# DEVELOPMENT OF A MAINTENANCE POSSESSION SCHEDULER FOR A RAILWAY

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## ABSTRACT

Maintenance of rail infrastructure is an important element in rail operations to keep traffic moving. However, maintenance causes infrastructure to be taken out of service, which impacts traffic flow. In this study, the requirements of a maintenance possession scheduler for a South African application were investigated and a proposed solution was developed. The main objective of the scheduler was to minimise the deviation of the train service on a subset of rail infrastructure while ensuring that the required maintenance was done. An application case – the railway infrastructure between Bellville and Wellington in the Western Cape province of South Africa – was identified. A novel mixed-integer linear programming model that could do possession scheduling for 24 hours on a microscopic level was formulated for this case, and implemented in the software Cplex, after which it was validated. Finally, several experiments were conducted to investigate the model's performance and the results. It was found that the model delivered optimal results in less than nine minutes, which makes it a feasible maintenance possession scheduler for day-to-day work in the immediate planning horizon.

## OPSOMMING

Instandhouding van spoorinfrastruktuur is ’n belangrike element in spoorwegoperasies ten einde verkeervloei te verseker. Instandhouding veroorsaak egter dat infrastruktuur uit diens geneem word wat verkeer weer belemmer. In hierdie studie was die vereistes van ’n besitskeduleerder vir instandhouding vir ’n Suid-Afrikaanse toepassing ondersoek, en die voorgestelde oplossing was daarna ontwikkel. Die hoofdoelwit van die skeduleerder was om die afwykings van die treindiens te minimeer op ’n gedeelte van spoorinfrastruktuur terwyl verseker word dat die nodige instandhouding gedoen word. ’n Gevallestudie vir toepassing van ’n besitskeduleerder vir instandhouding is identifiseer as die spoorweginfrastruktuur tussen Bellville en Wellington in die Wes-Kaap provinsie van Suid-Afrika. ’n Nuwe gemengde heeltal-lineêre programmeringmodel was geformuleer vir hierdie gevallestudie en in die programmatuur Cplex implementeer, waarna dit gevalideer is. Die model kan besitskedulering vir 24 uur doen op mikrovlak. Verskeie eksperimente is uitgevoer om die prestasie en resultate van die model waar te neem. Dit is bevind dat die model optimale resultate in minder as nege minute kon lewer, wat dit ’n aanvaarbare instandhouding besitskeduleerder maak vir dag-tot-dag werk in die nabye beplanningshorison.

## 1. PROBLEM BACKGROUND

This paper is about the integration of the tactical plans for rail operations and rail infrastructure maintenance. An existing mixed-integer linear programming model was adapted and applied to a South African railway. Maintenance of rail infrastructure is an important element in rail operations to keep traffic moving. However, maintenance causes infrastructure to be taken out of service, which impacts traffic flow. Maintenance *possessions*, also referred to as track *occupations*, provide maintenance personnel with the authority to occupy a track section for maintenance.

The *train schedule* allocates time and space on the rail network. A *train slot* is a specific series of sequential time-and-space allocations on the train schedule, while the number of train slots on a route is determined and limited by the rail network layout. Train slots are known by their origin, destination, planned departure, and arrival times. In a scheduled railway system, trains are planned to run in these train slots. The *possession schedule* determines when track sections are taken out of service for maintenance activities, and may interfere with the planned train service – that is, the train slots. A *possession notice* grants permission to a maintenance team to take possession of a track section, and indicates the place, time, date, duration, and nature of the work to be done.

There are three types of maintenance possession: major, minor, and unplanned. Major possessions prohibit the movement of trains in the occupied track section, while minor possessions allow trains to operate in the occupied track section. Unplanned possessions are authorised when there is an infrastructure breakdown with an operational impact. *Corrective preventive maintenance* corrects the condition of an asset when it has deteriorated beyond the specified standard. Examples of corrective preventive maintenance include replacing sleepers, rails, fasteners, and signs; fastening bolts; welding and grinding rails; repairing fences; and cutting trees. Depending on whether or not the maintenance work will have an impact on the train service, corrective preventive maintenance may be done during major or minor possessions, whereas *routine preventive maintenance* is done at regular intervals. Examples of routine preventive maintenance include condition-monitoring inspections, lubrication, and periodic minor replacements. These activities are usually done during minor possessions.

The operational impact of a major possession depends on the network layout. In the case of a single track, a major possession will restrict all train movements in the track section. In the case of a double track, a major possession may be authorised on one or both tracks, depending on the work required. If a major possession is authorised on both tracks of a double track, no train movements will be allowed in the track section. If a major possession is authorised on only one track of a double track, train movements may proceed on the unoccupied track. In this case, the operational impact is less than that of a total closure of the track section. The same principle applies in areas of the network that have multiple tracks in parallel with one another – for example, in marshalling yards. Examples of maintenance that require a major possession on both lines of a double-track are turnout replacements and substation maintenance. Turnouts – also referred to as ‘switches’ or ‘points’ – are track components that enable trains to move from one track to another. Examples of maintenance that only require a major possession on one line of a double-track line include rail welding, maintenance of the electrical overhead track equipment, and maintenance done with on-track maintenance machines, such as ballast tamping.

Since major track possessions remove track sections from service, the number of major possessions must be minimised to maximise track availability. The number of major possessions can be decreased by coordinating and combining major possessions among the different maintenance disciplines per track section. The benefits of coordinating possessions include better track availability and reduced costs through sharing resources. The latter includes vehicles and traction linesmen, who are responsible for electrically isolating the occupied track section. A drawback of coordinated possessions is that it may increase the complexity of the maintenance planning and execution teams, since they need to coordinate the work with one another.

Maintenance depots have to apply for possessions from an Operational Control Centre (OCC). These possession requests are then approved or cancelled, based on their operational impact. Train planners have three options for accommodating possessions on the train schedule: (1) reschedule the train service by departing trains earlier or later; (2) redirect trains to an alternative route if such a route exists; or (3) cancel the affected trains. If the operational impact of the possession request is deemed unacceptable, the request may be denied, in which case alternative dates and times are proposed to the requester. The process will then be repeated until a suitable date and time are agreed upon.

A conflict exists between scheduling major possessions and trains, since major possessions may interfere with the scheduled train service. Rail operations generate revenue, whereas maintenance is an investment in future revenue by providing capacity assurance, improved throughput, quality of operations, and reduced operating costs [1]. The minimum required amount of maintenance must be done to operate assets sustainably and to minimise the total cost of ensuring reliability. Deferred maintenance accelerates track degradation and shortens the track life. It may also increase the direct costs of restoring the track and the indirect costs from infrastructure breakdowns and unreliable operations. Therefore, the minimum required number of possessions must be scheduled while, at the same time, conflict between major track possessions and scheduled train services must be minimised.

Industrial engineers are integration specialists. This work demonstrates industrial engineering capabilities in the railway domain: the requirements of operations and maintenance departments are integrated, while the overall performance of the system is improved through operations research and fundamental knowledge of multidisciplinary railway engineering concepts.

The next section provides an analysis and synthesis of recent work published in the field of railway possession scheduling. The mathematical problem formulation is presented in Section 3. The model validation, experiments, evaluation, and results are presented in Sections 4, 5, 6, and 7 respectively, while Section 8 concludes the paper with proposed future work.

## 2. LITERATURE REVIEW

This section presents an analysis of recent work done in the field of possession scheduling. Fifty-seven articles were found and analysed to identify possession scheduling trends, based on the following characteristics:

- Tactical or operational applications
- Sequential or integrated planning approaches with regard to possession and train scheduling
- Classification into related work categories:
    1. Maintenance scheduling – traffic impact considered
    2. Train scheduling – with fixed maintenance closures
    3. Combined scheduling of maintenance and trains
- Cyclic (also referred to as periodic) possession and train scheduling
- Infrastructure representation: macroscopic, mesoscopic, or microscopic
- Allocation of maintenance resources
- Objective functions
- Model types
- Model formulation approaches
- Optimisation techniques
- Application information, such as:
    1. Rail network descriptions
    2. Freight, passenger, or mixed railway services
    3. Planning horizon
    4. Solution precision – that is, the size of the smallest time intervals
    5. Number of trains, stations, and block sections

The number of publications related to possession scheduling has increased significantly since 2016. Nine related works were found from 2011 to 2015, while 35 related works were found from 2016 to 2020. The references of the identified works are listed by the publication year in Table 1.

**Table 1: List of references for works related to possession scheduling**

| Year | References |
|---|---|
| 2020 | Kalinowski et al. [2], Zhang et al. [3], Zhang et al. [4], Bešinović et al. [5], Lidén [6] |
| 2019 | D'Ariano et al. [7], Bueno et al. [8], Zhang et al. [9], Bababeik et al. [10], Dao et al. [11], Zhang et al. [12], Pearce & Forbes [13] |
| 2018 | Zhang et al. [14], Arenas et al. [15], Zhu et al. [16], Lidén et al. [17], Lidén [18], Lidén [19], Kalinowski et al. [20], Dao et al. [21], Khalouli et al. [22] |
| 2017 | Van Aken et al. [23], Van Aken et al. [24], Lidén & Joborn [25], Luan et al. [26], Macedo et al. [27], Looij [28], Li & Roberti [29], Dao et al. [30], Su et al. [31] |
| 2016 | Veelenturf et al. [32], Lidén & Joborn [33], Lidén [34], Famurewa et al. [35],Vansteenwegen et al. [36] |
| 2015 | Savelsbergh et al. [37], Bahramian & Bagheri [38], Lidén [39] |
| 2014 | Louwerse & Huisman [40], Boland et al. [41] |
| 2013 | Forsgren et al. [42], Albrecht et al. [43], Boland et al. [44] |
| 2011 | Peng et al. [45] |
| 2010 | Pouryousef et al. [46] |
| 2009 | Burdett & Kozan [47], Budai-Balke [48] |
| 2007 | Van Zante-de Fokkert et al. [49], Caprara et al. [50] |
| 2006 | Budai et al. [51], Caprara et al. [52] |
| 2005 | Den Hertog et al. [53] |
| 2002 | Brucker et al. [54] |
| 2000 | Lake et al. [55] |
| 1999 | Higgins et al. [56], Cheung et al. [57] |
| 1998 | Higgins [58] |

Railway problems can be classified into strategic, tactical, and operational categories. Strategic problems have a long-term planning horizon, and usually include resource acquisition and the construction or modification of existing infrastructure. Tactical problems are concerned with allocating resources to the existing infrastructure. Operational problems occur during execution, when plans developed at the tactical level need to be adjusted because of disruptions such as late train arrivals, track maintenance, adverse weather conditions, or accidents. Lusby et al. [59] and Zhang et al. [3] provide classifications and examples of railway problems. Possession scheduling is usually treated as a tactical planning problem. Some publications consider the operational problem of rescheduling trains when a disruption occurs. With this approach, possessions may be handled as a disruption that blocks trains (e.g., Zhu et al. [16]).

Two types of possession planning approach were identified, namely sequential and integrated. Sequential approaches can be either:

- To plan the train timetable first, and then schedule the maintenance possessions while reducing the impact on the train service, or
- To plan the possessions first, and then schedule the trains around the possessions.

In contrast, integrated approaches schedule trains and possessions simultaneously. Both sequential and integrated train and possession planning approaches are used; but since 2017 the number of integrated approaches has exceeded the number of sequential approaches. Therefore, there has been a clear increase in the recent literature in the use of integrated approaches. Recent examples that use the sequential approach are Kalinowski et al. [2], Zhang et al. [3], Bešinović et al. [5], and Arenas et al. [15]; recent examples of integrated approaches are Zhang et al. [4], Lidén [6], D'Ariano et al. [7], Bueno et al. [8], and Bababeik et al. [10].

Lidén [6] sorted some of the possession scheduling publications into three related work categories:

1. Maintenance scheduling with traffic impact considered – e.g., Higgins [58], Budai et al. [51], Boland et al. [44], Savelsbergh et al. [37], and Van Zante-de Fokkert et al. [49].
2. Train scheduling with fixed maintenance closures – e.g., Caprara et al. [52], Brucker et al. [54], Vansteenwegen et al. [36], Veelenturf et al. [32], Louwerse and Huisman [40], Van Aken et al. [23], [24], Arenas et al. [15], and Zhu et al. [16].
3. Combined scheduling of maintenance and trains – e.g., Albrecht et al. [43], Forsgren et al. [42], Luan et al. [26], D'Ariano et al. [7], Lidén and Joborn [25], and Lidén et al. [17].

Among the publications before 2016, work related to the first category, 'maintenance scheduling with traffic impact considered', appeared most often. However, among the more recent publications, the other two categories dominated. Few articles related to the first category were found from 2016 onwards.

Train timetables can be cyclic or acyclic. A cyclic schedule repeats after a certain period – for example, one hour, one day, or one week. Only a few possession scheduling publications consider periodic problems. Examples of these are:

1. Cyclic scheduling of trains and maintenance windows – for example, Lidén [6].
2. Cyclic train scheduling with fixed maintenance closures – for example, Van Aken et al. [23], [24].
3. Cyclic possession scheduling with traffic impact considered – for example, Van Zante-de Fokkert et al. [49].

The rail network can be modelled at different levels of detail: macroscopic, mesoscopic, or microscopic. The scope of the timetable determines the detail of the infrastructure representation (Zhang et al. [3]). At the macroscopic level, stations are modelled as nodes and the track connections between them as arcs. The stations and tracks are given capacity limits (Van Aken et al. [23]). Only the arrival and departure times are designed and the running time between stations is calculated (Zhang et al. [9]). The operational feasibility of the proposed timetable at microscopic level is not guaranteed by macroscopic representations. Block sections are the basic microscopic elements needed to model train movements. A block section is the piece of track between two consecutive train authorisation signals. At most, one train may be in a block section at any given time. In microscopic representations, train movements are modelled on block sections. This guarantees that the timetable is operationally feasible – that is, that there are no conflicting train movements (Zhang et al. [3]). Further benefits of microscopic representations are that running times and minimum train headways are modelled with greater accuracy, which allows a better assignment of railway capacity to trains and a more efficient timetabling process because train conflicts are resolved. The main drawback of the microscopic modelling approach is that the higher level of detail dramatically increases the size of the models. Even so, the recent trend is to model train timetables as much as possible at the microscopic level (Zhang et al. [9]). Mesoscopic rail network representations combine elements from the macro and micro perspectives. For example, Zhang et al. [3] use micro representations for the stations and macro representations for the tracks between them. Among the possession-scheduling publications in Table 1, most authors use macroscopic rail network representations. However, from 2017 onwards, a few authors have used microscopic models (Arenas et al. [15]; D'Ariano et al. [7]; Luan et al. [26]; Zhang et al. [9]). One example of a mesoscopic model was found by Zhang et al. [3].

Maintenance resources must be assigned to the possessions to complete the work. These resources, such as crews and machines, may be subject to restrictions such as availability, worktime restrictions, and minimum rest times. Most of the reported work does not schedule maintenance resources. Some of the publications that do are Lidén [6], Kalinowski et al. [2], Lidén et al. [17], Lake et al. [55], Higgins et al. [56], and Higgins [58].

Four categories of objective function were identified, relating to:

1. Minimising deviations from a reference train timetable – for example, D'Ariano et al. [7], Arenas et al. [15], Luan et al. [26], Veelenturf et al. [32], and Forsgren et al. [42].
2. Minimising maintenance costs – for example, Lidén [6], Zhang et al. [4], Budai et al. [51], and Lake et al. [55].
3. Minimising train travel times – for example, Zhang et al. [3], Zhang et al. [9], Bababeik et al. [10], and Zhang et al. [14].
4. Capacity – for example, Kalinowski et al. [2] and Boland et al. [44].

Objective functions from the first category appeared most often. Objective functions from the second and third categories appeared second and third most often respectively, whereas only a few examples from the fourth category were identified.

For the possession scheduling problem, examples of integer programming (IP), integer linear programming (ILP), mixed integer programming (MIP), mixed-integer linear programming (MILP), and constraint programming models were found. The possession scheduling problem is mostly modelled with MILPs and MIPs. From 2017 onwards, mostly MILPs have been used. Recent examples of MILPs include Bešinović et al. [5], Lidén [6], D'Ariano et al. [7], and Zhang et al. [9], and Zhang et al. [12]. Recent examples of MIPs include Kalinowski et al. [2], Van Aken et al. [24], and Famurewa et al. [35]. A few authors used IPs (Higgins [58]; Louwerse and Huisman [40]) and ILPs (Veelenturf et al. [32]; Zhang et al. [4]), while one example of a binary IP (Zhang et al. [3]) and one example of a constraint satisfaction model (Cheung [57]) were identified.

Five modelling approaches were identified: time-space network, the Big-M method, the periodic event scheduling problem (PESP), job shop scheduling formulations, and simulation-based approaches. Of these, time-space network formulations appeared most, while few examples of job shop scheduling formulations and simulation-based approaches were identified. Examples of time-space network formulations include Zhang et al. [4], Zhang et al. [3], Lidén [6], Lidén and Joborn [25], and Luan et al. [26]. Examples of Big-M formulations include D'Ariano et al. [7], Zhang et al. [9], and Arenas et al. [15], while examples of PESP formulations include Bešinović et al. [5] and Van Aken et al. [23], [24]. Burdett and Kozan [47] is an example of a job shop scheduling formulation, whereas Bahramian and Bagheri [38] presented a simulation-based approach.

Commercial solvers are the most popular optimisation technique for possession-scheduling problems; examples can be found in Bešinović et al. [5], Lidén [6], Zhang et al. [12], and Zhang et al. [14]. Metaheuristics are the second most popular optimisation technique. Even so, only a few metaheuristics applications were found – for example, Khalouli et al. [22], Albrecht et al. [43], Burdett and Kozan [47], and Lake et al. [55]. A few examples of heuristics and Lagrangian relaxation were also found. Heuristic methods were used by Kalinowski et al. [2], Zhang et al. [9], Arenas et al. [15], Peng et al. [45], and Budai et al. [51]. Lagrangian relaxation was used by Zhang et al. [4], Luan et al. [26], Caprara et al. [52], and Zhang et al. [3].

Possession-scheduling problems are usually based on real-world railways or data. Examples were found for railways in:

- Australia – Kalinowski et al. [2], Boland et al. [41]
- China – Zhang et al. [3], Zhang et al. [4], Zhang et al. [12], Zhang et al. [14]
- France – Arenas et al. [15]
- Germany – Brucker et al. [54]
- The Netherlands – Bešinović et al. [5], Zhu et al. [16], Van Aken et al. [23], [24], Veelenturf et al. [32]
- Sweden – Lidén [6]

A railway may be used exclusively for either passenger or freight trains; otherwise a mix of passenger and freight trains operates on a railway. Most of the reported work focused on passenger trains. Examples of these are Zhang et al. [3], Zhang et al. [4], Zhang et al. [12], Zhang et al. [9], and Bababeik et al. [10]. Examples of possession planning on freight railways include Kalinowski et al. [2] and Bueno et al. [8], while examples of problems based on mixed-service railways include Lidén [6], Bešinović et al. [5], and Arenas et al. [15].

Planning horizons for most of the schedules range from one hour to seven days. One example was found with a schedule of less than an hour, and one example was found with a planning horizon of more than seven days. Examples of planning horizons are:

- 30 minutes – Van Aken et al. [23]
- Several hours – Zhang et al. [3], Bababeik et al. [10], Bešinović et al. [5], D'Ariano et al. [7], Zhu et al. [16]
- Several days – Lidén [6], Bueno et al. [8], Arenas et al. [15], Forsgren et al. [42], Albrecht et al. [43]
- Annual – Kalinowski et al. [2]

The solution precision – that is, the size of the smallest time intervals – ranges between seconds, minutes, and hours. Intervals of one minute are usually used. Examples of time intervals include:

- Seconds – Bešinović et al. [5], Zhang et al. [9], Zhu et al. [16]
- Minutes – Zhang et al. [4], D'Ariano et al. [7], Bueno et al. [8], Arenas et al. [15], Luan et al. [26]
- Hours – Kalinowski et al. [2], Lidén et al. [17], Lidén [18]

A wide range of schedules have been developed in respect of the number of trains, stations, and block sections included. The minimum, maximum, and average for these characteristics are:

- Number of trains: min = 10, max = 350, average = 120.
- Number of stations: min = 8, max = 60, average = 30.
- Number of block sections: min = 80, max = 1000, average = 540.

## 3. PROBLEM FORMULATION

In this case study, the possession scheduling problem was to find a possession schedule that minimised deviations from the normal train schedule while scheduling the required possessions. This section describes the developed model, and classifies it into the following categories presented in the literature review:

- Tactical problem
- Integrated planning approach – that is, simultaneous scheduling of maintenance and trains
- Related work category – 'combined scheduling of maintenance and trains'
- Microscopic infrastructure representation
- Does not schedule maintenance resources
- Objective function category – 'minimising deviations from a reference train timetable'
- MILP model
- Big-M modelling formulation
- Optimisation technique – commercial solver Cplex
- Based on real-world railway and data
- Mixed uses – that is, passenger and freight, railway in South Africa
- 24-hour planning horizon
- Solution precision – two-second intervals
- 17 trains, nine stations, 162 block sections.

The developed model is based on a microscopic representation of the rail network infrastructure. This level of detail allows train movements to be modelled in block sections. In the model, two types of block section are defined: departure block sections and arrival block sections. A departure block section is defined as a train route from a departure signal at one station to a home signal at the next station. An arrival block section is defined as a train route from a home signal outside a station to a departure signal in the same station. The two types of block section are illustrated in Figure 1. The other elements of the microscopic infrastructure representation are nodes, links, and cells. Figure 2 shows a microscopic station layout with numbered nodes, links, and cells. A node is a physical point on the network. The track between two adjacent nodes is referred to as a link. Turnouts are track components that enable trains to move from one track to another. Turnouts are represented by three connected links. As a train moves over a turnout, all of the links of the turnout are occupied and released at the same time. Cells are defined as the three links that represent a turnout, or an individual link that is not part of a turnout. Cells and block sections may only be occupied by one train at a time. The colours in Figure 2 highlight the different nodes, links, and cells respectively.

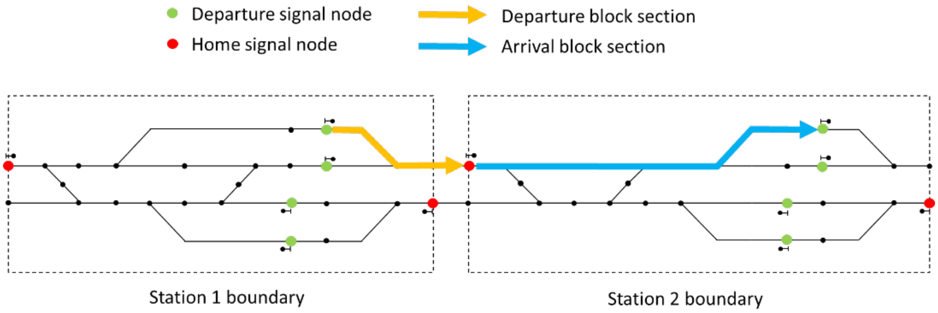


**Figure 1: Definition of block sections**

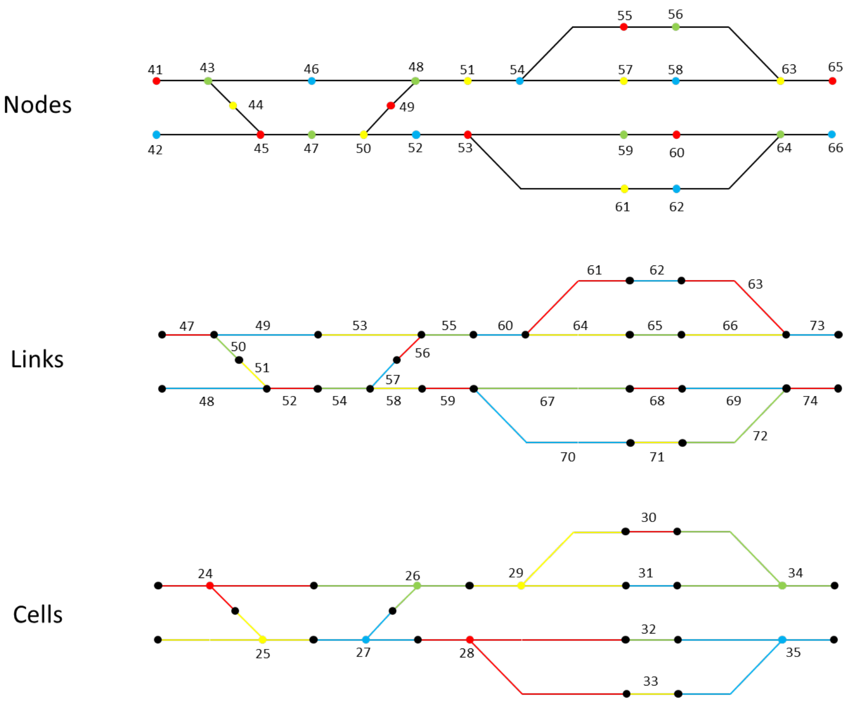


**Figure 2: Elements of a microscopic station layout**

The time for which a block section is used by a train is referred to as the blocking time – that is, the sum of the reservation, running, and release times. The reservation time is the safety time for which a block section is reserved for a train before it enters a block section. It consists of the time it takes to observe, approach, and clear the signal at the entrance of the block section. The running time begins when the head of the train enters the block section and ends when the head of the train reaches the end of the block section. The release time is the safety time for which a block section is unavailable to trains after a train has exited the block section. It consists of the time it takes to clear the train length at the signal at the end of the block section.

In the model, the running times on arrival block sections exclude the running time on the last cell of an arrival block section. In other words, once a train arrives on the last cell of an arrival block section, the preceding cells in the arrival block section are released. This allows other trains to arrive and depart from a station if a train is occupying the last cell of an arrival block section in the same station.

The model developed for this application was based on the model presented by Zhang et al. [9]. General differences from the model presented by Zhang et al. are that:

1. This model has a unique definition of departure block sections as determined by the rail infrastructure of the application case. Also, no passing block sections were defined, unlike in the model presented by Zhang et al., since they are not present in the rail infrastructure of the case of application.
2. The recovery times for robust train scheduling are not summed by the model, since these are already included in the train running times used for train planning in the railway where the model was applied.
3. In this model, reservation and release times are the same for all trains and block sections. This corresponds to the practice of the railway of application, train planners use the longest train headway on the route for train schedules where the train headway is equal to the sum of the reservation and release times.

These general differences are applied throughout the model formulation presented in this paper.

Specific differences of this model from the model presented by Zhang et al. [9] are that:

1. This model has a single and unique objective function that minimises the sum of the expected arrival time deviations of all trains at their destination nodes, whereas the model presented by Zhang et al. has two objective functions: the first minimises the total train travel time, while the second minimises the positive deviations of the train maintenance tasks from an initial maintenance schedule.
2. The model presented in this paper has unique running time constraints. In this model, the running time constraints use an 'equals to' rather than a 'greater than or equals to' formulation. The 'equals to' formulation has the advantage of preventing trains from creeping slowly on block sections, and forces a train to dwell on the last link of an arrival block section in a station if it needs to be delayed. This is true to real train operations, since trains are planned to dwell in stations and not in mainline track segments, and this allows the train plans to adhere to the designed speed profiles and train-handling techniques between stations.

Furthermore, based on the characteristics and requirements of the application case, several of the constraints presented by Zhang [9] were not used in the formulation presented in this paper. These were:

- A constraint that resolves conflicts between departing and arriving trains at origin node. This constraint was not applicable, since there are dedicated departure and arrival lines in the origin and destination stations of the application case.
- Constraints that ensure that adjacent possessions are planned within overlapping or contiguous time windows. These constraints were not applicable, since the maintenance possessions that can be combined are combined by maintenance planners before the possession scheduling process in the railway of the application case.
- Constraints that restrict the speeds of the first and second trains after a maintenance possession on the affected block sections. In the application case, it was not deemed necessary to include these running time variations at the train scheduling stage, since there is sufficient robustness in the train schedule to absorb these deviations during operations. The robustness is provided by the time supplements included in the train running times, since a maximum of 65 per cent of the theoretical train slot capacity is planned in the railway of application.
- Constraints that restrict the speed of trains that travel on tracks next to maintenance possessions. In this case, the robustness of the train schedule was also deemed sufficient to absorb these running time variations.

The following assumptions were made:

- The reservation and release times are the same for all trains on all block sections.
- Time supplements for robust scheduling have already been added to the running times used for train planning.
- At the origin and destination stations, there are dedicated departure and arrival lines for up and down trains respectively.
- No additional time is required to authorise trains during 'wrong road working' – that is, the practice of authorising trains to move against the normal direction of travel on a track next to a maintenance possession.
- The major possessions that can be combined are combined by the maintenance planning process. Therefore, possessions are not combined by the model.

The sets, parameters, and decision variables that are used in the model are defined in Tables 2, 3, and 4 respectively.

**Table 2: Set definitions**

| Set | Definition |
|---|---|
| $R$ | Set of trains, $r \in R$ |
| $S$ | Set of stations, $s \in S$ |
| $B$ | Set of block sections, $b \in B$ |
| $C$ | Set of cells, $c \in C$ |
| $L$ | Set of links, $l \in L$ |
| $N$ | Set of nodes, $n \in N$ |
| $MOT$ | Set of maintenance possessions, $m \in MOT$ |
| $S_r$ | Set of stations that train $r$ travels through, $S_r \subseteq S$ |
| $S'_r$ | Set of stations that train $r$ travels through, excluding the origin and destination stations, $S'_r \subset S$ |
| $B_r$ | Set of block sections that train $r$ may travel through, $B_r \subset B$ |
| $B^a$ | Set of arrival block sections, $B^a \subset B$ |
| $B^+_{r,n}$ | Set of block sections that flow out of node $n$ and train $r$ may travel through, $B^+_{r,n} \subset B$ |
| $B^-_{r,n}$ | Set of block sections that flow into node $n$ and train $r$ may travel through, $B^-_{r,n} \subset B$ |
| $B^{a,-}_{r,n}$ | Set of arrival block sections that flow into node $n$ and train $r$ may travel through, $B^{a,-}_{r,n} \subset B$ |
| $B_c$ | Set of block sections containing cell $c$, $B_c \subset B$ |
| $C_b$ | Set of cells in block section $b$, $C_b \subset C$ |
| $C_m$ | Set of cells included in maintenance possession $m$, $C_m \subset C$ |
| $L_b$ | Set of links for block section $b$, $L_b \subset L$ |
| $N_r$ | Set of block section nodes that train $r$ may travel through, excluding the origin and destination nodes, $N_r \subset N$ |
| $N_s$ | Set of departure block section nodes in station $s$, $N_s \subset N$ |
| $N_{r,s}$ | Set of nodes which are the end nodes of the arrival block sections that train $r$ may use to enter station $s$, $N_{r,s} \subset N$ |

**Table 3: Parameter definitions**

| | |
|---|---|
| $n_r^o$ | Origin node index of train $r$ |
| $n_r^d$ | Destination node index of train $r$ |
| $t_r^s$ | Earliest departure time of train $r$ from its origin node |
| $t_r^e$ | Latest departure time of train $r$ from its origin node |
| $mot_m^s$ | Earliest start time of maintenance possession $m$ |
| $mot_m^e$ | Latest start time of maintenance possession $m$ |
| $d_m$ | Minimum duration of maintenance possession $m$ |
| $s_r^o$ | Origin station index of train $r$ |

**Table 3: Parameter definitions (cont.)**

| Parameter | Definition |
|---|---|
| $s_r^d$ | Destination station index of train $r$ |
| $l_b^{last}$ | Last link of arrival block section $b$ |
| $n_b^+$ | Start node of block section $b$ |
| $n_b^-$ | End node of block section $b$ |
| $t_{r,l}$ | Running time of train $r$ on link $l$ |
| $\varepsilon_{b,b\prime}$ | 0–1 relationship parameter, equal to 1 if block sections $b$ and $b'$ have cells in common and these are not arrival block sections with the same last cell; 0 otherwise |
| $t_{r,s}^{dwell}$ | Minimum dwell time for train $r$ at station $s$ |
| $t_{res}$ | Reservation time required by a train before it can enter a block section |
| $t_{rel}$ | Release time required after a train has exited a block section before the next train may reserve the block section |
| $t_{r,n_r^d}^{arri}$ | The time that train $r$ is normally scheduled to arrive at its destination node |
| $p_r$ | The probability that train $r$ is confirmed to run on the weekly train plan |
| $M$ | A large number set for the constraints |

**Table 4: Definitions of decision variables**

| Variable | Definition |
|---|---|
| $y_{r,b}^{entr}$ | Entrance time of train $r$ on block section $b$ |
| $y_{r,b}^{exit}$ | Exit time of train $r$ on block section $b$ |
| $x_{r,b}$ | 0-1 route variable, equal to 1 if train $r$ uses block section $b$; 0 otherwise |
| $\mu_{r,b,r\prime,b\prime}$ | 0-1 sequence variable, equal to 1 if train $r$ is scheduled earlier on block section $b$ than train $r'$ on block section $b'$ that is conflicting with block section $b$; 0 otherwise |
| $t_{r,s}^{stop}$ | Actual dwell time of train $r$ at station $s$ |
| $t_m^{start}$ | Start time of maintenance possession $m$ |
| $t_m^{end}$ | End time of maintenance possession $m$ |
| $\alpha_{r,b,c}$ | 0-1 variable, equal to 1 if the entrance time of train $r$ on block section $b$ is larger than or equal to the end time of maintenance possession $m$ on cell $c$; 0 otherwise |

**Objective function:**

The objective function minimises the sum of the expected arrival time deviations of all trains at their destination nodes. The probability of each train being confirmed on the train plan is multiplied by the absolute value of the difference between its scheduled arrival time and its normal arrival time. The absolute value is used so that both positive and negative deviations from the normal train schedule are minimised. The scheduled arrival time of train $r$ is equal to the exit time of train $r$ on its final arrival block section plus the running time of train $r$ on the last link of the arrival block section. The objective function is

$$Minimise\ Z = \sum_{r \in R} p_r \sum_{b \in B^-_{r,n_r^d}} \left| y_{r,b}^{exit} + x_{r,b}\left(t_{r,l_b^{last}} - t_{r.n_r^d}^{arri}\right)\right|. \tag{1}$$

## 3.1. Train movement constraints

### *3.1.1. Block section usage constraints:*

A big M formulation is used in constraint (2) to ensure that train $r$ is assigned a positive entrance time on block section $b$ only if it uses block section $b$. Constraint (3) works in the same way for the exit time of train $r$ on block section $b$. These constraints are

$$y_{r,b}^{entr} \leq Mx_{r,b}, \quad \forall r \in R, b \in B_r \tag{2}$$

and

$$y_{r,b}^{exit} \leq Mx_{r,b}, \quad \forall r \in R, b \in B_r. \tag{3}$$

### *3.1.2. Running time constraints:*

For all of the departure block sections, except the departure block section selected from the origin node of train $r$, constraint (4) ensures that train $r$ is scheduled for the correct duration on block section $b$. That is, the exit time of train $r$ on block section $b$ must be equal to the sum of the entrance time of train $r$ on block section $b$ plus the sum of the running time of train $r$ on every link in block section $b$. The constraint is

$$y_{r,b}^{exit} = y_{r,b}^{entr} + x_{r,b} \sum_{l \in L_b} t_{r,l}, \quad \forall r \in R, b \in \{b |\, n_b^+ \neq n_r^o, b \in B_r \backslash B^a\}. \tag{4}$$

For the departure block section that is selected as the departure block section of train $r$ from its origin node, constraint (5) ensures that the actual dwell time of train $r$ at its origin station is included in the time that train $r$ is scheduled on its original departure block section. Furthermore, since the routing constraint (12) ensures that only one departure block section is selected for every train from its origin node, the sum formulation is used. The constraint is

$$\sum_{b \in B_{r,n_r^o}^+} y_{r,b}^{exit} = \sum_{b \in B_{r,n_r^o}^+} y_{r,b}^{entr} + \sum_{b \in B_{r,n_r^o}^+} x_{r,b} \sum_{l \in L_b} t_{r,l} + t_{r,s_r^o}^{stop}, \quad \forall r \in R. \tag{5}$$

Constraint (6) ensures that the running time of train $r$ on the last link of an arrival block section is excluded from the duration that train $r$ is scheduled on the block section, since trains start to release an arrival block section once they enter the last link of an arrival block section. The constraint is

$$y_{r,b}^{exit} = y_{r,b}^{entr} + x_{r,b} \sum_{l \in L_b \backslash l_b^{last}} t_{r,l}, \quad \forall r \in R, b \in B_r \cap B^a. \tag{6}$$

### *3.1.3. Departure time window constraints:*

Constraints (7) and (8) ensure that the scheduled departure times of trains at their origin node are larger than or equal to their earliest departure times and less than or equal to their latest departure times, as follows:

$$\sum_{b \in B_{r,n_r^o}^+} y_{r,b}^{entr} \geq t_r^s, \quad \forall r \in R \tag{7}$$

$$\sum_{b \in B_{r,n_r^o}^+} y_{r,b}^{entr} \leq t_r^e, \quad \forall r \in R. \tag{8}$$

### 3.1.4. *Exit time and entrance time transition between two consecutive block sections:*

For the transition of trains from arrival block sections to departure block sections at every station, except for the origin and destination stations, constraint (9) ensures that trains enter the departure block section only after the actual dwell time of trains on the station and the running time on the last link of the arrival block section have been completed. The constraint is

$$\sum_{n\in N_{r,s}}\sum_{b'\in B^{a,-}_{r,n}} y^{exit}_{r,b'} + t^{stop}_{r,s} + \sum_{n\in N_{r,s}}\sum_{b'\in B^{a,-}_{r,n}} x_{r,b'}(t_{r,l^{last}_{b'}}) = \sum_{n\in N_{r,s}}\sum_{b'\in B^{+}_{r,n}} y^{entr}_{r,b}, \quad \forall r\in R, s\in S'_{r}. \tag{9}$$

Constraint (10) ensures that the entrance time of a train on an arrival block section is equal to the exit time of the train on the preceding departure block section, except at the origin and destination nodes of train $r$, where there are no block sections that flow into the origin node or out of the destination node that train $r$ can use. The constraint is

$$\sum_{b'\in B^{-}_{r,n}, b'\notin B^{a}} y^{exit}_{r,b'} = \sum_{b\in B^{+}_{r,n}} y^{entr}_{r,b}, \quad \forall r\in R, n\in\{n|n\neq n^{o}_{r}, n\neq n^{d}_{r}, n\in N_r\backslash N_{r,s}, s\in S'_{r}\}. \tag{10}$$

### 3.1.5. *Minimum dwelling time constraints:*

Constraint (11) ensures that the actual dwell time of train $r$ at station $s$ is larger than or equal to the minimum dwell time specified for train $r$ at station $s$. The constraint is

$$t^{stop}_{r,s} \geq t^{dwell}_{r,s}, \quad \forall r\in R, s\in S_r \tag{11}$$

## 3.2. Train routing constraints

Constraint (12) ensures that a single route of connected block sections is selected for every train – that is, only one departure block section from the origin node, only one arrival block section into the destination node, and only one block section into and out of every node that is selected along the route. The constraint is

$$\textstyle\sum_{b\in B^{+}_{r,n}} x_{r,b} - \sum_{b\in B^{-}_{r,n}} x_{r,b} = \begin{cases} 1 & n=n^{o}_{r}, \\ -1 & n=n^{d}_{r}, \\ 0 & otherwise. \end{cases} \quad \forall r\in R. \tag{12}$$

## 3.3. Block section occupancy constraints

Conflicts between arrival block sections that share the same last link:

Constraints (13) and (14) determine the sequence of train $r$ and $r'$ if the trains make use of arrival block sections that share the same last link. Furthermore, constraints (13) and (14) ensure that the entrance time of the second train is greater than or equal to the exit time of the first train plus the sum of the release time, the reservation time, the actual dwell time of the first train, and the running time of the first train on the last link of the arrival block section.

Constraints (13) and (14) only limit the decision variables if both $x_{r',b'}$ and $x_{r,b}$ are equal to 1. If $x_{r',b'}$, $x_{r,b}$ and $\mu_{r,b,r',b'}$ are equal to 1, train $r$ is scheduled on block section $b$ before train $r'$ is scheduled on block section $b'$. In the other case, if $x_{r',b'}$ and $x_{r,b}$ are equal to 1 and $\mu_{r,b,r',b'}$ is equal to 0, then train $r$ is scheduled on block section $b$ after train $r'$ is scheduled on block section $b'$. The constraints are

$$M(1-x_{r',b'}) + M(1-x_{r,b}) + y^{entr}_{r',b'} - y^{exit}_{r,b} \geq t_{res} + t_{rel} + t^{stop}_{r,s} + t_{r,l^{last}_{b}} - M(1-\mu_{r,b,r',b'}), \tag{13}$$

$$\forall r, r'\in R, n\in N_s, n'\in N_s, b\in B^{a,-}_{r,n}, b'\in B^{a,-}_{r',n'}, r\neq r', s=s^{n}, l^{last}_{b} = l^{last}_{b'}, s\in S_r$$

and

$$M(1 - x_{r',b'}) + M(1 - x_{r,b}) + y_{r,b}^{entr} - y_{r',b'}^{exit} \geq t_{res} + t_{rel} + t_{r',s}^{stop} + t_{r',l_{b'}^{last}} - M\mu_{r,b,r',b'}, \quad (14)$$

$$\forall r, r' \in R, n \in N_s, n' \in N_s, b \in B_{r,n}^{a,-}, b' \in B_{r',n'}^{a,-}, r \neq r', s = s^n, l_b^{last} = l_{b'}^{last}, s \in S_{r'}.$$

Conflicts between other types of block section:

If train $r$ and $r'$ are selected to run on block sections that conflict with one another, but the block sections are not arrival block sections that share the same last link, constraints (15) and (16) ensure that the entrance time of the second train is larger than or equal to the exit time of the first train plus the sum of the release and reservation times. Constraints (15) and (16) only limit the decision variables if $x_{r',b'}$, $x_{r,b}$ and $\varepsilon_{b,b'}$ are equal to 1. If $x_{r',b'}$, $x_{r,b}$, $\varepsilon_{b,b'}$ and $\mu_{r,b,r',b'}$ are equal to one, train $r$ is scheduled on block section $b$ before train $r'$ is scheduled on block section $b'$. In the other case, if $x_{r',b'}$, $x_{r,b}$ and $\varepsilon_{b,b'}$ are equal to one and $\mu_{r,b,r',b'}$ is equal to zero, then train $r$ is scheduled on block section $b$ after train $r'$ is scheduled on block section $b'$. The constraints are

$$M(1 - x_{r',b'}) + M(1 - x_{r,b}) + y_{r',b'}^{entr} - y_{r,b}^{exit} \geq t_{res} + t_{rel} - M(1 - \mu_{r,b,r',b'}), \quad (15)$$

$$\forall r, r' \in R, b \in B_r, b' \in B_{r'}, r \neq r', \varepsilon_{b,b'} = 1$$

and

$$M(1 - x_{r',b'}) + M(1 - x_{r,b}) + y_{r,b}^{entr} - y_{r',b'}^{exit} \geq t_{res} + t_{rel} - M\mu_{r,b,r',b'}, \quad (16)$$

$$\forall r, r' \in R, b \in B_r, b' \in B_{r'}, r \neq r', \varepsilon_{b,b'} = 1.$$

### 3.4. Maintenance task scheduling constraints

#### *3.4.1. Maintenance task time constraints:*

Constraint (17) ensures that maintenance possession $m$ is scheduled on or after its earliest start time, while constraint (18) ensures that maintenance possession $m$ is scheduled on or before its latest start time. Constraint (19) ensures that maintenance possession $m$ is scheduled for at least the minimum duration. The constraints are

$$t_m^{start} \geq mot_m^s, \quad \forall m \in MOT, \quad (17)$$

$$t_m^{start} \leq mot_m^e, \quad \forall m \in MOT \text{ and} \quad (18)$$

$$t_m^{end} - t_m^{start} \geq d_m, \quad \forall m \in MOT. \quad (19)$$

#### *3.4.2. Maintenance task entrance constraints:*

Constraints (20) and (21) sequence trains and maintenance possessions that use the same cells. In the case where $x_{r,b}$ is equal to one and $\alpha_{r,b,c}$ is equal to zero, constraint (20) ensures that maintenance possession $m$ is only scheduled to start after the exit of train $r$ on block section $b$ plus the release time. In the case where both $x_{r,b}$ and $\alpha_{r,b,c}$ are equal to one, constraint (21) ensures that the entrance time of train $r$ on block section $b$ is greater than or equal to the end time of maintenance possession $m$ plus the reservation time. The constraints are

$$y_{r,b}^{exit} + t_{rel} \leq t_m^{start} + M(1 - x_{r,b}) + M\alpha_{r,b,c}, \quad \forall r \in R, m \in MOT, c \in C_m, b \in B_r \cap B_c \quad (20)$$

and

$$M(1 - x_{r,b}) + y_{r,b}^{entr} \geq t_m^{end} + t_{res} - M(1 - \alpha_{r,b,c}), \quad \forall r \in R, m \in MOT, c \in C_m, b \in B_r \cap B_c. \tag{21}$$

### 3.5. Domain of variables

The domain of the variables is defined by constraints (22) to (27). The entrance and exit times of trains on block sections, the start and end times of maintenance possessions, and the actual dwell times of trains are defined as integer variables. The remainder of the variables are defined as binary variables. The constraints are

$$y_{r,b}^{entr}, y_{r,b}^{exit} \in N, \quad \forall r \in R, b \in B_r, \tag{22}$$

$$x_{r,b} \in \{0, 1\}, \quad \forall r \in R, b \in B_r, \tag{23}$$

$$\mu_{r,b,r',b'} \in \{0, 1\}, \quad \forall r, r' \in R, b \in B_r, b' \in B_{r'}, r \neq r', \tag{24}$$

$$t_{r,s}^{stop} \in N, \quad \forall r \in R, s \in S_r, \tag{25}$$

$$t_m^{start}, t_m^{end} \in N, \quad \forall m \in MOT \text{ and} \tag{26}$$

$$\alpha_{r,b,c} \in \{0, 1\}, \quad \forall r \in R, m \in MOT, c \in C_m, b \in (B_r \cap B_c). \tag{27}$$

## 4. TESTING AND VALIDATION

The model validation consisted of the following steps:

1. Develop and implement the model on a small test case study. The test case study consisted of a single track mainline with four stations where trains can cross, and a mixed train service of seven trains scheduled over a five-hour period. Furthermore, the model was developed with subject-matter experts' inputs about railway signalling, block sections, train schedules, and infrastructure possessions.
2. Solve the model for different scenarios.
3. Observe and inspect the solution of every scenario for unexpected behaviour.
4. Evaluate the correct functioning of each constraint by comparing the expected output values with the output produced by the model.
5. Finally, the model solutions were tested with senior technical experts in train scheduling and maintenance who confirmed that the model conformed to the desired output requirements and produced realistic schedules for trains and maintenance possessions.

## 5. EXPERIMENTS

A set of experiments was formulated to test the capability of the model. This section describes these experiments and their results. The case of application is the railway between Bellville and Wellington in the Western Cape province of South Africa. It is a double-track railway, 53 km in length, with nine stations, and operates freight and passenger trains.

A 12-month sample of maintenance possession data was taken for the railway segment between Bellville and Wellington to develop realistic instances for the experiments. Only major possessions that remove tracks from service were considered. From the sample, the following observations were made:

- The majority of possessions are taken on a single line, have a duration of five hours, and start at 09:00 and finish at 14:00.
- Almost all of the possessions are on mainline track segments, with very few on station loop lines.
- Between zero and three possessions are scheduled per day.
- Most of the possessions are scheduled during the day-time working hours, although some of the possessions are scheduled during the night – i.e., between 18:00 and 06:00.
- Examples of the maintenance actions were replacement of rails, sleepers and contact wires, ballast screening and tamping, mast pole installation, and drainage repairs.

The set of experiments is listed in Table 5. The following settings were common to all of the experiments:

- All experiments were done with the Friday train schedule, which is the busiest day of the week.
- The possession durations were set to five hours.
- The reservation and release times were set to five minutes each to enforce a 10 minute headway between trains on conflicting block sections.
- "Wrong road working" was enabled on the mainline track next to each possession.
- Except for Experiment 1, all experiments use the actual probabilities of the trains. As defined in Table 3, each train is assigned a probability according to the chance that it is confirmed to run on the weekly train plan based on historical data.

**Table 5: List of experiments**

| Experiment | Description |
|---|---|
| 1 | No maintenance, 100 per cent probability for all trains. |
| 2 | No maintenance, actual probabilities for all trains. |
| 3 | One mainline possession on the down line, cell 36, between Kraaifontein and Muldersvlei. |
| 4 | One mainline possession on the down line, cell 36, between Kraaifontein and Muldersvlei. Possession start time limited to between 07:00 and 12:00. |
| 5 | Two mainline possessions on the down line: the first possession is on cell 36 between Kraaifontein and Muldersvlei, and the second possession is on cell 46 between Muldersvlei and Klapmuts. |
| 6 | Two mainline possessions on the down line: the first possession is on cell 36 between Kraaifontein and Muldersvlei, and the second possession is on cell 46 between Muldersvlei and Klapmuts. Possession start times limited to between 07:00 and 12:00. |
| 7 | Three mainline possessions: the first two possessions are the same as described in Experiment 5. The third possession is on cell 80 between Paarl and Huguenot on the up line. |
| 8 | Three mainline possessions: the first two possessions are the same as described in Experiment 5. The third possession is on cell 80 between Paarl and Huguenot on the up line. Possession start times limited to between 07:00 and 12:00. |
| 9 | One double track mainline possession on cells 22 and 33 between Brackenfell and Kraaifontein. Solving time limited to 30 minutes. |
| 10 | One double track mainline possession on cells 22 and 33 between Brackenfell and Kraaifontein. Solving time limited to 30 minutes. Possession start time limited to between 07:00 and 12:00. |

## 6. RESULTS

The results of the experiments are presented in Table 6. Figures 3 and 4 represent the solutions of Experiments 6 and 10 as train diagrams respectively. The trains are numbered, and the maintenance possessions are named m1 and m2. The trains are represented by the diagonal lines, while the possessions are represented by the rectangles.

**Table 6: Experiments' results**

| Exp. no. | Objective value *minutes* | Solving time *minutes:seconds* | Optimal |
|---|---|---|---|
| 1 | 1.93 | 3:13 | Yes |
| 2 | 1.88 | 3:09 | Yes |
| 3 | 1.88 | 3:36 | Yes |
| 4 | 1.88 | 5:51 | Yes |
| 5 | 1.88 | 6:58 | Yes |
| 6 | 1.88 | 4:09 | Yes |
| 7 | 1.88 | 3:29 | Yes |
| 8 | 1.88 | 8:26 | Yes |
| 9 | 58.17 | 28:46 | Best solution found within solving time, but not optimal |
| 10 | 210.66 | 11:44 | Best solution found within solving time, but not optimal |

In Figure 3, the train diagram shows that the first maintenance possession, m1, is scheduled to start at 07:00, while the second maintenance possession, m2, is scheduled to start at 08:11. As indicated by the red arrows, three trains are scheduled to pass by the track possessions. Since both possessions are on the downward line, trains travelling in the upward direction can pass by unhindered, while trains travelling in the downward direction may pass by on the track normally used for upward trains if there are no other trains. In Figure 4, both the upward and the downward tracks are occupied by the maintenance possession. In this case, no trains can pass by the track possession. In this figure, the red arrows indicate the two trains that are delayed at the stations on either side of the maintenance possession until the possession is completed.

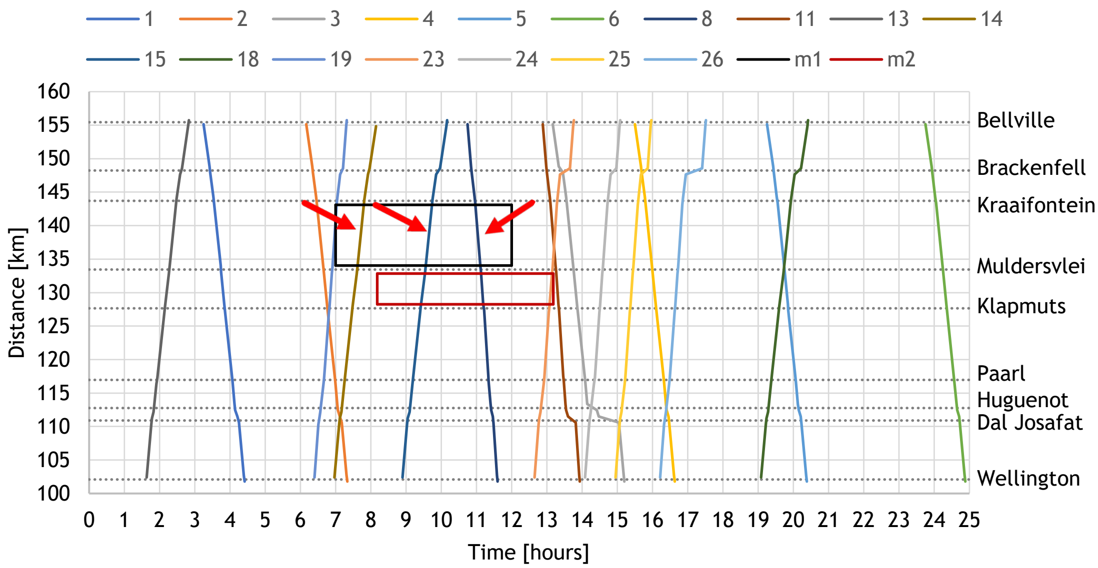


**Figure 3: Solution of Experiment 6**

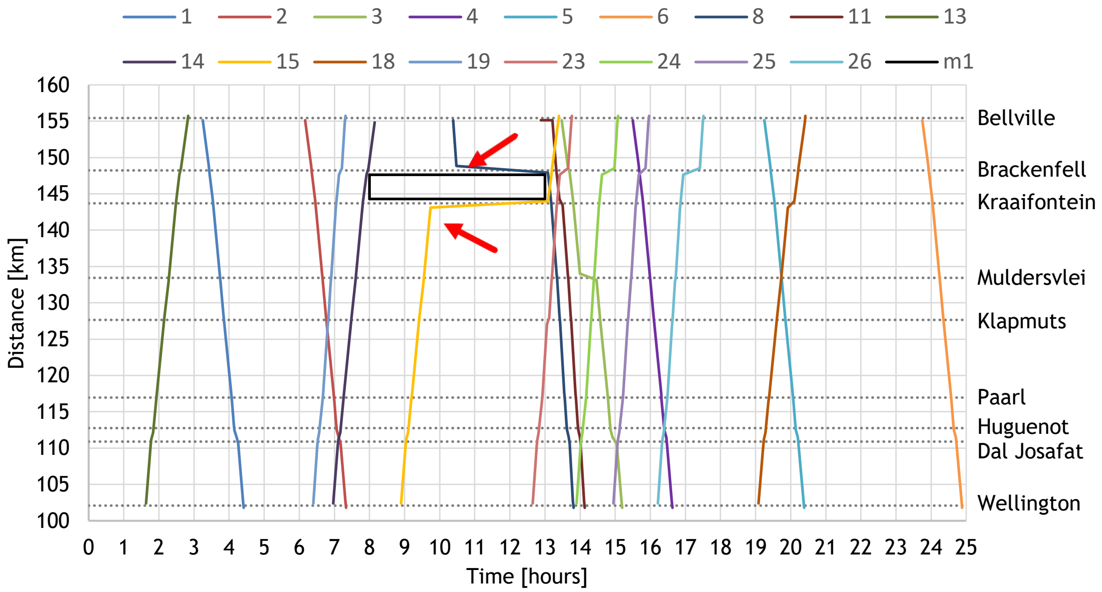


**Figure 4: Solution of Experiment 10**

## 7. EVALUATION OF RESULTS

The experiments have shown that the model is capable of producing solutions to typical possession scheduling instances within an acceptable computational time. Instances when one, two, or three single-line possessions were scheduled on the mainline tracks were solved to optimality in the longest run time of 8 minutes and 26 seconds. In the instances when a double-line possession was scheduled on a mainline track segment, the model was able to produce good solutions within a 30 minute solving time limit. These results indicate that the model will be useful as a decision-support tool, since it can produce optimal and good solutions at short notice.

Senior technical experts of train scheduling and railway maintenance evaluated the solutions and provided the following feedback:

- The visual solutions help greatly since they show the impact of possessions and how the trains are adjusted. This provides insight to the train planners, and helps them to choose better departure times for trains.
- Some of the expected benefits are improvements in the scheduling of trains, scheduling of train crews, throughput, and minimisation of human errors during the scheduling process.
- The possession scheduling process will be better with the train scheduler, since it is faster than the manual process, and there is currently no tool that shows the impact of possessions on the train schedule.

## 8. CONCLUSION

In this study, a maintenance possession scheduler was developed for the railway infrastructure between Bellville and Wellington in the Western Cape province of South Africa. An existing model in the literature was adapted to the local conditions. A novel objective function and constraints were formulated. The objective function minimised the total deviations from the normal train timetable, while the constraints ensured that the required trains and maintenance possessions were scheduled. The experiments demonstrated that the model could solve combined scheduling of trains and possessions for 24 hours on a microscopic level, and deliver optimal results in less than nine minutes, which makes it a feasible scheduler for work on the immediate planning horizon. For future work, it is proposed that the model be applied to larger railway networks and that new solution techniques be developed for the larger instances. Furthermore, the model could be developed and solved with multiple objectives – for example, by including a second objective that minimises the overtime costs of maintenance teams. Alternatively, the model could be solved with an objective function that minimises the start times of maintenance possessions.

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