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MULTI-OBJECTIVE OPTIMISATION OF TRAIN ALLOCATION TO MAINTENANCE IN FLEET ROSTERING

Kayode Owa[1,2], Robert John[1,2]

[1]*Department of Computer Science, University of Nottingham, United Kingdom*

[2]*ASAP Group, University of Nottingham, United Kingdom*

Corresponding Author: kayode.owa@nottingham.ac.uk

SUMMARY

Complex integrated problems occur in the rail industry that constantly diminish the maintenance efficiency of equipment, assets lifecycle and invariably shorten the life span of train systems. The research presented here is to optimally allocate trains to travel paths, avoids over-maintenance and at the same time minimise customer disruption. It is always difficult, time consuming and costly to coordinate fleet maintenance, timetabling, and crew management. There is another problem called "bunching" that exists where too many maintenance tasks of the same type scheduled relatively close to one another and therefore minimises train set availabilities and hinders the optimisation of maintenance resources; another difficulty is the dynamic and constant changing nature of train schedules.

In order to solve these aforementioned multi-objectives optimisation problems, there are two major two objective functions. The first is that the mileage limit cap cannot be exceeded so that trains are maintained before they reach their target. Minimising the difference between the cap and the actual set mileage will minimise preventive maintenance costs and optimise the use of time. The second is the minimisation of sets swaps that is essential in order to reduce customers' travel disruptions. There are also many other constraints, which make this an extremely difficult problem.

Multi-objective optimisation using artificial intelligence coupled with a simulated annealing optimisation strategy is designed to solve this novel problem, as there is currently not a single solution that exists within the train companies that can automatically solve the problem of optimally allocating trains to diagrams subject to maintenance, depot and train operation constraints. Empirical data from our partner were used to benchmark with historical results to ascertain the improvement of this novel approach. Research results show this approach has drastically reduced the planning allocation time, minimised set swaps and reduced over-maintenance.

1 INTRODUCTION

Train companies and their maintenance partners struggle with the task of allocation of trains to travel paths (or "diagrams") for the specific number of specified days. The number of days usually cover from one period of one maintenance (exam) to the next following exam time. The allocation is usually carried out by following a series of depot rules to consider and constraints to follow. The aim is to assign all the trains to their specific diagrams for the entire set period in order to enable the trains to attend their respective exams.

The allocation of trains to diagrams is a laborious and complex task. It takes approximately three hours for the maintenance fleet planner to allocate successfully a complete set of trains to diagrams. A complete set consists of 56 trains that must always be assigned and allocated to 56 diagrams. Changes to the already planned allocations by the planner usually occur when there are disruptions and other events that are inevitable. This could happen multiple times in a single day and which creates complicated problems for the fleet planner to handle.

2 PROBLEM DESCRIPTION

The allocation of all trains to all diagrams are subject to many conditions and scenarios. These diagrams have different specific mileages, which are made up of different specific individual legs. The trains need to undergo specific constant examinations in form of maintenance at certain fixed set times throughout the year.

There are seven major exam regimes. The frequency of these exams are either based on the mileages utilised, number of days worked or the numbers of weeks spent. All the seven exams must be programmed for all the 56 trains and for all the days that span across from one exam to the next. The mileages must not exceed certain limits for each of the seven exam regimes. The diagrams originate from one depot or outstation and terminates at another depot or outstation with different mileages.

Not all the exams can take in all the depots. There are depots available for some specific examinations. Some of the exams can either span for a period of 3 days, 2 days or they could be carried out as an overnight maintenance task. Either trains must arrive at respective depots at some specific times or sequences of trains' arrival before it can be qualified to sit for an exam. Likewise, they must also depart the depots with correct and specific timings.

There are instances where only one depot can service a particular exam for specific number of days: in this case, no other train will be allowed to arrive the depot until the current one finishes.

2.1 Complexity of the Problem.

One of the ways to understand the complexity of the problem is in the number of potential solutions. The total number of potential solutions is massive. This includes both the feasible and the infeasible solutions. This is denoted by the equation below:

$$\boldsymbol{\beta} = \boldsymbol{\delta}!^{(\boldsymbol{\mu})} \quad \textbf{(1)}$$

where β = global search space of solutions.
δ = number of trains and ! represents factorial. The number of trains must be equal to the numbers of diagrams in each depot at any time the allocation needs to take place.
μ = number of allocation days.
Note that:

$$\boldsymbol{\delta}! = \boldsymbol{\delta} * (\boldsymbol{\delta}-\mathbf{1}) * (\boldsymbol{\delta}-\mathbf{2}) \ldots\ldots * (\mathbf{1}) \quad \textbf{(2)}$$

For example: The calculation of the total search space for 1-day allocation is calculated as follows:

$$\boldsymbol{\beta} = (\mathbf{7.1} * \mathbf{10}^{(\mathbf{74})})^{(\mathbf{1})} \quad \textbf{(3)}$$

The calculation of the total search space for 23 days' allocation is calculated as follows:

$$\boldsymbol{\beta} = (\mathbf{7.1} * \mathbf{10}^{(\mathbf{74})})^{(\mathbf{23})} \quad \textbf{(4)}$$

As a result of the enormous potential number of solutions for the optimisation/allocation problem the best approach is to first eliminate as many infeasible (not possible) solutions as possible. It might be difficult to clearly identify the feasible solution space. The first step is to reduce the number of solutions by finding the permutation in each of the locations where trains reside overnight. The number of feasible space is given by the equation below:

$$\boldsymbol{\beta_r} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{d}}((\boldsymbol{T_{d_i}}!)!^{\boldsymbol{\mu_i}}) \quad \textbf{(5)}$$

Where d is the number of depot/outstations
T is the number of trains in each depot.
β_r is the reduced search space which gives the summation of all the solution space in each depot.
Further reduction in the solution search space can be made by the incorporation of artificial intelligence that guides the allocation of trains to diagrams.
The more the number of days for allocation, the more the solution search space (equation 1) and the greater the length of time involved in obtaining the optimal solutions. If there is no solution that exists through the allocation process, then the entire solution is nullified.

3 LITERATURE REVIEW

There has been recent research conducted in the operational scheduling of trains movement from origin to their respective destination and minimising delays [2-3]. Huntely et. al also designed an optimised routing and scheduling system [4] which is a computer aided routing and scheduling system (CARS) for transportation. Others have also conducted work in this area [5-8]. However, there is not yet reported work that combined all the above features of allocation and scheduling of trains from origin to destination in a predefined format and coupled it with the overall maintenance strategies to schedule each of the trains to attend a specified cycled maintenance examination in such a way that all trains in the fleet will continuously undergo in the entire maintenance cycle for the number of days required.

In this paper, the complexities of the problem and the multiple billions of solutions make it necessary to employ the use of an artificial intelligence strategy and multiple heuristic search algorithms that focus on simultaneously combining all the trains maintenance overall plans, allocation and scheduling of trains from their origin to their destination for a certain period of time. Part of the aim of this is to be able to forecast and predict in advance the kind of maintenance coming up on a particular trains and making sure that resources are available in a maintenance depot to carry out the specific task in a timely fashion.

4 OPTIMISATION OF TRAIN ALLOCATION

This multi-objective problem requires several conflicting objectives to be satisfied simultaneously. It is a difficult problem to solve in order to adequately meet all these defined objectives. In addition to the optimisation task, it is expected that the design should be robust enough to respond to changes and disruption on rail tracks. The tool processes the capacity to accept real time data and information and produces alternative optimal schedule within seconds. The end result is a Pareto solution front provided in order for the fleet planner to use his own discretion to determine the best option that will satisfy the current decision at the specific point in time from many solutions.

Minimisation of Train mileages

This involves the minimisation of all the mileages of the specific trains that are due for exams in that particular period. This refers to the mileages that remain on the trains before they finally depart for the specific examination. Throughout the whole period of assigning trains to diagrams, some trains reach their specific mileages limits that must not be exceeded. Each train mileage must not be more than 20,000 miles before it goes in for an exam. The task is to minimise the summation of all these mileages that remain just before their exams. Minimising these remaining mileages is a way of reducing the unwanted over maintenance. Technically, all trains will go in for an exam if the number of days for the allocation spans around 3 weeks. An average total diagram distance is about 1000 miles; this means that a distance of 20,000 miles would be covered for a period of 20+ days.

Minimisation of number of Swaps

A swap is the interchange of travel paths between train sets that had previously been assigned to them in order to channel some train sets to specific depots for maintenance purposes. It is almost impossible to achieve successful allocation and also ensure that trains arrive at its destination for exams since there are various limitations**.** Often needed and required diagrams are not available at a crucial time. In order to solve this, swaps are often required. Simply put, a swap occurs where two or more diagrams are inter-changed in order to achieve many tasks.
It is required that swaps occurrence should be minimised as part of the multi-objective task as this might cause disruptions for customers using their services. Swaps can only take place within a span of about 1 hour for all the trains involved in the process.

Ensuring priority of diagrams

There are a total of 56 Trains and 56 diagrams. The optimised tool is designed to be able to accept a varied number of trains and diagrams in case there are upgrades in the future. There are two types of diagrams: 11-diagrams and 9-diagrams for 11-car carriages and 9-car carriage trains. There are a total of 35 x 11-car and 21 x 9-car carriages and there are a total of 24 x 9-carriage and 32 x 11-carriage diagrams. So, there is a mismatch in the number of cars/diagrams sizes and this adds a level of complexity in the system. From time to time, it is required that certain legs of a diagram should be served by a train with 11 cars. This makes the diagram a priority diagram and must be obeyed. This ensures that specific diagrams that are marked are always prioritised and must be assigned to big trains (11 cars) rather than smaller ones. Most of the times, it could also be as result of the need to utilise these diagrams for specific reasons such as to satisfy football fans travelling on specific days. There is a constant weekly list of priority diagram legs that should always be considered in this task. Ensuring priority diagrams are covered by bigger trains is also part of the multi-objective task to be satisfied.

Satisfying “Controlled-Emission Toilets”

As part of the multi-objective tasks, it is required that some of the trains always need to be sent to any of the maintenance depot rather than any other outstation locations. The reason for this is for them to be able decant and service the toiletry system known as the “Controlled-Emission Toilets (CETs)”. The CETs are usually designed to ensure the safe, hygienic disposal of the contents of the toilet retention tanks on carriages. This also form part of the corrective maintenance works that need to be carried out in any of the trains that are ready to be programmed for the maintenance activity. This information is not readily available in advance but it is given to the optimised tool as an input every single day.

Incorporation of Examination regimes

Out of all the seven examinations, which are (i) B to G; this is a cycle of maintenance that starts from maintenance B and cycles through to G in a predetermined order with cycle distance of 20,000 miles’ interval between them. (ii) NDT - this is a Non-Destructive testing method which is used as a preventative measure against track catastrophic failures and possible derailment. (iii) UAT - ultrasonic axle testing is a periodic test of rail way axles to prevent unwanted occurrence and disaster. (iv) Chlorination are the liquid or gaseous elemental chlorine with a very low water content shipped in to rails cars for maintenance purposes; others time based exams are PHC, K-Exam and L-Exam. It is to be noted that only the class CL390 B-G 20000 cycle maintenance examination were used in the objective function for the minimisation of mileages to prevent over-maintenance. One of the reasons for this could be that it has the lowest frequency cycle of occurrence. The remaining six maintenance examinations with higher frequency of occurrence will be assigned and allocated alongside with the B-G 20K exam. The details of the output of all exams regimes are further discussed in the output section.

5 INPUTS

There are many inputs in to the optimised tool. They are given below.

Diagram Data

This is the most important input. This contains all the journeys that each of the trains needs to make for all the specified days in the data. The data is divided into diagrams and diagrams are further divided into many legs of various different numbers. The data contains the following: trains origins and destinations, start times and departure times of each journey, head-codes and the names of each diagrams. A typical snapshot sample of diagrams data is shown Table 1 displaying only some vital details.

Date	Diagram	Origin	Start Time	Destination	Finish Time	Distance	Leg Mile
05/04/2017	VW949	Lime St	05/04/2017 17:47	Euston	05/04/2017 20:04	840 mi.	195
05/04/2017	VW949	Euston	05/04/2017 15:07	Lime St	05/04/2017 17:20	840 mi.	190
05/04/2017	VW949	Euston	05/04/2017 20:30	Preston	05/04/2017 22:48	840 mi.	197
05/04/2017	VW949	ManchstrP	05/04/2017 07:55	Euston	05/04/2017 10:16	840 mi.	201
05/04/2017	VW949	WembleyID	05/04/2017 13:46	Euston	05/04/2017 14:05	840 mi.	10
05/04/2017	VW949	Preston	05/04/2017 23:03	LongstCMD	05/04/2017 23:57	840 mi.	28
05/04/2017	VW949	LongstCMD	05/04/2017 07:09	ManchstrP	05/04/2017 07:20	840 mi.	5
05/04/2017	VW949	Euston	05/04/2017 10:49	WembleyID	05/04/2017 11:08	840 mi.	10
05/04/2017	VW950	New St.	05/04/2017 18:50	Euston	05/04/2017 20:15	1135 mi.	209
05/04/2017	VW950	Euston	05/04/2017 20:40	ManchstrP	05/04/2017 22:48	1135 mi.	315
05/04/2017	VW950	New St.	05/04/2017 06:16	Edinburgh	05/04/2017 10:17	1135 mi.	594

Table 1: A sample diagram input data

Arrival Data

The arrival data contains the potential locations (depot or outstations) of each of the trains just before the allocation starts. Any data not captured in this data must be supplied by the fleet planner through the user interface.

Depot Rules

This file contains the comprehensive complex rules that guide the successful daily allocation of trains to diagrams. There exist a long list of depot rules but

Maintenance Location								
Preventative Type	Duration	Mon	Tue	Wed	Thu	Fri	Sat	Sun
B Exam	Overnight	2	2	2	2	1	-	1
C Exam	Overnight	1	1	1	1	-	-	-
D Exam	2 Days	1	1	1	1	1	1	1
E,F,G Exam	3 Days	1	1	1	1	1	1	1

Table 2 and Table 3 just give a sample snapshot of the complex depot rules for some of the examinations in one maintenance depot. Every other maintenance depot has similar but different rules that govern the arrival and departure of trains each time an examination needs to take place.

Maintenance Location								
Preventative Type	Duration	Mon	Tue	Wed	Thu	Fri	Sat	Sun
B Exam	Overnight	2	2	2	2	1	-	1
C Exam	Overnight	1	1	1	1	-	-	-
D Exam	2 Days	1	1	1	1	1	1	1
E,F,G Exam	3 Days	1	1	1	1	1	1	1

Table 2: Depot rules Part A

In

Maintenance Location								
Preventative Type	Duration	Mon	Tue	Wed	Thu	Fri	Sat	Sun
B Exam	Overnight	2	2	2	2	1	-	1
C Exam	Overnight	1	1	1	1	-	-	-
D Exam	2 Days	1	1	1	1	1	1	1
E,F,G Exam	3 Days	1	1	1	1	1	1	1

Table 2, for example a C Exam is carried overnight and can only take place from Monday to Thursday with a single train each night. The depot cannot accept any trains coming for C exam between Friday and Sunday. Similarly, a B exam can accept a maximum of 2 trains daily from Monday to Thursday.

Maintenance	Rules	Arrival	Departure
B Exam	2 x B or 1 x C per night	1st B 1st or 2nd arrival, second B up to Midnight.	1st leaves on the first, 2nd B last 3 departures.
C Exam		1st to 2nd arrival	Last 3 departures
D Exam		No restriction	No restriction
E,F,G Exams		1st to 3rd arrival	No restriction

Table 3: Depot rules Part B

Furthermore, the depot rules for B exam in Table 3 states that the depot in question can only accept a maximum of the trains coming for a B exam or only one train coming for a C exam. This implies that If the depot first receives a train coming for a C exam then there is no chance for any train to arrive the depot for B exam again. Arrival rules imply that the 1st of the 2 trains arriving for a B exam must either be programmed to arrive with either 1st or 2nd train that arrived that depot on that day whilst the 2nd train coming for a B exam could arrive up till 24:00 hour. There is no restriction for the D exam to arrive the depot whereas the E, F and G exams can arrive with either the 1st, 2nd or the 3rd train on that day. The departure rule is also similar to the arrival rules. Here, the 1st trains that just completed the B exam must leave the depot with the fist train whilst the 2nd train that completed the B exam can either depart with any of that last three trains for the day.

All Regimes Data

This file contains all the current mileages of each of the 56 trains for each of the seven exam regimes. It also contains the number of days left for each train to go for the next exam.

Graphical User Interface Inputs

Apart from the many parameter inputs, there are three major inputs to the graphical user interface (GUI) here.

Stable Trains

This contains the list of all the trains going to be stabled in each depot for some specific reasons. Stable trains are usually assigned to stable diagrams. Stable diagrams are the diagrams that have both origins and destinations in the same outstations. It could be that a train needs to undergo emergency repair work, which obviously are not captured in the input data. This is one of the cases whereby an override is required in the optimised tool in order to compulsorily direct a train to the desired depot.

On-going Examination details

This contains the list of trains that are currently undergoing examinations. It will be required to specify the remaining number of days and the depot where the exam is taking place for the completion of their respective examinations.

5.1 Other inputs

The lockdown feature is included in the optimised tool; it is also an input from the GUI. It is sometimes required to force the optimised tool to allocate a particular train to a particular diagram in a specific depot. The tool provides a column which will contain the list of specific trains that need to be locked down to specific diagrams. This decision is usually based on some reasons decided by the fleet planner.

Stations Names

All the station names can either be the maintenance depot names where exams can take place or other outstations where exams cannot take place such as Preston.

Trains and Diagrams Names

This file contains all the train names and diagrams names. This tool is designed in this form in such a way that new names can be added and updated in case of expansion of scope in the future. In addition, a fleet planner can carefully and easily update these files without changing the main codes.

Names of Maintenance Regimes

This file contains the names and the details of all the seven examination regimes.

6 CONSTRAINTS

Many constraints form a major part of the workability of the optimised tool. It is to be noted that these rules vary considerably and are not the same for the different days of the week.
Furthermore, there are many other constraints such as the specific depots required for some type of maintenance, the cycle for each maintenance, arrivals and departures constraints of train sets for the maintenance, number of locations where trains can visit for maintenance and the required type of exam that locations can handle. Moreover, there is a limitation on the number maintenance that could be handled daily and the respective durations of those maintenance tasks - these are sets of complex rules and constraints that must be strictly observed.
For example, and in general, a B examination can be carried out in 3 out of 5 depots while a C examination can only be done in 2 out of 5 depots; both B and C are overnight examinations. The examinations D (2 days' duration) and E, F and G (3 days' duration each), can all be done in a particular depot but at different timings (See

Maintenance Location								
Preventative Type	Duration	Mon	Tue	Wed	Thu	Fri	Sat	Sun
B Exam	Overnight	2	2	2	2	1	-	1
C Exam	Overnight	1	1	1	1	-	-	-
D Exam	2 Days	1	1	1	1	1	1	1
E,F,G Exam	3 Days	1	1	1	1	1	1	1

Table 2 and Table 3).

This section describes all the constraints involved.

Depot Arrival

There are two types of depot arrival rules. These rules apply each time any train wants to go for its next examination at the required depot. A train can either arrive any depot based on the specific arrival time or based on the arrival sequences of the trains that arrive that depot on that day. These rules vary and are not the same for the different days of the week (See

Maintenance Location								
Preventative Type	Duration	Mon	Tue	Wed	Thu	Fri	Sat	Sun
B Exam	Overnight	2	2	2	2	1	-	1
C Exam	Overnight	1	1	1	1	-	-	-
D Exam	2 Days	1	1	1	1	1	1	1
E,F,G Exam	3 Days	1	1	1	1	1	1	1

Table 2 and Table 3).

Depot Departure

There are three types of depot departure rules. These rules apply each time any of the trains wants leave the depot after the completion of an examination. A train can either depart any depot based on a specific departure time range or based on the departure sequences of all the trains that are planning to leave the depot on that day. Thirdly, the departure rule could also be based on the series of the last few departures numbers within the depot for any of the day (See

Maintenance Location								
Preventative Type	Duration	Mon	Tue	Wed	Thu	Fri	Sat	Sun
B Exam	Overnight	2	2	2	2	1	-	1
C Exam	Overnight	1	1	1	1	-	-	-
D Exam	2 Days	1	1	1	1	1	1	1
E,F,G Exam	3 Days	1	1	1	1	1	1	1

Table 2 and Table 3).

Depot Capacity

The depot capacity is a crucial factor and it is one of the major constraints. The depot capacity is closely linked with the number of available stable diagrams in each depot on every single day. The depot capacity gives the maximum number of trains that a depot can accommodate. This is also different for different exams in each of the different exam regimes (See

Maintenance Location								
Preventative Type	Duration	Mon	Tue	Wed	Thu	Fri	Sat	Sun
B Exam	Overnight	2	2	2	2	1	-	1
C Exam	Overnight	1	1	1	1	-	-	-
D Exam	2 Days	1	1	1	1	1	1	1
E,F,G Exam	3 Days	1	1	1	1	1	1	1

Table 2 and Table 3).

Depot Rules

The major details in the depot rules are the preventative maintenance types and the name of the depot where the examination can take place. Another important factor is the duration of each of the exams in the different exam regimes and the specific day of the week that the exam would occur.

Duration of Exams

Different examinations have different durations. The maximum is the E, F and G exams that span a period of three days. Since only one particular depot can handle the E, F and G exams, then no other exam can occur within the 3 days' period. On the other hand, B and C exams can be completed overnight. Other exams have different durations; the details are the in the depot rules.

Week Day Availability

There are variations in the capacities of exams that could happen on each day of the week and those available at weekends. There tends to be a reduction in the number of exams that can take place on weekend when compared with the ones that are available during the working days of the week.

7 METHODOLOGY

This section gives the details of the methodology involved in the design of the Optimised tool. The whole process starts with the generation of a problem instance. All the following sub-sections are embedded in the creation of the problem instance.

7.1 Optimisation Methods

The optimisation methods start with the first creation of a problem instance. This global search space is wide and uneven with high probability of being stuck in a local minima solution because of many constraints. The first task in the optimisation is to reduce the search space considerably putting into each depot all the arrival trains and their respective diagrams. The first major reason for this is that there is a hard constraint in making sure that all trains in a particular depot are assigned to diagrams in that same depot. This action has the potential to cut out many infeasible solutions that can slow down the optimisation process. If this approach is not complied with, then there is a greater chance of having trains with lower mileages than the minimum diagram distance and this could result in being stuck at a particular depot. The result of the optimisation problem instance is then passed across to the simulated annealing optimisation algorithm for further iteration in order to obtain better solution.

7.2 Futuristic Look Ahead 2-day Strategy

Embedded in the described optimisation process, the look ahead two-day strategy is employed in order to effectively plan for a two-day period ahead of time. This happens by intelligently determining trains in each depot that has the lowest mileages that can cover the addition of the maximum of all the diagrams in the current depot and the current day and the maximum of the all the diagrams in all the depots combined in the following day. This has many advantages: since it is looking to optimise in advance, there is a better chance of an early picking of the desired diagrams in order to avoid the need to swap diagrams again when occasion arises. It also has the potential for optimising the depot resources and capacities without the need for the optimised tool to run into a No-solution space. The result of this determines if the optimised tool will explore the one-day strategy approach or not.

7.3 Optimised One-day Strategy

The one-day strategy approach always come into play when there is not a single solution in the 2-day approach strategy at that point in time. This involves looking for diagrams that can fulfil all the depot rules and can convey the required trains to the desired depot for exams. Sometimes this may result in over-maintenance result if there is solution. The result of this strategy determines whether swapping will take place or not.

7.4 Diagrams Swapping Mechanisms

There are currently two types of swapping employed in this optimised tool. All the swapping mechanisms take place at one station. Both approaches have different reasons for the swaps to take place.

The first swap approach is used when a train needs to visit a depot for an exam and there is no available diagram.

The second swap approach is utilised when an 11-car train is urgently needed to service the legs of diagrams that are on the priority list.

7.5 Multi-Objective Optimisation

A total of four multi-objective function / fitness is required to be satisfied. These are listed below:

i. Minimising over-maintenance

Each of the trains must not exceed a certain mileage before it goes for an examination. That mileages that remains before it finally enters for an examination is referred to as mileage loss. The task is to reduce/minimise all mileages losses in the entire fleet for any given solution.

ii. Minimising the number of total swaps

A swap is needed each time a train need to proceed for an examination and there is not diagrams available within the depot that can successfully convey it to the required depot; another diagram is then employed. This activity is carried out at specific location within the whole network. Minimisation of swaps is necessary in order to reduce passenger's disruptions at rail stations by eliminating delays to customers and avoiding platform alterations. Swaps There are rules that must be followed before a successful swap can take place. Each of the trains must spend nothing less than 20 minutes from the time of their arrival and the whole process should not exceed 60 minutes afterwards.

iii. Capturing all priority lists with 11-cars

For some particular reasons some legs of certain diagrams are marked as priority-11 legs; this means that they must be served by an 11-car trains. Priority legs can occur at any position within any diagram. Swaps also comes into play if some priority legs need to be captured by an 11-car trains.

iv. **Ensuring CET is done on all trains on CET lists**.

Similarly, on each day of the allocation/optimisation task, trains that are marked to be sent for CET must be programmed and assigned to any of the maintenance depots and not any of the other outstations.

7.6 Embedded Parallel Search Strategy (PSS)

There are different levels of search involved through the entire allocation process. The optimised tool employs an embedded parallel internal heuristic search algorithm with allocation task. This ensures a faster optimisation and enhances better results in the whole strategy. This involves searching the entire depot and looking for diagrams with the correct depot rules (arrival and departure rules) that can successfully take the trains to the required depot for the next examination. The PSS is applied and used with both 2-day and 1-day strategies.

7.7 Multiple Artificial Intelligence Strategies

In order to reduce the level of stochasticity in the optimised tool, the approach used in this design uses embedded levels of artificial intelligence to make some useful decisions in many scenarios. As a result of the problem complexity, the designed algorithm is able to perform tasks pretty by incorporating vital aspect of human intelligence in the decision making process and thereby elimination billions of infeasible solution space. These are discussed as follows:

i. Mileage Control Strategy

Artificial intelligence strategy is employed in the mileage control strategies. The AI strategy here works by that perceiving the trains within its vicinity and environment and thereby looking for trains with similar mileages within a specific range that could potential cause bunching in the future. The AI quickly takes immediate actions that eliminates that problem. This is an act of taking useful and timely decision to forestall problems that will result into no solution. There are some reasons why this is required. This approach is commonly used for the E, F and G examinations under the B-G 20K exam regimes. There are instances whereby the mileages between two or more trains are very close. This is a big problem because there is only one slot per train in the Longsight depot for the E, F and G exams. In addition to the limitation posed by the depot space, the (E, F and G) exams span for a period of 3 days each in total. This implies that there will not be any solutions at all if any train with E, F and G exams are very close in mileage. For example, there are three trains in the April, 2017 data with mileages in the same range: *UK390002; G-Exam; 6783miles, UK390011; E-Exam; 8555miles, and UK390132; F-Exam; 6595miles*. The artificial intelligence strategy ensures that these three trains are spaced with a minimum of about around 3,000 miles between amidst them before a solution can ever be obtained.

ii. Swaps Reducing Strategy

Another major reason that contributes to the swaps situation is when there are trains in some undesired outstations. Artificial intelligence is also put into place to intelligently look for specific locations so that it will exclude certain trains with some specific mileages from arriving there on daily basis. In order words, the AI strategy makes sure that trains with higher mileages are sent to an outstation that is not actual depot maintenance locations.

iii. CET Capture Strategy

A similar approach to the one in Swaps Reducing Strategy section, the AI strategy is designed to ensure that all the trains programmed for CET are only sent to any of the maintenance depot. This is effected irrespective of their mileages.

7.8 Simulated Annealing (SA) Strategy

All the strategies already discussed have helped to reduce the optimisation search space considerably. The SA strategy works to finally find the optimal and improved solution out of the many solutions produced from the specified iterations. SA was introduced by Kirkpatrick et al. in 1982 [7-9] for solving combinatorial optimisation problems. SA derives its utilisation from annealing in metallurgy where there is heating and manipulated cooling of a substances in order to diminish material defects and enhance the size of its crystals. SA is good for avoiding local minima solutions and it is very efficient for problems with a large search solution space. The SA sends series of random stochastics inputs for the allocation of trains to diagram. The SA strategy uses all the four multi-objectives functions to ultimately determine and rank the best Pareto solutions.

8 OUTPUT RESULTS

This section gives details of the different outputs that the optimised tool will generate each time. This consist of the allocation of trains to diagrams and each of their schedule for the respective examinations. The resultant output file is very large; one of the trains is selected at random in order to analysis and explain the result details discussed as follows:

Train Name: UK390118
Next Exam: D
Duration of Exam: 2 days and 2 nights
Start Mileage: 3172.5 miles
Start date: Tuesday, 4th of April 2017 (Day 1).
Allocation period: 23 days.

The algorithm must ensure that train "*UK390118*" is assigned to some series of diagrams in such a way that the remaining mileage must not exceed zero or enters a negative zone but must be minimised before it enters for maintenance examination D and then proceeds for the next B examination.

Table 4 gives the filtered solution out of 173,780 rows for the allocation of train *UK390118* to diagrams for the whole period.

Days	Current De	Diagrar	Diag	Miles T	Final M	Next Ex	HeadCc	Origin	Start Time	Destina	Finish Time
Day 1	Preston	VW131	1260	1912.46		D3	5G39	Wolvrhptı	04/04/2017 22:36	Oxley CM	04/04/2017 22:41
Day 2	Oxley CMD	VW101	1057	855.46		D3	5H07	ManchstrI	05/04/2017 22:36	LongstCM	05/04/2017 22:47
Day 3	LongstCMD	VW949	840	15.46		D3	5H00	Preston	06/04/2017 23:03	LongstCM	06/04/2017 23:57
Day 4	LongstCMD	VW952	0	15.46		D3	Stbld	LongstCM	07/04/2017 02:31	LongstCM	07/04/2017 16:00
Day 5	LongstCMD	VW952	0	15.46	15.46	D3	Stbld	LongstCM	08/04/2017 02:31	LongstCM	08/04/2017 16:00
Day 6	LongstCMD	VW942	565	19435		B11	5A79	Euston	09/04/2017 21:34	Wembley	09/04/2017 21:53
Day 7	WembleyID	VW126	1207	18228		B11	5M18	WemblyC	11/04/2017 00:08	Wembley	11/04/2017 00:19
Day 8	WembleyID	VW126	1207	17021		B11	5M18	WemblyC	12/04/2017 00:08	Wembley	12/04/2017 00:19
Day 9	WembleyID	VW119	1206	15815		B11	5M17	Euston	12/04/2017 22:33	Wembley	12/04/2017 22:52
Day 10	WembleyID	VW126	1207	14608		B11	5M18	WemblyC	14/04/2017 00:08	Wembley	14/04/2017 00:19
Day 11	WembleyID	VW126	1205	13403		B11	5M18	Euston	14/04/2017 23:33	Wembley	14/04/2017 23:55
Day 12	WembleyID	VW118	1000	12403		B11	5M18	Euston	15/04/2017 23:11	Wembley	15/04/2017 23:34
Day 13	WembleyID	VW102	882	11521		B11	5F87	Crewe	16/04/2017 23:36	EdgeHIDH	17/04/2017 00:20
Day 14	EdgeHIDHS	VW110	1163	10358		B11	5F90	Crewe	17/04/2017 23:05	EdgeHIDH	17/04/2017 23:50
Day 15	EdgeHIDHS	VW112	1268	9090		B11	5G87	Wolvrhptı	19/04/2017 00:43	Oxley CM	19/04/2017 00:48
Day 16	Oxley CMD	VW103	1291	7799		B11	5H14	ManchstrI	20/04/2017 02:10	LongstCM	20/04/2017 02:29
Day 17	LongstCMD	VW125	1248	6551		B11	5H42	Preston	20/04/2017 23:29	LongstCM	21/04/2017 00:23
Day 18	LongstCMD	VW125	1248	5303		B11	5H42	Preston	21/04/2017 23:29	Wembley	22/04/2017 00:23
Day 19	WembleyID	VW111	985	4318		B11	5A68	Euston	22/04/2017 22:31	Wembley	22/04/2017 22:49
Day 20	WembleyID	VW102	882	3436		B11	5F87	Crewe	23/04/2017 23:36	EdgeHIDH	24/04/2017 00:20
Day 21	EdgeHIDHS	VW110	1163	2273		B11	5F90	Crewe	24/04/2017 23:05	EdgeHIDH	24/04/2017 23:50
Day 22	EdgeHIDHS	VW935	1183	1090		B11	5H10	ManchstrI	25/04/2017 23:31	LongstCM	25/04/2017 23:42
Day 23	LongstCMD	VW948	938	152	152	B11	5A67	Euston	26/04/2017 21:48	Wembley	26/04/2017 22:07

Table 4: Filtered solution 1 result for UK390118.

It can be seen from Table 4 that at the end of Day 3, the remaining mileage before the trains departed for examination is: 3172.46 - (1260+1057+840) = 15.46 miles.

Day 1 to day 3 allocation is carried out in such a way that the algorithm starts looking ahead right from day 1 in order to schedule the train to the right location for exam by the third day without the need to implement sets swap.

Day	***Diagram***	***Mileage (miles)***
Day 4-Exam Day1 (D)	*VW952*	*0 - Stable Diagram*
Day 5-Exam Day2(D)	*VW952*	*0 - Stable Diagram*
Day 23-Exam (Overnight B)	*VW948*	

Table 5: An excerpt from Table 4

At the end of day 5, the mileage of the train is reset back to 20,000 miles. The train was assigned to diagram VW942 (with 565 miles) on day 6; this implies that the train will have the mileage of 20,000-565 = 19435 at the end of day 6. The allocation continues in this fashion until it is ready for the next examination in the cycle. From these results, two examinations took place. The 2nd one occurred on the 23rd day. This time around, it is an overnight B examination. The sequence of the examination cycle is given in Table 6.

	B, C, D sequence										
Start	B	**C**	**B**	**C**	**D**	**B**	**C**	**B**	**C**	**E**	
	Repeat B, C, D sequence									**F**	
	Repeat B, C, D sequence									**E**	
	Repeat B, C, D sequence									**G**	**Go to Start**

Table 6: Preventive maintenance exam sequence

Allocations

This section gives details of all the train allocation to diagrams for the specified number of days. A sample snapshot of an allocation output file is shown in Table 7. Typically, an allocation for a 23 days period with 20 pareto solutions has a total of 173,780 rows in the in Table 7 results.

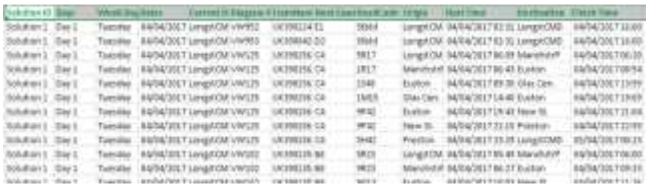

Table 7: Allocations solution results

8.1 Solution Parameters

This section shows the summary of the parameters used to obtain the solution in the allocation section. A sample snapshot of the solution parameters output file is given in Table 8. The nomenclature is described as follows:

A=Solution ID, B=Final Fitness, C=Total Swaps Made, D=Total Mileage Loss, E=CET Trains Not Covered, F=Total CET Trains, G=% Priority Legs Not Covered, H=Total Priority Legs, I=User Swaps % Input, J=User Mileage % Input, K=Number of Exams, L=Number of Iterations, M=Number of Solutions, N=Number of Days, O=Time (Seconds).

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	1.41	6	24077.92	0	15	0	107	12.37	87.63	55	20	20	23	482.68
2	3.62	10	20658.49	0	15	1.86	107	12.37	87.63	56	20	20	23	288.27
3	5.41	12	27632.47	0	15	2.81	107	12.37	87.63	55	20	20	23	207.04
4	5.92	12	24729.71	0	15	3.73	107	12.37	87.63	54	20	20	23	335.5
5	7.62	18	25618.26	0	15	4.67	107	12.37	87.63	55	20	20	23	120.25
6	8.48	8	26895.03	1	15	0	107	12.37	87.63	56	20	20	23	524.9
7	8.87	10	27817.59	1	15	0	107	12.37	87.63	57	20	20	23	99.94
8	9.22	12	25222.81	1	15	0	107	12.37	87.63	58	20	20	23	342.12
9	9.59	14	24638.36	1	15	0	107	12.37	87.63	58	20	20	23	462.35
10	9.72	12	19610.03	1	15	0.93	107	12.37	87.63	55	20	20	23	105.99
11	10.59	14	28683.93	1	15	0.93	107	12.37	87.63	55	20	20	23	140.91
12	10.71	10	25329.92	1	15	1.86	107	12.37	87.63	57	20	20	23	156.18
13	10.74	10	28121.61	1	15	1.86	107	12.37	87.63	57	20	20	23	392.18
14	10.96	18	28566.03	1	15	0.93	107	12.37	87.63	56	20	20	23	759.77
15	11.87	16	27322.7	1	15	1.86	107	12.37	87.63	58	20	20	23	566.46
16	11.87	16	26228.04	1	15	1.86	107	12.37	87.63	55	20	20	23	53.48
17	13.39	16	30111.7	1	15	3.73	107	12.37	87.63	58	20	20	23	525.58
18	14.66	18	25137.03	1	15	4.67	107	12.37	87.63	56	20	20	23	726.55
19	14.89	14	29764.13	1	15	5.61	107	12.37	87.63	55	20	20	23	341.14
20	15.62	16	26137.04	1	15	5.61	107	12.37	87.63	54	20	20	23	567.4

Table 8: Solutions parameters output file

Solution 1 out of the 20 solutions in Table 8 is better than the rest with columns E and G showing that all the 15 trains and all the 107 priority legs of diagrams are respected and covered respectively. Three sets swaps were carried out (column C); this occurred on three different occasions and each swap consists of two trains. All the mileage loss for the 55 trains is 24,077.92 miles with an average of 437.7miles per train for the 23-day period.

8.2 All Examination Regimes

This section gives the actual planned details for all the examinations for all the trains from one exam period to the next. It gives the summary of the number of days remaining for each of the train fleet for them to go for each of the examinations. A sample snapshot of the entire exam regimes output file is shown in Table 9.

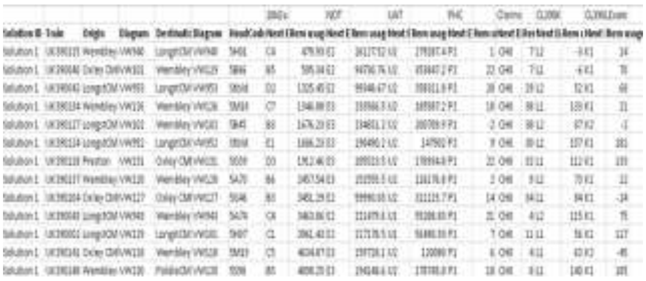

Table 9: Entire exam regimes output file

10 CONCLUSION

The task of allocating trains to diagrams is a very complex and a hard problem to solve; the global solution space is enormous. One of the reasons is because of the many constraints that contradict potential solutions. In addition, there are four objectives to simultaneously satisfy: (i) minimise over-maintenance (ii) minimise the number of swaps (iii) capture all priority legs of diagrams with 11-cars and (iv) ensures that all CETs are done. Sometimes, obtaining the required solution may result in a trade-off issue of deciding the optimal solution from the Pareto front. The optimisation design ensures availability, reliability and high utilisation percentage.

The complexities of this task could make it difficult to quickly find optimal solutions. This gives rise to employ an artificial intelligence approach in order to pave way for faster optimisation and reduce search solution space. The heuristics search technique also work in parallel at different levels to provide faster solutions. Using only a single approach will make it difficult to find solution in a reasonable amount of time. This algorithm produces optimal solutions within seconds. The comparison with the real data proved to be far better solution and approach.

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12 GLOSSARY

Exam: This is the periodically maintenance that trains undergo. There are many of them. Exams have different durations; there are specific depot that can handle some specific maintenance tasks.

Sets Swap: The interchange of travel paths between train sets that had previously been assigned to them in order to channel some train sets to specific depots for maintenance purposes.

Depot: This is a location where trains can visit for exams and can also stay overnight.

Diagrams: This consists of many legs and the number of legs could vary; this makes them to have different mileages.

Diagram Legs: The rail journey from one Depot/Outstation to another Depot/Outstation.

Stable Diagram: This is a diagram with just one leg. This leg originates from one depot and terminates at the same depot. It has zero mileage.

Outstation: This is a location where trains can stay overnight but cannot handle any exams.