M.Tech Project Dissertation

On

~~Crew Scheduling for Long-distance Passenger Railway Transportation~~

Submitted in fulfilment for the degree of
Master of Technology
in Industrial Engineering and Operations Research

by

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Abstract

This study considers the crew scheduling problem in rail operations with a focus on the long-distance passenger service of the Indian Railways. Crew scheduling problem consists of creating anonymous duties for the crew members to cover all the tasks for a defined period while satisfying all the operational and labour-union rules. Constructing efficient duties improves crew utilization and thus reduces operating costs. The study first implements an exact approach, which is a two-step methodology. The first step is a constraint programming model that tries to generate all the feasible duties, and the second step is a set covering formulation that tries to find the optimal set of duties. However, due to the explosion in the combination possibilities, this approach fails to solve real-life practical instances. Therefore, a heuristic approach has been proposed by extending the idea of a one-dimensional bin packing problem. The heuristic is capable of generating good quality solutions to large-size instances in a quick time. The computational experiments have been performed on the long-distance passenger service operated by the Mumbai Division. Subsequently, the impact on crew utilization in the case of section-wise and integrated crew planning and the possible outcomes of extending a crew beat along one of the rail sections have been discussed. Ultimately, this project aims to present a better alternative to the existing manual crew scheduling practice.

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Chapter 1

Introduction

Crew scheduling is an important activity in any transportation system and shares many similarities. However, each application has its unique features and challenges associated with it. Therefore, most research focuses on a particular application instead of a general case. As far as rail operations are concerned, transportation services are broadly classified into passenger and freight services. Passenger services are operated based on a pre-determined timetable, while freight services are a combination of scheduled and ad-hoc services. Further, passenger services are divided into three major categories: long-distance, suburban and urban, depending on their operational territory.

In the case of passenger railway transportation, a generic operational planning process involves many planning steps before crew planning as shown in fig. 1.1. It starts with the line planning problem that determines lines, their origin/destination/in-between stations, and types and frequencies of trains on each line to satisfy all the travel demands. Afterwards, train timetabling is carried out by fixing each train's arrival and departure times at each station in the section, ensuring all appropriate safety constraints. The next step is the train platforming, i.e., assigning the platforms to the trains at the stations they halt. The following is the rolling stock scheduling problem that assigns the rolling stock units (railway vehicles) to scheduled trains with a predefined timetable and platforms. Often, regular maintenance activities are integrated into this planning step. Further, during the night and no rush hour, when the trains are not in use or are in maintenance, they need to be parked in a shunting area near one of the stations or depots, and it is known as a train unit shunting problem.

Figure 1.1: Operational planning process in passenger railway transportation

The following two planning tasks concern the crew members, i.e., the crew scheduling and rostering problems. Crew scheduling consists of creating anonymous duties covering all the trains for a defined period based on a given timetable. Each duty specifies a sequence of tasks (or trips) satisfying operational constraints and labour union rules. Finally, the duties are combined for a larger time and assigned to individual crew members, known as crew rostering. A fair distribution of work, tracks and rolling stock knowledge, vacations, etc., are considered while assigning duties to crew members.

This study focuses on the crew scheduling problem associated with the long-distance passenger service of the Indian Railways. Here, the crew refers to the running staff involved in the actual operations of the train. Currently, in Indian Railways, a committee of experienced railway staff manually prepares the crew duties. They prepare a so-called 'detail book' based on the timetable, which lists groups of tasks to be operated by the assigned crew member in a day and is known as detail (Appendix A.2). Further, these details are arranged in a specific sequence to construct a few cycles, while considering factors like the type of trains - daily or non-daily, slow or fast, crew seniority, etc., such that after operating a particular detail, the crew operates the following detail in the cycle.

Although, the cyclic nature of the plan leads to a good balance of workload in the long term as everyone operates on every task. However, this way of preparing the duties is a labour-intensive process and takes a long-time to complete. Also, it is inefficient as the exercise has to be repeated every time the timetable updates and fulfilling all the crew-related constraints is difficult. Therefore, this study also aims to present a better alternative to an existing crew scheduling practice.

The remainder of this report is organized as follows. Chapter 2 contains a literature survey related to crew planning in railways. Chapter 3 provides an overview of Indian Railways regarding its scale of operations and organizational structure. It also describes the crew scheduling problem and the constraints involved in the Indian context comprehensively. The solution approaches and model formulation, their advantages and limitations are discussed in chapter 4. Chapter 5 contains a case study of the Mumbai Division, Central Railways. The case study results, including a comparison between section-wise and integrated crew planning, and a proposed scenario of extending a crew beat, are discussed in Chapter 6. Lastly, chapter 7 concludes this study and presents the key recommendations.

Chapter 2

Literature Review

The origins of the crew scheduling problem in the transportation industry date back to the 1950s and 1960s. [Arabeyre *et al.*, 1969] survey the different approaches studied by the airlines to optimize the allocation of crews to flights. The area gained greater momentum with the advances in computational power in the 1980s. [Wren, 1980] examines various methods that have been applied to bus and crew scheduling. In the 1990s, the railway industry came to the forefront of crew scheduling research activities due to the magnitude of potential savings achieved by Operation Research techniques. Further, the deregulation and privatization of railway transportation in Europe even increased the need for cost-efficient use of the resource. [Caprara *et al.*, 1997] outline different ways of modelling the crew scheduling and rostering problems and possible solution methods.

[Heil *et al.*, 2020] provide an extensive review of more than 120 articles on railway crew scheduling problems (RCSP) with a focus on more recent publications since 2000. Authors classify the literature according to transportation modes (freight or passenger, and in passenger, long-distance, sub-urban or urban), crew type (driver, conductor or security guard), model formulations (set covering problem, set partitioning problem, network flow problem, etc.), objectives (total cost, the total number of duties, etc.) and solution methods (integer programming methods, heuristics, meta-heuristics and simulations).

[Khosravi *et al.*, 2017] consider crew scheduling in the Iranian railway network and propose a comprehensive three-phase solution approach. Phase I generates all feasible sequences of the trips (pairings) using a depth-first search algorithm, while Phase II determines the optimal pairings out of all the feasible ones. Then, Phase III assigns the crew groups to the optimal pairings. [Khosravi & Tamannaei, 2017] further consider so-called 'transitions', i.e., multiple covered trips that lead to useless transfers and propose a mathematical model to minimize the costs of trips and transitions simultaneously. In both the papers, the authors consider the constraints related to crew location, working hours in a shift, and rest hours.

The article by [Han & Li, 2014] address the crew scheduling problem for a Taipei mass rapid transit system. The authors propose a constraint programming-based approach for duty generation and a set covering problem formulation for duty optimization. The objective is to minimize the total number of duties subject to constraints related to crew location, continuous driving time, rest and meal hours in a shift. [Lin & Tsai, 2019] propose a formulation that integrates crew scheduling and rostering problems. According to the authors, decomposition can make the problem easier to solve but may produce degraded solutions. Therefore, they develop a branch-and-price-and-cut algorithm and a depth-first search-based algorithm to solve the composite problem.

[Feng & Ruihua, 2010] address the case of China's urban rail transit system and treat crew scheduling as a one-dimension packing problem. The objective is to find the minimum number of drivers required, and constraints related to continuous driving time, total driving time in a day and rest time are considered. The paper proposes a best-fit algorithm to solve the problem. Further, [Qiao *et al.*, 2010] apply the bin-packing algorithm to a vehicle and crew scheduling problem for the bus transit system. The objective is to minimize the total costs of runs while covering all the tasks and consider the constraints related to crew location, working hours and meal breaks in a run.

In the context of Indian Railways, there are additional constraints related to the crew's home base (or headquarter), like differential rest rules for outstation and return journeys. Also, the rest rules depend upon the duration of the trips. Further, in the case of long-distance service, some tasks span multiple days, so the crew may not return home the same day. On top of this, there is heterogeneity in the number of trains on different days of the week, i.e., some trains run weekly, some once a week, some twice, etc. As a result, the problem is to be solved for a longer duration (at least a week) to generate a crew schedule that can be used repeatedly. However, it is found that the existing models and problem scenarios do not address these considerations. Hence, two new approaches, exact and heuristic, have been formulated to incorporate these problem characteristics.

Chapter 3

Problem Description

This chapter provides an overview of the scale of operations managed by Indian Railways (IR) and its organizational structure. Further, it comprehensively describes the crew scheduling problem in the Indian context and the various constraints governing it.

3.1 Indian Railways

IR is a statuary body that comes under the ownership of the Ministry of Railways, Government of India. The Indian railway network is one of the most extensive rail networks in the world. As of March 2021, it manages a total route length of 68,103 km, out of which 44,802 km (almost 66%) has been electrified. In the year before the outbreak of COVID-19, in FY 2019-20, IR generated INR 1,74,356 crores of revenue and carried 22.15 million passengers and 3.32 million tonnes of freight per day. Some of the key statistics associated with IR are summarized in table 3.1 and the railway map of India is shown in Fig. 3.1.

S.No.	Description	Units	2019-20	2020-21
1.	Route length	kilometers	67,956	68,103
2.	Locomotives	-	12,729	12,734
3.	Wagons	-	2,93,011	3,02,624
4.	Coaches	-	76,989	79,835
5.	Railway stations	-	7,325	7,337
6.	Regular employees	thousands	1,254	1,252
7.	Revenue	INR in crores	1,74,356	1,40,570
8.	Expenses	INR in crores	1,71,319	1,36,567
9.	No. of passenger trains daily	-	13,169	2,140
10.	No. of passenger carried per day	millions	22.15	3.42
11.	No. of goods trains daily	-	8,479	8,029
12.	Freight carried per day	millions tonnes	3.32	3.38

Table 3.1: Key statistics of Indian Railways
Source: Indian Railways Yearbook 2020-21, https://indianrailways.gov.in/

Regarding the organization structure, IR is headed by a railway board and divided into 17 zones for administrative purposes. Each zone is headed by general managers who report to the railway board. The zones are further subdivided into 68 smaller units called divisions, each headed by divisional general managers. Apart from these, IR is a major stakeholder in many public sector undertakings and other organizations related to rail transport in India.

In IR, each crew member is associated with a division and one of its crew bases (also known as a home base), often located at terminals or stations with a high frequency of train services. Specific to the case of long-distance services, the entire train journey is divided into smaller tasks, with the different crews taking up one of these tasks. The stations where crew changes are called crew change points (CCP), which are generally the major stations within the division or stations at the border of the division. CCPs are installed with basic facilities for the crew members to rest after performing a task. Note that every home base is a CCP but not vice versa.

Further, a territory between a pair of connected CCPs in which a crew operates a task is known as crew beat. Typically, every crew operates within the division's jurisdiction with which they are associated. Lastly, deadhead trips, a trip in which a crew member is transported as a passenger to a home base or another CCP, are also used in crew planning for better utilization and satisfaction of the workforce.

3.2 Objective and Governing Rules

The aim is to find the minimum number of duties required to cover all the tasks for a defined period (a week, in this case) based on the train timetable. Further in this report, a task refers to a trip that a crew can operate in a single stretch and is characterized by starting and ending time and location. On the other hand, duty refers to a sequence of tasks over a defined period, satisfying all the operational constraints and labour union rules, and can be assigned to a single operator.

In the Indian context, the crew-related constraints are governed by the Railway Servants (Hours of Work and Period of Rest) Rules, 2005, which occasionally get amended. At present, the important rules are as follows:

- Maximum running time of 9 hours in a single stretch
- Time from sign-on to sign-off should be less than 11 hours
- Maximum duty time of 104 hours in a fortnight
- Rest of at least 16 hours on returning to the home base
- Rest of at least 8 hours at outstation if traversal time of the previous task is more than 8 hours, else at least equal to traversal time of the previous task
- Crew should return within 72 hours after leaving the home base
- Preferred four periodical rest of 30 hours or five periodical rest of 22 hours in a month

The last constraint related to periodical rest is more specific to rostering level and hence not considered in the formulation.

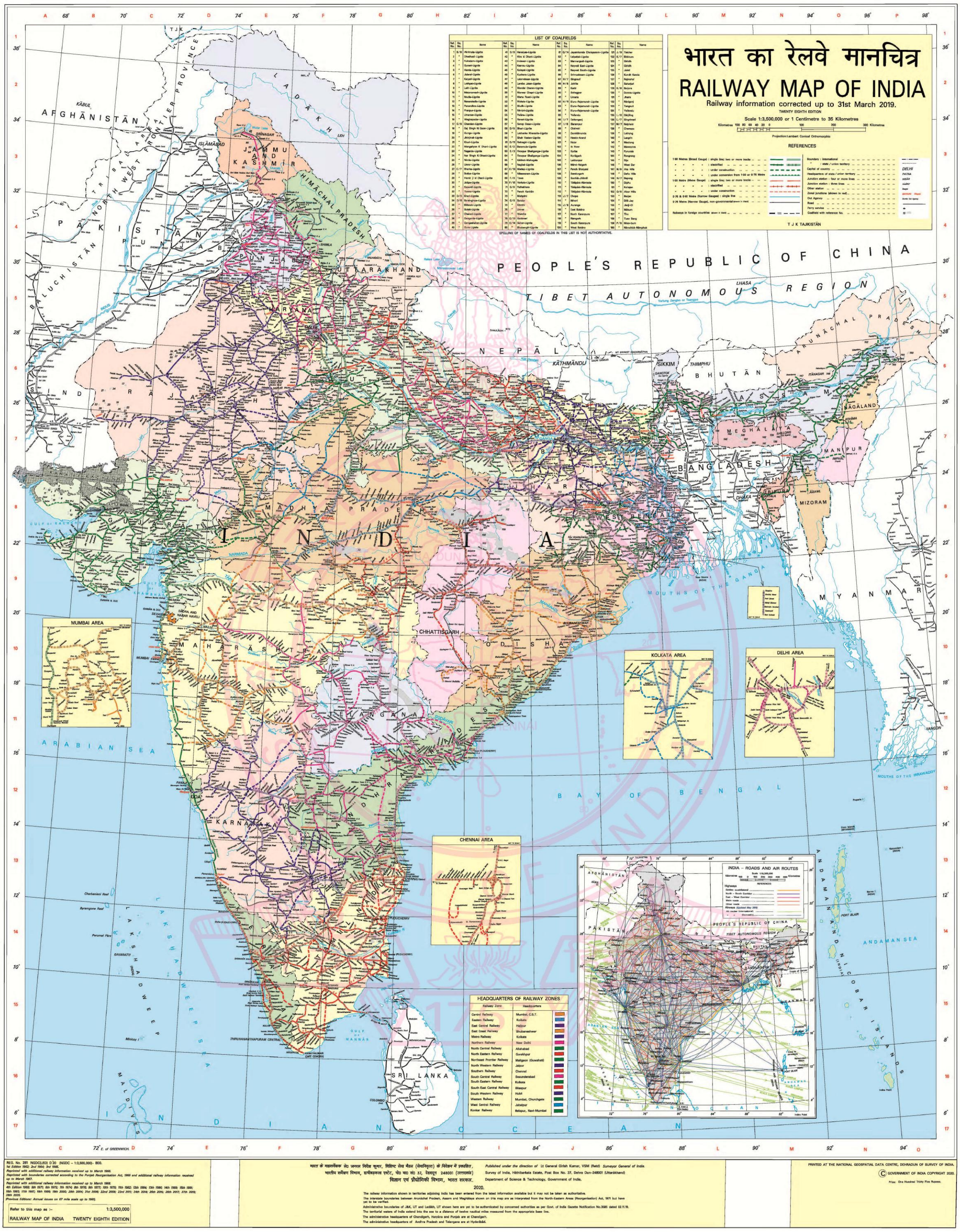

Figure 3.1: Railway map of India
Source: Survey of India, https://www.surveyofindia.gov.in

Chapter 4

Solution Methodology

This study first implements an exact approach to solve the complex crew scheduling problem. However, in further sections, it can be noticed that this approach fails to solve large-size practical instances due to an explosion in combination possibilities. Therefore, a heuristic approach has been proposed further, which is capable of generating good quality solutions to real-life problem scenarios quickly.

4.1 Exact Approach

The exact approach is a two-step methodology, with the Constraint Programming (CP) model for duty generation as the first and Set Covering Problem (SCP) formulation for duty optimization as the second step. The first step is essentially a constraint satisfaction problem, and the goal is to generate all the feasible duties, i.e., adhering to all the constraints. After that, the second step tries to find the optimal set of duties out of all the feasible duties.

4.1.1 CP model for Duty Generation

This step tries to generate all the feasible duties for a defined period based on a given train timetable. The key advantage associated with the CP is that complex real-life constraints can be incorporated easily. However, note that the model needs to be run as many times as the number of home bases exists while selecting one home base at a time.

A duty is defined as a sequence of tasks $\{x_1, x_2, ..., x_m\}$, where $x_i \in T$ is the i^{th} task of the duty. The representation of duty is shown in fig. 4.1. Further, each task in a duty is defined by five parameters: the train number (num_t), the origin station (org_t), the departure time ($dept_t$), the destination station ($dest_t$), and the arrival time (arr_t). For each of the train tasks (W), these parameters are derived from an actual train timetable (Appendix A.1). On the other hand, for a dummy task (d), a null value can be assigned to its train number, a big but same number to its departure and arrival times and any random code for its origin and destination station.

Figure 4.1: Representation of a duty

The parameter m limits the maximum number of tasks in a feasible duty and can be estimated based on the average traversal time, rest hours and the planning time horizon. However, most feasible duties cannot include as many as m train tasks, and when this happens, dummy tasks are assigned to the duty. The input data and parameters with their notations are summarized in table 4.1. The parameters, sign-on time (sn_t) and sign-off time (sf_t), are determined by providing some buffer to the scheduled arrival and departure time of a task. The crew utilizes this time for completing the paperwork and other checks before and after operating the task. The parameter, rh, defines the minimum rest to be provided after operating a task, whereas, dh, puts the limit to maximum permissible duty hours in a week. The other parameter, rn, sets the upper limit for the crew to remain away from the home base.

Notation	**Description**
T	Set of all tasks
W	Set of train tasks
d	A dummy task
$home$	Home base station
num_t	Train number of task t
org_t	Originating station of task t
$dest_t$	Destination station of task t
$dept_t$	Departure time of task t
arr_t	Arrival time of task t
sn_t	Sign on time for task t
sf_t	Sign off time for task t
pw	Time allotted for paper work and other checks
rh	Minimum rest to be provided after operating a task
dh	Maximum duty hours permissible in a week
rt	Maximum time within which crew should return to home base
m	Maximum number of task in a duty

Table 4.1: CP model: Input data and parameters

As this is a constraint satisfaction problem rather than an optimization problem, there is no objective function, and the goal is to generate all the feasible solutions (in this case, duties) subject to the following constraints:

$$sn_t = dept_t - pw, \ \forall \ t \in W \tag{4.1}$$

$$sf_t = arr_t + pw, \ \forall \ t \in W \tag{4.2}$$

Eq. 4.1 and 4.2 calculate sign-on and sign-off time for every train task by providing additional time before and after the scheduled departure and arrival, respectively.

$$x_{i+1} \in W \implies org_{x_{i+1}} = dest_{x_i} \ \forall \ i \in \{1, 2, ..., m-1\} \tag{4.3}$$

Eq. 4.3 is a location fit constraint that ensures the next train task in the duty originates from the same station where the previous task has ended.

The constraints of maximum running time and time from sign-on to sign-off in a single stretch are taken care of at the strategic level by appropriately dividing the entire train journey into smaller tasks using CCPs.

$$\sum_{i=1}^{m} sf_{x_i} - sn_{x_i} \leq dh \tag{4.4}$$

Eq. 4.4 ensures that total duty time in a week doesn't exceed the maximum permissible limit.

$$x_{i+1} \in W \implies sn_{x_{i+1}} - sf_{x_i} \geq rh, \; \forall \; i \in \{1, 2, ..., m-1\} \tag{4.5}$$

Eq. 4.5 is a mandatory rest hour constraint that ensures sufficient rest is provided between two consecutive train tasks.

In the Indian context, the rh is a function that defines the minimum rest hours based on the station where the rest is to be provided and the traversal time of the previous task operated.

$$rh = \begin{cases} 960, \; if \; dest_{x_i} = home \\ 480, \; if \; dest_{x_i} \neq home \;\; \& \;\; sf_{x_i} - sn_{x_i} \geq 480 \\ sf_{x_i} - sn_{x_i}, \; if \; dest_{x_i} \neq home \;\; \& \;\; sf_{x_i} - sn_{x_i} < 480 \end{cases} \tag{4.6}$$

Eq. 4.6 caters to the different possible cases as follows:

- if the previous task has ended at home base CCP, then the next train task in the duty can start after a rest of at least 16 hours.
- else if the previous task has ended at the outstation CCP, with traversal time of 8 hours or more, then the next train task in the duty can start after a rest of at least 8 hours.
- else if the previous task has ended at the outstation CCP, with a traversal time of lesser than 8 hours, then the next train task in the duty can start after a rest equal to the traversal time of the previous task.

$$org_{x_i} = home \;\; \& \;\; sf_{x_j} - sn_{x_i} \geq rt \;\; \& \;\; x_i, x_j \in W \implies \sum_{k=i}^{j-1} (dest_{x_k} = home) \geq 1, \; \forall \, i, \; j \; \in \{1, 2, ..., m\} \tag{4.7}$$

Eq. 4.7 ensures the return of a crew within a specific time frame after leaving the home base.

A couple of constraints could be added to the formulation to restrict the solution space, i.e., reduce the number of feasible duties. Firstly, a feasible duty should consist of minimum duty hours. Secondly, the crew should not wait beyond a certain limit after completing the mandatory rest and either be assigned a train task or a deadheading trip. The constraints will look very similar to eq. 4.4 and 4.5 respectively, but the parameters associated with these constraints would remain subjective as no hard rule defines them.

All the feasible duties generated in this step serve as an input to the second step, explained in the next section.

4.1.2 SCP model for Duty Optimization

Set covering problem (SCP) is a well-known NP-hard problem in combinatorial optimization. Given a set of elements, the SCP aims to find the minimum number of sets covering all these elements at least once. The other very similar problem is the set partitioning problem (SPP), where the objective is the same but covers all elements exactly once. As far as crew planning is concerned, SCP is commonly used in the case of bus or railway modes of transportation where the deadheading of a crew is not very costly. However, SPP is widely used in the airline industry, where deadheading a pilot is very expensive.

In this study, SCP has been used and modelled as an Integer programming. The input parameter and decision variables used in the model are summarized in table 4.2.

Notation	Description
F	Set of feasible duties
W	Set of train tasks
a_{ij}	feasible duty i contains train task j or not

Table 4.2: SCP model: Input data and parameters

The model is as follows

$$min \sum_{i \in F} y_i \tag{4.8}$$

subject to,

$$\sum_{i \in F} a_{ij} \times y_i \geq 1 \ \forall \ j \in W \tag{4.9}$$

$$a_{ij} = \begin{cases} 1, \ if \ duty \ i \ contains \ task \ j \ \forall \ i \in F, \ j \in W \\ 0, \ otherwise \end{cases} \tag{4.10}$$

$$y_i = \begin{cases} 1, \ if \ duty \ i \ is \ selected \ \forall \ i \in F \\ 0, \ otherwise \end{cases} \tag{4.11}$$

The objective, Eq. 4.8, is to select the minimum number of duties covering all tasks. Eq. 4.9 ensures that each train task is a part of at least one of the selected duties. Eq. 4.10 and Eq. 4.11 define the binary input data (a_{ij}) and decision variable (x_i) to the problem, respectively. If any task appears in more than one selected duty, it would be a deadheading trip in all those duties except one for which it would be a working task.

4.2 Heuristic Approach

The standard crew scheduling problem is NP-hard, and it is a challenge to solve practical scale problems exactly. Further, the train timetable changes frequently, thus requiring crew schedules to be changed quickly as well. Therefore, a heuristic approach has been proposed that extends the idea of a one-dimensional bin-packing problem to the crew scheduling setting with appropriate modifications. The bin packing problem is an optimization problem in which items of varying sizes must be packed into a finite number of bins, each of a fixed given capacity, in a way that minimizes the number of bins used.

Here, a task has been visualized as an item and a duty as a bin. Further, the duty is defined in the same manner as it was described in the exact approach, with the only difference being that the dummy tasks are not required here. The input data and parameters are summarized in table 4.3.

Notation	**Description**
W	The set of train tasks
$home$	Home base station
num_t	Train number of task t
org_t	Originating station of task t
$dest_t$	Destination station of task t
$dept_t$	Departure time of task t
arr_t	Arrival time of task t
sn_t	Sign on time for task t
sf_t	Sign off time for task t
pw	Time required for paper work
rh	Minimum rest to be provided after operating a task
dh	Maximum duty hours permissible in a week

Table 4.3: Heuristic: Input data and parameters

It is important to note the following applicability/limitation of this approach:

- The rail network should be a star-kind network, with the central node being the only home base and all the outstation CCP in the network connected to it. Additionally, no crew beats should exist between a pair of outstation CCP. It ensures that an away-to-home trip follows a home-to-away trip.

  The different kinds of rail networks possible with the applicability of the heuristic are shown in fig. 4.2. In case the network doesn't fit the above criteria, one can try to divide the whole network into sub-networks to apply the heuristic.

- The possibility of deadheading is not incorporated as it may lead to the imbalance of the number of crew available at a CCP, which eventually leads to instability in the number of duties generated.

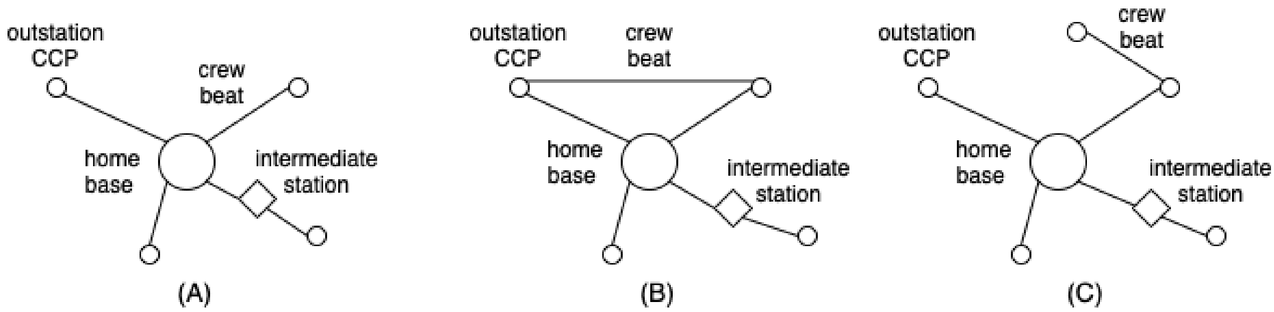

Figure 4.2: Railway networks types
(A) Applicable, (B) Not applicable, (C) Not applicable

The important characteristics of the heuristic solution are:

- The same set of duties generated can be repeated in every period until timetable changes
- The number of duties originating from a particular CCP is the same as the number of duties ending there

Both the above characteristics facilitate the linking of duties over periods and therefore help construct one or more cycles, similar to a detail book, and would lead to workload balance as every crew will operate on every task in the long run.

4.2.1 Algorithm for Duty Generation

The steps to constructively generate the duties are as follows:

1) Create a list of all the tasks to be assigned in a defined period
2) Calculate sign-on and sign-off times for every task based on departure and arrival times, and sort the list in the ascending order of sign-on times
3) Pick a task (T) lying at the top of the list, i.e. task starting at the earliest
4) Find duty(s) satisfying location-fit, mandatory rest-hour and maximum duty time constraints w.r.t T
   a) If any duty exists, add T to duty as per policy A/B
   b) Else, create a new duty and add T to it
5) Remove T from the list of unassigned tasks
6) Repeat steps (2) to (5) until all tasks are assigned to one of the duties
7) Run the algorithm for one more period and discard the solution of the first period

The first run is a warm-up because duties are created as and when needed, which leads to the imbalance of workload but gives the count of duties required. However, in the second run, the duties have already been created, and only the tasks need to be assigned to those, leading to fair work distribution. The two policies, A and B, mentioned in step 4 are described in the next section. Also, the flowchart depicting the algorithm is shown in fig. 4.3.

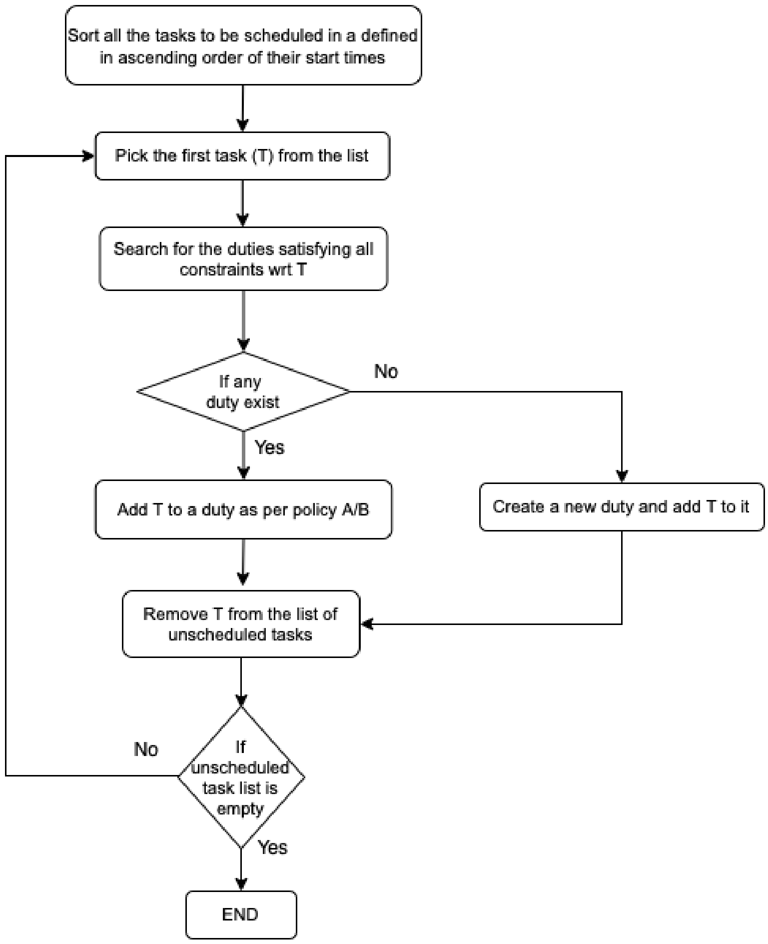

Figure 4.3: Heuristic algorithm: Flowchart

4.2.2 Policies for Task Allocation

The two policies differ in the way of assigning tasks to duties based on their originating station. Further, a secondary rule can be used to break a tie, if any.

- **Policy A**: Whether a task (T) originates from a home base CCP or an outstation CCP, assign it to a duty that completes the mandatory rest at the earliest (first available duty). The idea behind this policy is that no crew should wait for a next task at a station for a longer duration.
- **Policy B**: If the task (T) originates from an outstation CCP, assign it to a duty that completes the mandatory rest at the earliest (first available duty). On the other hand, if it originates from home base CCP, assign it to a duty with the least duty hours (least loaded duty) in that period. The idea behind this policy is that no crew should wait at an outstation for a longer duration. However, when the crew is at home and has operated for more hours than others, it could be given extra rest to balance the workload.

Policy	Primary rule		Secondary rule	
	Home CCP	Outstation CCP	Home CCP	Outstation CCP
A	First available	First available	Least loaded	Least loaded
B	Least loaded	First available	First available	Least loaded

Table 4.4: Policies for task allocation

Chapter 5

A case study: Mumbai Division

This study considers the case of the Mumbai Division, which comes under the central zone of the Indian Railways. The Central Railways is divided into five divisions; the other four are Bhusawal, Nagpur, Solapur and Pune. The system map of the Central Railways is shown in fig. 5.2.

Mumbai Division has its head office at Chatrapati Shivaji Maharaj Terminus (CSMT) and has the jurisdiction from CSMT (0 km) to Igatpuri (137 km) towards East, up to Lonavala (128 km) and Roha (144 km) towards the south and up to Vasai Road (84 km) towards the north. The total route of this division is 575.77 km with 107 stations and ranks 5^{th} in workload as per KPI over Indian Railways (source: Central Railway). In FY 2019-20, the division carried an average of 41.47 lakhs sub-urban and 1.75 non-suburban passengers daily. The railway map of the Mumbai Division (including the suburban) is shown in fig. 5.3.

Note that all the stations in Mumbai region (like CSMT, LTT, Kalyan, etc.) act as one CCP and have been referred to as 'Mumbai' in this study. Also, Mumbai is the only home base in this division, i.e., all the crew members are based out of here. The long-distance passenger trains in this division operate on the three routes, Mumbai - Igatpuri, Mumbai - Pune (ahead of Lonavala) and Mumbai - Ratnagiri (ahead of Roha), as shown in fig. 5.1. However, since Mumbai - Ratnagiri is a long journey, tasks of low-speed trains are split at Roha so that no task exceeds the maximum running time limit. In those cases, the Roha - Rantagiri part is operated by the crew of Ratnagiri Division, Konkan Railway. Lastly, it can be noticed that the network is indeed a star-type network.

The distance and traversal times for different crew beats (or sections) are summarized in table 5.1, and the distribution of tasks starting on different days of the week is summarized in table 5.2. In both the tables, the UP direction refers away from Mumbai, and the DOWN direction refers toward Mumbai. Further, IGP is the station code for Igatpuri, PUNE for Pune, ROHA for Roha and RN for Ratnagiri.

Sections	**Distance (in km)**	**Average traversal time (in mins) UP / DOWN**
Mumbai - IGP	135	157 / 162
Mumbai - PUNE	190	217 / 220
Mumbai - RN	344	350 / 402
Mumbai - ROHA	124	164 / 166

Table 5.1: Rail sections: Distance and traversal time

Sections	Direction	M	Tu	W	Th	F	Sa	Su	Total
Mumbai - IGP	UP	39	38	40	39	37	38	38	269
	DOWN	39	36	42	36	37	42	37	269
Mumbai - PUNE	UP	26	25	27	26	25	27	26	182
	DOWN	25	26	27	26	25	27	26	182
Mumbai - RN	UP	11	11	9	9	12	14	11	77
	DOWN	12	9	12	13	11	11	9	77
Mumbai - ROHA	UP	6	5	5	8	4	7	4	39
	DOWN	4	7	5	5	6	5	7	39
Total	-	162	157	167	162	157	171	158	1134

Table 5.2: Tasks distribution in a week

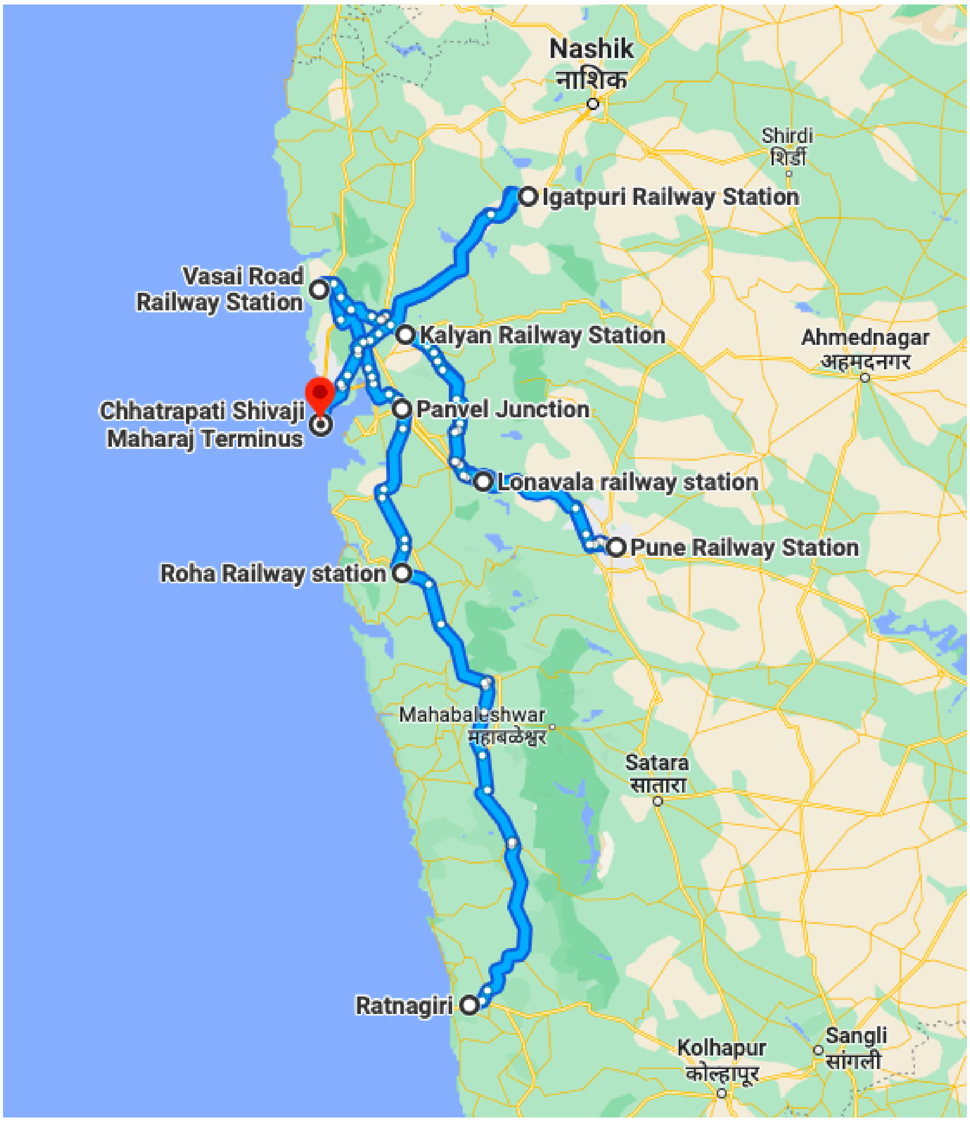

Figure 5.1: Mumbai Division: Route map
Source: Google Maps, https://www.google.com/maps/

Figure 5.2: Central Railway: System map
Source: Central Railway, https://cr.indianrailways.gov.in

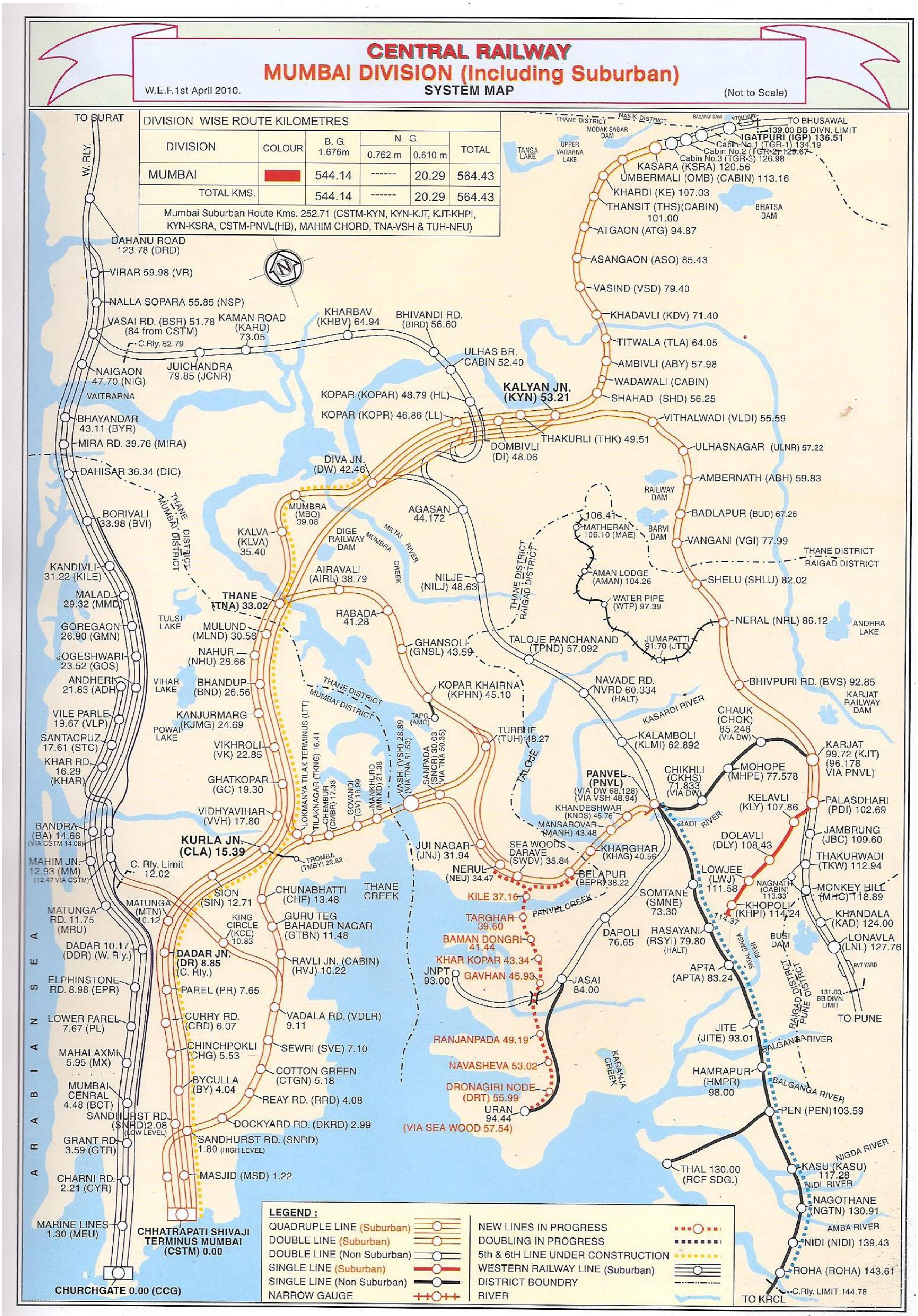

Figure 5.3: Mumbai Division: System map
Source: Central Railway, https://cr.indianrailways.gov.in

Chapter 6

Results and Discussion

This chapter presents the important results obtained from the case study. Section 6.1 discusses the effect on crew requirements between section-wise and integrated crew planning. The performance of the exact and heuristic approach has also been discussed in this section. Further, section 6.2 compares the heuristic's performance of policies A and B. Lastly, the possible outcomes of extending an existing crew beat have been analyzed in section 6.3.

The exact approach has been modelled in the academic version of IBM ILOG CPLEX Optimization Studio 22.1.0 (academic), and the heuristic has been coded in c++. Apart from these, google sheets have been used for data preparation and post-analysis. The computational experiments have been carried out on an Intel Xenon 3.5 GHz 64-bit personal computer with 16 GB RAM in a Windows 10 pro environment.

6.1 Section-wise v/s Integrated Planning

The results of the exact approach for the section-wise and integrated planning on tasks are presented in table 6.1. For every case, the method has been tried for different time horizons. It can be noticed that with the increase in number of tasks or/and time horizon, the number of feasible duties increases exponentially due to an explosion in combination possibilities. Therefore, the sections with fewer tasks (like Mumbai - ROHA) could be solved for a longer horizon than those with more tasks (like Mumbai- IGP). Regardless, as the problem size increases, the CP model fails to generate and print all the feasible duties in a reasonable time. Therefore, finding optimal duties for such scenarios is challenging. However, the partial solution obtained from this approach to the maximum possible time horizon serves as a reasonable lower bound to compare the heuristic solution.

The results of the heuristic approach using policies A and B are presented in tables 6.2 and 6.3, respectively. As expected, irrespective of the policy used, the number of duties generated is the same in each case, as the policy only differs in a way that who will take up the upcoming task out of all the available crew. Also, the key benefit is that the heuristic generates the complete solution in less than a second. The heuristic solution for Mumbai - RN section using policy B is shown in Appendix A.3.

The comparison of results obtained from exact and heuristic is presented in table 6.4. Irrespective of the approach, the number of duties required to cover all the tasks with integrated planning is considerably less than that of section-wise planning. It is because, with integrated planning, a crew has more possibilities for the next task and remains idle for a lesser duration, resulting in better utilization. With the heuristic, where a complete solution is obtained, it

Planning type		**Time horizon**	**Train tasks**	**Feasible duties**	**Optimal duties**	**CPU Time** (CP, SCP) (sec)
Section-wise	Mumbai - IGP	1 day	78	314	54	1, <1
		2 days	152	16,254	**54**	85, 2
		3 days	234	>100,000	-	-
	Mumbai - PUNE	1 day	51	103	40	<1, <1
		2 days	102	2,788	42	15, <1
		3 days	156	77,903	**43**	414, 11
		4 days	208	>100,000	-	-
	Mumbai - RN	1 day	23	38	19	<1, <1
		2 days	43	280	22	1, <1
		3 days	64	2,640	22	14, <1
		4 days	86	20,631	**24**	113, 2
		5 days	109	>100,000	-	-
	Mumbai - ROHA	1 day	10	17	7	<1, <1
		2 days	22	139	9	<1, <1
		3 days	32	930	9	5, < 1
		4 days	45	6,499	10	34, < 1
		5 days	55	44,936	**10**	239, 3
		6 days	67	>100,000	-	-
Integrated	Mumbai division	1 day	162	584	117	3, <1
		2 days	319	38,103	**120**	204, 10
		3 days	486	>100,000	-	-

SCP: Constraints = train tasks, Variables = feasible duties

Table 6.1: Exact method: Results

Planning type		**Train tasks** (week)	**Duties generated**	**CPU time** (sec)
Section-wise	Mumbai - IGP	538	57	<1
	Mumbai - PUNE	364	44	<1
	Mumbai - RN	154	27	<1
	Mumbai - ROHA	78	13	<1
Integrated	Mumbai division	1134	135	<1

Table 6.2: Heuristic method (Policy A): Results

Planning type		**Train tasks** (week)	**Duties generated**	**CPU time** (sec)
Section-wise	Mumbai - IGP	538	57	<1
	Mumbai - PUNE	364	44	<1
	Mumbai - RN	154	27	<1
	Mumbai - ROHA	78	13	<1
Integrated	Mumbai division	1134	135	<1

Table 6.3: Heuristic method (Policy B): Results

can be deduced that the number of duties generated is almost 4% less in the case of integrated planning. The average deviation of the heuristic solution from the lower bound derived from the partial solution obtained using the exact method is around 12%, which validates the performance of the heuristic. Further, there is a lesser deviation when the problem size is large.

Planning type		Duties Generated	
		Lower bound*	Heuristic method
Section-wise	Mumbai - IGP	54	57
	Mumbai - PUNE	43	44
	Mumbai - RN	24	27
	Mumbai - ROHA	10	13
	Total	131	141
Integrated	Mumbai division	120	135

*derived from partial solution obtained using exact method

Table 6.4: Exact v/s heuristic method: Duties generated

The existing detail book covers all the tasks of a week with 170 duties and almost 180 deadheading. The heuristic solution shows a possibility of operating all the tasks with 135 duties, i.e., almost 20% less. However, in each case, the actual crew requirement would be more than the duties to compensate for the crew members on leave, training, etc. The significant saving with the heuristic is because the existing way of planning is not fully integrated, and cycles have been constructed by considering factors like the train type (fast or slow, daily or non-daily), crew seniority, etc. This leads to under-utilization of the crew and numerous deadheading, resulting in more duties. However, this study doesn't distinguish based on the train type or crew type and assumes that any task can be assigned to any crew.

6.2 Heuristic Policy A v/s Policy B

From the previous section, it is clear that integrated planning results in better crew utilization. This is further established in the tables 6.5 and 6.6 that contains the statistics of the duty hours obtained with the heuristic using policy A and B, respectively. Note that in the case of section-wise planning, the average duty hours (or the crew utilization) is significantly low in the Mumbai - Roha section. It is due to the fact there are fewer tasks in the section to operate and that too of shorter duration, which results in longer layover time for the crew. Here, the crew utilization is a percentage of actual duty hours to the maximum possible.

Planning type		Average	Standard deviation	min	max	Crew utilization
Section-wise	Mumbai - IGP	34.86	1.89	31.58	40.0	67%
	Mumbai - PUNE	38.63	2.17	35.75	43.07	74%
	Mumbai - RN	40.17	3.66	33.08	46.58	77%
	Mumbai - ROHA	22.17	0.65	21.22	23.53	43%
Integrated	Mumbai division	37.48	3.25	28.05	46.05	72%

Table 6.5: Heuristic method (policy A): Duty hours in a week

Although the average duty hours are the same irrespective of the policy, the standard deviation is much less with policy B, i.e., the duty hours are less dispersed across the duties, hence better workload balance. The same can be observed in fig. 6.1 and 6.2, which depict the histograms

Planning type		Average	Standard deviation	min	max	Crew utilization
Section-wise	Mumbai - IGP	34.86	1.35	32.67	37.95	67%
	Mumbai - PUNE	38.63	1.64	36.75	41.83	74%
	Mumbai - RN	40.17	2.66	35.33	43.33	77%
	Mumbai - ROHA	22.17	0.69	21.02	23.43	43%
Integrated	Mumbai division	37.48	2.29	32.67	45.55	72%

Table 6.6: Heuristic method (policy B): Duty hours in a week

of duty hours obtained from the heuristic approach policy A and B, respectively.

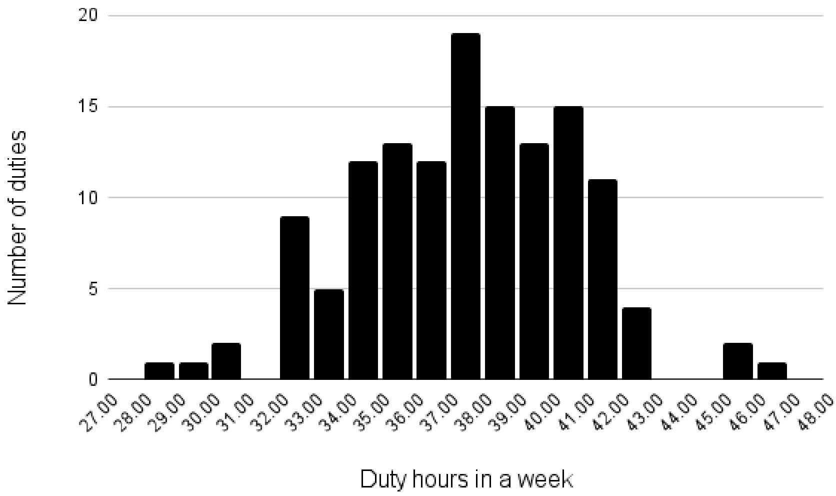

Figure 6.1: Heuristic method (policy A): Histogram of duty hours

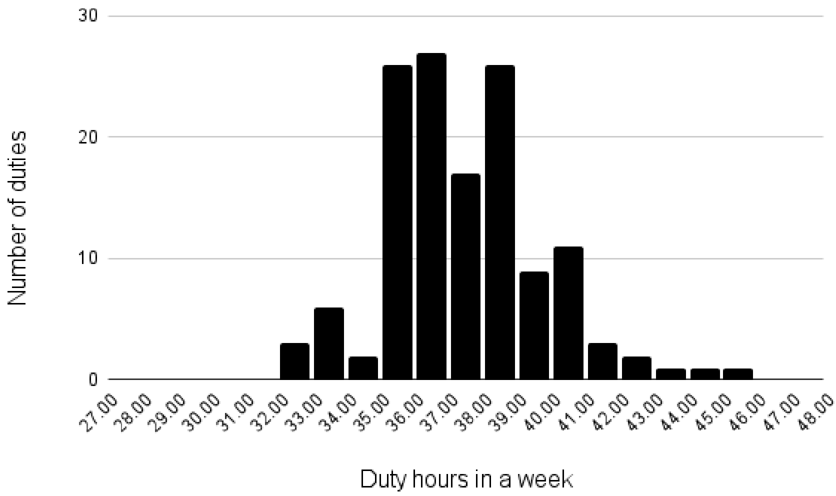

Figure 6.2: Heuristic method (policy B): Histogram of duty hours

The statistics of the waiting hours at a station after completing mandatory rest using policies A and B are shown in tables 6.7 and 6.8, respectively. The numbers are the same for every station except Mumbai, and it is because the policies differ only in the way of allocating tasks at the home base CCP (Mumbai in this case). The standard deviation is more in the case of policy B because, at the home base, the upcoming task is allocated with a sense to balance the workload among duties and not in the order of completing mandatory rest, which leads to more randomness in the waiting hours. Also, at outstation CCPs, with a high frequency of trains (like IGP and PUNE), the waiting hours are significantly lower than that with a low frequency of trains (like RN and ROHA), where it can go up to 24 hours.

CCP	Average	Standard Deviation	min	max
IGP	3.79	1.42	0.13	6.83
PUNE	4.35	2.54	0.67	9.08
RN	12.58	5.76	0.42	23.75
ROHA	14.09	4.98	4.63	21.25
Mumbai	4.84	2.19	0.33	9.38

Table 6.7: Heuristic method (policy A): Waiting hours at a CCP

CCP	Average	Standard Deviation	min	max
IGP	3.79	1.42	0.13	6.83
PUNE	4.35	2.54	0.67	9.08
RN	12.58	5.76	0.42	23.75
ROHA	14.09	4.98	4.63	21.25
Mumbai	4.84	4.68	0.08	22.83

Table 6.8: Heuristic method (policy B): Waiting hours at a CCP

From the above results, it can be noticed that although the number of duties generated is the same irrespective of the policy used, policy B performs better than policy A, as it leads to a better workload balance between duties.

6.3 Effect of extending existing Crew Beat

The Mumbai Division is considering the possibility of operating all the trains on the Mumbai - Ratnagiri route up to RN. At present, the crew of this division operates almost two-thirds of the trains up to RN and the remaining slow-speed trains up to ROHA only because of the long journey between Mumbai - RN. However, with improvement in railway infrastructure, quality of locomotives, electrification, etc., the speed of trains is increasing. Therefore, it would be possible to operate all trains up to RN in the near future. In this context, this is an attempt to analyze the possible outcomes of such a decision. Keeping everything else as it is, the updated distribution of train tasks starting on different days of a week is shown in table 6.9.

In further discussion, current scenario refers to planning with existing crew beats, and proposed scenario refers to crew beats after extending the Mumbai - ROHA to Mumbai - RN. Further, the results used for drawing a comparison across the scenarios have been obtained using the integrated crew planning and heuristic policy B; as from the previous two sections, it is clear that the former results in better performance and later improves the workload balance.

Although the number of tasks is the same in both scenarios, the total running time (or workload) has increased in proposed scenario due to the extension of a crew beat. However, it requires a

Sections	Direction	M	Tu	W	Th	F	Sa	Su	Total
Mumbai - IGP	UP	39	38	40	39	37	38	38	269
	DOWN	39	36	42	36	37	42	37	269
Mumbai - PUNE	UP	26	25	27	26	25	27	26	182
	DOWN	25	26	27	26	25	27	26	182
Mumbai - RN	UP	17	16	14	17	16	21	15	116
	DOWN	16	16	17	18	17	16	16	116
Total	-	162	157	167	162	157	171	158	1134

Table 6.9: Proposed scenario: Tasks distribution in a week

duty less to cover all the tasks as shown in table 6.10. Moreover, all tasks between ROHA - RN are also covered, which otherwise have to be operated by crew of Ratnagiri division.

Scenario	Duties Generated	
	Lower bound*	Heuristic method
Current	120	135
Proposed	121	134

*derived from partial solution obtained using exact method

Table 6.10: Proposed v/s current scenario: Duties generated

The duty hours statistics obtained in both the scenarios, shown in table 6.11, also suggest that the crew utilization improves significantly in scenario II. The histogram of duty hours in proposed scenario is shown in fig. 6.3.

Scenario	Average	Standard deviation	min	max	Crew utilization
Current	37.48	2.29	32.67	45.55	72%
Proposed	40.48	2.71	35.08	51.0	78%

Table 6.11: Proposed v/s current scenario: Duty hours in a week

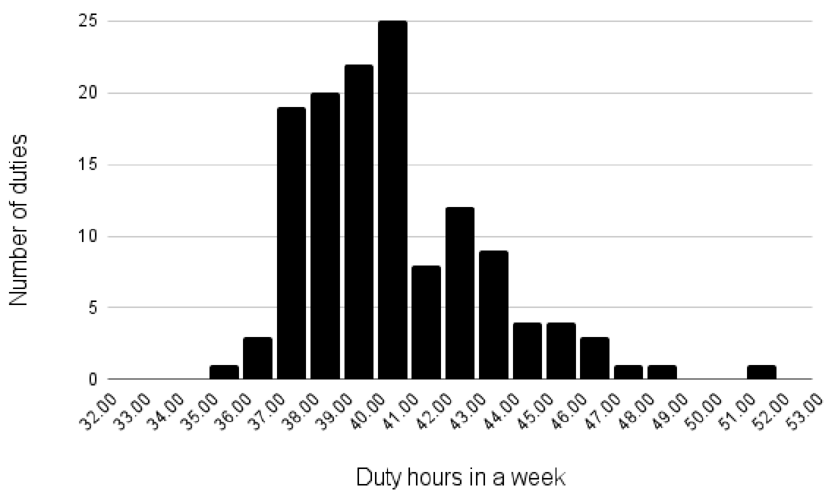

Figure 6.3: Proposed scneario: Histogram of duty hours

The improvement in crew utilization is mainly because of two complementary reasons. Firstly, the Mumbai - ROHA crew beat with lower crew utilization will no longer exist. Secondly, due to the increased number of tasks in the Mumbai - RN crew beat, the layover time for the crew at RN will reduce. The same can be observed by comparing the average and maximum waiting times at RN in table 6.12 to that in table 6.8.

CCP	**Average**	**Standard Deviation**	**min**	**max**
IGP	3.79	1.42	0.13	6.83
PUNE	4.35	2.54	0.67	9.08
RN	7.20	3.14	0.42	14.50
Mumbai	4.83	5.37	0.08	30.08

Table 6.12: Proposed scenario: Waiting hours at a CCP

Therefore, the above results show a substantial positive impact on the duty requirement and crew utilization after extending the crew beat Mumbai - ROHA up to RN.

Chapter 7

Conclusion

Crew scheduling problems are complex, and finding an optimal solution for large-size, real-life instances is a challenge due to an explosion in combination possibilities. The critical difference between the literature reviewed and crew scheduling in the Indian context is the constraints that govern it, like mandatory rest after every task depending on the station and traversal time of the previous task, return of the crew to home within a stipulated time, etc. Also, in the case of long-distance service, there are additional challenges due to the heterogeneity of tasks on different days of the week and tasks spanning over multiple days.

This work first implements an exact approach based on a combination of constraint programming and set covering formulations. However, this approach can only be used for solving smaller problem instances. Therefore, to counter this limitation, a heuristic approach has been proposed by extending the idea of the classic bin-packing problem, which is the main deliverable of this study. The heuristic is computationally efficient and capable of generating good-quality solutions quickly, providing a better alternative to the existing manual crew scheduling procedure. Additionally, it provides a means to foresee the possible consequences of any crew-related decisions.

The heuristic performs well on Mumbai Division real data sets and shows a possibility of reducing the total duties requirement by around 20%. The study also recommends integrated crew planning over section-wise planning as the former result in better crew utilization. Specific to the Mumbai Division, their intent to extend a crew beat of Mumbai - ROHA up to RN seems to be a viable option as it could further improve crew utilization. Lastly, the heuristic approach can be extended to other railway networks in different geographies with appropriate modifications.

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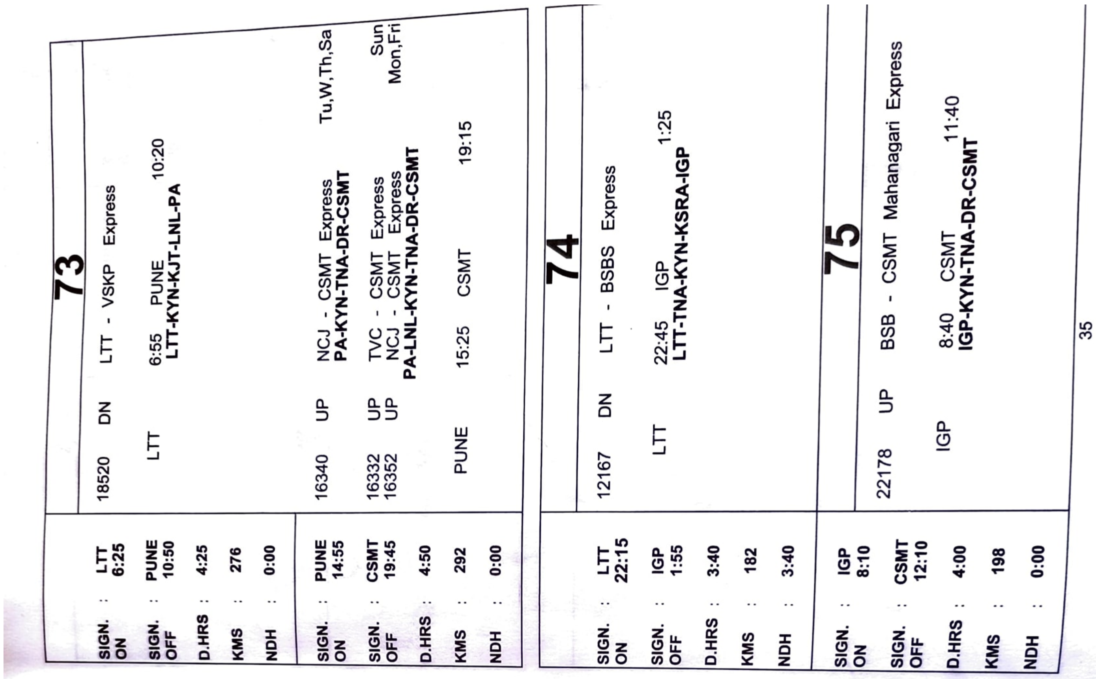
Appendix A

Appendix

A.1 Snapshot of train timetable

Train Number	Train Name	Origin	Departure Time	Destination	Arrival Time	Travel Time	Days of Run						
							M	Tu	W	Th	F	Sa	Su
11003	TUTARI EXPRESS	DR	00:05	ROHA	02:50	02:45:00	Y	Y	Y	Y	Y	Y	Y
22177	MAHANAGARI EXP	CSMT	00:10	IGP	03:00	02:50:00	Y	Y	Y	Y	Y	Y	Y
12811	HATIA EXPRESS	LTT	00:15	IGP	02:50	02:35:00	Y	N	N	N	N	N	Y
12879	LTT BBS EXP	LTT	00:15	IGP	02:50	02:35:00	N	N	Y	N	N	Y	N
22848	LTT VSKP EXP	LTT	00:15	IGP	02:50	02:35:00	N	Y	N	N	N	N	N
22865	LTT PURI EXP	LTT	00:15	IGP	02:50	02:35:00	N	N	N	Y	N	N	N
22538	KUSHINAGAR EXP	LTT	00:35	IGP	03:15	02:40:00	Y	Y	Y	Y	Y	Y	Y
12741	VSG PATNA EXP	RN	00:35	KYN	07:27	06:52:00	N	N	N	Y	N	N	N
11099	MAO DOUBLEDECK	LTT	00:45	ROHA	03:15	02:30:00	N	N	N	N	N	Y	N
18519	VSKP LTT SPL	PUNE	00:50	LTT	04:15	03:25:00	Y	Y	Y	Y	Y	Y	Y
22115	LTT KRMI EXP	LTT	00:50	RN	06:25	05:35:00	N	N	N	Y	N	N	N
12702	HUSSAIN SAGAR	PUNE	01:15	CSMT	04:55	03:40:00	Y	Y	Y	Y	Y	Y	Y
22104	AYC LTT EXP	IGP	01:25	LTT	03:55	02:30:00	N	N	N	Y	N	N	N
12102	SHM LTT SUF EXP	IGP	01:25	LTT	03:55	02:30:00	N	Y	Y	N	Y	Y	N
11140	GDG CSMT EXP	PUNE	01:25	CSMT	05:10	03:45:00	Y	Y	Y	Y	Y	Y	Y
18030	Express	IGP	01:40	LTT	04:05	02:25:00	Y	Y	Y	Y	Y	Y	Y
12810	HWH CSMT SF EXP	IGP	01:50	CSMT	04:25	02:35:00	Y	Y	Y	Y	Y	Y	Y
12132	Express	IGP	02:00	DR	04:30	02:30:00	Y	N	Y	N	Y	N	N
22158	MS CSMT EXP	PUNE	02:00	CSMT	05:50	03:50:00	Y	Y	Y	Y	Y	Y	Y
11022	TEN DR EXPRESS	PUNE	02:10	DR	05:30	03:20:00	N	N	Y	N	N	Y	Y
11036	SHARAWATI EXP	PUNE	02:10	DR	05:30	03:20:00	Y	N	N	N	N	N	N
11006	CHALUKYA EXP	PUNE	02:10	DR	05:30	03:20:00	N	Y	N	Y	Y	N	N
20104	GKP LTT SF EXP	IGP	02:15	LTT	04:35	02:20:00	Y	Y	Y	Y	Y	Y	Y
11028	PVR DR EXPRESS	PUNE	02:28	DR	06:35	04:07:00	N	Y	Y	N	N	N	Y
11042	SNSI DR EXP	PUNE	02:28	DR	06:35	04:07:00	Y	N	N	Y	Y	Y	N
11402	Nandigram Express	IGP	02:45	CSMT	05:35	02:50:00	Y	Y	Y	Y	Y	Y	Y
12116	SIDDHESHWAR EXP	PUNE	02:55	CSMT	06:35	03:40:00	Y	Y	Y	Y	Y	Y	Y
12545	KARMBHOOMI EXP	IGP	03:00	LTT	05:30	02:30:00	N	N	N	N	N	Y	N
12152	SHM LTT SUF EXP	IGP	03:00	LTT	05:30	02:30:00	Y	N	N	N	N	N	Y
15101	CPR LTT EXP	IGP	03:00	LTT	05:30	02:30:00	N	N	N	Y	N	N	N
12174	PBH LTT EXPRESS	IGP	03:00	LTT	05:30	02:30:00	N	N	Y	N	Y	N	N
17317	UBL DR EXPRESS	PUNE	03:10	DR	07:00	03:50:00	Y	Y	Y	Y	Y	Y	Y
15267	JANSADHARAN EXP	IGP	03:15	LTT	05:50	02:35:00	Y	N	N	N	N	N	N
15547	ANTYODYA EXP	IGP	03:15	LTT	05:50	02:35:00	N	N	Y	N	N	N	N
12361	ASN CSMT EXP	IGP	03:15	CSMT	06:00	02:45:00	N	Y	N	N	N	N	N
11004	TUTARI EXPRESS	ROHA	03:33	DR	06:40	03:07:00	Y	Y	Y	Y	Y	Y	Y
12112	AMI CSMT SF EXP	IGP	03:35	CSMT	06:15	02:40:00	Y	Y	Y	Y	Y	Y	Y
17412	MAHALAXMI EXP	PUNE	03:35	CSMT	07:25	03:50:00	Y	Y	Y	Y	Y	Y	Y
12106	VIDARBHA EXP	IGP	03:50	CSMT	06:50	03:00:00	Y	Y	Y	Y	Y	Y	Y
12618	MNGLA LKSDP EXP	IGP	03:55	PNVL	07:00	03:05:00	Y	Y	Y	Y	Y	Y	Y
22144	BIDR CSMT EXP	PUNE	04:15	CSMT	07:55	03:40:00	Y	N	N	N	Y	N	Y
22108	LATUR CSMT EXP	PUNE	04:15	CSMT	07:55	03:40:00	N	Y	Y	Y	N	Y	N
12978	MARU SAGAR EXP	BSR	04:15	RN	10:00	05:45:00	N	N	N	N	N	Y	N
17058	Devgiri Express	IGP	04:25	CSMT	07:10	02:45:00	Y	Y	Y	Y	Y	Y	Y

A.2 Snapshot of detail book



73

SIGN. ON	:	LTT 6:25
SIGN. OFF	:	PUNE 10:50
D.HRS	:	4:25
KMS	:	276
NDH	:	0:00

18520 DN LTT - VSKP Express
LTT 6:55 PUNE 10:20
LTT-KYN-KJT-LNL-PA

SIGN. ON	:	PUNE 14:55
SIGN. OFF	:	CSMT 19:45
D.HRS	:	4:50
KMS	:	292
NDH	:	0:00

16340 UP NCJ - CSMT Express Tu,W,Th,Sa
PA-KYN-TNA-DR-CSMT
16332 UP TVC - CSMT Express Sun
16352 UP NCJ - CSMT Express Mon,Fri
PA-LNL-KYN-TNA-DR-CSMT
PUNE 15:25 CSMT 19:15

74

SIGN. ON	:	LTT 22:15
SIGN. OFF	:	IGP 1:55
D.HRS	:	3:40
KMS	:	182
NDH	:	3:40

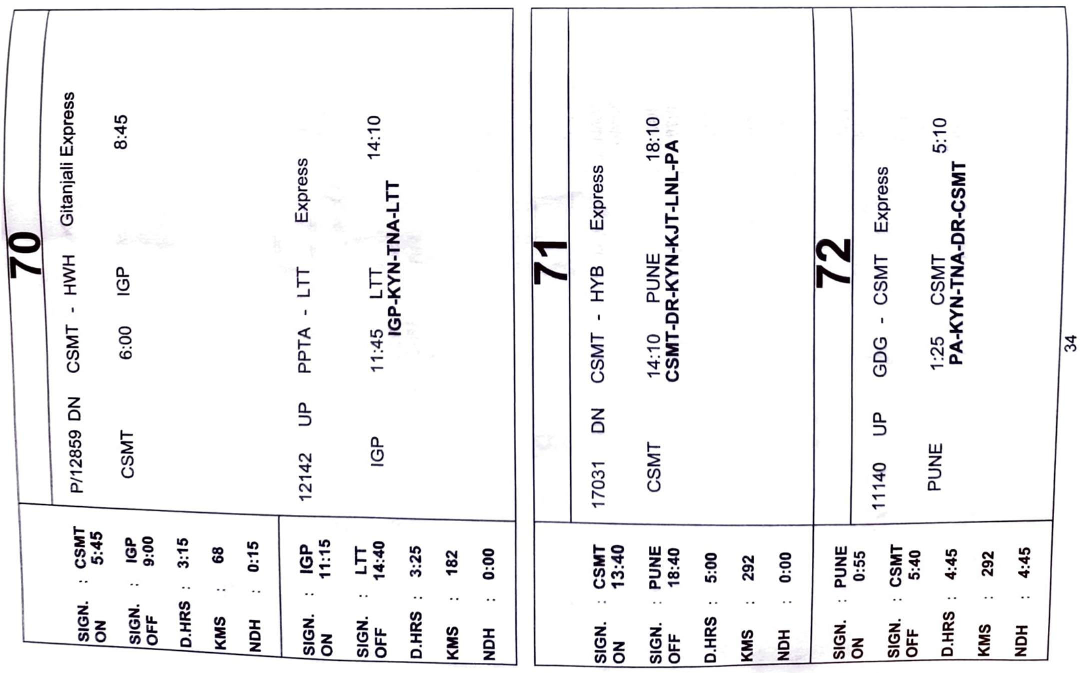
12167 DN LTT - BSBS Express
LTT 22:45 IGP 1:25
LTT-TNA-KYN-KSRA-IGP

75

SIGN. ON	:	IGP 8:10
SIGN. OFF	:	CSMT 12:10
D.HRS	:	4:00
KMS	:	198
NDH	:	0:00

22178 UP BSB - CSMT Mahanagari Express
IGP 8:40 CSMT 11:40
IGP-KYN-TNA-DR-CSMT

35



70

SIGN. ON	:	CSMT 5:45
SIGN. OFF	:	IGP 9:00
D.HRS	:	3:15
KMS	:	68
NDH	:	0:15

P/12859 DN CSMT - HWH Gitanjali Express
CSMT 6:00 IGP 8:45

SIGN. ON	:	IGP 11:15
SIGN. OFF	:	LTT 14:40
D.HRS	:	3:25
KMS	:	182
NDH	:	0:00

12142 UP PPTA - LTT Express
IGP 11:45 LTT 14:10
IGP-KYN-TNA-LTT

71

SIGN. ON	:	CSMT 13:40
SIGN. OFF	:	PUNE 18:40
D.HRS	:	5:00
KMS	:	292
NDH	:	0:00

17031 DN CSMT - HYB Express
CSMT 14:10 PUNE 18:10
CSMT-DR-KYN-KJT-LNL-PA

72

SIGN. ON	:	PUNE 0:55
SIGN. OFF	:	CSMT 5:40
D.HRS	:	4:45
KMS	:	292
NDH	:	4:45

11140 UP GDG - CSMT Express
PUNE 1:25 CSMT 5:10
PA-KYN-TNA-DR-CSMT

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A.3 Heuristic solution (policy B): Mumbai - RN

Duty	Tasks - Run 1	Tasks - Run 2	Tasks - Run 3
1.	1 24 41 91 109 140	11 39 65 103 122 150	23 44 71 102 119 144
2.	2 15 42 58 108 125 153	29 46 74 98 116 138	10 51 77 112 132
3.	3 19 47 65 121 147	20 50 76 95 128 152	25 54 82 97 126 151
4.	4 16 45 62 104 124 146	19 38 64 91 109 149	21 45 73 99 118 142
5.	5 21 69 80 113 134	12 36 59 79 113 134	12 36 59 79 113 134
6.	6 27 48 70 83 133	6 27 55 94 111	2 30 68 86 121 147
7.	7 38 56 81 95 130	1 28 57 104 124 146	19 38 64 91 109 149
8.	8 32 52 89 105 136	8 32 58 106 127	4 31 53 78 117 143
9.	9 34 54 90 107 137	9 37 62 90 107 140	11 39 65 103 122 150
10.	10 39 57 85 97 135	7 47 75 110 131	3 33 88 101 130
11.	11 37 55 88 101 129 154	26 56 81 96 135	7 47 75 110 131
12.	12 29 46 64 94 111	2 30 68 86 121 147	20 50 76 95 128 152
13.	13 30 51 67 126 151	24 52 85 100 123 148	22 49 72 93 136
14.	14 31 53 71 115 141	14 41 70 92 133	6 27 55 94 111
15.	17 33 68 79 103 122	4 31 53 78 117 143	17 43 66 84 129 154
16.	18 35 60 74 102 119	3 33 88 101 130	1 28 57 104 124 146
17.	20 40 63 75 120 145	18 48 69 87 115 141	14 41 70 92 133
18.	22 36 59 73 98 116 144	16 42 67 108 125 153	29 46 74 98 116 138
19.	23 44 61 82 96 138	10 51 77 112 132	5 35 63 83 114 139
20.	25 43 66 77 112 132	5 35 63 83 114 139	13 40 60 80 120 145
21.	26 49 72 87 128 152	25 54 82 97 126 151	24 52 85 100 123 148
22.	28 50 76 92 114 139	13 40 60 80 120 145	18 48 69 87 115 141
23.	78 99 118 142	15 34 61 89 105 137	9 37 62 90 107 140
24.	84 106 127 150	23 44 71 102 119 144	16 42 67 108 125 153
25.	86 110 131 149	21 45 73 99 118 142	15 34 61 89 105 137
26.	93 117 143	17 43 66 84 129 154	26 56 81 96 135
27.	100 123 148	22 49 72 93 136	8 32 58 106 127