Chapter 5

A Two-stage Stochastic Programming Model for Optimal Location of Accident Relief Facilities on a Railroad Network

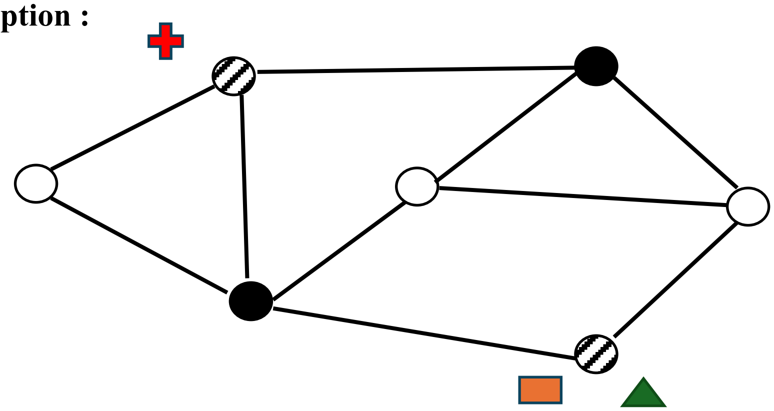
5.1. Introduction :

In this chapter, we have extended the scope of the problem of optimally locating and deploying the accident relief equipment in the Indian Railway network considering demand uncertainty. The further exploration of a completely different dimension of the problem dealt in chapter 4, which stems from the conclusions and insights made in the process of study.

In this study, a two-stage stochastic programming modelling framework is proposed for the problem where the optimal location of relief equipment is the first stage decision and the deployment of the same in case of an accident on a network link is a second stage decision. The objective is to minimize the total cost including the cost of purchase, installation and maintenance of relief equipment, the cost of deploying relief equipment in case of an accident and the cost of not responding to an accident. Various accident profiles are defined to understand the actual demand for the relief equipment after the occurrence of a specific type of accident that is the type of train that meets with an accident and the demand for the number of specific types of equipment deployed for the rescue, restoration exercise. The probability of occurrence of an accident profile is estimated from the past data of accidents in a rail network. The same network as considered in earlier chapters is considered and the case study and several managerial insights are developed.

The rest of the chapter is organized as follows; the rest of the article is organized as follows. The description of the problem is given in Section 5.2. The optimization framework is developed in Section 5.3, followed by an outline of the realistic case study setting in Section 5.4. Section 5.5 explains the method of calculation of various parameters and cost considered for the decision making, while Section 5.6 presents computational experiments. Section 5.7 introduces the concept of disutility and conducts the computational experiments. Section 5.8 discusses the results of the experiment. Section 5.9 reveals in-depth managerial insights and finally; conclusion and directions of future research is provided in the Section 5.10.

5.2. Problem Description :



	Legend		
○	Node – station/junction	🟧	ART
●	Potential station for location	✚	ARMV
▨	The existing location of relief equipment	▲	Crane

Figure 5.1: An Illustrative Example of a Network Considered in the Study.

For expositional reasons, we illustrate the problem under consideration using Figure 5.1 where nodes (represent stations) and arcs (represent links or track section connecting stations). Each track section is uniquely characterized in terms of the technical specification of rail, the flow patterns, distribution of various types of traffic over the link such as passenger trains, loaded goods trains, empty goods trains, movement of empty coaches and other miscellaneous traffic. From the disaster management perspective, the vulnerability of the link, as described in chapter 1, is considered from the point of intensity of accident, which is assumed to be depending on the type of traffic. The passenger carrying track is the most important and vulnerable section of the network because the value of human life cannot be quantified and compared to the cost of detention or any collateral damage in case of disruption of goods traffic. The point at which an accident occurs is a demand point for deployment of the relief equipment. Since an accident can occur anywhere on a rail link, each point of the arc can be considered a potential demand point.

Indian Railways maintains three types of accident relief equipment at different locations across the network, and they are accident relief train (ART), accident relief medical Equipment (ARME), and Crane. In brief, ART refers to a dedicated fleet of rolling stock that could be used for housing re-railing and rescue equipment, AMRE consists of coaches modified to host medical facilities including doctors and operation theatres, and Crane for removing structurally damaged wagons/railcars (Safety Directorate, 2016). It is pertinent that cranes cannot be deployed without ART, and that other auxiliary assets such as locomotives, trained crew, etc., are prerequisites.

Note that the three equipment have both structural and operational differences, and thus carry distinct cost and are deemed separate entities in this study. They can be demanded and operated separately or in combination with one another in the event of an accident. Operationally during an event requiring more than one of the assets like ART or Crane, it can be provided from two different ends for operational effectiveness. The possibility of an accident of specific nature and intensity, governing the demand of equipment as a combination of the equipment i.e. ART, ARMV or ART,ARMV, Crane, etc. and their deployment from a location is a primary decision. In such cases, the demand for equipment would be satisfied by supplying the necessary assets from more than one location. The demand for various types of accident relief equipment is satisfied if the relief facility available at a location can be deployed to the demand point in a specified time uniformly accepted by disaster management experts. For example, the stipulated response times for ART, ARMV and Crane to an accident site are 3 hours, 2 hours, and 4 hours, respectively. If the equipment can reach the accident site within these stipulated times, it can cover the demand or else the site is uncovered. If for any reason an accident site cannot be attended to within time, it might result in damage to the railway property, loss of revenue due to resulting congestion and most importantly loss of human life.

Given the uncertainty associated with the location and magnitude of the accident and the resulting demand for relief equipment, locating different types and quantities of relief equipment in the entire railway network is a non-trivial decision. The problem is further complicated because some nodes already possess this equipment, while new equipment might have to be purchased and installed at potential locations or they might have to be transferred from existing locations to facilitate adequate coverage to all incidents. To capture the pertinent problem dimensions, a two-stage stochastic programming framework with recourse is proposed in the next section.

5.3 Model Formulation :

In this section, we first present a two-stage stochastic programming model with recourse which is further combined as a unified optimization model.

5.3.1 Two-Stage Recourse Model :

In the two-stage recourse model, the first stage deals with the strategic decision of the location of relief equipment in the rail network either by purchasing the new equipment or by relocating the existing equipment in the network. The second stage decisions concern the deployment of relief equipment to the accident site and the coverage of accident nodes.

The mathematical model for these two stages is developed using the following notation.

Sets and Indices

J_e	Set of nodes that currently have relief equipment
J_n	Set of candidate locations for hosting the relief equipment
$J = J_e \cup J_n$	Set of all nodes (existing + new) that can host the relief equipment
F	Set of relief equipment (ART, ARMV, Crane)

<u>First-Stage Problem :</u>

Parameters :

B_j^f	Fixed cost of acquiring and installing relief equipment f *at* location $j \in J$
M_j^f	Maintenance cost for relief equipment f at location $j \in J$
C_{jk}^f	Cost of relocating relief equipment f from node $j \in J_e$ to node $k \in J$
Δ_j^f	1 if equipment type f is available at existing facility $j \in J_e$

Decision Variables :

x_j^f	1 if equipment type f is purchased/installed at $j \in J$, 0 otherwise
y_{jk}^f	1 if equipment type f is relocated from $j \in J_e$ to any other node $k \in J$, 0 otherwise
v_j^f	1 if relief equipment type f is maintained at node $j \in J$, 0 otherwise

Objective Function :

$$\textbf{Min } \sum_{f\in F}\sum_{j\in J} B_j^f x_j^f + \sum_{f\in F}\sum_{j\in J} M_j^f v_j^f + \sum_{f\in F}\sum_{j\in J_e}\sum_{k\in J} C_{jk}^f y_{jk}^f \tag{1}$$

s.t.

$$\sum_{k\in J} y_{jk}^f \le \Delta_j^f, \quad \forall j \in J_e, f \in F \tag{2}$$

$$v_j^f = x_j^f + \sum_{k\in J_e} y_{kj}^f \ , \ \forall j \in J_n, f \in F \tag{3}$$

$$v_j^f = \left(\Delta_j^f - \sum_{k\in J} y_{jk}^f\right) + \sum_{k\in J_e} y_{kj}^f \ , \ \forall j \in J_e, f \in F \tag{4}$$

$$\mathrm{v}_j^{Crane} \le \mathrm{v}_j^{ART}, \forall j \in J \tag{5}$$

$$x_j^f \in \{0,1\}, \forall j \in J, f \in F \tag{6}$$

$$y_{jk}^f \in \{0,1\}, \forall j \in J_e, k \in J, f \in F \tag{7}$$

$$v_j^f \in \{0,1\}, \forall j \in J, f \in F \tag{8}$$

The objective function (1) aims to minimize the total cost which is the sum of equipment purchase and installation cost, the fixed operational (maintenance) cost of the equipment and the cost of relocating relief equipment in the network. Constraint (2) ensures that a relief equipment can be relocated from a node only if it already exists at the node. Constraint (3) enforces that relief equipment can be operated from a candidate node only if the equipment is either purchased/established at that node or is relocated from a node that already has it. Similarly, an existing location can maintain relief equipment only if it already has the equipment (that is NOT relocated anywhere) or it has obtained the equipment through relocation from another node. It is ensured through Constraint (4). Constraint (5) warrants that for housing a Crane, ART is a pre-requisite for any node. Finally, Constraints (6)-(8) define the nature of the decision variables.

Second Stage Problem :

Random variables associated with an outcome ω: $\zeta(\omega) = (i, a)$ where

$i \in I$: Set of possible accident locations (or links)

$a \in A$: Set of possible accident profiles

Parameters

p_{ia}	Probability of accident of type *a* at the link *i*.
E_{ia}	Cost of Not covering (i.e. penalty associated with) accident of type *a* at link *i*.
R_{ija}^f	Cost of responding with a relief equipment *f* from facility $j \in J$ to an accident of type a at site *i*

α_{ij}^{f}	1 if to accident site *i* can be covered (responded) by a node at $j \in J$ by a facility *f* within a predefined threshold limit, 0 otherwise
D_{a}^{f}	Demand (requirement) of relief equipment of type *f* in case of an accident type a

<u>Decision variables :</u>

η_{ia}	1 if the accident of type *a* at link *i* is covered; 0 otherwise
ϖ_{ija}^{f}	1 if relief equipment *f* is deployed from facility *j* to cover an accident of type a at link i, 0 otherwise.

Now, for any first stage solution $(V) : v_j^f, \forall j \in J, f \in F$ that is response facilities where relief equipment *f* is operated/maintained and for any given scenario (i, a) the second stage recourse problem is $Q = (V, i, a) = Q(V, \zeta)$:

$$\textbf{Min. } \sum_{a\in A}\sum_{i\in I} E_{ia}(1-\eta_{ia}) + \sum_{f\in F}\sum_{a\in A}\sum_{j\in J}\sum_{i\in I} R_{ija}^{f}\varpi_{ija}^{f} \tag{9}$$

s.t.

$$\varpi_{ija}^{f} \le \alpha_{ij} v_j^{f}, \quad \forall j \in J, f \in F \tag{10}$$

$$\sum_{j\in J}\varpi_{ija}^{f} \ \ge\ \left(\mathrm{D}_a^{f}\right)\eta_{ia}, \ \forall i \in I, a \in A, f \in F \tag{11}$$

$$\eta_{ia} \in (0,1), \ \forall i \in I, a \in A \tag{12}$$

$$\varpi_{ija}^{f} \in (0,1), \forall i \in I, a \in A, f \in F \tag{13}$$

In this model, the Objective function (9) is to minimize the total cost of not responding to an accident and the cost of deploying equipment at the accident site from the given location. Constraint (10) is a dual intent constraint. It ensures that relief equipment can be responded from a facility to an accident site only if the facility is within the critical distance α_{ij} and the facility has the desired equipment operative that is $v_j^f = 1$ for equipment $f \in F$ at node $\in J$. Here, it should be noted that the value of variable v_j^f are obtained from the solution of the first stage problem. Constraint (11) requires that the accident of type a at node (arc) i is assumed to be covered only if the node receives the required number of response equipment. Finally, Constraints (13) and (14) depict the nature of the decision variables.

5.3.2 The Unified Model :

As presented in (Birge & Louveaux, 1988), the two-stage stochastic programming problem with recourse can be modelled as a single optimization model that has both deterministic and stochastic elements. Accordingly, we present a unified single optimization problem for our case as follows.

Objective Function :

Min. $\sum_{f\in F}\sum_{j\in J} B_j^f x_j^f + \sum_{f\in F}\sum_{j\in J} M_j^f v_j^f + \sum_{f\in F}\sum_{j\in J_e}\sum_{k\in J} C_{jk}^f y_{jk}^f + \sum_{i\in I}\sum_{a\in A} p_{ia}\left(E_{ia}(1-\eta_{ia}) + \sum_{j\in J}\sum_{f\in F} R_{ija}^f \varpi_{ija}^f\right)$ (14)

s.t.

$$\sum_{k\in J} y_{jk}^f \leq \Delta_j^f, \quad \forall j \in J_e, f \in F \qquad (15)$$

$$v_j^f = x_j^f + \sum_{k\in J_e} y_{kj}^f, \ \forall j \in J_n, f \in F \qquad (16)$$

$$v_j^f = \left(\Delta_j^f - \sum_{k\in J} y_{jk}^f\right) + \sum_{k\in J_e} y_{kj}^f, \ \forall j \in J_e, f \in F \qquad (17)$$

$$\mathrm{v}_j^{Crane} \leq \mathrm{v}_j^{ART}, \forall j \in J \qquad (18)$$

$$\varpi_{ija}^{f} \leq \alpha_{ij} v_j^{f}, \quad \forall j \in J, f \tag{19}$$

$$\textstyle\sum_{j \in J} \varpi_{ija}^{f} \;\geq\; (\theta_a^{f}) \eta_{ia}, \; \forall i \in I, a, f \tag{20}$$

$$x_j^{f} \in \{0,1\}, \forall j \in J, f \in F \tag{21}$$

$$y_{jk}^{f} \in \{0,1\}, \forall j \in J_e, k \in J, f \in F \tag{22}$$

$$v_j^{f} \in \{0,1\}, \forall j \in J, f \in F \tag{23}$$

$$\eta_{ia} \in (0,1), \; \forall i \in I, a \in A \tag{24}$$

$$\varpi_{ija}^{f} \in (0,1), \forall i \in I, a \in A, f \in F \tag{25}$$

The objective function and the constraints of the unified model bear the same meaning as explained in the case of the individual problems.

5.4 The Case Study:

The vast railroad network in India is strategically divided into 16 zones. For the purpose of this study the same network as considered earlier is taken as base for the case study. The North Central Railway (NCR), one of the most important zones, provides the realistic infrastructure for the case study. NCR plays a crucial role in the transportation of freight and passenger over its 10K km network and connects major ports to important inland terminals (Indian Railways, 2016). Figure 5.2 provides the geographical overview of the NCR network, which spans five states and is divided into three divisions: Prayagraj; Jhansi; and Agra. It is important to note that this network is larger and denser than many national networks around the world.

Disaster management is a centrally controlled exercise, and the location of equipment in the zone is decided by the headquarters situated at Prayagraj. The capital-intensive relief equipment is shared both by adjacent divisions, and railway zones. Consequently, we have considered the coverage of nearby zones and those of assets located in neighbouring divisions DDU (Deendayal Upadhyay), NDLS (New Delhi), JP (Jaipur), and BINA (Bina). The network of NCR railways is considered with the approach that any section connecting two major stations forming a vital link of the network can be modified by augmenting intermediate stations and making the connecting link smaller for practical purposes. Therefore, bigger sections initially considered for the study are fragmented into smaller sections with intermediate stations. The modified network gives mathematical flexibility for the calculation of various data related to the characteristics of the section. After the above modifications, we have 132 links and 105 nodes representing the entire network including the neighbouring stations of the adjacent zonal railway. In addition, there are 12 ART, 8 ARMV, and 7 Cranes available in the NCR network to be sited. The average travel speed of relief facilities is 75 kmph and, as indicated earlier, the maximum allowable response times are 3 hours for ART, 2 hours for ARMV, and 4 hours for Cranes. Finally, a total of 33 candidate sites have been identified for locating the relief facilities. Table 5.1 provides a snapshot of the relief assets at different stations across the NCR and neighbouring divisions.

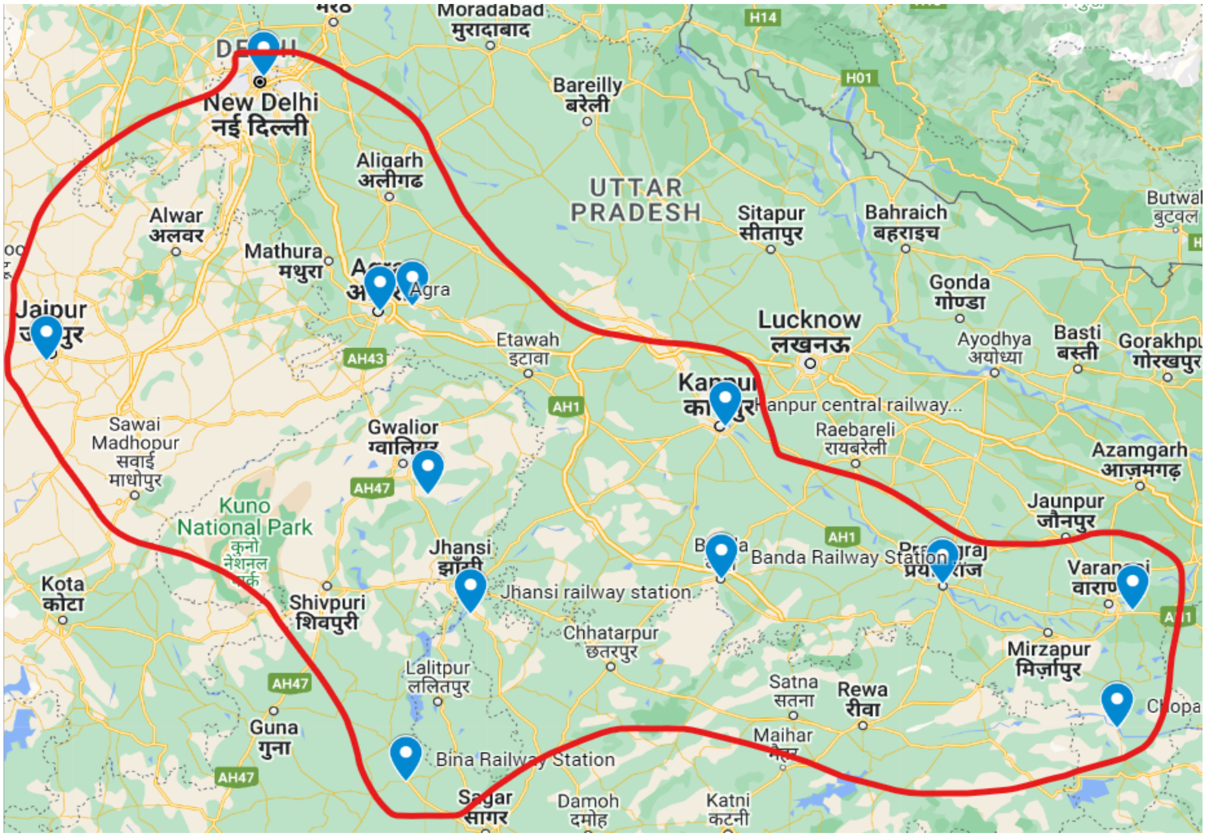


Figure 5.2: Existing Relief Facility Locations in NCR Zone

It should be noted that Tables 5.1 is reproduced from chapter 4 (Tripathi et al., 2022) . For the comparison, we have followed the same rail network of the NCR zone of Indian railways by keeping all the parameters the same. The previous concluded that the suggestion for site location made by the railway authority was restrictive and hence new sites were explored in the process of study. The above study had thrown open new dimensions of study from different perspectives.

The major difference between the two studies is the consideration of uncertainty in demand and analysis of the past accident data. The parameters related to the uncertainty and other newly introduced parameters are explained in detail in the subsequent section.

Table 5.1: Current Location of the Accident Relief Facilities

Sr. No.	Station name	Station Code	Zone	Relief facilities		
				ART	ARMV	Crane
1	Prayagraj	PRYJ	NCR	✓	✓	
2	Kanpur	CNB		✓	✓	✓
3	Banda	BANDA		✓		
4	Tundla	TDL		✓		
5	Jhansi	JHS		✓	✓	✓
6	Agra	AGC		✓	✓	✓
7	Gwalior	GWL		✓		
8	Deendayal Upadhyay	DDU	ECR	✓	✓	✓
9	Jaipur	JP	NWR	✓	✓	✓
10	Bina	BINA	WCR	✓	✓	✓
11	Chopan	CPU	ECR	✓		
12	New Delhi	NDLS	NR	✓	✓	✓

5.5. Estimation of Probability :

In this section, we provide details on how pertinent parameters were estimated for the case study.

5.5.1 Probability of an Accident :

We have relied on extant literature to identify pertinent factors that can cause a railroad accident, and they are: total track length of the section being studied; total number of trains operating on that section in a specific time period (monthly for our study); and total number of a specific train type operating on the section. In this case study, the network traffic is divided into 4 types of trains: passenger trains; freight trains; freight trains hauling empty wagons; and, other miscellaneous movements required for maintenance, repositioning of passenger cars or engines, etc. We define the probability of an accident on track-section *S* of length *l* as:

$$\mathrm{P}(\mathrm{S}_l) = \frac{\mathrm{s_l}}{\mathrm{S_T}} \qquad (26)$$

where, $\mathrm{s_l}$ is the track length of the section and $\mathrm{S_T}$ is the total track length of the network. The probability of an accident of a train in a specific section of the network is defined as:

$$\mathrm{P}(\mathrm{t_{SN}}) = \frac{\mathrm{T_{St}}}{\mathrm{T_{Nt}}} \qquad (27)$$

where, $\mathrm{T_{St}}$ is the total number of trains in the section and $\mathrm{T_{Nt}}$ is the total number of trains over the rail network. The total number of trains in a section (i.e., T_{St}) is equal to the sum of the number of passenger trains (T_p), number of freight trains (T_g), number of freight trains hauling empty wagons (T_w), and the number of miscellaneous trains (T_{ms}), i.e., $T_{St} = T_p + T_g + T_w + T_{ms}$. On the other hand, the total number of trains in the network $T_{Nt} = \sum_s T_{St}$.

Consequently, the probability of accident of a specific train type *A* on a given section is the ratio of the number of trains of the given type ($\mathrm{T_a}$) to the total number of trains (T_{St}), i.e.,

$$\mathrm{P}(\mathrm{S_{At}}) = \frac{\mathrm{T_a}}{T_{St}} \qquad (28)$$

Hence, the probability of an accident of a specific type of train on a given section of the network is:

$$P(S_{AN}) = P(S_l) * P(t_{SN}) * P(S_{At}) \qquad (29)$$

i.e., the probability of an accident of a specific type of train on a given section of the network is the product of three probabilities: the probability of an accident in the given section; the probability of an accident of a train in the section depending on the total number of trains in the section; and the probability of the accident of a specific type of train in the section.

5.5.2 Estimation of Equipment Demand :

The demand for relief equipment is the number of units of that equipment ordered in case of an accident. This demand varies based on magnitude and location of accident. For example, in case of a minor derailment, ART is sufficient to restore the traffic whereas a major derailment needs both ART and Crane. Similarly, in case of collision and potential human injuries, ARMV is also requested in addition to the other equipment. It is also a common practice to request two similar pieces of equipment from different locations in case of a major accident or if an accident occurs at a remote location. From the analysis of past accident data from North Central Railway (NCR) from April 2003 to December 2021, we have identified 106 total accidents in which relief equipment were demanded and six different combinations of such equipment use. The same was also verified with the officers and staff who order the movement of ART/ARMV/CRANE during the actual situation. Thus, we have identified six possible patterns in which the relief equipment can be deployed/ordered, and they are termed as Demand Patterns as indicated in Table 5.2.

Table 5.2: Demand Patterns for Relief Equipment

Demand Pattern	**Number of relief equipment requested**			**Frequency**	**Probability**
	ART	**ARMV**	**Crane**		
Demand Pattern I	1	0	0	19	0.179
Demand Pattern II	1	0	1	41	0.386
Demand Pattern III	1	1	0	26	0.245

Demand Pattern IV	1	1	1	12	0.113
Demand Pattern V	2	2	2	6	0.056
Demand Pattern VI	2	0	2	2	0.018
			Total	106	

As is already mentioned above, any equipment can be ordered as an individual or a combination of them as a single consist. Depending on the severity of the accident the demand for multiple numbers of equipment of the same type as two ARTs or a combination of more than one equipment is needed to be deployed at the accident site. The combination of the demand requiring more than 2 sets is practically infeasible because these assets are linearly deployed along the track. There are only two ends of a track where the demand might have occurred due to an accident in the section. The probability of occurrence of these demands, $P(D)$, is calculated from the frequency of occurrence observed from historical data. For example, the demand pattern I (only ART) is observed in 19 out of a total 106 accidents. Thus, the probability of Demand Pattern I is calculated as 0.179. The frequency of specific demand patterns and the corresponding probability are as given in columns 5 and 6 of Table 3, respectively. This probability is used to calculate the probability of an accident profile as explained in the next subsection. Details mentioned in Annexure-B

5.5.3 Enumeration of Accident Profiles :

As indicated earlier, four specific types of train traffic considered in this study: passenger train; goods train; empty wagon; and miscellaneous train traffic. Therefore, an accident refers to involvement of a specific type of train. These four train traffic types in the combination of six different demand patterns (as explained in the previous sub-section) would result in 24 accident profiles as shown in Table 5.3.

Table 5.3: Construction of Accident Profiles

Type of rail involved in accident in a section	**Demand patterns**					
	Demand Pattern I	Demand Pattern II	Demand Pattern III	Demand Pattern IV	Demand Pattern V	Demand Pattern VI
Passenger train	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6
Goods train	Profile 7	Profile 8	Profile 9	Profile 10	Profile 11	Profile 12
Empty wagon train	Profile 13	Profile 14	Profile 15	Profile 16	Profile 17	Profile 18
Miscellaneous train	Profile 19	Profile 20	Profile 21	Profile 22	Profile 23	Profile 24

Thus, the accident profile is defined as the combination of the type of the train involved in the accident and the demand for relief equipment for rescue and restore operations. For example, the accident of a passenger train that needs only ART to be called for restoration (Demand Pattern I) indicates Accident Profile 1. Similarly, a major accident of Goods train that requires all three-relief equipment – ART, ARMV and Crane for relief operations (Demand Pattern IV) defines profile 10. In this way, a total 24 profiles are defined in Table 5.3.

The probability of occurrence of an accident profile (Af) can be calculated as the product of the probability of accident of a specific train in a section (S_{AN}) and the corresponding demand profile for that train (D), as given in equation (34).

$$P(Af) = P(S_{AN}) * P(D) \tag{34}$$

5.5.4 Calculation of Various Costs Considered in the Problem :

5.5.4.1 Cost of Purchase of New Assets :

The cost of the assets is taken based on market survey and existing orders of manufacturing of the equipment by Indian Railways. In fact, the Crane is assembled at a workshop owned by the Eastern Railway. The orders for manufacturing of CRANES are placed by various zonal railways after the due sanction is granted by the Ministry of Railways. The 'ART' and 'ARME' are assembled out of old and refurbished coaches suitably modified in the maintenance workshops. The modified coaches are then equipped with desired components by procuring them from the open market. So, while calculating the cost of an asset like ART or ARME various factors and associated costs are considered to arrive at the approximate cost of the final asset. Based on these data the cost is approximately calculated as INR 40,000,000 for ART; INR 100,000,000 for Crane and INR 5,000,000 for ARMV, respectively.

5.5.4.2 Cost of Construction of the Facility for Homing the Assets :

The cost of construction of the facility is taken as the approximate cost of constructing a shaded facility for housing the assets which are INR 50,000,000. All three assets are assumed to be homed at the newly constructed facility. The cost of construction is estimated based on the actual requirement of the shaded area, the track length required for housing the assets, the construction of a pit for the regular requirement of under gear examination, and the minimum facility required for staff for their official functioning.

The store requirement for keeping spare and consumables is also considered while estimating the cost of construction of a new asset. However, for practical purposes, the cost of the asset is varied for the case where one or two assets are already available. The existing facility is only needed to be augmented for capacity by adding certain additional facilities to an existing facility. Therefore, it is assumed that the cost of argumentation of a facility is only 10 % of the cost of constructing a new facility if the existing facility houses at least two assets. Similarly, the cost of construction of augmenting a facility is assumed to be 30 % of the cost of constructing a new facility if the existing facility homes one of the assets.

5.5.4.3 Cost of Maintenance of the Assets :

The cost of maintaining an asset is assumed to be a fixed percentage of the cost of the asset itself. The maintenance cost includes the depreciation cost of the asset. In this study the maintenance cost of the asset is considered to be affected by the location of the assets. Because these assets are unique and dedicated for railways use, therefore availability of expert staff, suitable spares and technical support available at the proximity of the location of the assets has a bearing on the overall maintenance cost of the assets. In this case, the cost is assumed to vary with the number of assets available at a specific location. In case, the location already hosts at least one facility, it is always possible to get the benefit of sharing the resources like manpower and common consumables. The previous existing facility at a location has the possibility of having induced a suitable market for the maintenance requirements. Therefore, a cost of half of the maintenance cost of an individual asset is considered to be added to the overall maintenance cost where one of the facilities already exists and one-third of the cost is considered to be added to existing expenditure in case there are two facilities already existing.

5.5.4.4. Cost of Response and Cost of Not Responding to an Accident :

The performance of the location decision is majorly dependent on the cost of responding to an event on the network. This cost consists of three primary costs viz. cost of transportation of assets to the accident site from their base location, the cost of restoration including the man and material needed at the accident site and the detention costs of the trains which are detained during an accident.

It can be assumed with fair accuracy that given all other parameters being the same, these costs depend only on the time taken in the exercise of transportation and rescue of operation.

5.5.4.4.1 Minimum Travel Time : In our study, the potential location for siting relief equipment is considered as a junction point on the network from where equipment can be deployed in the minimum possible time. The shortest distance between all the points in the network is obtained using Floyd-Warshall Algorithm (Amoako, 2019) using Python pandas (McKinney, 2022) and functionalities available with the NetworkX library (Aric A. Hagberg, 2008). The minimum distance is used to calculate the coverage function and the actual minimum time taken to reach the site of the accident. The minimum time to travel is calculated assuming the average speed of movement of assets as 75 kmph. This time is a vital parameter in the calculation of total response time.

5.5.4.4.2 Restoration Time :

Based on the historic data the time taken in the restoration exercise is considered and the maximum time taken for the specific type of accident profile has been taken. This time indicates the maximum possible detention of the traffic after arrival of the relief train at the site.

5.5.4.4.3. Cost of Responding to an Accident :

The cost of response for an accident profile from a specific site location is defined as:

'Minimum travel time to the accident site from the location of facility' + 'Restoration time'

5.5.4.4.4 Detention Cost of the Traffic in Case the Traffic is Blocked :

As per the railway board's circular No. TC-I/2021/efile/I (33440110), (GOI, 2022) the cost of detention per unit train is calculated as the haulage charges levied on the customers.

Following assumptions are made for the calculation of detention costs:

a) It is assumed the number of trains which could have crossed the section during the total detention period would be the number of trains affected by the accident.
b) The train operation has an absolute block system of working, in which a gap of at least 5 kilometres is maintained between two trains running in series.
c) The operation of trains is assumed to be performed in such a manner that the trains are distributed along the track as per uniform distribution. And, at any given time there is a train at an interval of 5 kilometres of track length.

d) In the case of an accident, all the trains which could have crossed the section in the period of detention are assumed to be detained at the outer signal of the section. They are assumed to be stabled in series one after the other.

e) The train will move one after another once the section is cleared, in FIFO fashion.

The time taken in clearing the section by the first train after the restoration of the traffic will be equal to the travel time to clear the section by this train itself. However, the train following it would have to wait for a time equal to the time of section clearance by preceding trains. In this manner, if D is the detention time and t_s is the time to clear the section by train. The time taken to commence the onward journey will be:

Time taken by first train = D

Time taken by 2nd train = D+ t_s

Time taken by 3rd train = D+2*t_s

………

Time taken by nth train = D+ (n-1)$* t_s$.

Therefore, the total detention time for n train = D*n/2(n+1).

The cost of detention or not responding to an accident is calculated by multiplying the detention or demurrage charge of a 58 BOXN wagon length train and locomotive haulage charges with the total detention time as stipulated in the Ministry of Railways Circular (GOI, 2022).

5.6. Computational Experiments :

All the experiments are conducted on a personal computer equipped with an Intel core i-3 2 GHz processor, 8 GB RAM, and Windows 10 Operating System. The model is implemented using Python in GUROBI 9.1, a state-of-the-art math programming solver with Google Collaboratory (Colab) IDD. The results of the computational experiments are as follows.

5.6.1 Result of the Base Model :

The network of NCR zone as described in Section 5 is considered for experiments. For this network, the probability of accident for all sections is calculated as explained in Section 6 and these values are used to conduct computational experiments. This is referred to as the 'base case' for the experimentation. The two-stage stochastic model for the base case is solved directly using GUROBI. As the network consists of 132 sections and we have considered 24 accident profiles, theoretically the base case model has a total of 3168 scenarios. However, as the probability of any accident in several sections is estimated to be zero; a total of 501 scenarios are considered for the base case. The number of binary variables In the model are 253,386 and continuous variables are zero while the total number of constraints in the model is 46,860. It was found that GUROBI is quite efficient in solving the model with an overall runtime of 6 minutes. The objective function value is 749,878 INR and the breakup of the total cost is as shown in Figure 5.3.

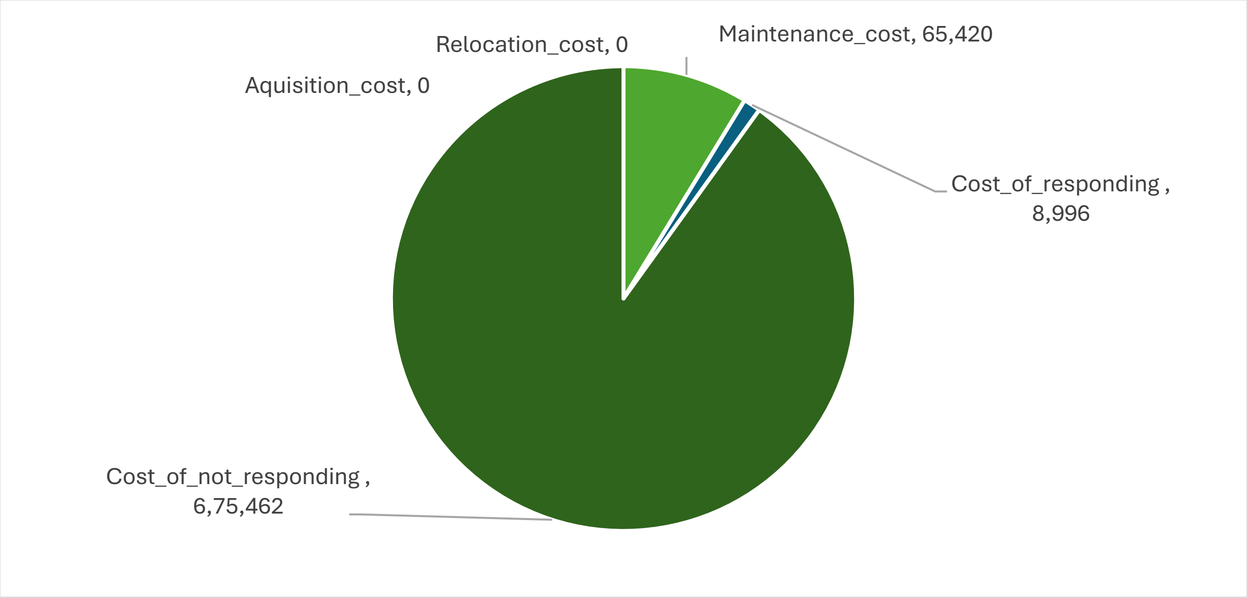


Figure 5.3: Breakup of the Total Cost

It was noticed from the solution of the base case that the program does not offer any change in the location of the assets or any advice for further investment in procurement or maintenance of assets at a new location. Therefore, no acquisition or relocation cost incurred. The decision of the allocation of assets for various possible scenarios is also economically decided by the two-stage stochastic program. However, it is noted that the program conveniently leaves some of the accident profiles unattended in the solution. The total coverage offered in this primary solution is only 93.21 %. In fact, the cost of not responding is the largest cost element in the objective function value. An in-depth perusal of the data would reveal that the cost of acquisition is many times higher in comparison to the cost of attending and not attending the accident. However, the implications of not attending an accident might be much larger than the simple mathematical definition and its values adopted in this study. Therefore, the concept of 'disutility' as defined above is used to obtain a more practical and reliable solution, as explained in the next sub-section.

5.7 The Concept of Disutility Factor :

The Concepts of Utility and Disutility is popular amongst economists and has been in wide practice in various areas of research. Disutility values are often expressed as a negative value, to represent the impact of the constraint on the use of goods or services.

The concept is further extended to our study to assess the impact of disutility on the overall cost of the objective function by varying the disutility factor. A disutility factor is a mathematical number assigned for the penalty of attending or not attending an accident over a section of the network. It obviously has an impact on the overall objective value of the problem and finally the decision of location and allocation of the assets. To understand the impact of the disutility factor, we re-ran the base case by varying the disutility factor from 1 to 10,000,000 progressively and the results are summarized in Table 5.4.

Table 5.4: Impact of Disutility Factor

		First stage costs				Second stage costs				
Disutility factor	Objective function value	Acquisition cost	Relocation cost	Maintenance cost	Total first stage cost	Cost of respond-ing	Cost of not responding	Total second stage cost	Total adjusted second stage cost	Total cost
1	0.750	0.000	0.000	0.065	0.065	0.009	0.675	0.684	0.684	0.750
5	3.488	0.000	0.000	0.065	0.065	0.009	0.675	0.684	3.422	0.750
10	6.910	0.000	0.000	0.065	0.065	0.009	0.675	0.684	6.845	0.750
50	34.288	0.000	0.000	0.065	0.065	0.009	0.675	0.684	34.223	0.750
100	61.109	21.667	0.000	0.075	21.742	0.010	0.384	0.394	39.367	22.136
500	136.794	21.667	100.393	0.109	122.169	0.011	0.019	0.029	14.626	122.198
1000	151.420	21.667	100.393	0.109	122.169	0.011	0.019	0.029	29.251	122.198
5000	196.390	76.667	66.919	0.119	143.704	0.011	0.000	0.011	52.686	143.715
10000	249.076	76.667	66.919	0.119	143.704	0.011	0.000	0.011	105.372	143.715
50000	670.563	76.667	66.919	0.119	143.704	0.011	0.000	0.011	526.859	143.715

100000	1197.421	76.667	66.919	0.119	143.704	0.011	0.000	0.011	1053.717	143.715
500000	5395.354	131.667	16.784	0.125	148.576	0.010	0.000	0.010	5246.778	148.587
1000000	10580.778	248.333	83.985	0.165	332.484	0.010	0.000	0.010	10248.294	332.494
2000000	20771.177	483.333	100.680	0.245	584.259	0.010	0.000	0.010	20186.918	584.269
3000000	30782.265	893.333	83.985	0.303	977.622	0.010	0.000	0.010	29804.644	977.631
4000000	40672.581	1165.000	67.201	0.353	1232.554	0.010	0.000	0.010	39440.027	1232.564
5000000	50510.375	1345.000	67.117	0.403	1412.520	0.010	0.000	0.010	49097.855	1412.530
6000000	60322.571	1400.000	67.117	0.423	1467.540	0.010	0.000	0.010	58855.030	1467.550
7000000	70115.730	1756.667	117.091	0.485	1874.243	0.010	0.000	0.010	68241.487	1874.252
8000000	79849.795	1996.667	117.073	0.525	2114.265	0.010	0.000	0.010	77735.530	2114.275
10000000	99258.711	2196.667	66.901	0.565	2264.133	0.010	0.000	0.010	96994.578	2264.143

****All values are in millions.**

It is noted that there is no change in the solution until the disutility factor increases to 50. This is evident from the same first stage, second stage and the total cost columns in Table 5.5. The disutility factor only impacts the value of objective function for the same solution. Thereafter, with increase in the value of disutility factor, the objective function value as well as total cost changes in a non-decreasing fashion. In general, the acquisition cost and maintenance costs tend to increase with increase in disutility factor. As a result, total first stage cost increases. On the contrary, there is a reduction in the total second stage cost when the disutility factor is high. This is evident from a clear decrease in the cost of not responding. In fact, with a disutility factor of 5000, the cost of not responding to an accident is zero implying 100% coverage of the entire network. The cost of responding increases initially and then starts decreasing. This can be attributed to a greater number of acquisitions and better strategic positioning/relocations of relief equipment for the higher disutility factors. The effect of disutility factor on the coverage is graphically shown in Figure 5.4.

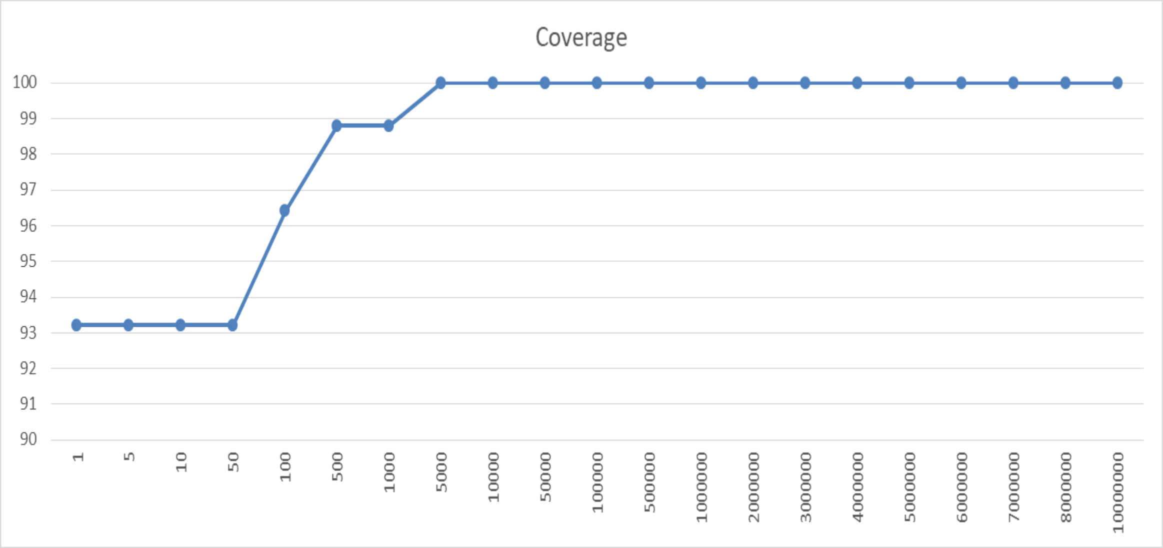


Figure 5.4: Coverage of the Accident Profiles with Varying Disutility Factor

The pattern of coverage observed in Figure 5.4 corroborates the results from Table 5.5. For the disutility factor till 50, there is no change in the coverage as there is no change in the solution. The coverage gradually increases with an increase in disutility factor, and it reaches to a convergence at a disutility value of 5000. After that the coverage remains the same.

In the light of change in objective function value, actual cost, and total coverage, it is important to note the change in the position of relief equipment that are purchased and/or relocated in the network with change in the value of disutility factor. This information is summarized in Table 5.5.

Table 5.5: Impact of Disutility Factor on Asset Positions and Coverage

	Equipment Purchased			Equipment Relocated			Total Equipment operated				
Disutility Factor	**ART**	**ARMV**	**CRANE**	**ART**	**ARMV**	**CRANE**	**ART**	**ARMV**	**CRANE**	**Total**	**Coverage (%)**
1	0	0	0	0	0	0	12	8	7	27	93.21
5	0	0	0	0	0	0	12	8	7	27	93.21
10	0	0	0	0	0	0	12	8	7	27	93.21
50	0	1	0	0	0	0	12	9	7	28	93.21
100	0	1	0	0	0	0	12	9	7	28	96.41
500	0	1	0	0	2	0	12	9	7	28	98.80
1000	0	2	0	0	2	0	12	10	7	29	98.80
5000	0	2	0	0	2	0	12	10	7	29	100
10000	0	2	0	0	2	0	12	10	7	29	100
50000	0	2	0	0	2	0	12	10	7	29	100
100000	0	3	0	0	1	0	12	11	7	30	100
500000	0	3	1	1	1	0	12	11	8	31	100
1000000	0	3	1	1	1	1	12	11	8	31	100
2000000	2	4	1	1	2	1	14	12	8	34	100
3000000	2	6	3	1	1	1	14	14	10	38	100
4000000	3	8	4	1	0	1	15	16	11	42	100
5000000	5	8	4	1	0	1	17	16	11	44	100

6000000	5	9	4	1	0	1	17	17	11	45	100
7000000	6	9	6	1	0	2	18	17	13	48	100
8000000	7	9	7	1	0	2	19	17	14	50	100
10000000	8	11	7	0	0	2	20	19	14	53	100

It is clear that till the value of disutility factor is 50, there is no purchase of new equipment and no relocation of existing equipment. As a result, the same number of equipment is operated till this point. This explains the same coverage and same total cost till this point. At a disutility factor of 100, the first procurement of an ARMV is suggested. There is no relocation of any asset at this stage, but the coverage of the network increases to 96.40%. Further, with a value of disutility factor of 500, the solution suggests procurement of a new ARMV and relocation of two of the existing ARMVs. This increases the coverage of the network to 98.8%. Complete coverage of the probable accident profiles is not obtained till the disutility factor varies up to the value of 5000. At this stage, the program suggests the procurement of two ARMVs and the relocation of two ARMVs from their current locations. The newly procured assets are located at 'BANDA' and 'ETAWAH' stations. Out of these two locations BANDA (see, Table 4) is already maintaining ART whereas ETAWAH is a new site to be opened. In this solution, the trade-off between construction costs of new facilities, the impact of maintenance costs due to the opening of a new site etc. viz-a-viz the impact of attending and not attending the accident is properly captured. Procurement and relocation of AMRV sounds the most logical suggestion for the fact that the time permitted to travel to the accident site is the minimum of the time permitted to other assets to travel to the same point. The relocation also appears to be logical for the fact that the current location of the asset might not be the best, given the probability of the accident in a certain area being more than that in others. The cost of not responding to an accident for all the evaluations after this stage remains zero. This means that all the accidents happening as per historical data are being attended to in every situation. It is clear that the solution obtained suggests the investment in the first stage decision I.e. procurement, installation and maintenance of the assets and keeps the cost of no response to a minimum for all the cases.

Table 5.6 provides another interesting insight with respect to the purchase of new relief equipment. There is a sharp increase in the total number of equipment purchased and operated with an increase in the disutility factor. Intuitively, the number of equipment operated should be stagnant once the convergence of coverage is attended. However, even after the convergence as the value of disutility factor increases, the model tries to minimize the total cost of responding to an accident by deploying more equipment in the network. This explains the additional purchase and/or reallocation of various combinations of relief equipment as the value of disutility increases.

5.7.1 Experiment with Other Probabilities :

The results obtained so far are fairly encouraging for the practical application and for providing a decision tool for the management for installation, relocation, and maintenance of the assets at a certain location. It also offers a handy tool for deciding the allocation of the assets in case of an eventuality. However, to address all the possibilities and mitigate the impact of any odds of the event, the program is also run with various combinations of probabilities to achieve the most practical solution. In particular, probability of accidents and in turn, the number of accident scenarios calculated in three different ways are explained in the following sub-sections.

5.7.1.1 Experiment with Probability Variation 1 :

In this variation, probability of occurrence of an accident profile is calculated directly from historical data of the demand patterns without considering other factors such as length of the section, traffic in a section or type of trains involved in an accident. That is, equation (34) is modified in this case as

$$P(Af) = P(S_d) \tag{35}$$

where S_d is the probability of occurrence of a demand pattern *d* in section *S*. The historical data for various demand patterns for different sections of the considered network is given in Table 5.6.

Table 5.6: Demand Patterns on Various Sections of the Network

	Demand Pattern						
Section	**I**	**II**	**III**	**IV**	**V**	**VI**	**Total requirement**
DDU-KYT	0	1	0	0	0	0	**1**
CAR-MZP	0		1	0	0	0	**1**
LINK-SRJ	0	1	1	0	0	0	**2**
PCOI-NYN	0		1	0	0	0	**1**
NYN-PRYJ	0	1	1	0	0	0	**2**
PRYJ-BRE	0	1	2	0	0	0	**3**
BRE-KGA	1	0	0	0	0	0	**1**
KGA-FTP	0	1	1	0	0	0	**2**
FTP-BKO	0	1	2	1	0	0	**4**
CNB-RURA	1	4	1	2	1	0	**9**
RURA-PHD	2	2	0	0	1	0	**5**
PHD-ETW	0	1	1	0	0	0	**2**

ETW-SKB	0	1	1	0	0	0	**2**
SKB-FZD	1	0	0	0	0	0	**1**
FZD-TDL	0	0	0	1	0	0	**1**
TDL-MTI	0	1	0	0	1	0	**2**
BRN-HRS	0	0	1	0	0	0	**1**
HRS-ALJN	0	0	1	0	0	1	**2**
ALJN-KHURJA	3	4	1	1	0	0	**9**
BRN-ETH	1	0	0	0	0	0	**1**
ETW-MNQ	0	3	0	0	0	0	**3**
CNB-BZM	0	0	1	0	1	0	**2**
ATA-ORAI	1	0	0	0	0	0	**1**
ORAI-AIT	0	0	1	0	0	0	**1**
NEW-MRPR	2	0	0	0	0	0	**2**
GTI-MBA	0	1	0	0	0	0	**1**
MBA-KID	0	0	0	1	0	0	**1**
KID-BANDA	0	1		2	0	0	**3**
BANDA-ATE	0	0	0	0	1	0	**1**
ATE-CKTD	0	0	0	1	0	0	**1**
ETUE-MTI	1	0	0	0	0	0	**1**
AGC-BHA	0	1	1	1	0	0	**3**
BHA-JJ	0	1	0	0	0	0	**1**
IDH-BTE	1	0	0	1	0	0	**2**
AH-BTE	0	1	0	0	0	0	**1**
BTE-NBI	0	1	1	0	0	0	**2**
BTE-BXN	1	0	0	0	0	0	**1**
MHF-SRMT	0	1	0	0	1	0	**2**

MRA-GWL	0	2	2	0	0	0	**4**
KURJ-ISHN	0	1	0	0	0	0	**1**
ISHN-TKMG	0	1	0	0	0	0	**1**
GWL-DBA	0	0	1	0	0	0	**1**
BIX-UDMR	1	0	0	0	0	0	**1**
UDMR-ETW	0	1	0	0	0	0	**1**
GWL-MRA	0	0	1	0	0	0	**1**
DHO-JJ	0	2	0	0	0	0	**2**
FTH-MTJ	0	0	1	0	0	1	**2**
MTJ-BRBD	0	2	0	0	0	0	**2**
BRBD-HDL	0	0	0	1	0	0	**1**
MTJ-GDO	0	0	2	0	0	0	**2**
DEEG-BINR	2	1	0	0	0	0	**3**
IDH-AH	1	0	0	0	0	0	**1**
BTE-KL	0	1	0	0	0	0	**1**
KL-BKI	0	1	0	0	0	0	**1**
Total	**19**	**41**	**26**	**12**	**6**	**2**	**106**

A total of 54 sections of the network experienced accidents and needed relief equipment in different combinations (expressed as demand patterns) in the past, and these sections are considered for experiments. As seen from Table 5.7, a total of 83 non-zero entries and each of them is regarded as a different accident profile. Computing the probability of accident profile in this case is straightforward – dividing each element by total demand in that section. For example, the probability of demand pattern II and III in the LINK-SRJ section would be 0.5 and 0.5, respectively.

It can also be noted that this variation heavily relies on the past data and Ignores any potential requirement of relief equipment at a section that has not experienced any accident in the past.

5.7.1.2 Experiment with Probability Variation 2 :

Like variation 1, this variation also estimates the probability of an accident profile from the past data of equipment demand ignoring the sectional length and traffic characteristics. However, this variation treats the past accidents and the demand of relief equipment in each case with an equal probability for each section. For Variation 2, the probability of accident profile is expressed as

$$P(Af) = \frac{1}{N} \tag{35}$$

Where N is the total number of accidents. This probability is assumed to be the same for each section of the network. As per historical data, a total of 106 events are recorded in 13 years. Therefore, for Variation 2 the probability of accident profile is assumed to be equal 1/106.

5.7.1.3 Experiment with Probability Variation 3 :

As explained in Section 6, an accident profile is constructed based on type of train and demand pattern. A total of 24 such profiles are considered in this study as given in Table 4. In the third probability variation, it is assumed that the probability of each accident profile is the same for each railway section. That is, an accident of any train type that needs a specific equipment combination is equally likely to happen on every section of the network. Therefore, a probability of 1/24 is assigned to each accident profile.

Table 5.7: Summary of Results for Probability Variations

		First stage costs				Second stage costs				
Case	**Objective function value**	**Acquisition cost**	**Relocation cost**	**Maintenance cost**	**Total first stage cost**	**Cost of responding**	**Cost of not responding**	**Total second stage cost**	**Total adjusted second stage cost**	**Total cost**
Base Case	**0.749**	**0**	**0**	**0.065**	**0.065**	**0.009**	**0.675463**	**0.684**	**0.684459**	**0.749**
Variation 1	726.979	76.666	66.918	0.118	143.704	583.275	0	583.275	583.275	726.979
Variation 2	153.247	76.666	66.918	0.118	143.704	9.543	0	9.543	9.543	153.247
Variation 3	1189.663	471.666	5.258	0.250	477.175	712.488	0	712.488	712.488	1189.663

****All values are in Millions**

5.8 Results of the Experiment :

The results for each of the three probability variations and their comparison with the base case scenario is given in Table 8. It can be seen that all probability variations result in a complete coverage of the network in case of accidents. Thus, the cost of not responding to an accident is zero in each of these cases. They also result in acquisition and relocation of relief equipment and their objective function value is much higher than that in the base case scenario.

It Is also noteworthy that these results are without considering disutility factors. However, the detailed results of each of these variations vary and are interesting to note.

The layout of equipment purchased and operated in case of Variation 1 is presented in Table 5.8.

Table 5.8 : Results of Variation 1

	Equipment	**Station code**
Operational status	ART	DDU, PRYJ, CNB, BANDA, TDL, JHS, AGC, BINA, GWL, JP, NDLS, CPU
	ARMV	DDU, CNB, **BANDA**, AGC, BINA, **GWL**, JP, NDLS, **MKP**, **BZM**
	Crane	DDU, CNB, JHS, AGC, BINA, JP, NDLS
New Purchase	ART	--
	ARMV	BANDA, BZM
	Crane	--

Transfer	ART	--
	ARMV	PRYJ→MKP; JHS-→GWL
	Crane	--

In case of Variation 1 where probability is calculated by historical data for the demand of a combination of equipment without considering the type of trains, the program provides 100% coverage to the network with suggestions for procuring two ARMV and relocating two ARMVs without assigning disutility for the attending or not attending the accident. The newly procured ARMV's are located at BANDA and BZM, and ARMV's from PRYJ and JHS are relocated to MKP and GWL respectively. Here, MKP is a new site whereas GWL is already open and supports assets there. In this case too, the program offers trade-off between the existing facilities and opening of new facilities considering huge investment cost involved in procurement cost of assets, construction cost of a new facility along with other cost parameters described in earlier paragraphs. The cost of not responding is zero and the cost of responding is progressively decreasing with an increase in the disutility factor. The cost of procurement, cost of relocation, cost of maintenance etc. becomes constant after the disutility factor of 5000 (Figure 5.5). At this stage, it is noted that huge investment is sought to be made in procurement and maintenance of an asset almost at every possible location. A slightly more in-depth analysis of the data obtained would reveal that the model is suggesting procurement and placement of assets at every possible location in order to minimize the cost of response. This is mathematically logical but practically penalizing heavily on the precious resources of the organization. It is clear from the above analysis that coverage is the primary parameter which needs to be monitored while making decisions on location of an asset. Though the differences in the results obtained in this case are vastly different from the results in the base case, the same can be explained by the nature of the distribution of the event over the network. The moot issue remains that the data points and their pattern of spread across the network governs the strategic decision of investment in the critical facility location decision as one in the consideration in this study.

Table 5.9: Results of Variation 2

	Equipment	**Station code**
Operational status	ART	DDU, PRYJ, CNB, BANDA, TDL, JHS, AGC, BINA, GWL, JP, NDLS, CPU
	ARMV	DDU, CNB, **BANDA**, AGC, BINA, **GWL**, JP, NDLS, **MKP**, **BZM**
	Crane	DDU, CNB, JHS, AGC, BINA, JP, NDLS
New Purchase	ART	--
	ARMV	BANDA, BZM
	Crane	--
Transfer	ART	--
	ARMV	PRYJ→MKP; JHS→GWL
	Crane	--

When an equal probability is considered for each of the past accidents (Variation 2), 100% coverage is achieved without applying the disutility function. The program suggests procurement of two ARMVs and relocation of two ARMV like the previous case, as shown in Table 5.9. However, the cost of the second stage and first stage establishes after the disutility factor of 50000 (Table 5.5). Similar inferences as already enunciated in preceding paragraph may be derived for the case as well. The pattern of the location and allocation decision of the assets is observed to be quite similar.

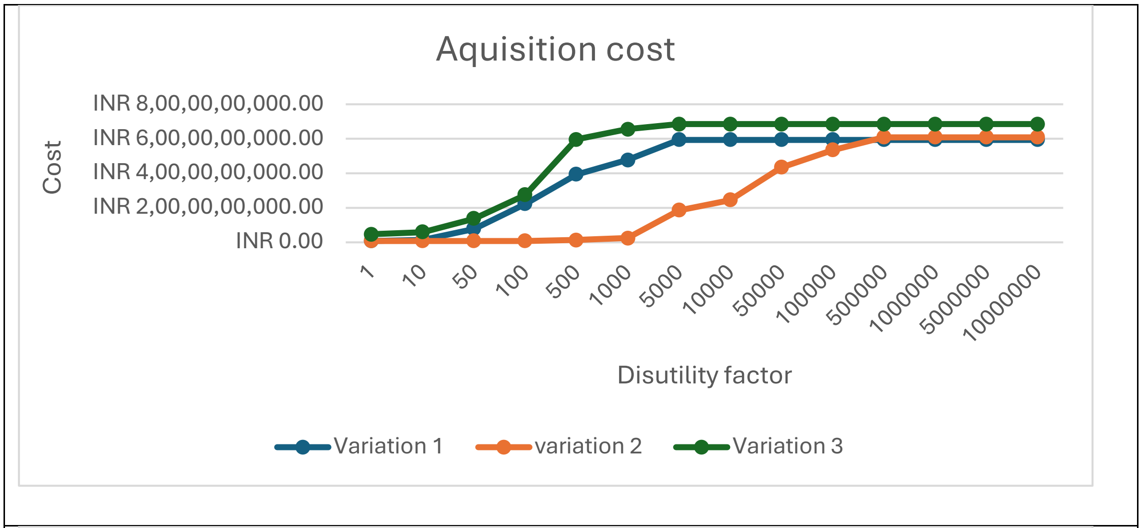
For the third variation, each accident profile is considered to have equal probability of occurrence on the network. Here also the coverage is 100 % without assigning any disutility value in the objective function. Similarly, progression of the decision as already discussed in Variation 1 and 2 is obtained. In this case, the model suggests procurement of 11 ARMV's and relocation of one CRANE from CNB to PRYJ, as shown in Table 5.10.

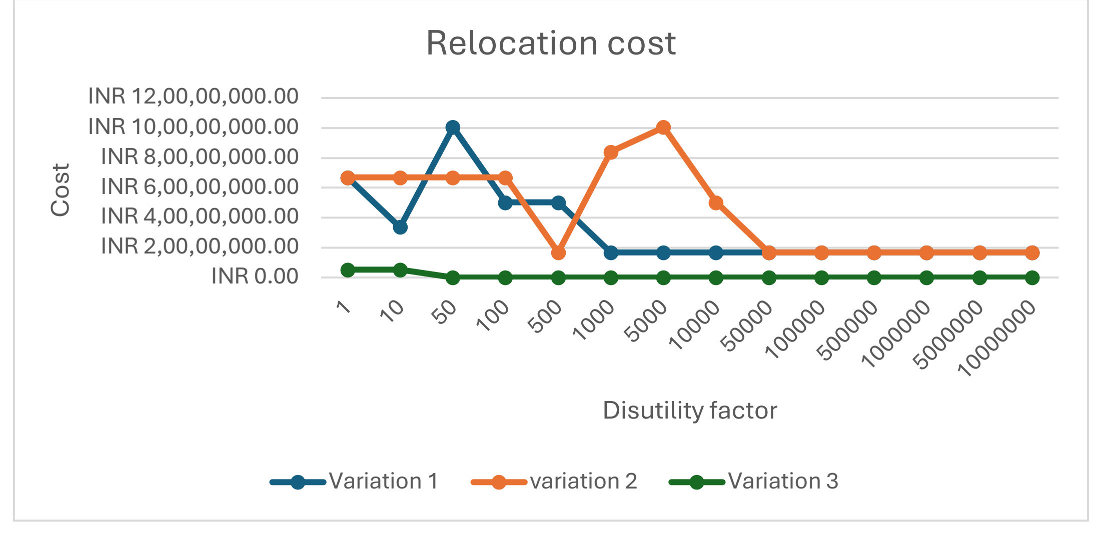
Table 5.10: Result of Variation 3

	Equipment	Station code
Operational status	ART	DDU, PRYJ, CNB, BANDA, TDL, JHS, AGC, BINA, GWL, JP, NDLS, CPU
	ARMV	DDU, PRYJ, **BANDA**, **TDL**, JHS, AGC, BINA, **GWL**, JP, NDLS, **MBA, CPU, CAR, NYN, LAR, AWR, PWL, BZM**
	Crane	DDU, PRYJ, JHS, AGC, BINA, JP, NDLS
New Purchase	ART	--

	ARMV	**BANDA, TDL, GLW, MBA, CPU, CAR, NYN, LAR, AWR, PWL, BZM**
	Crane	--
Transfer	ART	--
	ARMV	--
	Crane	CNB→PRYJ

The pattern of solution offered by the model is fairly similar but the numbers of the assets to be procured in this case are extremely high. Though, the suggestion for procurement of ARMV is absolutely in line with the analysis done so far. The suggestion of high numbers may be intriguing at first sight. But again, the behaviour of the data needs to be critically reviewed before passing judgments on the efficacy of the model. In previous cases, the data distribution was completely dissimilar to the data obtained in this consideration. There were certain points in previous cases where the probability of occurrence was zero or extremely low. This factor had a decisive impact on the outcome of the results. There were only 508 node points with nonzero probability in the cases discussed so far. However, in this case there are a total of 2520 node points and every node has equal probability. Therefore, the large number of procurement suggestions appears to be justified at firsthand. However, this makes the case more deterministic in nature than a problem to be solved through stochastic modelling. The important fact is that for a deterministic model the financial resources are primary governing constraints whereas in this case coverage is the primary factor. Therefore, the decision is apparently extravagant at first appearance. But it must be noted that the procurement of ARMV's remains constant after the first iteration and in further iterations the effort to minimize the second stage cost is made by the model in similar fashion.


Aquisition cost


Relocation cost

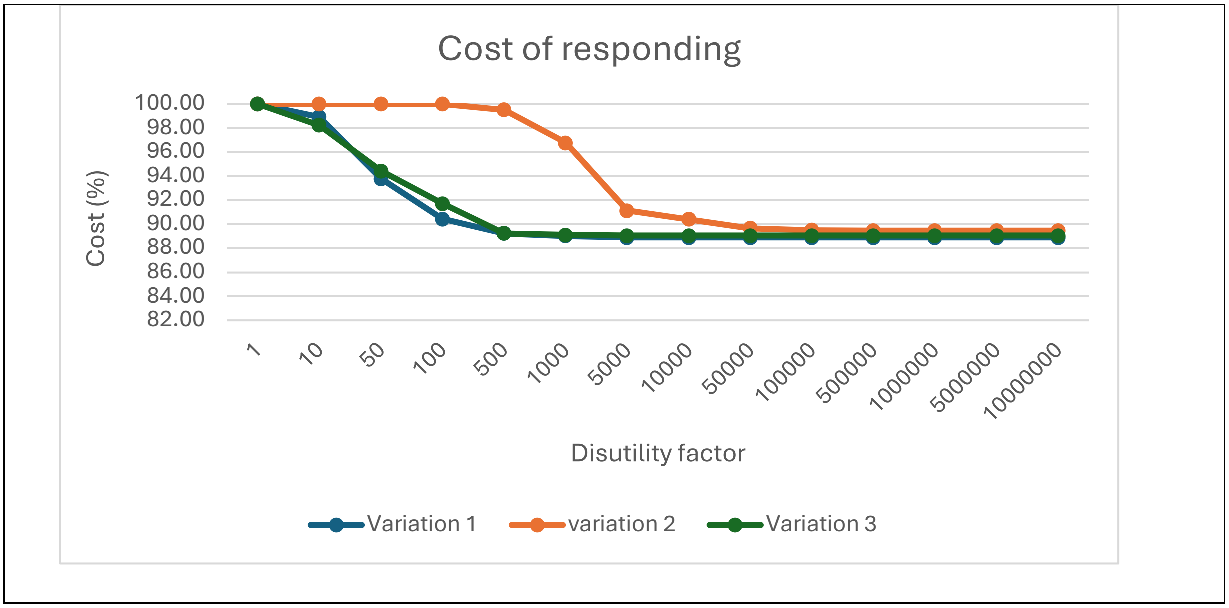


Figure 5.5: Impact of Disutility Factor on Various Cost Elements

Further iterations provide similar results, indicating a reduction in second stage cost with an increase in disutility factor. In other cases, also final stability in overall cost is achieved with a disutility factor of 5000. A summary of the effect of varying disutility factor on various cost elements is as shown in Figure 5.5.

The nature of impact of disutility factor on each of the variations is similar with difference in the magnitudes as shown in Figure 5.5. For example, an increase in the disutility factor tends to increase the acquisition cost and decrease the relocation cost. Also, the cost of responding seems to be decreasing progressively. In general, most of the probability variations suggest procurement of a large number of equipment and strategic placement of it in the network to respond to any accident that might occur. The prominence of the nature of the data influencing the decision and robustness of the model with sensitivity is therefore validated through the above experiments.

5.9 Managerial Insights :

The results of computational experiments generated several interesting insights for decision makers. The *first* insight is regarding the impact of a method for calculation of probability of an accident profile. Considering only the sections that experienced accidents in the past would ensure complete coverage of them, but this approach does not lead to global coverage and leaves out several sections unattended. On the contrary, consideration of equal probability of accidents on each section of the network for all train types would result in a higher cost of purchase of equipment and/or relocation. Thus, estimation of probability of accident considering the section length, total traffic in a section and type of trains would lead to a more balanced solution in terms of cost and coverage of the network. The *second* important insight is the use of the disutility factor in the model. It is observed that higher the value of the disutility factor, more the equipment purchased/relocated and operated in the network. Although this ensures global coverage, it forces us to operate more than the necessary number of equipment to cut down the response time and cost. Thus, a disutility factor should be selected to balance the total first stage cost (purchasing, relocating and maintenance cost) and the total second stage cost (cost of responding and cost of not responding to an accident). The *third* insight is the choice of new equipment for purchasing. Most often, the purchase of new equipment is subject to budgetary restriction. Therefore, if the choice is between different types of equipment, a preference can be given to ARMV due to its lowest response time requirement. The overall coverage of the network can be significantly improved with purchase and/or relocation of ARMV – as evident from the experiments. Another insight is in terms of choice of optimal location for placement of relief equipment. As argued in chapter 4, the selection and development of even smaller/remote stations in the network would lead to substantial improvement in the coverage and response time. In addition to the major stations and junctions that currently host the relief facilities, several smaller stations are considered as potential locations, and the model indeed suggests selecting them to site different relief equipment.

5.10. Conclusion :

Location of relief and rescue equipment is one of the most vital decisions for an economically viable railway organization. It provides and ensures timely measures to mitigate the impact of an accident or derailment on the flow of the network and thereby reduces the perilous effect on the earning potential of the assets operating in service. In a country like India where rail transport is the primary mode of transport for passenger traffic for various commutation needs, the location of relief assets becomes more pertinent because it has the potential to save precious human lives. The current practice of locating these assets over networks of India Railways is a standalone decision based on experience acquired over the long existence of the organization, which has a history older than a century. But hardly there is any mathematical background to support the decision made by the railway authority nor is there any method to evaluate the efficacy of the decision being adopted on the ground.

In this work, we proposed a two-stage stochastic programming model for the decision on the purchase of assets, location of newly purchased assets or relocation from an existing place to a better and more desired location, and the allocation of relief equipment as per accident profile i.e., the actual demand of the number of equipment based on historical data has been considered over a railway network. It is distinct and unique from other works in the following ways: *First*, we have considered actual historical data for the calculation of the probability of the requirement of the asset in case of an accident. The quantitative requirement of an asset depends on the type of rolling stock involved in the mishap and the intensity of the accident. *Secondly*, the probability of the occurrence of an accident has been considered by taking the traffic pattern of the section. *Thirdly*, we have proposed an optimization program for evaluating the conflicting parameters of detention of the train in the section viz-a-viz the cost of restoration when equipment is deployed from a specific location. The cost of purchase, installation and maintenance is considered as a fixed cost decision or a deterministic decision. *Fourth,* various scenarios of accident and demand profiles are considered, and the best solution is achieved by solving the two-stage problem. *Fifth,* the conceptual solution proposed is validated through a case study based on the North Central Railways, and thus the insights are unique and distinct. Thus, we contribute to the theory and practice with this work.

This work can be extended in several ways in future. In the present work, we considered a two-stage stochastic modelling approach to handle uncertainty. Alternate approaches to model uncertainty are robust optimization and/or simulation. In particular, simulation provides a practical way to consider the uncertainty associated with the location and magnitude of an accident. A simulation-based optimization framework can also be used for obtaining alternate solutions. Another research dimension would be consideration of risk in addition to uncertainty of accidents. We reserve these approaches as future scope of research.

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