The Integrated Locomotive Assignment and Crew Scheduling Problem

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ABSTRACT:
Crew scheduling is an important part of the railway optimization process, but it is also a difficult problem to solve, due to the size of the problem and the complexity of the real life constraints. In this paper, an overview of the crew scheduling problem is given and crew scheduling problem is integrated to locomotive assignment problem and solved by using mixed integer linear programming model.

KEYWORDS: *Crew scheduling, integer programming, locomotive assignment, mathematical modeling.*

I. INTRODUCTION

Crew management is a major problem for transportation systems such as airlines, railways and public bus transportation. Advances on scheduling methodologies and decision support systems have been substantial in the last years, but they still need improvement, especially from the computational efficiency and practical point of view. Since the privatization and deregulation of most European railroad companies, it has become increasingly important to reduce the overall costs of operations. Labor cost is one of the largest factors in company expenses, so experienced managers are looking for methods to reduce costs.

Crew management is essential to improve productivity, safety and quality of service in many domains, but especially important for transportation systems. In general, crew management involves the construction of efficient sequences of work and rest periods to meet transportation demands and to satisfy constraints. In particular, crew scheduling has been studied from several points of view such as network flow models, mathematical programming, heuristics and dynamic programming.

There are three main approaches for the crew scheduling problem [1]: the run-cutting heuristic, the matching algorithm and the set covering formulation. The run-cutting algorithm was used in the 1970's, this is a constructive algorithm used by manual schedulers. The matching method is divided into three parts: block partition of the timetable, graph generation and duty achievement. Although in the early eighties several researchers recognized the need to integrate vehicle and crew scheduling, most of the algorithms published in the literature still follow the sequential approach where vehicles are scheduled before, and independently of, crews. In the operations research literature, only a few applications address a simultaneous approach to vehicle and crew scheduling. None of those publications makes a comparison between simultaneous and sequential scheduling [2].

II. LITERATURE ON LOCOMOTIVE ASSIGNMENT AND CREW SCHEDULING

Booler [3] proposed a Lagrangean relaxation method for solving an integer programming model of the locomotive assignment problem. Cordeau et al. [5] presented a survey of recent optimization models for the most commonly studied rail transportation problems. They described the problem of simultaneous assignment of locomotives and cars to passenger trains. An exact algorithm, based on Bender's decomposition, is proposed to solve the problem. Kron and Fsichetti [6] described the intelligent information systems that are used by Dutch railway operator for supporting the scheduling of drivers and guards. Their model is a set covering model and they solved the model by applying dynamic column generation techniques, Lagrangean relaxation and powerful heuristics.

Cordeau et al. [7] proposed a heuristic solution approach based on mathematical optimization for the assignment of locomotives and cars to scheduled trains. Ernst et al. [8] presented a model for integrated optimization model for train crew management. They used mathematical programming model for solving the problem. Walker et al [9] prepared the train time table and crew roster at the same time. They solved the problem in two phases. In the first phase they prepare train time tale, and in the second phase according to train time table they prepared crew roster. They used branch and bound algorithm for solving two phases.

Rouillon et al. [10] addressed the operational locomotive assignment problem of providing sufficient motive power to pull a set of scheduled trains at minimum cost while satisfying locomotive availability and maintenance requirement. Godwin et al [11] solved the locomotive assignment problem in two phases. In the first phase, they assigned locomotives with partial scheduling with the objectives of minimizing total deadheading time and total coupling delay. They used a genetic algorithm to find non-dominant locomotive assignment solutions and proposed a method for evaluating its performance. The solutions are then ranked using two approaches, based on the decision maker's preferences. In the second phase, they selected a locomotive assignment solution based on the ranking and find the lower bound on the arrival time of freight trains at their destinations. They used a genetic algorithm again to schedule the freight trains in the passenger rail network, with prescribed locomotive assignment precedence constraints with the objective of minimizing total tardiness. Ghoseiri and Morshedsolouk [12] developed an algorithm for the train scheduling problem using the ant colony system meta-heuristic called ACS-TS. The problem is considered as a traveling salesman problem (TSP) where in cities represent the trains.

III. Proposed Approach

Crew scheduling is characterized as the construction of duties in such a way that the timetable is covered adequately [8]. The aim of this study is to integrate locomotive assignment and crew scheduling problem by using mixed integer linear programming approach. Decisions about repositioning engines and crews made mainly on the basis of expert judgment. If extra engines and crews cannot be carried by regularly scheduled trains, engines are dispatched in light moves from the nearest yard and crews are moved from one yard to another without an engine. The planning horizon for crew scheduling is one week.

The definitions of the key parameters and decision variables of the proposed model can be developed as follows:

Indices

j, k Set of yards

i Set of days

Parameters

J Number of yards under consideration

F_{jk} Fixed cost of moving light engines from $Yard_j$ to $Yard_k$ in dollars

V_{jk} Variable cost of moving one light engine from $Yard_j$ to $Yard_k$ in dollars per engine

D_{ij} Number of engines required on Day_i at $Yard_j$

G_{ij} Number of engines gained or lost on Day_i at $Yard_j$

S Size of locomotive fleet

L Size of crew fleet

C_{jk} Variable cost of delivering a crew from $Yard_j$ to $Yard_k$ in dollars without an engine

T_{ij} Number of crews required on Day_i at $Yard_j$

K_{ij} Number of crews gained or lost on Day_i at $Yard_j$

Decision variables

$$b_{ijk} \begin{cases} 1 & \text{if a light engine move takes place on Day}_i \text{ from Yard}_j \text{ to Yard}_k \quad (k \neq j) \\ 0 & \text{otherwise} \end{cases}$$

x_{ijk} Number of light engines moved on Day_i from $Yard_j$ to $Yard_k$

y_{ij} Number of engines available at the beginning of Day_i at $Yard_j$

z_{ijk} Number of crews moved on Day_i from $Yard_j$ to $Yard_k$ with an engine

p_{ijk} Number of crews moved on Day_i from $Yard_j$ to $Yard_k$ without an engine

m_{ij} Number of crews available at the beginning of Day_i at $Yard_j$

The integrated locomotive utilization and crew scheduling problem may be formulated as the following mixed integer linear program:

$$\text{Minimize } Z = \sum_{i=1}^{7}\sum_{j=1}^{J}\sum_{\substack{k=1\\k\neq j}}^{J}[(F_{jk}\, b_{ijk} + V_{jk}\, x_{ijk}) + p_{ijk}\, C_{jk} \tag{1}$$

Subject to

$$y_{ij} \geq D_{ij}, \quad 1 \leq i \leq 7,\ 1 \leq j \leq J \tag{2}$$

$$\sum_{\substack{n=1\\n\neq j}}^{J} x_{ijn} \leq y_{ij} + G_{ij}, \quad 1 \leq i \leq 7,\ 1 \leq j \leq J \tag{3}$$

$$y_{ij} + G_{ij} + \sum_{\substack{m=1\\m\neq j}}^{J} x_{imj} - \sum_{\substack{n=1\\n\neq j}}^{J} x_{ijn} = y_{i+1,j}, \quad 1 \leq i \leq 6,\ 1 \leq j \leq J \tag{4a}$$

$$y_{7j} + G_{7j} + \sum_{\substack{m=1\\m\neq j}}^{J} x_{7mj} - \sum_{\substack{n=1\\n\neq j}}^{J} x_{7jn} = y_{1,j}, \quad 1 \leq j \leq J \tag{4b}$$

$$x_{ijk} \leq 15\, b_{ijk}, \quad 1 \leq i \leq 7,\ 1 \leq j \leq J, 1 \leq k \neq j \leq J \tag{5}$$

$$\sum_{j=1}^{J} y_{ij} \leq S, \quad 1 \leq i \leq 7 \tag{6}$$

$$b_{ijk} \in \{0,1\}, \quad 1 \leq i \leq 7,\ 1 \leq j \leq J,\ 1 \leq k \neq j \leq J \tag{7}$$

$$x_{ijk} \text{ and } y_{ij} \text{ integer}, 1 \leq i \leq 7,\ 1 \leq j \leq J, 1 \leq k \neq j \leq J \tag{8}$$

$$m_{ij} \geq T_{ij}, \quad 1 \leq i \leq 7,\ 1 \leq j \leq J \tag{9}$$

$$\sum_{\substack{n=1\\n\neq j}}^{J} z_{ijn} + \sum_{\substack{n=1\\n\neq j}}^{J} p_{ijn} \leq m_{ij} + K_{ij}, \quad 1 \leq i \leq 7,\ 1 \leq j \leq J \tag{10}$$

$$m_{ij} + K_{ij} + \sum_{\substack{m=1\\m\neq j}}^{J} z_{imj} + \sum_{\substack{m=1\\m\neq j}}^{J} p_{imj} - \sum_{\substack{n=1\\n\neq j}}^{J} z_{ijn} - \sum_{\substack{n=1\\n\neq j}}^{J} p_{ijn} = m_{i+1,j},$$
$$1 \leq i \leq 6,\ 1 \leq j \leq J \tag{11a}$$

$$m_{7j} + K_{7j} + \sum_{\substack{m=1\\m\neq j}}^{J} z_{7mj} + \sum_{\substack{m=1\\m\neq j}}^{J} p_{7mj} - \sum_{\substack{n=1\\n\neq j}}^{J} z_{7jn} - \sum_{\substack{n=1\\n\neq j}}^{J} p_{7jn} = m_{1,j},$$
$$1 \leq j \leq J \tag{11b}$$

$$z_{ijk} \leq L\, b_{ijk}, \quad 1 \leq i \leq 7,\ 1 \leq j \leq J, 1 \leq k \neq j \leq J \tag{12}$$

$$\sum_{j=1}^{J} m_{ij} \leq L, \quad 1 \leq i \leq 7 \tag{13}$$

$$z_{ijk}, p_{ijk} \text{ and } y_{ij} \quad \text{integer}, 1 \leq i \leq 7,\ 1 \leq j \leq J, 1 \leq k \neq j \leq J \tag{14}$$

The objective function to be minimized includes fixed and variable costs for engine movements and also variable cost for crew transfers without an engine. The constraints (2,3,..,8) are related with the engine utilization and the others are related with crew allocation. Constraints2 used to satisfy the number of engines available at each yard at the start of each day to be large enough to haul the scheduled outgoing trains. In Constraints 3, the number of light engines moved out of each yard on each day is limited to the sum of the engine availability at the beginning of the day at the yard and the net gain or loss of engines determined by the incoming and outgoing trains. Constraints 4a and 4b are ensured that, at each yard, the total number of engines available at the beginning of each day is equal to the initial availability plus the net gain or loss of engines due to various light engine moves in the previous day. In particular, constraints 4b are included to bridge the gap between the Sunday of one week and the Monday of the next so that the cyclical nature of the engine flows are preserved. Constraints5 stated that the number of engines moved in any deadheading trip on any day must be smaller than or equal to 15, which is an operating rule. Constraints6 specified that, at the beginning of each day, the total number of engines available at the various yards do not exceed the current locomotive fleet size. While this inequality involves seven distinct constraints, one for each day of the week, it can be easily proven that only one of them is needed due to the flow conservation of engines within the closed railroad system as required by constraints 4a and 4b. Finally, in Constraints7, b_{ijk} is defined as a binary variable whereas both x_{ijk} and y_{ij} are to take on only non-negative integer values in Constraints8.

Constraints9 provide the required crews for each yard at the start of each day to be able to schedule necessary crew for outgoing trains. The number of crews moved out of each yard on each day with or without engine is limited to the sum of the crews available at the beginning of the day at the yard and the net gain or loss of crews determined by the incoming and outgoing crews are declared in Constraints10. Constraints 11a and 11b are guaranteed that at each yard, the total number of crews available at the beginning of each day is equal to the initial availability plus the net gain or loss of crews due to various crew deliveries in the previous day. Constraints 12 assure that if there is a move from $Yard_i$ to $Yard_j$ then all of the required crews can be delivered by that engine, if not the required crews should be delivered with another way by paying variable transport costs. The total number of crews available at the various yards does not exceed the total crew size, at the beginning of each day is ensured in Constraints 13. Constraints 14 include the binary and integer restrictions.

IV. AN ILLUSTRATIVE APPLICATION

The data sets including the crew and engine requirements at $Yard_j$ (j=1,2,3) and fixed costs and variable cost are determined by expert judgment. The data sets that include engine and crew requirements for each yard for each day are displayed in Appendix A. Also, the variable and fixed costs for moving engines and delivering crew without an engine are shown in Appendix B.

Solving the mathematical program using LINDO, the following solutions are observed: (b^*_{112}, b^*_{332}, b^*_{612}, b^*_{632}, b^*_{712}, b^*_{723},).=(1,1,1,1,1,1), (x^*_{112}, x^*_{332}, x^*_{612}, x^*_{632}, x^*_{712}, x^*_{723})=(3,2,2,2,4,1), (y^*_{11}, y^*_{12}, y^*_{13}, y^*_{21}, y^*_{22}, y^*_{23}, y^*_{31}, y^*_{32}, y^*_{33}, y^*_{41}, y^*_{42}, y^*_{43}, y^*_{51}, y^*_{52}, y^*_{53}, y^*_{61}, y^*_{62}, y^*_{63}, y^*_{71}, y^*_{72}, y^*_{73})=(6,7,3,5,7,4,7,6,3,6,7,3,8,6,2,7,7,2,5,9,2), (p^*_{421}, p^*_{521}=(6,3), (z^*_{332}, z^*_{632}, z^*_{712})=(16,2,5), (m^*_{11}, m^*_{12}, m^*_{13}, m^*_{21}, m^*_{22}, m^*_{23}, m^*_{31}, m^*_{32}, m^*_{33}, m^*_{41}, m^*_{42}, m^*_{43}, m^*_{51}, m^*_{52}, m^*_{53}, m^*_{61}, m^*_{62}, m^*_{63}, m^*_{71}, m^*_{72}, m^*_{73})=(9,8,8,6,8,10,7,5,18,5,19,6,6,14,4,8,13,3,8,14,3) which means that, light engine should be moved from $Yard_1$to $Yard_2$ on Monday, from $Yard_3$ to $Yard_2$ on Wednesday, from $Yard_1$to $Yard_2$ on Saturday; and so on. Three light engines should be moved from $Yard_1$to $Yard_2$ on Monday, 4 light engines should be moved from $Yard_1$to $Yard_2$ on Sunday; and so on. There should be six engines at $Yard_1$, seven engines at $Yard_2$ on Monday, five engines at $Yard_1$, and four engines at $Yard_3$ on Tuesday. Six crews should be moved without an engine from $Yard_2$ to $Yard_1$ on Thursday, three crews should be moved without an engine from $Yard_2$ to $Yard_1$ on Friday. 16 crews should be moved with engine from $Yard_3$ to $Yard_2$ on Wednesday, two crews should be moved with engine from $Yard_3$ to $Yard_2$on Saturday, five crews should be moved with engine from $Yard_1$to $Yard_2$ on Sunday. There should be nine crews at $Yard_1$, eight crews at $Yard_2$,eight crews at $Yard_3$ on Monday, seven crews at $Yard_1$, five crews at $Yard_2$ on Wednesday. The objective function value is z^*=4938,22.

V. CONCLUSIONS

Crew scheduling is a well-known problem in Operations Research, and until recently has been associated with many real life examples. The crew scheduling problem for railways has been a major topic for researchers and increased computing power allows solving of crew scheduling problems optimally even for large instances.

To our knowledge there is not adequate number of study in literature, integrating crew scheduling problem with locomotive assignment. In this paper integrated locomotive assignment and crew scheduling problem is proposed by using mathematical linear programming model and solved optimally with LINDO in very short time. Optimization model is validated by a numerical example and achieved results show that integrated crew scheduling and locomotive assignment model is an effective tool. Future research can be studying the integrated model with larger number of instances and also developing heuristic algorithm in real-life applications.

APPENDIX A

Engine/crew requirements and availabilities are shown below:

Engine Requirements

Day of Week	From\to	Yard 1	Yard 2	Yard 3	Total Outbound	Net gain/loss
Monday	Yard 1	0	4	2	6	2
	Yard 2	5	0	2	7	-3
	Yard 3	3	0	0	3	1
	Inbound	8	4	4		
Tuesday	Yard 1	0	4	1	5	2
	Yard 2	5	0	0	5	-1
	Yard 3	2	0	0	2	-1
	Inbound	7	4	1		
Wednesday	Yard 1	0	3	2	5	-1
	Yard 2	2	0	2	4	-1
	Yard 3	2	0	0	2	2
	Inbound	4	3	4		
Thursday	Yard 1	0	3	1	4	2
	Yard 2	4	0	0	4	-1
	Yard 3	2	0	0	2	-1
	Inbound	6	3	1		
Friday	Yard 1	0	4	1	5	-1
	Yard 2	3	0	0	3	1
	Yard 3	1	0	0	1	0
	Inbound	4	4	1		
Saturday	Yard 1	0	5	2	7	0
	Yard 2	5	0	2	7	-2
	Yard 3	2	0	0	2	2
	Inbound	7	5	4		
Sunday	Yard 1	0	4	1	5	5
	Yard 2	8	0	1	9	-5
	Yard 3	2	0	0	2	0
	Inbound	10	4	2	16	

Crew Requirements

Day of Week	From\to	Yard 1	Yard 2	Yard 3	Total Outbound	Net gain/loss
Monday	Yard 1	0	8	3	11	-3
	Yard 2	5	0	3	8	0
	Yard 3	4	0	0	4	2
	Inbound	9	8	6		
Tuesday	Yard 1	0	4	8	12	-5
	Yard 2	5	0	2	7	-3
	Yard 3	2	0	0	2	8
	Inbound	7	4	10		
Wednesday	Yard 1	0	3	3	6	-2
	Yard 2	2	0	3	5	-2
	Yard 3	2	0	0	2	4
	Inbound	4	3	6		
Thursday	Yard 1	0	3	2	5	1
	Yard 2	4	0	0	4	1
	Yard 3	2	2	0	4	-2
	Inbound	6	5	2		
Friday	Yard 1	0	4	2	6	-1
	Yard 2	3	0	0	3	2
	Yard 3	2	1	0	3	-1
	Inbound	5	5	2		
Saturday	Yard 1	0	6	2	8	0
	Yard 2	5	0	2	7	-1
	Yard 3	3	0	0	3	1
	Inbound	8	6	4		
Sunday	Yard 1	0	4	1	5	6
	Yard 2	8	0	7	15	-11
	Yard 3	3	0	0	3	5
	Inbound	11	4	8	23	

APPENDIX B

Light engine move costs and variable cost per crew transfer without engine are shown below.

Light engine move costs

From\to	Yard 1	Yard 2	Yard 3
Fixed cost per move			
Yard 1		463,84	1284,96
Yard 2	463,84		896,34
Yard 3	1284,96	896,34	
Variable cost per engine			
Yard 1		37,57	135,33
Yard 2	37,57		100,31
Yard 3	135,33	100,31	
Variable cost per crew transfer without engine			
Yard 1		2	4
Yard 2	2		3
Yard 3	4	3	

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