assume the input data from Table 2. The optimization results for 4 to 9 takeoffs are presented in Table 3. We present optimized schedule for six different numbers of takeoffs and corresponding costs in dollars. Please note that within “other costs” we consider storage, penalty, loading and unloading cost. Moreover, by marginal savings in other costs we consider savings in storage, penalty, loading and unloading cost due to introducing an additional roundtrip flight.

Table 1. *Vehicle size and roundtrip duration*

Feeder route	Average roundtrip duration $1/\lambda_i$ [hr]	Number of trucks in feeder route
1	1.23	3
2	1.97	4
3	1.73	1
4	2.10	2
5	2.16	1
6	1.94	2
7	2.18	5
8	1.86	2
9	1.68	1
10	2.00	3

Table 2. *Input data*

Airplane capacity	A_c	50 truckloads	In-terminal cost	C_{td}	25 $/truckload
Flight cost	C_A^1	7,000 $/roundtrip	In-terminal cost	C_{ti}	45 $/truckload
Terminal storage capacity	S_c	87.5 truckloads	Time of the last takeoff	t_n^1	15 hrs
Storage multiple (safety factor)	m_s	0.8	Minimum headway	$t_{\min}$	0.8 hrs
Storage cost	C_{DT}	4 $/truckload-hr	Arrival rate based on the data from Table 1	λ^1	12.95 veh/hr
Amount of time	d	15 min	Penalty function	$f_p(t)$	0 if t≤2 125t-250 if 2<t≤10 1000 if t>10

Table 3. Optimized Schedules and Costs

Number of flights	Airline cost [$10^3$$]	Other cost [$10^3$$]	Marginal savings in other cost	Total cost [$10^3$$]	Optimized takeoff times for the given number of flights [hr]								
					Fl.1	Fl.2	Fl.3	Fl.4	Fl.5	Fl.6	Fl.7	Fl.8	Fl.9
4	28	151	NA	179	3.6	7.3	11.1	15.0	NA	NA	NA	NA	NA
5	35	143	8	178	2.5	5.0	7.5	11.3	15.0	NA	NA	NA	NA
6	42	139	4	181	2.0	4.0	6.0	8.0	11.5	15.0	NA	NA	NA
7	49	136	3	185	2.0	3.6	5.2	6.8	8.4	11.7	15.0	NA	NA
8	56	134	2	190	2.0	3.3	4.7	6.0	7.4	8.7	11.9	15.0	NA
9	63	133	1	196	2.0	3.2	4.3	5.5	6.6	7.8	8.9	12.0	15.0

The results presented in Table 3 show that the minimum total cost occurs in the case with five takeoffs. Therefore we can conclude that at the cost of 7000 $/flight, one more flight than necessary to satisfy the demand should be introduced. Moreover, we can observe that storage, penalty and loading/unloading cost decrease with the increase in the number of takeoffs. This outcome was expected and it confirmed the tradeoff between types of cost that was explained in the problem statement. We also note that the marginal savings in storage, penalty and loading/unloading cost decreases with the number of aircraft roundtrips, which is another anticipated outcome.

Based on the values for storage, penalty and loading/unloading cost we can explore how different flight costs affect the optimized number of takeoffs and thereby the schedule. In Fig. 3 we plot total cost for the case of 4, 5, 6, 7, 8 and 9 roundtrips vs. aircraft roundtrip cost. Fig. 3 also shows five threshold values for airplane roundtrip cost which determine the optimal number of takeoffs. Those values are 1357, 1871, 2771, 4277 and 7509 dollars, respectively. Clearly, for a relatively low cost per plane roundtrip, the total system cost is optimized by scheduling more takeoffs than necessary to satisfy the demand. As the airline cost increases, the optimal number of takeoffs decreases until it eventually drops to the minimum number needed to satisfy the demand.

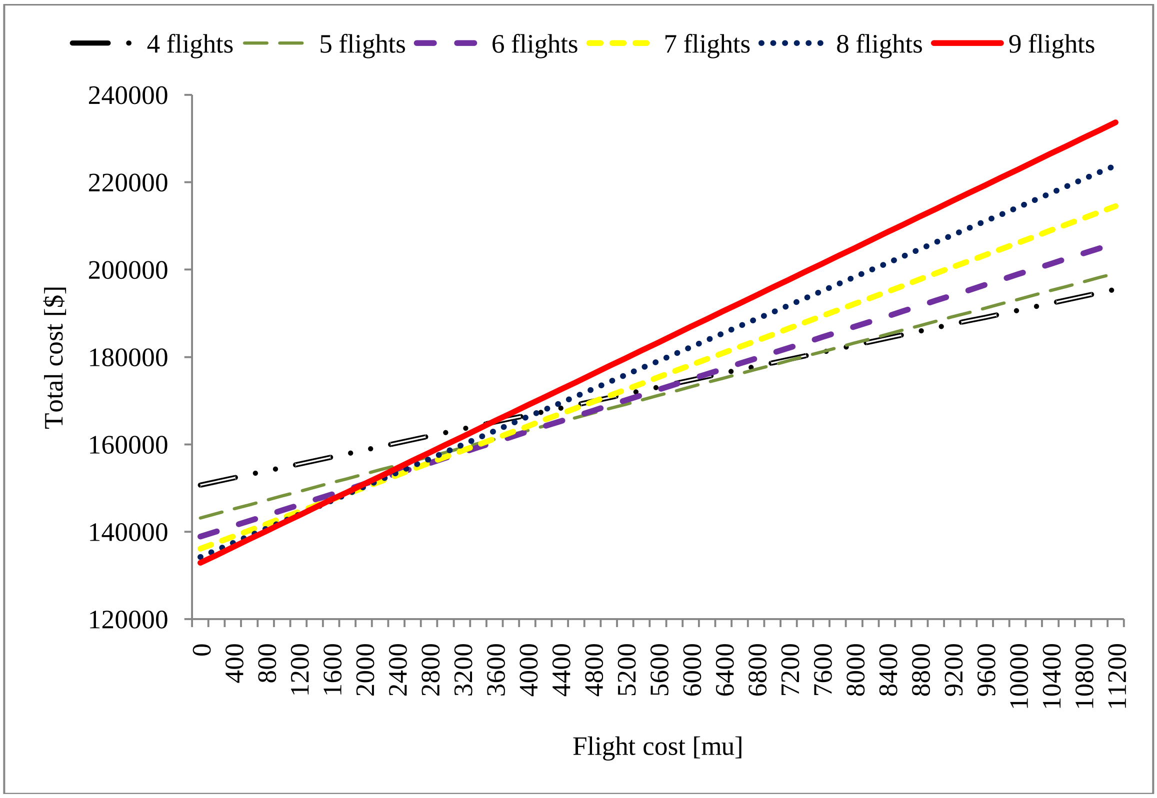

Fig. 3. *Sensitivity Analysis*

5.2 Case Study with Multiple Airline Routes

Here we consider the case of multiple feeder routes connecting to three air routes of similar lengths. Since we consider the case with three dozen feeder routes, we do not present the expected roundtrip duration and the number of vehicles on each route, as we did in the previous example. Instead, we provide here the computed arrival rates of vehicles connecting to three air routes. Moreover, we assume the same values from the previous numerical example, but this time we include time windows into our analysis. The aforementioned data are provided in Table 4. Please note again that, for each route, all the freight arriving at the terminal by the time of the last flight has to be loaded into airplanes and transported to its destination.

Table 4. *Input data*

Flight cost on all routes	C_A^l	9,000 $
Arrival rate on route 1	λ^1	8.0 veh/hr
Arrival rate on route 2	λ^2	8.5 veh/hr
Arrival rate on route 3	λ^3	7.5 veh/hr
Time windows for route 1	(a_1^1, b_1^1)	(1.5,2.5)
	(a_2^1, b_2^1)	(3.1,4.5)
Time windows for route 2	(a_1^2, b_1^2)	(1.2,3.6)
	(a_2^2, b_2^2)	(4.5,6.4)
	(a_3^2, b_3^2)	(7.0,10.0)
Time windows for route 3	(a_1^3, b_1^3)	(2.3,4.2)
	(a_2^3, b_2^3)	(5.2,6.5)
Minimum time interval between any two flights	$t_{\min}$	0.5 hrs
Last takeoff on route 1	t_n^1	15 hrs
Last takeoff on route 2	t_n^2	14 hrs
Last takeoff on route 3	t_n^3	16 hrs

The optimization results for the case study with three main routes are given in Table 5. NA stands for the cases when no feasible solution is found either due to overloading of the terminal storage or not delivering all the freight that has arrived by the time of the last takeoff on each air route.

Table 5. *Optimized cost*

Case	Number of Flights on Route l			Total Cost [$10^3$$]
	l=1	l=2	l=3	
1	3	3	3	NA
2	4	3	3	NA
3	3	4	3	NA
4	3	3	4	NA
5	4	4	4	378
6	4	4	5	387
7	4	5	4	386
8	5	4	4	384
9	5	5	4	390
10	5	4	5	389
11	4	5	5	394
12	5	5	5	396

From Table 5 we conclude that at 9000 $/flight, the total cost is optimized by scheduling 4 flights on each main route (case 5), which also equals the minimum number of flights needed to provide a feasible solution. Finally, in Table 6 we provide the optimized schedule for all 8 feasible combinations of flights from Table 5.

Table 6. *Optimized schedule*

Case	Route	Optimized Schedule on Route
5	1	2.19|4.50|8.75|15.00
	2	2.69|5.51|8.12|14.00
	3	3.19|6.26|9.33|16.00
6	1	2.19|4.50|8.75|15.00
	2	2.69|5.40|8.12|14.00
	3	3.19|6.22|9.25|12.63|16.00
7	1	2.17|4.50|8.75|15.00
	2	2.69|5.12|7.57|10.79|14.00
	3	3.17|6.25|9.33|16.00
8	1	2.19|4.50|7.27|11.13|15.00
	2	2.69|5.40|8.12|14.00
	3	3.19|6.26|9.33|16.00
9	1	2.15|4.43|6.71|8.73|15.00
	2	2.65|5.04|7.44|9.83|14.00
	3	3.15|6.21|9.33|16.00
10	1	2.19|4.37|6.56|8.75|15.00
	2	2.69|5.34|8.12|14.00
	3	3.19|5.84|7.62|11.81|16.00
11	1	2.18|4.50|8.75|15.00
	2	2.68|5.04|7.40|9.75|14.00
	3	3.18|6.21|9.25|12.63|16.00
12	1	2.01|4.27|6.51|8.75|15.00
	2	2.51|4.77|7.01|8.25|14.00
	3	3.01|5.37|7.72|11.86|16.00

6 CONCLUSIONS

This paper studied the recovery of a single-terminal intermodal freight system from a disruption. A model was developed that optimizes the schedule of vehicles on main routes assuming Poisson arrivals on feeder routes. A genetic algorithm was used to optimize several case studies and sensitivity analysis confirmed the anticipated tradeoff in types of cost. Moreover, the model developed in this paper was applied to case studies including feeder truck routes and main airline routes. However, this model could be applied to other combinations of transportation modes without many modifications, as long as the arrivals do not deviate much from Poisson distributions.

Since the arrivals were modeled as a Poisson process, the computational efficiency of the model is fairly insensitive to the number of feeder routes or operating vehicles. Therefore the proposed scheduling model can be successfully applied to optimize the performance of busy intermodal systems with numerous vehicle arrivals.

Several assumptions built into this paper may be relaxed in the future in order to make the model more general. The current model could be improved to provide good robust solutions even for the case when some of the three properties of the Poisson process listed in section 1 do not hold. Moreover, the current analysis assumes fixed numbers of vehicles operating on the feeder routes. Future work may consider variable fleet sizes on feeder routes and thereby nonstationary arrival intensities.

7 NOTATION

The following symbols are used in this paper:

λ_i^l	parameter of the exponentially distributed duration of truck roundtrip on feeder route i connecting to main route l
i	index of feeder route
I	set of feeder routes
I^l	set of feeder routes connecting to main route l; clearly $I^l \in I$
j	index of takeoffs on route l
J^l	set of takeoffs on route l
l	index of main route
k^l	index of the takeoff on route l prior to time p_t
L	set of main routes
t_j^l	time of the j^{th} takeoff on route l
n^l	number of takeoffs on main route l
n_i	number of trucks on feeder route i
r_i	arrival rate on feeder route i
A_c	capacity of an airplane
S_c	capacity of terminal's storage
m_s	storage multiple
C_{DT}	in-terminal dwell cost
C_A^l	flight cost on route l
SC^l	storage cost associated with freight connecting to main route l
SC	storage cost
d	the amount of time, such that truck arriving within $(t_j - d, t_j)$ interval will take its truckload directly to the airplane
S_j^l	inventory level of freight connecting to main route l, after the j^{th} takeoff
b_d	the expected number of truckloads that will be transferred directly from trucks to airplanes
C_{ti}	cost of in-terminal operations
C_{td}	cost of in-terminal operations when truck takes its truckload directly to the airplane
IC	overall cost for in-terminal operations
$f_p(t_j^l)$	penalty function per truckload loaded into airplane at moment t_j^l
PC	overall penalty cost
AC	overall airline cost
TC	total cost
$t_{\min}$	minimum time interval between any two takeoffs
a_j^l	a lower bound for the j^{th} takeoff on route l
b_j^l	an upper bound for the j^{th} takeoff on route l
A_j^l	amount of freight carried in the j^{th} takeoff on route l
p_t	control parameter used to check the inventory level
R_+	set of nonnegative real numbers
Z_+	set of nonnegative integers

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