LOCOMOTIVE SCHEDULING IN FREIGHT AT MPOPOMA TRAIN STATION

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Abstract:

This paper presents use of Locomotive Scheduling Problems (LSP) planning version where there are multiple types of locomotives in solving delay problems experienced at Mpopoma Train Station. A study on the current scheduling system was done and key variables were identified. The decision variables were used to develop an integrated model that determines a set of active and deadheaded locomotives for each train and light train. Consist-bustings were explicitly considered and 20 restricted decision variables were optimised on 32 constraints. The solution obtained from running the model coded in LINGO 10.0 saved 38 locomotives which can translate to a significant amount of financial savings per year from the current way of scheduling wagons.

Keywords: Wagons, Trains, Locomotive, Deadhead, Light travel, Consist-busting

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1.0 Introduction

Transportation of goods by railroads is an integral part of most developing economies. This has made railroads play a leading role in multi-modal and container transportation. The strong competition facing rail carriers (most notably from trucking companies) and ever-increasing speed of computers have motivated the use of optimisation models at various levels in railroad organisations. This has resulted in a growing interest for optimisation techniques in railroad problems. Locomotive scheduling problems are important problems especially to growing economies like the Zimbabwean economy. Authors like Kim and Park (2005) highlighted that train scheduling is one of the most challenging and difficult problems in rail transport management. These challenges arise due to availability of a wide variety of types of locomotives, diverse geographic networks as well as many different types of trains (Ahuja et al. 2002). In addition, the cost of running locomotives is ever increasing with new types being introduced. These running costs coupled with maintenance costs make the rail transport business inefficient. This is one of the reasons why National Railways of Zimbabwe (NRZ) is so much invested with serious inefficiencies. Powell and Topaloglu (2002) also noted that actual railroad networks are complex. All sources of uncertainty should be identified when planning for train scheduling. They further went on to identify the most annoying source of uncertainty for rail as the transit times, which might range between two and eight days between a pair of cities. Anyway, in solving the locomotive scheduling problem at Mpopoma we adopt the approach used by Ahuja et al. (2002) when studying a locomotive problem scheduling problem experienced by CSX Transportation. They developed linear programming based greedy algorithms to determine values for the fixed charge variables that are introduced by modelling the light travel and consist-bustings. The values obtained are then used in optimisation of a formulated Mixed Integer Programming (MIP) problem. That is, in our study we apply the approach Ahuja and friends demonstrated to solve the Mpopoma train scheduling problem. As a result, we formulate the MIP problem, code it into LINGO 10.0 and run for optimality.

1.1 Current Locomotive Assignment System

All freight trains in the NRZ system start and terminate at Mpopoma station in Bulawayo and all trains go to the reception first, when they enter the station yard. The engine-men are notified by the station-master at the signal cabin as to which rail to move into out of the nine rails available. Wagons are then checked if still fit to continue with the journey, if fit they are marshalled into either the *Departure* or *Exchange* depending on their destinations. In the departure section, trains in transit are classified according to their destination and to which locomotives are required to haul the wagons. It has six rails. The exchange section caters for terminal traffic going to Bulawayo. Trains are categorised according to their destinations which are Belmont, Kelvin North or New-Grain. If a train is unfit to proceed with its journey, then it is marshalled to the *Repair* sidings. This happens when a defect is found, train needs general service or is scheduled for repair. A certain level of fluidity is maintained by ensuring that as soon as wagons are assembled a train is started. This way of scheduling results in starting times not being aligned to a time table. That is, the current scheduling system just follow estimated customers' productions and demand peaks in order to avoid maximum wagon accommodation capabilities per time period. As a result, the current system assumes that locomotives are always immediately available which might be unrealistic. That is why most wagons lie idle for long without forming a train because all locomotives will be busy.

1.2 Locomotive Scheduling Models

Locomotive scheduling problems are among the most important problems in railroad scheduling and Cooper (1990) highlighted that rail transportation industry is very rich in terms of problems that can be modelled and solved using mathematical optimisation techniques. However, research in railroad scheduling has experienced a slow growth and, until recently, most contributions used simplified models or in some instances fail to incorporate the characteristics of real-life applications. Glancey (2005) stated that locomotive assignment and freight train scheduling considers the movement of freight trains through a passenger rail network, which is common in many developing countries including Zimbabwe. Passenger trains run according to a fixed schedule while freight trains need to be accommodated and run on the same track, ensuring that they do not interfere with passenger train movements. As a result, Arronson et al. (2006) concluded that the flexibility of scheduling rail freight timetables is greater than that of passenger railways as long as customer requirements are met. In addition, after studying the CSX Transportation scheduling problem, Sharma (2002) deduced that locomotive scheduling problems can be studied at planning and operational levels. The planning level is focused on locomotive type assignment whilst the operational takes into account of fuelling, maintenance needs of the locomotives etc. Researchers like Javanovic and Harker (1991), Kim and Park (2005) also studied freight and passenger transportation and found that application of mathematical optimisation techniques in rail road scheduling problems yields optimal solutions that utilize the rail network efficiently.

A mixed-integer programming formulation of the locomotive assignment was also used to solve the South African Railways (SAR) train-scheduling problem they were facing. The

Transportation Research Database (2002) confirms that the model accounted for consist busting, light travelling and consistency of a solution in a unified framework. The solution produced satisfied the constraints and business rules specified by SAR. It offered considerable savings. However, the problem could not be solved to optimality or near optimality in acceptable running times using commercial available software. Suhl and others had to decompose the problem, use integer programming and did a very large scale neighbourhood search.

According to Fugenschuh (2006) a similar integer programming model was found practical at Green Cargo Railways the largest freight rail operator in Sweden. The problem was non-capacitated but allowed non-binary flows of vehicles between transports with departure time's variable within fixed intervals. The transport schedule was repeated after a fixed period i.e. the problem was periodic and the transports were trains transporting with a fixed schedule whose departure times were relaxed from ±15 up to ±90 minutes and vehicles considered were the engineers used to pull the trains. The main objective was to minimise the number of vehicles turned over the cycle time limit. A term in the cost function was introduced which penalised the use of additional vehicles for transports that do not need them.

In this paper, thus we adopt the mixed-integer programming (MIP) formulation as well as the penalty approach applied at Green Cargo Railways. In our model, in addition to their approaches, we introduce cost functions of having idle wagons and deadheading locomotives as long as idle times of wagons are not desired. Furthermore, the number of locomotives that could be potentially saved if some wagon transfers are missed will be factored into the model. As a result, of the nature of the decision variables the model will be an integer-programming problem.

2.0 Model Formulation

2.1 Definition of Decision Variables

We shall let L be the set of trains that pulled by a locomotive from their origin to destinations where a train schedule is assumed to repeat from week to week. If the same train runs for five different days a week then we shall consider that there are five different trains. We define;

- T_l as the tonnage required for the l^{th}, ($l \in L$) train where tonnage is the minimum pulling power needed to pull the train.
- B_l as the horsepower per tonnage required for the l^{th}, ($l \in L$) train. We note that the greater the horsepower per tonnage the faster the train can move and different classes of trains have different horsepower per tonnage.

- $H_l (= B_l T_l)$ as the horsepower required for the l^{th}, ($l \in L$) train where tonnage is the minimum pulling power needed to pull the train.
- E_l as a penalty for using a single locomotive consist of the l^{th}, ($l \in L$) train.
- $F^{(k)}$ is the cost of light travelling of a group of the k^{th}, ($k \in K$) type locomotives.

If we consider a set K (={DE6,DE9}) to be a set of types of locomotives then, $h^{(k)}$ becomes the horsepower provided by a locomotive of the k^{th}, ($k \in K$) type (DE6 diesel locomotive hauls an average gross load of 1050 tonnes whilst the DE9 can haul an average gross load of 800 tonnes);

- $\alpha^{(k)}$ is the number of axles in the k^{th}, ($k \in K$) type locomotive ,
- $C^{(k)}$ is the ownership cost of a k^{th}, ($k \in K$) type locomotive and
- $\beta^{(k)}$ becomes the size of fleet of the k^{th}, ($k \in K$) type locomotive available for assignment.

The costs of the combinations of train and locomotive type can be identified as,

- $c_l^{(k)}$, which is the cost incurred in assigning an active locomotive of type k the l^{th}, ($l \in L$) train i.e. the economic asset cost of the locomotive for the train duration , fuel and maintenance costs,
- $d_l^{(k)}$, which is the cost incurred in assigning a deadheaded locomotive of type k the l^{th}, ($l \in L$) train i.e. also an economic asset cost, reduced maintenance cost at zero fuel cost, and
- $t_l^{(k)}$ is the tonnage pulling capacity provided by an active locomotive of type k of the l^{th}, ($l \in L$) train,

where deadheading means a locomotive driving under its own power without pulling a train whilst when a locomotive is said to be active, it will be pulling a train. Within a train we have got either the "*most preferred*", "*less preferred"* or "*prohibited*" locomotive. "*less preferred"* locomotives are acceptable but not preferred which means that amongst the same type of locomotives there are some which are just acceptable and those that go beyond being acceptable to most preferred. The "*prohibited*" locomotives are not allowed to form a train. Having described the constitution of a single train, we can then define the main decision variables as follows.

- $x_l^{(k)} \in Z^+$ is the number of active locomotives of type k, ($k \in K$) assigned to the l^{th}, ($l \in L$) train.
- $y_l^{(k)} \in Z^+$ is the number of non-active locomotives deadheading, light-travelling or idling of type k, ($k \in K$) assigned to the l^{th}, ($l \in L$) train.
- $s^{(k)} \in Z^+$ is the number of unused locomotives of type k.

We introduce what we call ground nodes and connection arcs at the train station. This allows flow of locomotives from an inbound train to an outbound train. A corresponding arrival node with same attributes is created for each arrival node and similarly for a departure node. This is done for a weekly space-time as shown in the figure 1 below.

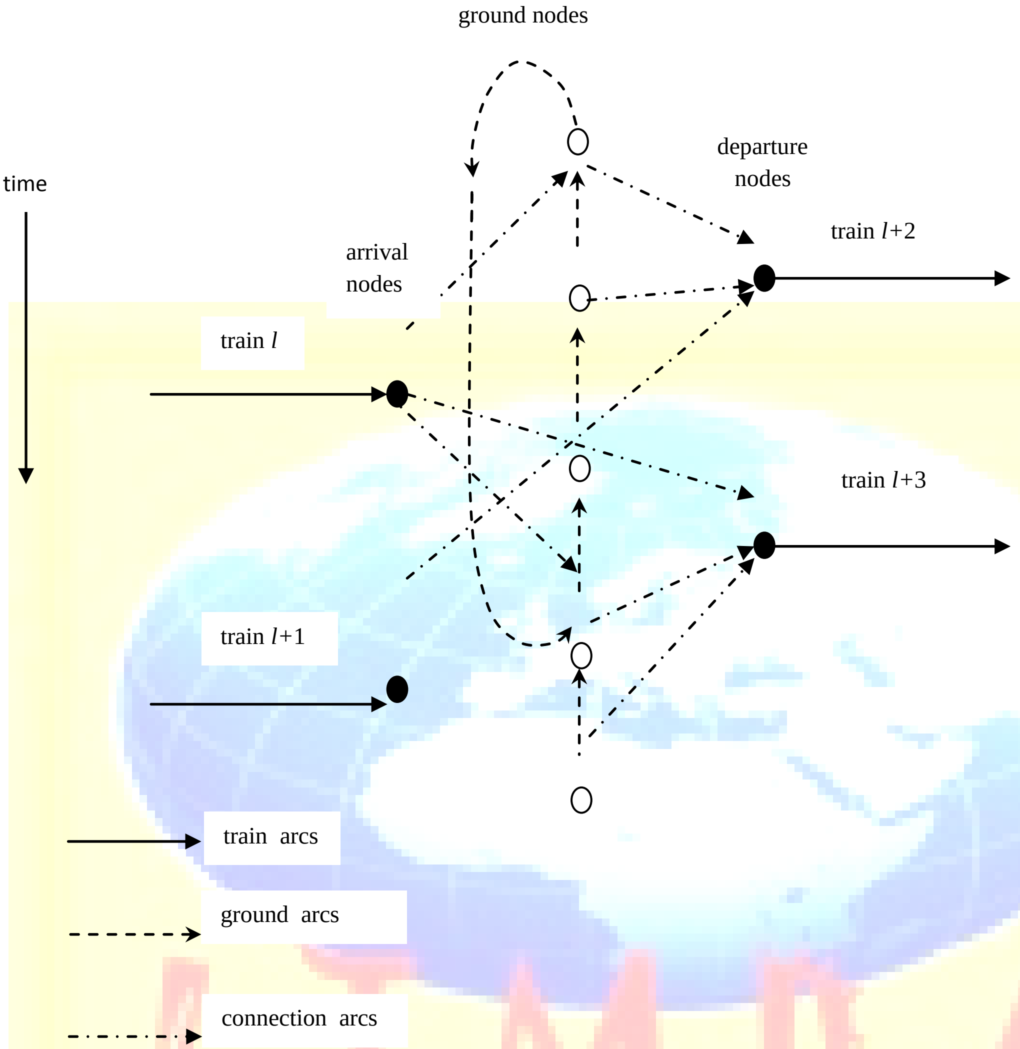

Figure 1. A part of the weekly space-time

Now, incoming trains are directed to shunting yards as they approach the station where they are disaggregated. That is, coming up with the concept of ground nodes and connection arcs. This means that no train arrives without connecting to a ground node before departing the station. From the diagram above, it can be seen that there is also a possibility of connecting from a ground node to another ground node. This usually happens when a group of at least a locomotive is travelling in the shunting yard without pulling any wagon. The operation is light travelling and has a fixed cost. It is important to note that there are locomotives that are always inbound of the station i.e. they never leave the station but always scheduled for shunting work. Each train has a start and a destination i.e. starting times and arrival times are known in advance. The difference of these times gives the trip duration and some can last up to 3 days. In addition, train weekly frequencies vary and in our model formulation we consider the same train running on different days as a different train i.e. if the same train runs five days a week we count that five different trains were scheduled.

2.2 Objective Function Formulation

Since the goal is to minimize total locomotive operating cost at the station then the objective function becomes the sum of following operating expenses.

1. Ownership, maintenance and fuelling costs i.e. the cost of actively pulling locomotives on train arcs.
2. Active and deadheaded locomotives costs.
3. Light travelling (i.e. movement of locomotives in a group on their own without pulling a train for reposition) locomotive cost.

   i.e. $$\sum_{l\in L} F^{(k)} z_l$$

4. Penalty for consist-busting (a normal phenomenon in railroads because of the needs for outgoing locomotives at a station do not precisely match the incoming needs).

   i.e. $$\sum_{l\in L} B_l z_l$$

5. Inconsistency in locomotive assignment and train-to-train connection penalty.

6. Penalty for using a single locomotive consist.

   i.e. $$\sum_{l\in L} E_l w_l$$

The sum of the total costs can be represented mathematically in the following way.

$$Min \quad C = \sum_{l\in L}\sum_{k\in K}\left(c_l^{(k)} x_l^{(k)} + d_l^{(k)} y_l^{(k)}\right) + \sum_{l\in L}\left(\left(F^{(k)} + B_l\right) z_l + E_l w_l\right) - \sum_{k\in K} C^{(k)} s^{(k)} \qquad (1)$$

where $z_l = \begin{cases} 1, & \text{if at least one locomotive is connected} \\ 0, & \text{otherwirse} \end{cases}$

$w_l = \begin{cases} 1, & \text{flow of a single locomotive on train arcs} \\ 0, & \text{otherwirse} \end{cases}$

and the last term represents the savings accrued from not using some of the locomotives.

2.3 Constraints

We would want to ensure that locomotives assigned to a train provide the required minimum tonnage.

i.e. $$\sum_{k \in K} t_l^{(k)} x_l^{(k)} \geq T_l \tag{2}$$

The assigned locomotive must also provide the train with the required minimum horsepower. That is, the product of train tonnage requirement and horsepower per tonnage is the minimum horsepower.

i.e. $$\sum_{k \in K} h^{(k)} x_l^{(k)} \geq B_l T_l \tag{3}$$

Under normal circumstances, active axles assigned to a train must not exceed 24, i.e.

$$\sum_{k \in K} \alpha^{(k)} x_l^{(k)} \leq 24, \qquad \forall \quad l \tag{4}$$

and the maximum number of locomotives assigned to a train should be 12.

$$\sum_{k \in K} x_l^{(k)} + y_l^{(k)} \leq 12, \qquad \forall \quad l \tag{5}$$

Whenever a positive flow takes place on a connection arc or light arc, we would want the variable z_l to take up a value of 1 so as to ensure that no more than four locomotives flow on any light arc.

$$\sum_{k \in K} y_l^{(k)} \leq 4 \sum_{l \in L} z_l \tag{6}$$

All inbound locomotives use only one connection. That is, either all the locomotives go to the associated ground node (in which consist-busting takes place) or all of the locomotives go to another outbound train (in which consist-busting does not take place and there is no train-to-train connection),

i.e. $$\sum_{l \in L} z_l = 1 \tag{7}$$

Similarly, w_l is assigned a value of 1 whenever a single locomotive consist is assigned to train l.

i.e. $$\sum_{k \in K} x_l^{(k)} + y_l^{(k)} + w_l \geq 2, \qquad \forall \quad l \tag{8}$$

The sum of the flow of locomotives on all arcs crossing the *checktime* is the number of locomotives used in a week such that the number of locomotives saved ($s^{(k)}$) becomes the difference between the number of locomotives used from the number of locomotives available.

i.e. $$\sum_{l \in L} x_l^{(k)} + y_l^{(k)} + s^{(k)} \geq \beta^{(k)}, \qquad \forall \quad k \tag{9}$$

We have once classified locomotives into three grades of which we would not want a "*prohibited*" locomotive to be used at all on any train arc.

i.e. $$x_l^{(k)} = 0, \text{ for each } k \in \ \mathit{Prohibited}[l] \tag{10}$$

The Locomotive Schedule Model Summary: Model 1

$$Min \quad C = \sum_{l \in L} \sum_{k \in K} \left(c_l^{(k)} x_l^{(k)} + d_l^{(k)} y_l^{(k)} \right) + \sum_{l \in L} \left(\left(F^{(k)} + B_l \right) z_l + E_l w_l \right) + \sum_{k \in K} C^{(k)} s^{(k)}$$

Subject to,

$$\sum_{k \in K} t_l^{(k)} x_l^{(k)} \geq T_l$$

$$\sum_{k \in K} h^{(k)} x_l^{(k)} \geq B_l T_l$$

$$\sum_{k \in K} \alpha^{(k)} x_l^{(k)} \leq 24, \qquad \forall \quad l$$

$$\sum_{k \in K} x_l^{(k)} + y_l^{(k)} \leq 12, \qquad \forall \quad l$$

$$\sum_{k \in K} y_l^{(k)} \leq 4 \sum_{l \in L} z_l$$

$$\sum_{k \in K} x_l^{(k)} + y_l^{(k)} + w_l \geq 2, \qquad \forall \quad l$$

$$\sum_{l \in L} x_l^{(k)} + y_l^{(k)} + s^{(k)} \geq \beta^{(k)}, \qquad \forall \quad k$$

$$x_l^{(k)} = 0, \text{ for each } k \in \; Prohibited[l]$$

$$\sum_{l \in L} z_l = 1, \qquad w_l, z_l \text{ restricted on } (0,1), \qquad x_l^{(k)}, y_l^{(k)} \geq 0 \text{ and integer}$$

3.0 Collection of Data

Secondary data from existing records on the performance of locomotives and wagons at Mpopoma Train Station was gathered through the authorization from the Planning Branch of NRZ. The station schedules three types of trains namely HSI, DSI and COV, and their specifications are as shown in table 1 below. Train locomotive preference is also as highlighted in the next table 2.

Table 1. Tonnage and horsepower required for different trains

Train (l)	Required Tonnage (T_l)	Horsepower per 20 tonnes-Watts (B_l)	Horsepower-Watts (H_l)	Single Locomotive Consist Penalty-USD (E_l)
HSI	180	756	6804.00	250
DSI	165	756	6237.00	200
COV	175	756	6693.75	230

Table 2. Locomotive Preference

Train (l)	Most Preferred	Less	Prohibited

		Preferred	
HSI	DE6	-	DE9
DSI	DE9	DE6	-
COV	DE6	DE9	-

DE9 locomotive is prohibited to haul the HSI train because that the HSI train usually ferry heavier tonnages that the locomotive can haul. The DE9 locomotive is mostly preferred to haul the DSI train and allowed to haul the COV train. Locomotive specifications are also as shown in table 3 below.

Table 3. Locomotive Properties

Locomotive Type (*k*)	**Horsepower** $(h^{(k)})$	**Number of Axles** $(\alpha^{(k)})$	**Ownership Cost** $(C^{(k)})$	**Fleet Size** $(\beta^{(k)})$	**Light Travelling Cost - USD** $(F^{(k)})$
DE6	39690	16	550	40	400
DE9	30240	14	300	38	400

4.0 Results and Analysis

The data presented above is fitted into Model 1 and coded as an Integer Programming Problem (IPP) into LINGO 10.0 mathematical programming software. The optimal solution is that the DE6 locomotive will have 2 active locomotives for each of the train types and zero non-actives. The DE9 locomotive will have no active and non-active locomotives. That is, DE6 locomotive is the one which is connected to any of the 3 types of wagons and no non-active are obtained for both locomotive types. The results also show that the possibility of having at least one locomotive connected to wagons and that of flowing a single locomotive is available only for the COV train. In addition, running the model yields an optimum value to the total weekly operating expenses of USD35, 156.00.

5.0 Sensitivity Analysis

In order to obtain high quality feasible solutions and keep the total running time of the algorithm small, we eliminate fixed charge variables from the model. These variables are in two groups of those corresponding to light travelling and those corresponding to deadheading.

5.1 Effect of Light Travelling

We can determine the effect of light travelling by eliminating all variables corresponding to the factor from the model such that we have the following modified model.

Model 2

$$Min \quad C=\sum_{l\in L}\sum_{k\in K}\left(c_l^{(k)}x_l^{(k)}+d_l^{(k)}y_l^{(k)}\right)+\sum_{l\in L}\left(E_l w_l\right)+\sum_{k\in K}C^{(k)}s^{(k)}$$

Subject to,

$$\sum_{k\in K}t_l^{(k)}x_l^{(k)}\geq T_l$$

$$\sum_{k\in K}h^{(k)}x_l^{(k)}\geq B_l T_l$$

$$\sum_{k\in K}\alpha^{(k)}x_l^{(k)}\leq 24, \qquad \forall \quad l$$

$$\sum_{k\in K}x_l^{(k)}+y_l^{(k)}\leq 12, \qquad \forall \quad l$$

$$\sum_{k\in K}y_l^{(k)}\leq 4\sum_{l\in L}z_l$$

$$\sum_{k\in K}x_l^{(k)}+y_l^{(k)}+w_l\geq 2, \qquad \forall \quad l$$

$$\sum_{l\in L}x_l^{(k)}+y_l^{(k)}+s^{(k)}\geq \beta^{(k)}, \qquad \forall \quad k$$

$x_l^{(k)}=0$, for each $k\in$ *Prohibited*[*l*], w_l restricted on (0,1), $x_l^{(k)}, y_l^{(k)}\geq 0$ and integer

Running the above model gives the same number of active and non-active locomotives as Model 1. However, no train would have a possibility of flow of a single locomotive. Elimination of these variables corresponding to light travelling reduces the saved number of locomotives by 13 and 8 for the DE6 and DE9 engines, respectively. The total weekly scheduling cost when eliminating the fixed charge variables of light travelling becomes USD34, 400.00.

5.2 Effect of Deadheading

Similarly, we determine the effect of deadheading by eliminating all variables corresponding to the fixed charge from the model such that we have the following modified model.

Model 3

$$Min \quad C=\sum_{l\in L}\sum_{k\in K}\left(c_l^{(k)}x_l^{(k)}\right)+\sum_{l\in L}\left(D_l z_l+E_l w_l\right)+\sum_{k\in K}C^{(k)}s^{(k)}$$

Subject to,

$$\sum_{k\in K}t_l^{(k)}x_l^{(k)}\geq T_l$$

$$\sum_{k\in K} h^{(k)} x_l^{(k)} \geq B_l T_l$$

$$\sum_{k\in K} \alpha^{(k)} x_l^{(k)} \leq 24, \qquad \forall \quad l$$

$$\sum_{k\in K} x_l^{(k)} + y_l^{(k)} \leq 12, \qquad \forall \quad l$$

$$\sum_{l\in L} x_l^{(k)} + y_l^{(k)} + s^{(k)} \geq \beta^{(k)}, \qquad \forall \quad k$$

$$\sum_{l\in L} z_l = 1$$

$x_l^{(k)} = 0$, for each $k \in$ *Prohibited*[*l*], $\sum_{l\in L} z_l = 1$, w_l, z_l restricted on (0,1), $x_l^{(k)}, y_l^{(k)} \geq 0$ and integer

Running the above model also gives no possibility of flow of a single locomotives but the number of active locomotives would be as shown in the table 4 below. The elimination of deadheading variables results the unused number of locomotives reduced to 30 and 32 for the DE6 and DE9 engines, respectively whilst the total costs amount to USD28, 900.00.

Table 4. Locomotives Used in a Weekly Schedule

Type of Locomotive	**Train**	**Active Locomotives**			**Non-active Locomotives**		
		Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
DE6	HSI	2	2	2	0	0	0
DE6	DSI	2	2	1	0	0	0
DE6	COV	2	2	1	0	0	0
DE9	HSI	0	0	0	0	0	0
DE9	DSI	0	0	2	0	0	0
DE9	COV	0	0	2	0	0	0

6.0 Comparison of Results from the Three Models

6.1 Active Locomotives

The bar multiple bar chart in Figure 2 below shows Model 1 and 2 have equal numbers of active locomotives for the DE6 type connected to 3 different types of wagons per time period. Model 3 has a lesser number and the number of active locomotives in the current system is notably greater than that of all the models. That is, achieving a decrease in the number of active locomotives. In addition, Model 1 and 2 have no active DE9 locomotives connected to the wagons per time period but Model 3 has got 2 locomotives connected of each of the DSI and COV type. The current system has the greatest number of active locomotives.

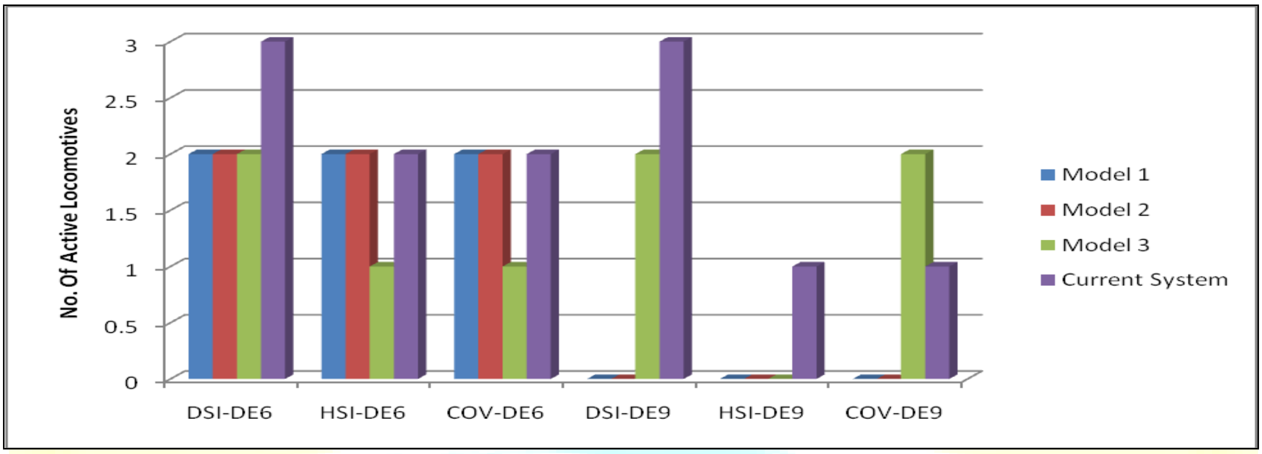

Figure 2. Comparison of Active Locomotives

We can also deduce that the DE6 locomotive is more active amongst the three. This means that, most wagons should be connected to a DE6 locomotive may becuase of its hauling capability and speed. This agrees with what other authors discovered together with the fact that the DE9 locomotive is prone to failures.

6.2 Unused Locomotives

Section 1.1 highlighted that on the current scheduling system all of the locomotive fleet at Mpopoma station would be busy at any given time. There are 78 locomotives in total but none would not be running for a significant time space. As a result, the cost savings logic is in terms of minimising the number of locomotives in use. If more locomotives are not operational and yet there is optimal running of the ones in use then we can save more money on scheduling operations at the station. Figure 3 exhibits that Model 1 has got the highest number of unused locomotives and the current system has got the lowest. The idea of saying as long as enough wagons are assembled any available locomotive is assigned the train irrespective of the possibilities of light travelling, deadheading and associated costs with that train proves to use more locomotives than needed.

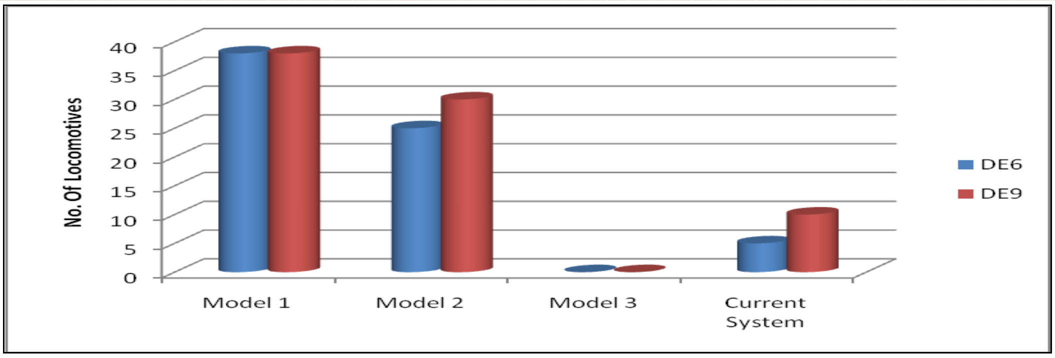

Figure 3. Comparison of Unused Locomotives

7.0 Conclusions

It has been discovered that the three scheduling models, if applied at Mpopoma Train Station, can improve the number of saved locomotives and number of used locomotives. That is, reducing operational expenses. Possibilities of deadheading and light travelling can also be reduced to a minimum. All of this is achieved when applying Model 1 and at most wagons should be connected to the DE6 locomotive because of its greater hauling capability, speed and is stronger than the DE9 engine.

8.0 Acknowledgements

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