Train Schedule Optimization: A Case Study of the National Railways of Zimbabwe

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Train Schedule Optimization: A Case Study of the National Railways of Zimbabwe

Philimon Nyamugure¹, Siphosenkosi Dube Swene², Edward T. Chiyaka³, Farikayi K. Mutas³

Abstract

The locomotive assignment problem involves assigning a set of locomotives to each train in a pre-planned train schedule so as to provide sufficient power to pull them from their origins to their destinations. An integrated model that determines the set of active and deadheaded locomotives for each train, light travelling locomotives and train-to-train connections is presented. The model explicitly considers consist-busting and consistency. A Mixed Integer Programming (MIP) formulation of the problem that contains about 92 integer variables and 56 constraints is presented in the study. Three models are discussed for assigning locomotives to wagons and coaches and the results are compared amongst the models themselves and compared to the existing scenario at National Railways of Zimbabwe (NRZ). The models generally improve the number of saved locomotives and number of used locomotives. The Locomotive Assignment Model (LAM) solution obtained showed savings of over 70 locomotives, which translates into savings of over one-hundred thousand dollars weekly.

Key Words: Mixed Integer Programming, Locomotive Assignment Model, locomotive, train, Consist.

1. Introduction

The layout for the rest of this paper is that in section 1 there are three subsections namely background, definition of terms, and delimitation of the study. Section 2 gives a brief review of literature, section 3 outlines the methodology, section 4 shows the data collected and the presentation. The analysis of the results are in section 5. Lastly, section 6 discusses and concludes the paper.

Background

The National Railways of Zimbabwe (NRZ), deals with hundreds of train departures per week. Many trains have long hauls and take several days to travel from their origins to their destinations. To power these trains, several locomotives of different types are used. Currently NRZ is using the Locomotive Assignment Model (LAM), where a set of locomotives is assigned to each train in the weekly train schedule so that each train gets sufficient tractive effort and sufficient horsepower, and the assignment can be repeated indefinitely week after week. At the same time, assigning a single locomotive to a train is undesirable because if that locomotive breaks down, the train gets stranded on the track and blocks the movement of other trains. An additional feature of the LAM is that some locomotives may be deadheaded on trains. Deadheading is important in locomotive assignment models because it allows extra locomotives to be moved from the places where they are in surplus to the places where they are in short supply. Locomotives also light travel. A set of locomotives in light travel forms a group, and one locomotive in the group pulls the others from an origin station to a destination station. Light travel is different from deadheading of locomotives since it is not

¹Department of Statistics and Operations Research, National University of Science and Technology, Bulawayo, Zimbabwe
²Department of Insurance, National University of Science and Technology, Bulawayo, Zimbabwe
³Department of Applied Mathematics, National University of Science and Technology, Bulawayo, Zimbabwe
⁴Department of Applied Mathematics, National University of Science and Technology, Bulawayo, Zimbabwe

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limited by the train schedule. In general, light travel is faster than deadheading (Ahuja et al., 2005). Since a set of locomotives (or a consist) is assigned to trains, there is need to account for consist-busting. In an ideal schedule, maximizing the train-to-train connections of locomotives is desired and thus minimize consist-busting. A major contribution of this study is to explicitly model the economic impacts of consist-busting, and to reduce its impacts on the system. This paper reports the development of a locomotive scheduling model that models the assignment of active and deadheaded locomotives to trains, light travelling of locomotives, consistency and consist-busting decisions in an integrated model. The solution is required to provide sufficient power to every train in a timely fashion to meet their prescribed schedules. It is hoped that the findings of this study will help the rail industry realise that not providing enough service capacity results in excessive waiting times. It is also hoped that the results of this study will enable the industry to schedule trains in such a way that the trains fully cater for all trips as this will reduce their operating costs. The aim of this study is to assign locomotives to wagons and coaches in a way that minimises the total cost, which is the sum of the active locomotive costs, deadheading costs, light travel costs, consist-busting costs, locomotive usage costs, and the penalty for using single locomotive consists. This research emphasises the planning part of the locomotive assignment problem for several reasons. The problem is to come up with a scheduled railroad for locomotives and trains to be operated on. The inherent value of a repeatable, routine, scheduled set of decisions will ultimately not only minimize total locomotive costs but also total operating costs while improving the service product (Ahuja et al., 2005). Secondly, the planning system could be used as part of a network planning tool to evaluate which engines to buy in future and to study the impact of modifying their schedule. Thirdly, any technology developed for the planning problem could possibly be extended to deal with tactical decisions in an operational setting.

**Definition of Key Terms**

**Train**
A train (also called production trip) consists of several wagons, several coaches and several locomotives. Each train has a start and a destination. The passenger stations or railroad shunting yards are the starting and destination points for different trains. The starting times and arrival times of the trains are known. These are usually intervals, in which the start or the arrival has to take place. Trains can be of different length and weight and thus require locomotives with sufficient driving power.

**Train Schedule**
A train schedule consists of the assignment of several locomotives to several wagons and coaches.

**Rolling Stock**
Rolling stock is the fleet of all the wheeled vehicles owned by a railroad or government that can be rolled on railroad tracks.

**Wagon**
A wagon is a rolling stock for freight transport. The wagons have to be delivered between a source and a destination point (goods station) within the network.

**Coach**
A coach is a rolling stock for passenger transport. The coaches have to be delivered between a source and a destination point (passenger station) within the network.

**Locomotive**
A wheeled vehicle consisting of a self-propelled engine that is used to draw trains along railway tracks. The main difference between the locomotives is the driving power of the engines.

**Consist**
A consist is a set of locomotives.
Consist-busting

A consist is said to be busted when the set of locomotives coming on an inbound train is broken into subsets to be reassigned to two or more outbound trains.

Axle

Axles are shafts on which a wheel rotates.

Deadheading

A locomotive is either active, (i.e., pulling a train), or deadheading, (i.e., driving under its own power without pulling a train from the destination station of one train to the start of another train). The duration for a deadhead trip depends on the distance between these two points, and on the type of the locomotive.

Light Travel

Light travel of locomotives is travelling of locomotives in a group on their own between different stations so as to reposition themselves.

Horsepower

Sufficient horsepower is sufficient speed.

Tractive effort

A sufficient tractive power is the sufficient pulling power.

Robustness

Norio (1994) gives a definition of robustness as: “A timetable is robust if we can cope with unexpected troubles without significant modifications” (Tomii, 2005).

Headway

Headway is the interval of time between two trains boarded by the same unit at the same point.

Delimitation of the Study

The mathematical models and algorithms in this paper will be tested on practical instances obtained from the rail-links of National Railways of Zimbabwe (NRZ). The study will be limited to the following passenger stations serviced by NRZ: Harare, Bulawayo, Mutare, Victoria Falls, Chiredzi, Beitbridge and Lobate. Because passenger trains work nationwide and are not exactly allocated to particular stations, it is difficult to carry out a research on the chosen passenger stations only. This study will thus assume that each passenger station has particular trains allocated to it i.e. only a certain type of train may leave and arrive at a particular station.

2. Literature Review

The LAM is substantially different to locomotive scheduling models studied previously by many researchers. Single locomotive models have been studied by (Forbes et al. 1991), and (Fischetti and Toth, 1997). Multi-commodity flow based models for planning decisions have been studied by (Florian et al. 1976), (Smith and Sheffi, 1988), (Nouet al. 1997). Multi-commodity flow based models for operational decisions have been developed by (Chihet al. 1990), and (Ziaratiet al. 1997, 1999). This multi-commodity flow based model for planning decisions has more features than any of the existing planning models. The locomotive scheduling problem is a very large-scale combinatorial optimization problem. In this study, it is formulated as a mixed integer programming (MIP) problem, which is essentially an integer multi-commodity flow problem with side constraints. The underlying flow network is the weekly space time network where arcs denote trains, nodes denote events (that is, arrival and departure of trains), and different locomotive types define different commodities. Since the model assigns only integer number of locomotives to trains, integer multi-commodity flow problems are obtained. The constraints that the locomotives assigned to a train must
provide sufficient tonnage and horsepower and that the number of locomotives of each type is in limited quantity gives rise to the side constraints. In addition, the formulations in this paper have fixed charge variables which result from modelling the light travel and consist-busting.

3. Methodology

Model Formulation

The variables and constraints used in this paper for the locomotive assignment model (LAM) are the same as those outlined in Ahuja et al. (2005) except that for the consist size constraints at most 4 locomotives (including the active and deadheaded) can be assigned to a train according to the NRZ business policy. The other addition is that a consist must not haul less than 10 coaches and wagons combined and not more than 14 wagons and coaches combined. The objective function also comprise the terms somewhat similar to those in Ahuja et al. (2005), that is; cost of ownership, maintenance, and fuelling of locomotives; cost of active and deadheaded locomotives; cost of active and deadhead wagons and coaches; cost of light travelling locomotives; penalty for consist-busting; penalty for inconsistency in locomotive assignments and train-to-train connections; and penalty for using single locomotive consists.

Model Notation

Train Data

Locomotives pull a set $l$ of freight wagons and a set $J$ of passenger coaches. The train schedule is assumed to repeat form week to week. Trains have different weekly frequencies; some trains run every day, while others run less frequently. This model will consider the same train running everyday as different trains; that is, if a train runs three days a week, it will be considered as three different trains. The indices $l$ and $j$ are used to denote a specific train. The required to nage and horsepower per train is specified. The tonnage of a train represents the minimum pulling power needed to pull the train. The horsepower required by the train is its tonnage multiplied by the factor that is called the horsepower per tonnage.

The greater the horsepower per tonnage, the faster the train can move. Different classes of trains have different horsepower per tonnage.

- $T_{i,j}$: Tonnage requirement for wagon $i$ and coach $j$.
- $B_{i,j}$: Horsepower per tonnage for wagon $i$ and coach $j$.
- $H_{i,j}$: Horsepower requirement of wagon $i$ and coach $j$, which is defined as $B_{i,j}T_{i,j}$.
- $E_{i,j}$: The penalty for using a single locomotive consist for wagon $i$ and coach $j$.

Locomotive Data

The set of all locomotive types is denoted by $K$, and the index $k$ represents a particular locomotive type. The data for locomotives is outlined below:

- $h^{(k)}$: Horsepower provided by a locomotive of type $k$.
- $a^{(k)}$: Number of axles in a locomotive of type $k$.
- $G^{(k)}$: Ownership cost for a locomotive of type $k$.
- $\beta^{(k)}$: Fleet size of locomotives of type $k$, that is, the number of locomotives available for assignment.

Active and Deadhead Locomotives, Wagons and Coaches

The following data is needed for train-locomotive type combinations:
The following cost aspects are considered by the model:

- Fixed cost per scheduled period per wagon per coach. This cost includes depreciation cost, capital cost, fixed maintenance cost or cost for overnight parking.
- Active locomotive cost per wagon per coach. This captures the asset cost of the locomotive for the duration of the trip and the fuel and maintenance costs.
- Deadhead locomotive cost per wagon per coach. This cost captures the asset cost, a reduced maintenance cost, and zero fuel cost.

Also specified for each wagon and coach are the disjoint sets:

- Most preferred [i]: The classes of locomotives most preferred for wagon i.
- Most preferred [j]: The classes of locomotives most preferred for coach j.
- Less preferred [i]: The acceptable (but not preferred) classes of locomotives for wagon i.
- Less preferred [j]: The acceptable (but not preferred) classes of locomotives for coach j.
- Prohibited [i]: The prohibited classes of locomotives for wagon i.
- Prohibited [j]: The prohibited classes of locomotives for coach j.

When assigning locomotives to a train, only locomotives from the classes listed as Most preferred [i], Most preferred [j], Less preferred [i] and Less preferred [j] are assigned. However, a penalty is associated for using Less preferred.

**Decision Variables**

The decision variables which will be used for this problem are:

- Integer variable representing the number of active locomotives of type $k \in K$ for wagon i \( \in I \) and coach j \( \in J \);
- Integer variable representing the number of non-active locomotives deadheading, light-travelling or idling of type $k \in K$ for wagon i \( \in I \) and coach j \( \in J \);
- Integer variable representing the number of active wagons of i \( \in I \) and the number of active coaches of j \( \in J \) for locomotive of type $k \in K$;
- Integer variable representing the number of non-active wagons of i \( \in I \) and the number of non-active coaches of j \( \in J \) for locomotive of type $k \in K$;
- Binary variable which takes value 1 if at least one locomotive is connected, and 0 otherwise;
$w_{i,j}$ - Binary variable which takes value 1 if there is a flow of a single locomotive on train arcs (routes) and 0 otherwise;

$s^{(k)}$ - Integer variable indicating the number of unused locomotives of type $k \in K$.

These decision variables actually represent the objectives stated in this study. The objective function for the mixed integer programming (MIP) model which contains eight terms is also similar to (Ahuja et al., 2005). In this paper there is an addition of fixed costs for active and deadhead wagons and coaches:

$$\text{Min } Z (\text{Total Cost})$$

$$= \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} C^{(k)}_{i,j} x^{(k)}_{i,j}$$

$$+ \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} d^{(k)}_{i,j} y^{(k)}_{i,j} + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} e^{(k)}_{i,j} p^{(k)}_{i,j} + \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} D^{(k)}_{i,j} u^{(k)}_{i,j}$$

$$+ \sum_{i \in I} \sum_{j \in J} p^{(k)}_{i,j} z_{i,j} + \sum_{i \in I} \sum_{j \in J} B_{i,j} z_{i,j} + \sum_{i \in I} \sum_{j \in J} E_{i,j} w_{i,j} - \sum_{k \in K} G^{(k)} s^{(k)}$$

The first term denotes the cost of actively pulling locomotives on train arcs. The second term captures the cost of deadheading locomotives on train and light travel arcs, and the cost of idling locomotives. The variable cost of consist-busting in the definition of the term is also included. The third term denotes the fixed cost of active wagons and coaches. The fourth term denotes the fixed cost of deadheading wagons and coaches. The fifth term denotes the fixed cost of light travelling locomotives. The sixth term denotes the fixed cost of consist-busting. The seventh term denotes the penalty associated with the single locomotive consists; and the eighth term represents the savings accrued from not using all the locomotives.

**Constraints**

The constraints are as outlined below. Some brief explanations are given on each constraint to show that the model correctly represents the MCSP.

$$\sum_{k \in K} t^{(k)}_{i,j} x^{(k)}_{i,j} \geq T_{i,j} \forall i, j$$

(1)

The constraint ascertains that the locomotive assigned to a train provide the required minimum tonnage for the wagons and coaches it has been assigned to.

$$\sum_{k \in K} h^{(k)}_{i,j} x^{(k)}_{i,j} \geq B_{i,j} T_{i,j} \forall i, j$$

(2)

The constraint ensures that the locomotives assigned provide the required minimum horsepower for the wagons and coaches it has been assigned to.

$$\sum_{k \in K} h^{(k)}_{i,j} x^{(k)}_{i,j} \leq 24 \forall i, j$$

(3)

The constraint models the constraint that the number of active axles assigned to a train does not exceed 24.

$$\sum_{i \in I} \sum_{j \in J} z_{i,j} = 1 \forall i, j$$

(4)

The constraint states that for each inbound train, all the inbound locomotives use only one connection arc; either all the locomotives go to the associated ground node (in which case consist-busting takes place) or
all the locomotives go to another out bound train (in which case consist-busting does not take place and there is a train-to-train connection).

\[
\sum_{k \in K} y_{i,j}^{(k)} \leq 4 \sum_{i \in I} \sum_{j \in J} z_{i,j} \quad \forall i, j
\]

(5)

The constraint makes the fixed charge variable \(z_{i,j}\) equal to 1 whenever a positive flow takes place on a connection arc or a light arc; this constraint also ensures that no more than 4 locomotives flow on any arc.

\[
\sum_{k \in K} \left( x_{i,j}^{(k)} + y_{i,j}^{(k)} \right) \leq 12 \quad \forall i, j
\]

(6)

The constraint models the constraint that every train is assigned at most 12 locomotives, both active and non-active combined.

\[
\sum_{i \in I} \sum_{j \in J} \left( x_{i,j}^{(k)} + y_{i,j}^{(k)} \right) + s^{(k)} = \beta^{(k)} \quad \forall k \in K
\]

(7)

The constraint counts the total number of locomotives used in the week; which is the sum of the flow of locomotives on all the arcs crossing the Check time. The difference between the numbers of locomotives available minus the number of locomotives used gives the number of locomotives saved(\(s^{(k)}\)).

\[
\sum_{k \in K} \left( x_{i,j}^{(k)} + y_{i,j}^{(k)} \right) + w_{i,j} \geq 2 \quad \forall i, j
\]

(8)

The constraint makes the variable \(w_{i,j}\) equal to 1 whenever a single locomotive consist is assigned to a wagon \(i\) and a coach \(j\).

\[
10 \leq \sum_{i \in I} \sum_{j \in J} \left( p_{i,j}^{(k)} + u_{i,j}^{(k)} \right) \leq 14 \quad \forall i, j
\]

(9)

The constraint assures that exactly one train type runs along a particular point in a railway at a particular time. By this constraint, enough headway is given between different trains. The constraint ascertains that the number of coaches \(j\) and wagons \(i\) in a train are within the required number of wagons and coaches in a train.

\[
x_{i,j}^{(k)} = 0 \text{ for each } k \in \text{Prohibited}[i] \text{ and Prohibited}[j] \forall i, j
\]

(10)

Finally, the constraint ensures that prohibited locomotives are never used on train arcs.

\[
x_{i,j}^{(k)}, y_{i,j}^{(k)}, p_{i,j}^{(k)}, u_{i,j}^{(k)} \geq 0 \text{ and integer } \forall i, j, k \quad z_{i,j} \in \{0,1\} \forall i, j \quad w_{i,j} \in \{0,1\} \forall i, j \quad s^{(k)} \in \{0,1\} \forall k
\]

(11)

**Sensitivity analysis**

In order to obtain high quality feasible solutions and to keep the total running time of the algorithm small, the fixed charge variables from the MIP formulation was eliminated using heuristics. In the formulation, there are two kinds of fixed charge variables, one corresponding to consist-busting and the other one corresponding to deadheading. Firstly the fixed charge variables corresponding to consist-busting (Model A) are considered and then the fixed charge variables corresponding to deadheading (Model B) are considered.
Determining the effect of consist-busting and light travelling

This procedure eliminates the fixed charge variables corresponding to consist-busting and light travelling. This is done to investigate the effectiveness of the consist-busting variables in the MCSP model. Thus the mixed integer programming problem is solved, which is the same as the MCSP problem save that it excludes all fixed charge variables corresponding to consist-busting and light travelling.

Data

The set of locomotives \( (k) \) used at NRZ consists of the DE6 locomotive and the DE9 locomotive. The set of wagons \( (i) \) used consists of the following wagons: High-Sided wagons (HSI), Drop-Sided wagons (DSI) and Covered wagons (COV). The set of coaches \( (j) \) consists of the First Class (F), the Second Class (S) and Economy Class (E).

The minimum tonnage, minimum horsepower requirement and penalties for using each train are summarized in Table 1.

The weekly ownership costs, fleet sizes, horsepower, number of axles and fixed costs of light travelling are shown in Table 2.

Active locomotives and deadhead locomotives data is summarised in Table 3.

The fixed costs for active and deadhead wagons and coaches are summarised in Table 4.

For the HSI wagon, the DE9 locomotive is prohibited to haul it due to the fact that the HSI wagon usually hauls heavier tonnages than the DE9 locomotive is capable to haul. In most cases, if a DE9 locomotive is allowed to haul the HSI wagon, it fails before it reaches its destination, especially with long distances. The DE9 locomotive is preferred with the DSI wagon and less preferred with the COV wagon.

4. Analysis and Results

The data provided by the Zimbabwean Railroad Company specified that there are 495 trains, each of which operates several days in a week, 3 locomotive types, 3 wagon types and 3 coach types. The optimality of the MIP was arrived at with the use of LINGO 10.

Computational Results for the MCSP

Active DE6 Locomotive

Deadhead DE6 Locomotives

From the results in Table 5.2 and Table 5.3, not more than 4 locomotives are connected in a particular train. Also not more than 14 wagons and coaches combined are connected to a consist. Therefore the assignment of locomotives to the wagons and coaches shown in Table 5.2, 5.3, 5.4 and 5.5 is efficient as it does not waste resources.

Active DE9 Locomotive

Deadhead DE9 Locomotives

Table 5.7 shows the numbers of saved locomotives for the MCSP model. When compared to the numbers of locomotives available for assignment at NRZ, the numbers of saved locomotives as shown by the results of the MCSP model is quite sensible.

The objective function value, which is the sum of active locomotives, wagons and coaches costs, deadheading costs, light travel costs, consist-bustings costs, locomotive usage costs and the penalty for using single locomotive costs, as computed he MCSP model is $135 310.
Computational Results of Model A

Active DE6 Locomotive

The following table shows the number of active DE6 locomotives and wagons and coaches connected to it using Model A.

Deadhead DE6 Locomotives

Table 5.9 shows the number of non-active DE6 trains.

From the results in Table 5.8 and 5.9, no non-active locomotives are obtained by this model for the DE6 locomotive.

Active DE9 Locomotive

The following table shows the number of active DE9 locomotives and wagons and coaches connected to it.

Deadhead DE9 Locomotives

From the results in Table 5.10 and 5.11, no non-active locomotives are obtained by this model for the DE9 locomotive.

Table 5.12 shows that there is no possibility of connecting trains to single locomotive consist with this model, for all wagons and coaches.

Table 5.13 shows the numbers of saved locomotives for the MCSP model. When compared to the numbers of locomotives available for assignment at NRZ, the numbers of saved locomotives as shown by the results of Model A is quite reasonable. However, the weakness of Model A is that it shows that no locomotives, wagons and/or coaches are deadheading. This is practically impossible because there should be definitely be a point where some locomotives are deadheading as not only one locomotive is attached to a set of wagons and coaches. Whilst one locomotive is hauling the whole load, the other support locomotives are deadheading. Some wagons and coaches when making return trips may not be as full as they would be in the initial journey, thus they deadhead. The objective function value, which is the sum of active locomotives, wagons and coaches costs, deadheading costs, locomotive usage costs and the penalty for using single locomotive costs, as computed using this model is $68320.00.

Computational Results of Model B

Active DE6 Locomotive

Table 5.14 shows that no assignment of DE6 locomotives is made to the DSI wagon as this is less preferred. From the results in table 5.14, not more than 4 locomotives are connected in a particular train. Also not more than 14 wagons and coaches combined are connected to a consist. Therefore the assignment of locomotives to the wagons and coaches is efficient as it does not waste resources.

Active DE9 Locomotive

Table 5.15 shows that no assignment of DE9 locomotives is made to the HSI wagon as this is prohibited.

Table 5.16 shows that the possibility of connecting trains to single locomotive consists is only possible for the HSI wagon with the Economy class, DSI wagon with the First class and the COV wagon with the First class.

Table 5.17 shows the numbers of saved locomotives for the MCSP model. When compared to the numbers of locomotives available for assignment at NRZ, the numbers of saved locomotives as shown by the results of this model is quite sensible. The objective function value, which is the sum of active locomotives, wagons and coaches costs, light travel costs, consist-bus tings costs, locomotive usage costs and the penalty for using single locomotive costs, as computed using this model is $106110.00.
Comparison of Results of the 3 models

Problem Size and Solution Time

Table 5.19 compares the solution obtained by LAM with the solutions obtained when investigating the effects of light-travelling, consist-bus tings and deadheading and the status quo at NRZ. The LAM solution is substantially superior to the latter models; it dramatically decreases the number of locomotives used. The LAM handles consist assignment and locomotive scheduling separately, and in the locomotive scheduling phase, considers each locomotive type one by one. The number of locomotives is dramatically reduced by substantially reducing the fraction of the locomotives that deadhead. Table 5.19 presents the statistics on the numbers of locomotives that are actively pulling the trains, deadheading on trains, light traveling, or idling at stations (for maintenance or just waiting to be assigned to out-bound trains). It is observed that in the LAM solution the number of unused locomotives is about 14.9% more than the other models. Hence the LAM solution significantly increases the locomotive productivity. It is also observed that in the LAM solution, the number of locomotives that are deadheading on trains is considerably less than in the Model A and Model B solutions.

Comparison of LAM, Model A, Model B and the Status quo

The 3 models are, in this section, compared to the current status quo at NRZ on several performance measures.

Table 5.19 is also illustrated graphically in Figures 5.1 and 5.2

The LAM locomotive assignment yields the least number of active locomotives. This means that a few locomotives are assigned to trains, using the LAM model formulation, to satisfy all discussed constraints.

From Figure 5.2, it is noticed that the LAM locomotives assignment obtains the least number of deadhead locomotives. This is ideal as it satisfies the second objective of this study.

From Figure 5.3, it is observed that the LAM locomotive assignment gives the most number of saved locomotives as compared to the other models and the status quo.

5. Conclusions and Recommendations

The LAM model discussed achieves all the set objectives of minimising total operational costs, which is the sum of deadhead costs, light-travelling costs, fixed costs of wagons and coaches, active locomotive costs, consist-bustings costs and the penalty for using single locomotive consists. The model that is thus recommended is LAM, since most wagons should be connected to the DE6 locomotive as it has a greater hauling capability, greater speed and generally stronger than the DE9 locomotive. The DE9 locomotive is prone to frequent failures. If connection is made to the DE9 locomotive, some DE6 locomotives should be connected as well so that should the DE9s fail, there is immediate back up. In that way, quite a number of locomotives will be saved thus as few locomotives as possible are used. The model helped quantify the network benefits of re-centering the fleet composition. In the future, NRZ should consider expanding on this work to include locomotive fuelling and servicing constraints into the model as well including penalties associated with using less preferred locomotives for different wagons and coaches.

References


Table 1: Tonnage and Horsepower for trains

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<th>Horsepower per 20 tonnes (Watts) ($B_{ij}$)</th>
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<tr>
<td>DSI</td>
<td>Second Class 205</td>
<td>800</td>
<td>200</td>
<td>160 000</td>
</tr>
<tr>
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<td>Economy Class 205</td>
<td>800</td>
<td>200</td>
<td>160 000</td>
</tr>
<tr>
<td>COV</td>
<td>First Class 235</td>
<td>800</td>
<td>230</td>
<td>184 000</td>
</tr>
<tr>
<td>COV</td>
<td>Second Class 235</td>
<td>800</td>
<td>230</td>
<td>184 000</td>
</tr>
<tr>
<td>COV</td>
<td>Economy Class 235</td>
<td>800</td>
<td>230</td>
<td>184 000</td>
</tr>
</tbody>
</table>

Table 2: Locomotive Properties

<table>
<thead>
<tr>
<th></th>
<th>Horsepower ($h^{(k)}$)</th>
<th>Number of axles ($a^{(k)}$)</th>
<th>Ownership Costs ($G^{(k)}$)</th>
<th>Fleet size ($\beta^{(k)}$)</th>
<th>Fixed Cost for light-travelling ($F^{(k)}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE6</td>
<td>36 690</td>
<td>16</td>
<td>550</td>
<td>40</td>
<td>400</td>
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<tr>
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<td>30 240</td>
<td>14</td>
<td>300</td>
<td>38</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 3: Active and Deadhead Locomotives Data

<table>
<thead>
<tr>
<th></th>
<th>Costs for Active Locomotives ($c_{i,j}^{(k)}$)</th>
<th>Costs for Deadhead Locomotives ($d_{i,j}^{(k)}$)</th>
<th>Tonnage pulling capability ($t_{i,j}^{(k)}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE6</td>
<td>HSI First Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI Second Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI Economy Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI First Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI Second Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI Economy Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE6</td>
<td>COV First Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE6</td>
<td>COV Second Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE6</td>
<td>COV Economy Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI First Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI Second Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI Economy Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI First Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI Second Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI Economy Class 750</td>
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<td>350</td>
</tr>
<tr>
<td>DE9</td>
<td>COV First Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE9</td>
<td>COV Second Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>DE9</td>
<td>COV Economy Class 750</td>
<td>1000</td>
<td>350</td>
</tr>
</tbody>
</table>


Table 4: Fixed Costs for Active and Deadhead wagons and coaches

<table>
<thead>
<tr>
<th>$i$</th>
<th>$j$</th>
<th>Costs for Active wagons and coaches ($p_{i,j}^{(k)}$)</th>
<th>Costs for non-active wagons and coaches ($u_{i,j}^{(k)}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSI First Class</td>
<td>890</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>HSI Second Class</td>
<td>890</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>HSI Economy Class</td>
<td>890</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>DSI First Class</td>
<td>750</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>DSI Second Class</td>
<td>750</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>DSI Economy Class</td>
<td>750</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>COV First Class</td>
<td>920</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>COV Second Class</td>
<td>920</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>COV Economy Class</td>
<td>920</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Preferences of locomotives

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HIS First Class</td>
<td>DE6</td>
<td>DE6</td>
<td>-</td>
<td>-</td>
<td>DE9</td>
<td>DE9</td>
<td></td>
</tr>
<tr>
<td>HSI Second Class</td>
<td>DE6</td>
<td>DE6</td>
<td>-</td>
<td>-</td>
<td>DE9</td>
<td>DE9</td>
<td></td>
</tr>
<tr>
<td>HSI Economy Class</td>
<td>DE6</td>
<td>DE6</td>
<td>-</td>
<td>-</td>
<td>DE9</td>
<td>DE9</td>
<td></td>
</tr>
<tr>
<td>DSI First Class</td>
<td>DE9</td>
<td>DE9</td>
<td>DE6</td>
<td>DE6</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>DSI Second Class</td>
<td>DE9</td>
<td>DE9</td>
<td>DE6</td>
<td>DE6</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>DSI Economy Class</td>
<td>DE9</td>
<td>DE9</td>
<td>DE6</td>
<td>DE6</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>COV First Class</td>
<td>DE6</td>
<td>DE6</td>
<td>DE9</td>
<td>DE9</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>COV Second Class</td>
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<td>DE6</td>
<td>DE9</td>
<td>DE9</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>COV Economy Class</td>
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<td>DE6</td>
<td>DE9</td>
<td>DE9</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Number of active locomotives, wagons and coaches used by Weekly Schedule

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Number of active locomotives</th>
<th>Number of active wagons</th>
<th>Number of active coaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>First Class</td>
<td>2</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>Second Class</td>
<td>2</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>Economy Class</td>
<td>3</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>First Class</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>Second Class</td>
<td>3</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>Economy Class</td>
<td>4</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 5.2 shows that no assignment of DE6 locomotives is made to the DSI wagonas this is less preferred. Table 5.3 shows the number of deadhead locomotives, wagons and coaches.

**Table 5.3: Number of non-active locomotives, wagons and coaches used by Weekly Schedule**

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Number of non-active locomotives</th>
<th>Number of non-active wagons</th>
<th>Number of non-active coaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>First Class</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>Second Class</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>Economy Class</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>First Class</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>Second Class</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>Economy Class</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.4 shows that no assignment of DE9 locomotives is made to the HSI wagonas this is prohibited. Table 5.5 shows the number of deadhead locomotives, wagons and coaches for the DE9 locomotive.

**Table 5.4: Number of active locomotives, wagons and coaches used by Weekly Schedule**

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Number of active locomotives</th>
<th>Number of active wagons</th>
<th>Number of active coaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>First Class</td>
<td>2</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>Second Class</td>
<td>3</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>Economy Class</td>
<td>3</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>First Class</td>
<td>1</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>Second Class</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>Economy Class</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5.5 shows the number of non-active locomotives, wagons and coaches used by Weekly Schedule.
Table 5.6: Possibility of connecting trains to single locomotive consists

<table>
<thead>
<tr>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Possibility of at least one locomotive connected</th>
<th>Possibility of flow of a single locomotive consist</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIS</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HIS</td>
<td>Second Class</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>HIS</td>
<td>Economy Class</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>DSI</td>
<td>First Class</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>DSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COV</td>
<td>First Class</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>COV</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COV</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.6 shows that the possibility of connecting trains to single locomotive consists is only possible for the HIS wagon with the Economy class, DSI wagon with the First class and the COV wagon with the First class.

Table 5.7: Number and Type of Unused Locomotives used by Weekly Schedule

<table>
<thead>
<tr>
<th>Type of Locomotive</th>
<th>Number of unused locomotives</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE6</td>
<td>36</td>
</tr>
<tr>
<td>DE9</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 5.8: Number of active locomotives, wagons and coaches used by Weekly Schedule

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Number of active locomotives</th>
<th>Number of active wagons</th>
<th>Number of active coaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>First Class</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>Second Class</td>
<td>2</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>Economy Class</td>
<td>3</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>First Class</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>Second Class</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>Economy Class</td>
<td>3</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5.9: Number of non-active locomotives, wagons and coaches used by Weekly Schedule

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Number of non-active locomotives</th>
<th>Number of non-active wagons</th>
<th>Number of non-active coaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 5.10: Number of active locomotives, wagons and coaches used by Weekly Schedule

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Number of active locomotives</th>
<th>Number of active wagons</th>
<th>Number of active coaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>First Class</td>
<td>2</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>Second Class</td>
<td>3</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>Economy Class</td>
<td>3</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.11: Number of non-active locomotives, wagons and coaches used by Weekly Schedule

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Number of non-active locomotives</th>
<th>Number of non-active wagons</th>
<th>Number of non-active coaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.12: Possibility of connecting trains to single locomotive consists

<table>
<thead>
<tr>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Possibility of at least one locomotive connected</th>
<th>Possibility of flow of a single locomotive consist</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COV</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COV</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COV</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 5.13: Number and Type of Unused Locomotives used by Weekly Schedule

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>Number of unused locomotives</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE6</td>
<td>28</td>
</tr>
<tr>
<td>DE9</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 5.14: Number of active locomotives, wagons and coaches used by Weekly Schedule

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Number of active locomotives</th>
<th>Number of active wagons</th>
<th>Number of active coaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>First Class</td>
<td>2</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>Second Class</td>
<td>2</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>HSI</td>
<td>Economy Class</td>
<td>3</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>DSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>First Class</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>Second Class</td>
<td>3</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>DE6</td>
<td>COV</td>
<td>Economy Class</td>
<td>4</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5.15: Number of active locomotives, wagons and coaches used by Weekly Schedule

<table>
<thead>
<tr>
<th>Type of locomotive</th>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Number of active locomotives</th>
<th>Number of active wagons</th>
<th>Number of active coaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>HSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>First Class</td>
<td>2</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>Second Class</td>
<td>3</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>DE9</td>
<td>DSI</td>
<td>Economy Class</td>
<td>3</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>First Class</td>
<td>1</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>Second Class</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>DE9</td>
<td>COV</td>
<td>Economy Class</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5.16: Possibility of connecting trains to single locomotive consists

<table>
<thead>
<tr>
<th>Type of wagon</th>
<th>Type of coach</th>
<th>Possibility of at least one locomotive connected</th>
<th>Possibility of flow of a single locomotive consist</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSI</td>
<td>First Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HSI</td>
<td>Second Class</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>HSI</td>
<td>Economy Class</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>DSI</td>
<td>First Class</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>DSI</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DSI</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COV</td>
<td>First Class</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>COV</td>
<td>Second Class</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>COV</td>
<td>Economy Class</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 5.17: Number and Type of Unused Locomotives used by Weekly Schedule

<table>
<thead>
<tr>
<th>Type of Locomotive</th>
<th>Number of unused locomotives</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE6</td>
<td>30</td>
</tr>
<tr>
<td>DE9</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 5.18: Summary of problem size and solution times

<table>
<thead>
<tr>
<th>Problem</th>
<th>Problem Size</th>
<th>Solution Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCSP for the weekly locomotive assignment problem.</td>
<td>The weekly locomotive problem has 92 decision variables and 56 constraints.</td>
<td>The MIP problem took 2 minutes computation time to be solved.</td>
</tr>
<tr>
<td>Model A for investigating the effect of light travelling and consist-busting.</td>
<td>This model consists of 72 decision variables and 45 constraints.</td>
<td>The MIP problem took 1.5 minutes computation time to be solved.</td>
</tr>
<tr>
<td>Model B for investigating the effect of deadheading</td>
<td>This model consists of 56 decision variables and 31 constraints</td>
<td>The MIP problem took 2 minutes computation time to be solved.</td>
</tr>
</tbody>
</table>

Table 5.19: Comparison of LAM, Model A, Model B and the Status quo

<table>
<thead>
<tr>
<th>Performance measure</th>
<th>LAM</th>
<th>Model A</th>
<th>Model B</th>
<th>Status quo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active locomotives</td>
<td>191</td>
<td>200</td>
<td>194</td>
<td>204</td>
</tr>
<tr>
<td>Deadhead locomotives</td>
<td>15</td>
<td>25</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>Saved locomotives</td>
<td>74</td>
<td>40</td>
<td>63</td>
<td>20</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$135,310</td>
<td>$68,320</td>
<td>$106,110</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.1: Active Locomotives

Figure 5.2: Deadhead Locomotives
Figure 5.3: Saved Locomotives