Transit Dependent Evacuation Planning for Kathmandu Valley: A Case Study*

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Abstract

Due to the increasing number of natural or man-made disasters, the application of operations research methods in evacuation planning has seen a rising interest in the research community. From the beginning, evacuation planning has been highly focused on car-based evacuation. Recently, also the evacuation of transit depended evacuees with the help of buses has been considered.

In this case study, we apply two such models and solution algorithms to evacuate a core part of the metropolitan capital city Kathmandu of Nepal as a hypothetical endangered region, where a large part of population is transit dependent. We discuss the computational results for evacuation time under a broad range of possible scenarios, and derive planning suggestions for practitioners.

Keywords: Case study; disaster management; bus-based evacuation

1 Introduction

Nepal faces a variety of natural disasters, including earthquakes, floods, landslides, fires and drought epidemics. The necessary data base to prepare for disaster management, hospital management, traffic planning and urban planning of Kathmandu or even locational planning does not seem to be strong enough. The capital city is densely populated with mostly transit dependent inhabitants, visitors and tourists. Most of the houses are constructed without earthquake proof, and may be in dangerous conditions. Also, an efficient traffic planning in emergencies or regular busy hour routing is lacking. A number of studies in social and applied sciences have shown that the country is not sufficiently prepared in case of a disaster, see [NSE10]. Realizing the potential problems, we apply operations research methods to this city network and present a case study as most probably the first systematic approach to evacuation planning of Kathmandu using scientific tools.

During the response phase in evacuation management, research that uses operations research methodology is highly focused on car-based evacuation planning. For survey works on models and algorithms of car-based evacuation problem, we refer to, e.g., [AGI06, CMH08, CJ03, Dha15, HT01, YAM08]. However, in large cities and developing countries, many people fall into the low-mobility population after any kinds of disaster that has

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little access to personal vehicles, unable to drive due to age, sickness, or any other reason. Recently, also the research on transit-based models has received increasing attention. We study transportation models used during the transit-based evacuation.

Bish [Bis11] considered the advance-notice scenarios and deals with a transit based evacuation planning problem. He introduced a bus-based evacuation planning problem (BBEP) as a unique variant of the well-known vehicle routing problem (VRP), for instance, see [EVR09]. A version of transit based no-notice evacuation problem incorporating traffic flow dynamics has been introduced in [SE10].

For the BBEP, a number of depots where initially a number of buses with defined capacity are situated, a number of pickup locations (sources) where evacuees should be gathered for their transit, a number of safe distinctions (shelters or sinks) with available minimum requirements for evacuees like beds, blankets, food, etc. are given. The number of evacuees at the sources and the capacities at the sinks are known in advance. The problem of the BBEP is to transport evacuees from sources to sinks in the minimal amount of time, i.e., the minimal duration of evacuation by routing and scheduling a set of homogeneous and capacitated buses. The duration of evacuation is defined as the time span between when the first bus leaves its depot until the last evacuees is reached to the sinks.

For the BBEP, Goerigk et al. [GGH13] developed branch and bound algorithms. They presented four greedy algorithms to construct feasible solutions, and three algorithms to obtain lower bounds on evacuation time. Then, these lower bounds and upper bounds have been integrated into a branch and bound framework. Furthermore, they described different branching rules and several node pruning techniques. By solving evacuation problems modeled after real-world data, they concluded that the branch and bound algorithms obtain near optimal solution and the computation times are significantly smaller than for a commercial mixed-integer programming (MIP) solver.

The problem BBEP is extended to a robust bus-based evacuation problem (RBBEP) by assuming that the number of evacuees is not known exactly but a set of estimates for the number of evacuees at each source is given in [GG14]. As BBEP, also RBBEP is an NP-complete problem as can be seen by a reduction from scheduling problems on parallel machines. They presented a MIP formulation for the RBBEP and two lower bounds. Furthermore, a tabu search heuristic has been presented that gives considerably improved evacuation times in comparison with the direct application of a MIP solver.

For more extensions of the BBEP, we also refer to [GDH14, GGH14, GDT13], where multi-criteria variants are considered. Also, Hua et al. [HRCR14] presented a multimodal integrated contraflow model for uncertain arrivals of evacuees in an evacuation region with low mobility population. The integrated strategy contains non-contraflow to shorten the strategy setup time, full-lane contraflow to minimize the evacuation network capacity and bus contraflow to realize the transit cycle operation. The transit-based evacuation problem is solved with a minimum cost flow model in first priority. Then the auto-based evacuation problem is addressed with a bi-level network flow model.

Overview and contributions. In this paper, we apply the nominal and robust bus evacuation models and solution algorithms from the recent literature to solve a case study modeling an emergency in central Kathmandu. By varying problem parameters extensively, we are able to derive long-term planning strategies for practitioners. In Section 2, we introduced required denotations for bus-based evacuation problems. Different mixed-integer formulations and models are recapitulated in Section 2.2, and solution approaches are described in detail in Section 3. The main part of this paper is the case study using real-world data in Sections 4 and 5. Section 6 concludes the paper.

2 Preliminaries

2.1 Problem Definition and Notation

Standing on the model of Bish [Bis11], Goerigk et al. [GGH13] presented the following version of the BBEP. Let $S = \{1, \ldots, s\}$ be the set of sources or pickups. Let $D = \{1, \ldots, d\}$ be the set of safe destinations or sinks. Each source $i \in S$ has given number of evacuees (lower bounds) $l_i > 0$ and each sink $j \in D$ has a fixed capacity (upper bounds) $u_j > 0$. The total number of evacuees is denoted by $\sum_{i \in S} l_i$ which is known in advance. For the evacuation, a set of buses $B = \{1, \ldots, m\}$ is available with a uniform capacity q for each $b \in B$. The travel times between sources and sinks are denoted by a travel time matrix $\mathrm{T} = (\tau_{ij})_{i \in S, j \in D}$. A round is a movement of a bus from a source to a sink. Let t be the maximum number of trips (rounds) the evacuation process might possibly take, let $R = \{1, \ldots, t\}$. A pair of source and sink node (i, j) denotes a tour. We assume that there are $S \times D$ routes in the evacuation network so that all tours $(i, j) \in S \times D$. A list of tours is a tour plan.

In a large evacuation scenario, the total number of evacuees $\sum_{i \in S} l_i$ is much larger than the number of sources $|S|$. Therefore, they made the simplifying assumption that each source $i \in S$ has a number of evacuees in terms of integer multiples of the bus capacity, i.e., $l_i = k_i q$ with $k_i \in \mathbb{N}$. In the following, we will simply denote by l_i the number of evacuees in terms of bus loads instead of single persons, and assume that every bus has a capacity of one. Under this assumption, we may also assume without loss of generality that the shelter capacities u_j are given as multiples of bus loads. In the worst case the number of rounds is $t = \sum_{i \in S} l_i$, as a trivial upper bound. They also ignored the inter-movement between sources to sources and between sinks to sinks. It is assumed that, the given route (i.e., the set of tours) cannot be changed anymore after the buses start to move. The problem is to find a schedule for the set of buses B such that all evacuees are transported to the capacity restricted sinks D from the sources S so that the evacuation time is minimized.

Example 1. *A single depot BBEP instance is represented by a Figure 2.1 with three sources and three sinks. The sources have demand of evacuees $l = (5, 3, 4)$ and the sinks have capacities $u = (3, 6, 5)$. The distance from depot to source given by $\tau = (4, 2, 3)$ and the distances between S to D are given by*

$$\mathrm{T} = \begin{pmatrix} 9 & 8 & 10 \\ 11 & 14 & 12 \\ 10 & 13 & 15 \end{pmatrix}$$

The number of buses are given to be 5.

A feasible solution of this instance is represented in Table 1 which is also optimal. The critical path of the optimal plan is calculated as $\tau_3 + \tau_{31} + \tau_{11} + \tau_{12} + \tau_{21} + \tau_{12} = 3 + 10 + 9 + 8 + 8 + 8 = 46$ for Bus 4 or Bus 5.

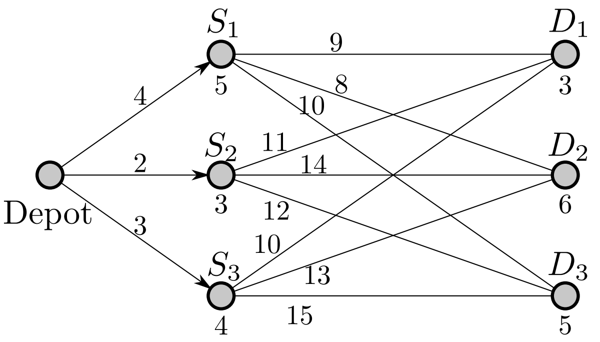

Figure 1: Example of a BBEP instance

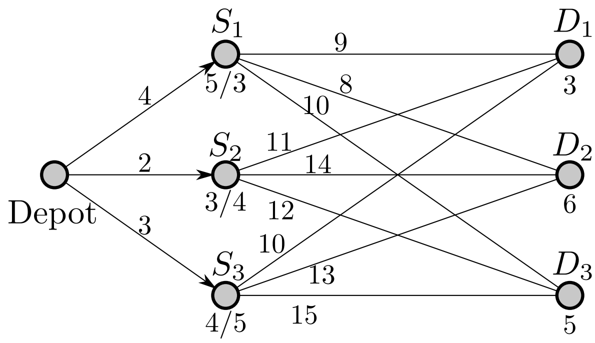

Figure 2: Example of RBBEP instance

To deal the case when the exact number of evacuees is not known in advance, a robust bus-based evacuation problem (RBBEP) has been introduced by Goerigk and Grün [GG14] with the same single depot scenario as in

Trip no.	1	2	3	Duration
Bus 1	(2,3)	(3,2)	-	42
Bus 2	(2,3)	(3,1)	-	39
Bus 3	(2,3)	(1,2)	-	32
Bus 4	(3,1)	(1,2)	(1,2)	46
Bus 5	(3,1)	(1,2)	(1,2)	46

Table 1: Optimal solution of BBEP

Trip no.	1	2	3	Duration
Bus 1	(3,1)	(3,1)	(1,2)	50
Bus 2	(2,3)	(1,2)	(1,3)	50
Bus 3 Sc 1	(2,2)	(3,3)	-	49
Bus 4 Sc 1	(1,3)	(3,3)	-	49
Bus 5 Sc 1	(1,2)	(2,2)	-	45
Bus 3 Sc 2	(2,2)	(2,2)	-	49
Bus 4 Sc 2	(3,3)	(3,1)	-	48
Bus 5 Sc 2	(2,2)	(3,3)	-	49

Table 2: Optimal solution of RBBEP

[GGH13]. In RBBEP, a discrete set of scenarios $U = \{l^1, \dots, l^p\}$ is estimated for the number of evacuees at each source according to the gathering of evacuees where the length of vector l^z is equal to the total number of sources $|S|$ and l_i^z represents the number of evacuees at source i in scenario $z \in Z = \{1, \dots, p\}$. The buses B are divided into two categories: here-and-now buses $B^{hn} = \{1, \dots, m^{hn}\}$ and wait-and-see buses $B^{ws} = \{1, \dots, m^{ws}\}$. A here-and-now bus leaves the depot immediately after the disaster, when there is no exact information about the evacuees available. But a wait-and-see bus starts to move after exact information about scenario is available. The time which is required to get exact information about the realized scenario is called p_{wait} time. Thus, a wait-and-see bus cannot move before the p_{wait} time. With a given set of buses B, sources S, sinks D, scenarios U, a distance matrix of source-sink travel times $\mathrm{T} = (\tau_{ij})_{i \in S, j \in D}$, a vector of depot-source travel times $\tau = (\tau_i)_{i \in S}$, a matrix of scenario-dependent number of evacuees $L = (l_i^z)_{i \in S, z \in Z}$, a vector of sink capacities $u = (u_j)_{j \in D}$, and a waiting penalty p_{wait}, the RBBEP is the problem of deciding, for each bus, if the bus should be transmitted immediately or if it should wait and find a tour plan minimizing the maximum travel time over all buses such that all evacuees are dropped to the fixed capacity sinks.

Example 2. *We consider the problem instance as shown in Figure 2.1 in which we divide the load of sources in two scenarios: In the first scenario, the number of evacuees at the source nodes* (S_1, S_2, S_3) *is* $(5, 3, 4)$*, while in the second scenario it is* $(3, 4, 5)$*. The waiting time is considered as* $p_{wait} = 5$ *and there are 5 buses available. Here, two buses: Bus 1 and Bus 2 are used as here and now bus, and remaining three Bus 3, Bus 4 and Bus 5 are used as wait and see buses. The optimal plan leads by the critical path obtained by Bus 1 or Bus 2 which is* $3 + 10 + 10 + 10 + 9 + 8 = 50$ *or* $2 + 12 + 10 + 8 + 8 + 10 = 50$.

Goerigk and Grün [GG14] presented a mixed-integer programing formulation for the RBBEP. Their robust optimization approach aims at minimizing the maximum travel time over the region of RBBEP feasibility if and only if $\sum_{i \in S} l_i \leq \sum_{j \in D} u_j$. If the scenario is not defined and the number of evacuees gathered at all sources are known in advance, then the RBBEP is reduced to the BBEP as considered in [GGH13]. To solve the RBBEP, a tabu search heuristic is proposed.

2.2 Mathematical Models

In the following, we recapitulate the mixed-integer program that models the BBEP. To this end, we introduce binary variables x_{ij}^{br} to denote if bus b goes from collection point $i \in S$ to shelter $j \in D$ in round R. Additionally, three types of auxiliary variables are used to measure the evacuation time: d_{to}^{br} gives the time for buses traveling from collection points to shelters, d_{back}^{br} is the time back from shelter to collection point, and $\mathcal{T}_{\max}$ is the total evacuation time. We use the shorthand R^{-t} for $R \setminus \{t\}$, i.e., the set of all rounds except the last.

$$\text{minimize} \quad \mathcal{T}_{\max} \tag{1}$$

$$\text{such that} \quad \mathcal{T}_{\max} \geq \sum_{r \in R} (d_{\text{to}}^{br} + d_{\text{back}}^{br}) + \sum_{i \in S} \sum_{j \in D} \tau_i x_{ij}^{b1} \ \forall \ b \in B \tag{2}$$

$$d_{\text{to}}^{br} = \sum_{i\in S}\sum_{j\in D}\tau_{ij}x_{ij}^{br} \;\forall\, b\in B,\ r\in R \tag{3}$$

$$d_{\text{back}}^{br} \geq \tau_{ij}\left(\sum_{k\in S}x_{kj}^{br}+\sum_{l\in D}x_{il}^{b,r+1}-1\right)\forall\, b\in B,\ r\in R^{-t},\ i\in S,\ j\in D \tag{4}$$

$$\sum_{i\in S}\sum_{j\in D}x_{ij}^{br} \leq 1\;\forall\, b\in B,\ r\in R \tag{5}$$

$$\sum_{i\in S}\sum_{j\in D}x_{ij}^{br} \geq \sum_{i\in S}\sum_{j\in D}x_{ij}^{b,r+1}\;\forall\, b\in B,\ r\in R^{-t} \tag{6}$$

$$l_i \leq \sum_{j\in D}\sum_{b\in B}\sum_{r\in R}x_{ij}^{br}\;\forall\, i\in S, \tag{7}$$

$$u_j \geq \sum_{i\in S}\sum_{b\in B}\sum_{r\in R}x_{ij}^{br}\;\forall\, j\in D, \tag{8}$$

$$x_{ij}^{br} \in \{0,1\}\;\forall\, i\in S,\ j\in D,\ b\in B,\ r\in R \tag{9}$$

$$d_{\text{to}}^{br}, d_{\text{back}}^{br} \in \mathbb{R}_+\;\forall\, b\in B,\ r\in R \tag{10}$$

$$\mathcal{T}_{\max} \in \mathbb{R}_+ \tag{11}$$

The objective function (1) is to mnimize the total evacuation time, i.e., the time until the last evacuee is brought to a shelter. Constraints (2) are used to ensure that the evacuation time equals the maximum driving time over all buses. This uses the auxiliary travelling time variables d_{to}^{br} and d_{back}^{br}, whose values are determined with the help of Constraints (3) and (4). Constraints (5) ensure that a bus can make at most one trip per round, while Constraints (6) model that trips need to be performed consecutively. Finally, Constraints (7) and (8) ensure that all evacuees are picked up, and shelter capacities are respected.

To include robustness, the above BBEP model is extended to a new formulation, called RBBEP. To this end, scenario-dependent variables x_{ij}^{brz} are introduced, and new decision variables y_b for every bus $b\in B$ to determine if this is a here-and-now, or wait-and-see bus. The detailed model definition for RBBEP can be found in Appendix A.

3 Solution Strategies

In this section, we discuss exact and heuristic approaches developed for solving the BBEP and the RBBEP. Goerigk et al. [GGH13] presented branch and bound algorithms for BBEP. When the exact number of evacuees is not available but their arrival scenarios are known in advance, that is, for the RBBEP, Goerigk and Grün [GG14] presented a tabu search heuristic for finding solutions of acceptable quality within short computation time.

3.1 Branch and Bound Algorithms for BBEP

Branch and bound algorithms with four different upper bounds, three different lower bounds, three branching rules and two tree reduction strategies for BBEP are presented in [GGH13].

The four upper bounds construct heuristic feasible solutions making use of partially fixed solutions in polynomial time complexity. All three lower bounds algorithms are polynomial time that work for given partial plans. The first lower bound is based on estimating travel times from sources to shelters and from shelters to source separately. The procedure of estimating the second lower bound relies on the fact that a lower bound for the maximum travel time is the average travel time. It is based on the network flow formulation with the sum objective (12), that is, one replaces (1) and (2) by

$$\text{minimize} \sum_{b\in B}\sum_{r\in R}\left(d_{\text{to}}^{br}+d_{\text{back}}^{br}\right)+\sum_{i\in S}\sum_{j\in D}\tau_i x_{ij}^{b1} \tag{12}$$

in the MIP formulation of BBEP. A relaxation of this MIP-problem gives a pure minimum cost flow problem where the flow cost is equal to the sum of the travel times.

The third lower bound is obtained by simplifying the MIP model for BBEP. Here, all sources are considered as a super-node S_0 with $l_{s_0} = \sum_{i\in S} l_i$ by neglecting the distances between sources. Let $\tau_j = \min_{i\in S}\tau_{ij}$ be the distance between S_0 and sinks $j \in D$ and $\tau = \min_{i\in S}\tau_i$ be the distance between depot and source. Since the distance τ is same for all buses, it is neglected in optimization process. Then, the IP formulation for this simplified BBEP is as follows.

$$\text{minimize } \mathcal{T}_{\max} \tag{13}$$

$$\text{such that} \quad \mathcal{T}_{\max} \geq \sum_{j\in D}\tau_j\left(x_j^b+y_j^b\right)\ \forall b\in B \tag{14}$$

$$\sum_{b\in B}\sum_{j\in D}x_j^b \geq l_{S_0} \tag{15}$$

$$\sum_{b\in B}x_j^b \leq u_j\ \forall j\in D \tag{16}$$

$$\sum_{j\in D}y_j^b = \sum_{j\in D}x_j^b-1\ \forall j\in D \tag{17}$$

$$x_j^b, y_j^b \in \mathbb{N}\ \forall\, b\in B,\ j\in D \tag{18}$$

$$\mathcal{T}_{\max}\in\mathbb{R}_+ \tag{19}$$

The variables x_j^b and y_j^b are the number of tours for the bus $b \in B$ from S_0 to sink $j \in D$ and back, respectively. The third lower bound is obtained by solving the LP relaxation of $(13-18)$.

To include the obtained lower bounds and upper bounds to a branch and bound framework, three branching rules are described in [GGH13]. The full branching where one node is created for each bus, source, and sink with positive residual capacity is the first branching rule. The drawback of this is that there may be more branching steps than required. In order to improve the full branching avoiding unnecessary branches, a second branching rule is defined with first buses first operation. The third branching rule is the minimal offset bus first, where it branches those buses with the smallest offset first. Also tree reduction procedures (lexicographic pruning and subtour pruning) have been developed. Several branches are discarded with these pruning. For the purposes of this case study, the combination of algorithms and parameters is chosen which performed best in [GGH13].

3.2 Tabu Search Heuristic for RBBEP

In order to keep track of recently visited solutions in local search and to avoid the same solution again to leave local minima with respect to the neighborhood, a tabu search meta-heuristic is developed in [GG14]. In tabu search, different neighborhood moves are made to modify the current solution such as: any tour (i, j) can be changed to $(i', j'), i' \in S, j' \in D$; a tour plan of any bus can be extended by a tour (i, j) or have a tour removed; a here-and-now or wait-and-see bus can be added or removed with its tour plan for every scenario; the last tour (i, j) of the tour plan of any bus can be moved to the end of another tour plan of another bus; a here-and-now bus can be changed to a wait-and-see bus by copying its tour plan for every scenario; by choosing any two tours from any two buses their positions can be swapped. The solutions obtained by applying any of these moves gives the neighborhood of the current solution.

Let $\mathcal{T}_{\text{max}}$ be the objective value of a feasible solution with at least one here-and-now bus. Since this bus can be changed to wait-and-see bus by replacing its tour plan, the objective value will be at most $\mathcal{T}_{\text{max}} + p_{\text{wait}}$. The remaining all moves might make the current feasible solution infeasible. By searching infeasible regions, it can also be advantageous to escape local minima. The search for infeasible solution is allowed by using dynamically updated penalty parameters that are decreased for any sequence of feasible solutions, and increased for sequences of infeasible solutions.

Let inf^{sat}, inf^{cap} and inf^{bus} be the total number of non-evacuated persons over all scenarios, the total number of shelter capacity violations over all scenarios and the number of buses exceeding $|B|$, respectively. Let p_{sat}, p_{cap} and p_{bus} be the respective penalty parameters. Then, the objective value of a solution during the tabu search is as follows.

$$\text{obj}_{\text{tabu}} = \mathcal{T}_{\text{max}} + p_{\text{sat}}\text{inf}^{\text{sat}} + p_{\text{cap}}\text{inf}^{\text{cap}} + p_{\text{bus}}\text{inf}^{\text{bus}} \quad (20)$$

The obtained tabu list consists of complete solutions. The number of iterations (called idle) that do not improve the current best solution is counted in every step. With a given number max_idle of idle iterations the search is restarted. That is, the tabu list is emptied, infeasibility penalties are reset to their beginning values, and the current best solution is restored. A feasible solution in the neighborhood that improves the current best solution is always favored over any infeasible solutions. Among the obtained solutions that have an equal best objective value, a solution that has the smallest tour length variance is chosen with a lexicographic optimization scheme. Such a solution applies buses with tours of balanced lengths.

In [GG14], a starting solution is constructed by a polynomial greedy heuristic with only two buses; one here-and-now bus and another wait-and-see bus. Let $\alpha_i := \min_{z \in Z} l_i^z, i \in S$ be the minimum number of evacuees over all scenarios and $\beta_i^z = l_i^z - \alpha_i, i \in S, z \in Z$ be the residual demand. The here-and-now bus transports $\alpha_i, i \in S$ evacuees where wait-and-see bus transports the residual evacuees β_i^z.

For this case study (where the number of buses is considerably larger than in their instances), we use a different starting solution: We set half of the buses as here-and-now and the other half as wait-and-see, and distribute the α and β loads uniformly over the respective sets of buses.

4 Disaster Scenarios of Nepal

Nepal enjoys quite large variations in natural environment, having alpine, temperate and tropical climates from the north to the south. As a result, ice/snow avalanche, glacier lakes, debris flow, flood, fire, landslide, hailstorm, drought and heavy rains have been experienced every year. The country also varies its tectonic structure with respect to major faults and thrusts. The plain southern part is composed of alluvial deposits, whereas the extreme northern weak Himalaya rocks make the region very fragile. Resulting from the weak geological characteristics and very monsoonal climate, most parts of the country experience unpredictable earthquakes and rain falls. Also because of these and high population growth, there is a migration to urban areas.

Earthquake, landslide, flood, drought, epidemics and fire are the major hazards reported in Nepal. There have been altogether 15,388 disasters of different magnitude killing 27,256 people and affecting a quite large number in the years 1971-2007, see Table 3. Reports show that Nepal's world-wide risks position is eleventh from earthquakes, thirtieth from floods, and the country is one of the global hot-sports for natural disasters.

The population of the mountain-surrounded, bowl-shaped capital city of Nepal, Kathmandu valley ($665km^2$), increases rapidly and is estimated as 25,17,023 in the year 2011 [GN14]). The total population in the valley has been estimated to be about 40,000,000 very recently. This number may still be a low estimate, because of the fast migration rate and temporary residents. Kathmandu is weakly connected to the rest of the valley, with only one international airport and two major highways of not very significant width and speed. The valley is like a basin filled with soft sediments and it has five faults. In 1934, an earthquake of Richter scale 8.4 had been

Event type	No. of events	Population deaths	Population affected	Buildings damaged
Flood	2,720	2,936	33,67,974	1,54,104
Landslide	2,184	3,987	4,79,972	25,451
Earthquake	94	873	4,539	89,020
Fire, Forest Fire	3,978	1,125	2,28,456	66,395
Epidemics	3,129	15,741	4,61,952	-
Drought	152	-	1,512	-
Cold Wave	192	298	1,453	-
Heat Wave	31	25	261	-
Famine	20	2	83,902	-
Avalanche	90	217	1,012	28
Hydro-meteorological	2,123	1,166	2,81,661	9,144
Others	675	886	13,868	1,781
Total	15,388	27,256	49,36,562	3,49,923

Table 3: Disaster events during 1971-2007 in Nepal [NSE10]

recorded with loss of a lot of property and lives. If one looks at the house construction in Kathmandu, the densely populated core area where most of the business occurs is mostly covered with old houses – buildings without any earthquake proof. Also, there are narrow roads which make it difficult for bigger-sized vehicles to enter in normal or emergency cases. Likewise, rural areas are covered with houses of similar strength. Even newly constructed houses in urban areas are not sufficiently stable in case of an earthquake. Among the above mentioned types of natural disasters, an earthquake is the major concern for Kathmandu because of its high sensitivity to seismic waves, the number of faults, soil composition, poorly built constructions and narrow road structure of the valley. We refer to [NSE10] and the references therein for an overview of possible disaster scenarios and responsible organizations working on it.

There are various governmental and nongovernmental organizations responsible for preparedness, planning, response and recovery for disaster risk management. Few of them include, Ministry of Physical Planning and Work, Ministry of Home Affairs, Kathmandu valley Town Development Committee, Department of Urban Planning and Building Construction, Town Development Executive Committee, Local Government, Municipalities, Town Development Executive Committee, Nepal Army, Nepal Police, NGOs and INGOs supported by international agencies as well, and the highest level institution National Commission for Disaster Risk management. There exist many Acts, Policies, Plans and Laws released for planning, programs, emergency risk reduction, house and building construction, shelter delivery, logistic supports and rehabilitation. However, the scientific research aspect seems to be very weak and only some academic institutions have initiated these aspects only very recently. To the best of our knowledge, there is no mathematical programming model used in this direction so far.

Lessons from past disasters indicate that people in Kathmandu valley have unsafe feelings from possible hazards. Earthquake experiences proof that even if a small-sized earthquake happens without destroying road structure and the relatively newly structured constructions besides the core old city areas, houses should be made empty for a certain period of time. Additionally, many houses may be under risk or cracked in the core areas and residents might have to be evacuated outside of it. Yet, another example, it may be any big exposition inside the dense area and the people have to be evacuated to the safe places. From the vehicle ownership viewpoints, very negligible number of people have their own cars and most of the people depend on public transport, so transit dependent dominated population exist in the valley. Therefore, we consider the bus-based evacuation planning problem concentrated on densely populated core area of Kathmandu valley.

5 Case Study

5.1 Scenario Description

Assume the following hypothetical scenario: An earthquake with a magnitude of approximately 6 on the Richter scale occurs in the evening or night time with unknown epicenter at that moment, like the Udayapur (south-east Nepal about 165km far from Kathmandu) earthquake of magnitude 6.6 Richter occurred in 1988. But the people in the considered area have a feeling of a swarm earthquake of magnitudes 3.9 to 4.2 Richter like it happened in 1993 with epicenter about 40km north of Kathmandu. This creates a great fear among the people and almost all people run down to the streets and seek support for the security of their lives. A few old houses and building are already damaged but there is a feeling of cracks in a lot, meaning most of the people have insecure feelings in their residents. Fortunately, the roads around and in the valley are not unusably destroyed except the disturbances from the surrounding people in the houses nearby. The assumptions should be realistic as there were not too many roads damaged except blockage by collapsed buildings in dense areas learned from past experiences, see [NSE10]. However, the solution approach we have considered here would equally be applicable in any other emergency scenario such as a bomb blast or defuse at the center of the location.

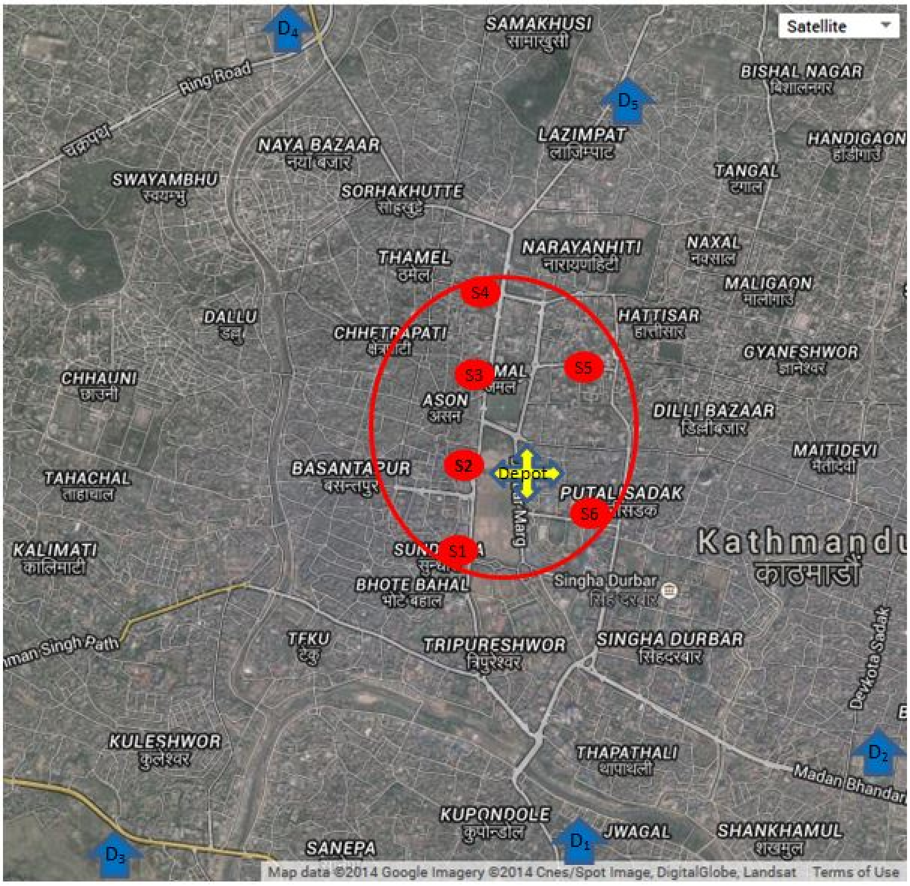

Figure 3: Map of core city Kathmandu [WEB14]

For our test data sets, we consider the old core city in Kathmandu valley surrounded by red mark as shown in the Figure 3. Excluding the visitors or tourists, the total residential population in this approximately 1.45km^2 area (c.f. [WEB14]) is 25,672 (c.f. [GN14]), that is, a density of 17,704 people per km^2 (c.f. Table 4). We select the convenient bus-station pickups as marked by red circles where people can reach these open areas from nearby residents and the shelters marked by blue spot where evacuees should be brought by buses of uniform capacity. The shelters are either schools-colleges or government buildings where sufficient open areas would be available (at least $3m^2$ per person) up to their capacity. All pickup-shelter links can be seen by the connected roads on the map. The single depot is chosen to be the existing old bus park of Kathmandu.

Ward No.	Voters	Non-voters	Total pop.	Affected pop.	50% pop.	60% pop
22	2902	1219	4121	1374	687	824
24	2624	1102	3726	2484	1242	1490
27	3545	1489	5034	3356	1678	2014
26	2147	902	3049	1016	508	610
28	2527	1061	3588	2392	1196	1435
30	4815	2022	6837	6837	3419	4102
29	1542	648	2190	730	365	438
17	6272	2634	8906	1113	557	668
16	1869	785	2654	885	442	531
31	3863	1622	5485	5485	2743	3291

Table 4: Approximate population of evacuation region

	Population at 6-sources		Population at 5-sources	
Source: Place	50 percent	60 percent	50 percent	60 percent
S_1: Sundhara	2836	3403	3880	4656
S_2: Mahankal	3306	3967		
S_3: Jamal	2150	2581		
S_4: Kesharmahal	1801	2161	2111	2533
S_5: Kamaladi	1646	1975	1646	1975
S_6: Pradashani Marg	1097	1316	1097	1316
S_7: Ratnapark			4103	4923

Table 5: Population distribution for Branch and Bound

We now describe different variants to model this evacuation scenario. By choosing the excess exterior areas as sources (i.e., pickups), we vary them to be 6 or 5. The five sources are considered by merging the sources S_2 and S_3 and creating a new source S_7 which lies in between the former two sources. The Table 5 represents the number of evacuees with respect to six sources and five sources. Likewise, the appropriate sinks (i.e., shelters) are also selected to be 4 or 5 with known capacity (c.f Table 6). All buses are of uniform capacity but they may carry people from 60 to 90 with comfortable travel or adjustable travel standing without seats in emergency period. We consider the examples with extreme cases with 60 or 90 persons per bus capacity. Likewise speed of a bus may range from 4 minutes to 5 minutes per km, we assumed that the speed of a bus is $15km/hr$ in the best case and $12km/hr$ in the worst case, see Table 7.

We assume that few buildings are relatively stronger, some people may lose chances of evacuation facility or some may be adjusted with the relatives or friends in the neighborhood of the evacuation region. This, we consider 50 percent and 60 percent people to be evacuated, see Table 4. The buses available for evacuation may also vary but they are assumed to be available at the time of evacuation. We consider the number of buses to be 100 or 140 for branch and bound.

For the uncertain evacuation problem, we set $p_{wait} = 20$ in accordance with the travel times from Table 7. We derived four possible scenarios which describe different outcomes for evacuees at collection points. Table 8 shows these estimated population arrivals for five and six sources.

Sinks	Place of sinks	Area in m^2	Capacity in persons	60 persons/bus	90 persons/bus
D_1	Pulchok Campus	15000	5000	83	56
D_2	BICC Banesor	12000	4000	67	44
D_3	Sc. Block TU	9000	3000	50	33
D_4	Balaju	12000	4000	67	44
D_5	BMC Lazimpat	6000	2000	33	22

Table 6: Capacity of sinks

	D_1	D_2	D_3	D_4	D_5	Depot
S_1	12	13	19	15	14	4
	15	16	24	18	17	4
S_2	13	13	20	13	12	3
	17	17	25	16	15	4
S_3	16	16	23	11	10	3
	20	20	28	13	12	3
S_4	18	18	25	9	8	5
	23	23	31	11	10	6
S_5	14	14	26	12	12	4
	17	18	32	15	14	5
S_6	11	11	24	16	14	2
	13	14	30	20	18	3
S_7	14	14	21	12	11	2
	18	18	26	15	13	3

Table 7: Travel time matrix ($15km/hr$ upper) and ($12km/hr$ lower)

	Scenarios with 6-sources								Scenarios with 5-sources							
	Bus capacity 60				Bus capacity 90				Bus capacity 60				Bus capacity 90			
Sources	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
S_1	47	51	51	40	32	35	38	34	65	70	67	63	43	47	44	42
	57	60	58	61	38	40	37	35	78	76	74	73	52	50	48	55
S_2	55	51	50	50	37	34	31	35								
	66	63	60	58	44	38	39	38								
S_3	36	39	39	50	24	18	22	26								
	43	44	49	44	29	33	32	33								
S_4	31	33	22	24	20	26	23	18	35	33	35	43	24	23	28	32
	36	35	33	37	24	25	28	30	42	48	52	50	28	33	36	32
S_5	27	21	33	25	18	13	15	16	28	30	25	21	18	19	17	16
	33	30	31	33	22	21	19	18	33	30	29	34	22	20	19	23
S_6	18	19	19	25	12	17	14	14	18	18	23	25	12	12	14	15
	22	25	26	24	15	15	17	18	22	25	26	23	15	17	18	14
S_7									68	63	64	62	46	42	40	38
									82	78	76	77	55	52	51	48

Table 8: Estimated population load with 50 % (upper) and 60 % (lower)

5.2 Experimental Results

In this section we analyze the numerical results on the best objective values obtained by executing $2{\cdot}2{\cdot}2{\cdot}2{\cdot}2{\cdot}2 = 64$ instances for 15 minutes each. We test the branch and bound algorithms once. Due to its randomized nature, the tabu search algorithm was tested three times and the best solution was recorded. All experiments were conducted on a compute server with a 16-core Intel Xeon E5-2670 processor, running at 2.60 GHz (up to 3.3 GHz with turbo boost) with 20 MB cache, 32 GB RAM and Ubuntu 12.04. The code was written in C++ using gcc v.4.5.4. with compile flag -03.

The instance-wise best results obtained by the branch and bound implementation are as follows.

The best evacuation time of 29 minutes (respectively, 36 minutes) is achieved at 6 or 5 sources and 5 sinks for 50 percent population (respectively, 60 percent population) using 140 buses having 90 evacuees per bus capacity and $15km/hr$ speed (c.f Figure 8). Fixing the travel time to $12km/hr$, the best evacuation time is 35 minutes at 6 sources and 5 sinks for 50 percent population using 140 buses having 90 evacuees per bus capacity (c.f Figure 9). The best solution with 60 evacuees per bus capacity is 39 minutes at 6 sources and 5 sinks for 50 percent population using 140 buses and $15km/hr$ speed (c.f Figure 10). With 100 buses the best evacuation time is 38 minutes at 6 sources and 5 sinks for 50 percent population using 90 evacuees per bus capacity and $15km/hr$ speed (c.f Figure 11). Decreasing the number of sinks increases the evacuation time from 29 minutes to 32 minutes (c.f. Figure 13). As expected, the experiments show that the domain of optimal solutions remains on larger number of buses with higher capacity and speed irrespective of the population chosen. We made several attempts of these experiments and have observed that best objectives values could be obtained even in less time efficiently.

The instance-wise best results obtained by the tabu search algorithm are as follows.

The best evacuation time is 44 minutes at 5 sources and 5 (or 4 sinks) for 50 percent (or 60 percent population), using 140 buses having 90 evacuees per bus capacity and $15km/hr$ speed (c.f Figure 14). Fixing the travel time $12km/hr$ the best evacuation time is 53 minutes at 6 sources and 5 sinks for 50 percent population using 140 buses having 90 evacuees per bus capacity (c.f Figure 15). The best solution with 60 evacuees per bus capacity is 64 minutes at 5 sources, and 4 and 5 sinks for 50 percent population using 140 buses and 15km/hr speed (c.f Figure 16). With 100 buses the best evacuation time is 50 minutes at 6 and 5 sources, and 4 and 5 sinks for 50 percent population using 90 evacuees per bus capacity and $15km/hr$ speed (c.f Figure 17). The choice of the number of sources and sinks does not play a significant role (c.f. Figures 18 and 19). As expected, the experiments show that the domain of optimal solutions remains on larger number of buses with higher capacity and speed irrespective of the population chosen.

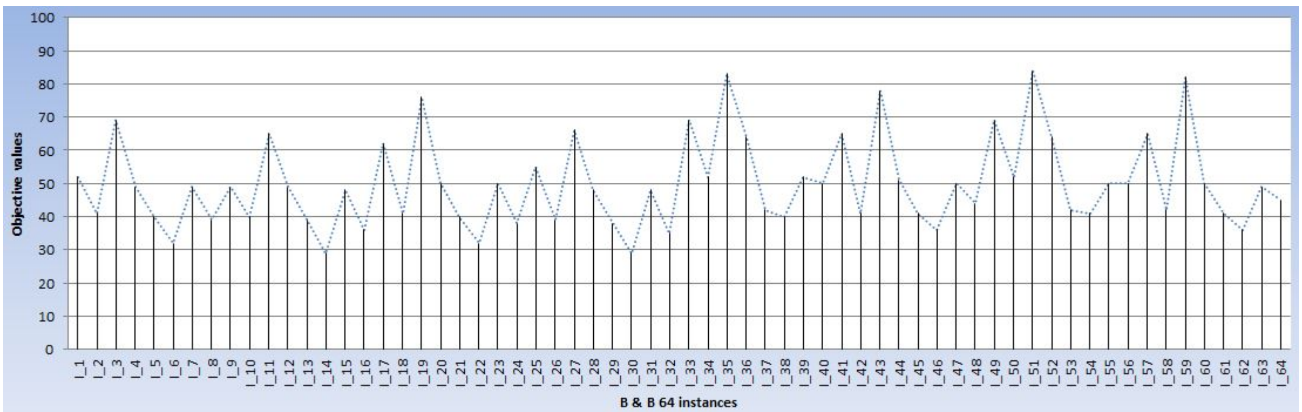

Figure 4: Case study overview for BBEP using branch and bound

Table 9 represents summary of results illustrating the minimum, average and maximum evacuations times

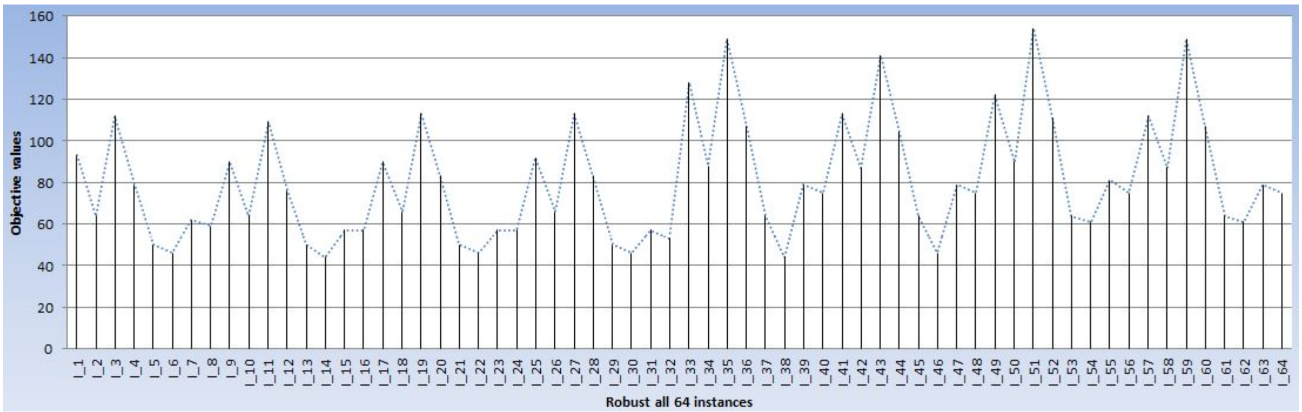

Figure 5: Case study overview for RBBEP using tabu search

	BBEP			RBBEP		
Instances	Minimum	Average	Maximum	Minimum	Average	Maximum
P50: 50% population	29	46	76	44	70	113
P60: 60% population	36	54	84	44	82	154
T4: 4 min/km	29	45	69	44	72	128
T5: 5 min/km	35	55	84	53	90	154
q60: 60 evacuees/bus	39	58	84	64	101	154
q90: 90 evacuees/bus	29	42	52	44	60	81
B100: 100 buses	36	57	83	50	90	154
B140: 140 buses	29	43	64	44	71	111
S5: 5 sources	29	50	83	44	80	149
S6: 6 sources	29	50	84	46	82	154
D4: 4 sinks	32	52	84	44	82	154
D5: 5 sinks	29	48	82	44	80	149

Table 9: Evacuation times for BBEP (branch and bound) and RBBEP (tabu search).

obtained by both algorithms branch and bound and tabu search implemented separately. Figure 6 separately illustrates the minimum, average and maximum evacuation times obtained by both algorithms. The figures measure the gap between the minimum, average and maximum evacuation times. A comparison of average, and minimum and maximum evacuation times obtained by both algorithms are represented by Figure 7. The experiments show that – as expected – the results obtained by branch and bound algorithms for the BBEP with perfect information are always better than that of tabu search for the RBBEP with uncertainty in the cases of minimum, average and maximum evacuation times. For more detailed results we refer to Appendix B.

We can use these results to derive suggestions for high-level planning strategies for practitioners in the Kathmandu area. We would like to stress that such suggestions are only valid within the considered framework of modeling assumptions and may not carry over to practical, much more considerations. Our conclusions are: a) The calculated evacuation times may be considered as lower bounds on actual evacuation times. In this sense, one may assume that an evacuation of the considered area will not be possible in less than 45 minutes. b) The difference in evacuation times between the BBEP and the RBBEP shows the value of information in evacuation planning. In particular, perfect knowledge of the evacuation scenario makes a difference of around 30 minutes on average to an uncertain scenario. c) Using 140 buses instead of 100 buses yields an approximate improvement in evacuation time between having 90 instead of 60 passengers on board of a bus. Thus, from a financial point of view, the acquisition of less, larger buses instead of more, smaller buses may be helpful. And d) Both the

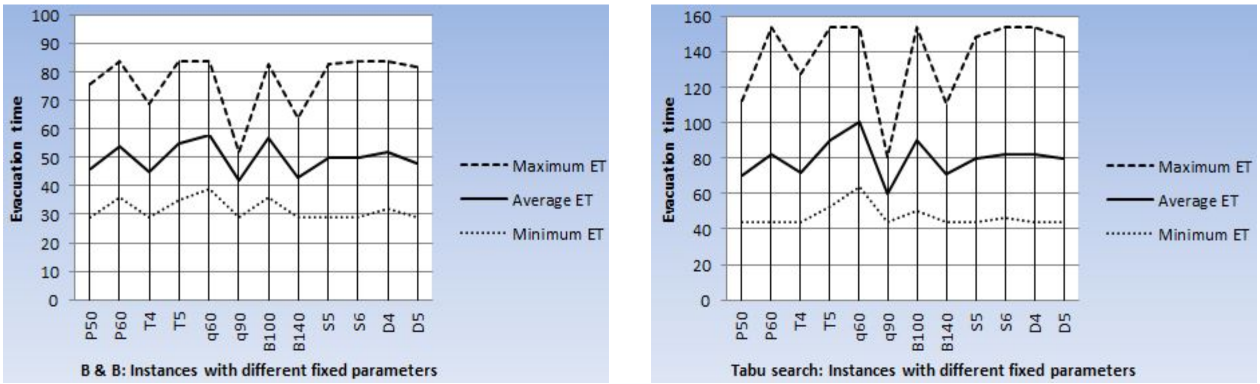

Figure 6: Comparison of minimum, average and maximum evacuation time

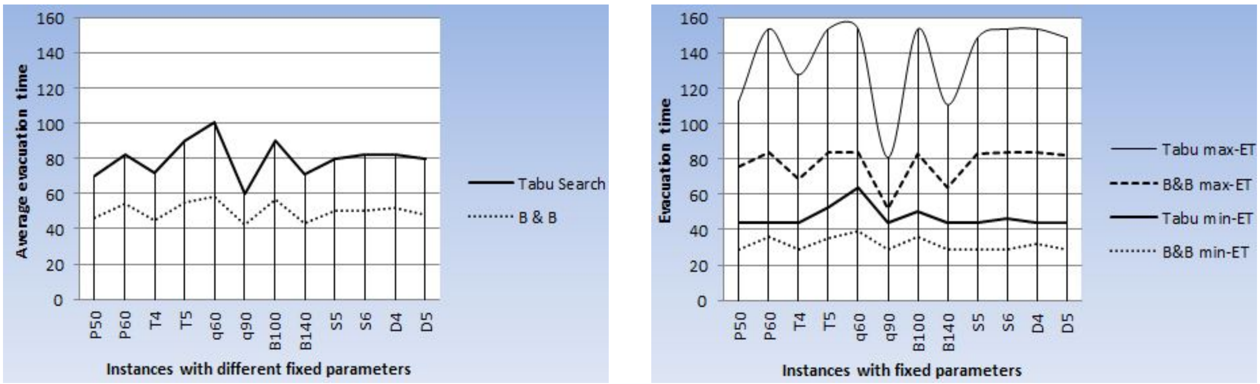

Figure 7: Comparison of evacuation time of B & B and tabu search

number of sources (5 or 6) and the number of shelters (4 and 5) have only minor impacts on evacuation times.

6 Conclusions

The objective of this study was to formulate a mathematical model of the densely populated metropolitan capital city Kathmandu of Nepal and implement an evacuation plan using available efficient software. In this case study, we discussed the problem of evacuating a part of core city of Kathmandu with the help of buses. The evacuees at depots are either given in advance or arrive depending on given scenarios. These approaches optimize the evacuation of transit dependent people with the help of managed public transport infrastructure in the case of an emergency. Both case studies are the implementations of the approaches in [GGH13, GG14]

We applied two solution algorithms; branch and bound for the BBEP and tabu search for the RBBEP. The computational results of branch and bound and tabu search heuristics had been separately presented in the Figure 4 and Figure 5, respectively. The choice of number of sources and sinks have not played significant roles in both approaches.

To the best of our knowledge this is the first case study conducted in the case of a core city of Kathmandu using mathematical modeling. This case study has motivated to conduct a number of further research, for example multi-depot multi-model evacuation planning with car and bus-based evacuation and a problem with contraflow. Analyzing encouraging results of the considered evacuation scenarios with respect to few number of buses, sources, sinks and a single depot, we would recommend several other case studies of Kathmandu valley with increased number of these parameters. Several evacuation issues are left open in this region.

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A MIP Formulation for RBBEP

Before the formulation of MIP for RBBEP, we introduce some variables. The variable x_{ij}^{br} decides if the here-and-now bus $b \in B$ travels from source i to sink j in round $r \in R$. The variable x_{ij}^{brz} decides if the wait-and-see bus $b \in B$ travels from source i to sink j in round $r \in R$ with scenario $z \in Z$. When visiting a source, the possibility of here-and-now bus that do not take evacuees is modeled using the variable Δ_{ij}^{brz} that determines if the here-and-now bus b picks up evacuees on its trip form source i to sink j in round r. The variable y_b indicates that b is a here-and-now bus if it set to 1 otherwise it is wait-and-see bus. Here, d_{to}^{br} and d_{back}^{br} are the travel times of the here-and-now bus b in round r from the source to sink and from the sink to next source, respectively. Also d_{to}^{brz} and d_{back}^{brz} are analogously defined for the wait-and-see buses. The objective $\mathcal{T}_{\max}$ denotes the maximum total travel distance over all buses.Then, the MIP formulation of the RBBEP is presented as follows as defined in [GG14].

$$\text{minimize} \quad \mathcal{T}_{\max} \tag{21}$$

$$\text{such that} \quad \mathcal{T}_{\max} \geq \sum_{r\in R}(d_{\text{to}}^{br} + d_{\text{back}}^{br}) + \sum_{i\in S}\sum_{j\in D}\tau_i x_{ij}^{b1} \;\forall\, b \in B \tag{22}$$

$$\mathcal{T}_{\max} \geq p_{\text{wait}}(1-y_b) + \sum_{r\in R}(d_{\text{to}}^{brz} + d_{\text{back}}^{brz}) + \sum_{i\in S}\sum_{j\in D}\tau_i x_{ij}^{b1z} \;\forall\, b \in B,\; z \in Z \tag{23}$$

$$d_{\text{to}}^{br} = \sum_{i\in S}\sum_{j\in D}\tau_{ij} x_{ij}^{br} \;\forall\, b \in B,\; r \in R \tag{24}$$

$$d_{\text{to}}^{brz} = \sum_{i\in S}\sum_{j\in D}\tau_{ij} x_{ij}^{brz} \;\forall\, b \in B,\; r \in R,\; z \in Z \tag{25}$$

$$d_{\text{back}}^{br} \geq \tau_{ij}\left(\sum_{k\in S} x_{kj}^{br} + \sum_{l\in D} x_{il}^{b,r+1} - 1\right) \forall\, b \in B,\; r \in R^{-t},\; i \in S,\; j \in D \tag{26}$$

$$d_{\text{back}}^{brz} \geq \tau_{ij}\left(\sum_{k\in S} x_{kj}^{brz} + \sum_{l\in D} x_{il}^{b,r+1,z} - 1\right) \forall b \in B, r \in R^{-t}, i \in S, j \in D, z \in Z \tag{27}$$

$$\sum_{r\in R}\sum_{i\in S}\sum_{j\in D} x_{ij}^{br} \leq |R| y_b \;\forall\, b \in B \tag{28}$$

$$\sum_{r\in R}\sum_{i\in S}\sum_{j\in D} x_{ij}^{brz} \leq |R|(1-y_b) \;\forall\, b \in B,\; z \in Z \tag{29}$$

$$\sum_{i\in S}\sum_{j\in D} x_{ij}^{br} \leq 1 \;\forall\, b \in B,\; r \in R \tag{30}$$

$$\sum_{i\in S}\sum_{j\in D} x_{ij}^{brz} \leq 1 \;\forall\, b \in B,\; r \in R,\; z \in Z \tag{31}$$

$$\sum_{i\in S}\sum_{j\in D} x_{ij}^{br} \geq \sum_{i\in S}\sum_{j\in D} x_{ij}^{b,r+1} \;\forall\, b \in B,\; r \in R^{-t} \tag{32}$$

$$\sum_{i\in S}\sum_{j\in D} x_{ij}^{brz} \geq \sum_{i\in S}\sum_{j\in D} x_{ij}^{b,r+1,z} \;\forall\, b \in B,\; r \in R^{-t},\; z \in Z \tag{33}$$

$$\Delta_{ij}^{brz} \leq x_{ij}^{br} \;\forall i \in S,\; j \in D,\; b \in B,\; r \in R,\; z \in Z \tag{34}$$

$$l_i^z \leq \sum_{j\in D}\sum_{b\in B}\sum_{r\in R}\left(\Delta_{ij}^{brz} + x_{ij}^{brz}\right) \;\forall\, i \in S,\; z \in Z \tag{35}$$

$$u_j \geq \sum_{i\in S}\sum_{b\in B}\sum_{r\in R}\left(\Delta_{ij}^{brz} + x_{ij}^{brz}\right) \;\forall\, j \in D,\; z \in Z \tag{36}$$

$$
\begin{aligned}
x_{ij}^{br} &\in \{0,1\}\;\forall\, i \in S,\ j \in D,\ b \in B,\ r \in R && (37)\\
x_{ij}^{brz} &\in \{0,1\}\;\forall\, i \in S,\ j \in D,\ b \in B,\ r \in R,\ z \in Z && (38)\\
\Delta_{ij}^{brz} &\in \{0,1\}\;\forall\, i \in S,\ j \in D,\ b \in B,\ r \in R,\ z \in Z && (39)\\
y_b &\in \{0,1\}\;\forall\, b \in B && (40)\\
d_{\text{to}}^{br}, d_{\text{back}}^{br} &\in \mathbb{R}_+\;\forall\, b \in B,\ r \in R && (41)\\
d_{\text{to}}^{brz}, d_{\text{back}}^{brz} &\in \mathbb{R}_+\;\forall\, b \in B,\ r \in R,\ z \in Z && (42)\\
\mathcal{T}_{\max} &\in \mathbb{R}_+ && (43)
\end{aligned}
$$

The objective value (21) is as large as the maximal travel time of all buses given by the constraint (22) and (23), i.e., the maximum evacuation time over all here-and-now and wait-and-see buses, respectively. The travel times from a source to a sink and from the sink to a next source are defined by constraints (24) and (26) for here-and-now buses, and by (25) and (27) analogously, for the wait-and-see buses, respectively. The constraints (28) and (29) ensure that a bus is either here-and-now or wait-and-see. In one round, a bus can only travel from one source to one sink as described by the constraint (30) and (31). The travel from a sink to a source is possible for next tour if a bus travels from a source to the sink first. So, according to the constraint (32) and (33), the bus tours are connected and can stop whenever they like. In constraint (34), it is ensured that Δ can only be one, if the corresponding x variable is one, too. The demand constraint (35) ensures that all the evacuees are transported to the sinks without violating the capacity constraint (36) of the sinks.

B Detailed Results

In the following, we compare evacuation times for one considered parameter at a time (50 or 60% population; 4 or 5 minutes per km; 60 or 90 persons per bus; 100 or 140 buses; 5 or 6 sources; 4 or 5 sinks). We first present results for BBEP, and then for RBBEP.

B.1 Results for BBEP

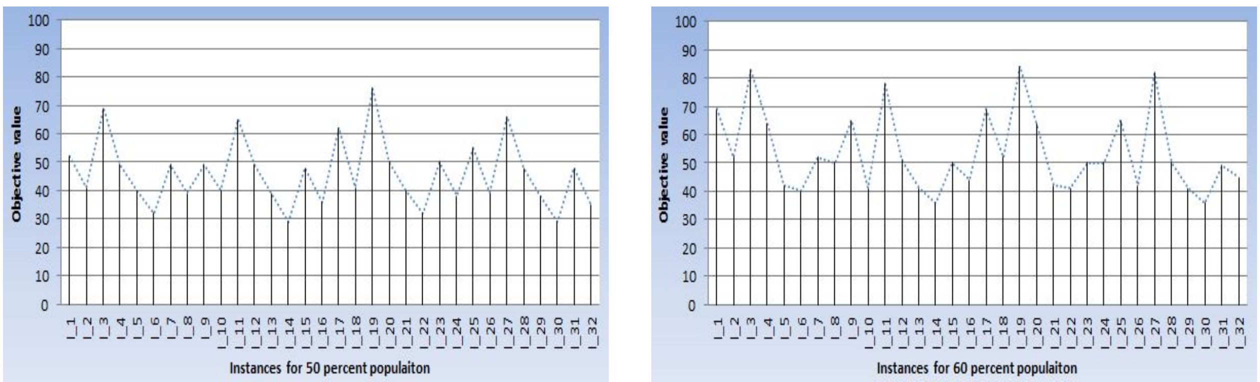

Figure 8: Branch and bound results with varying population

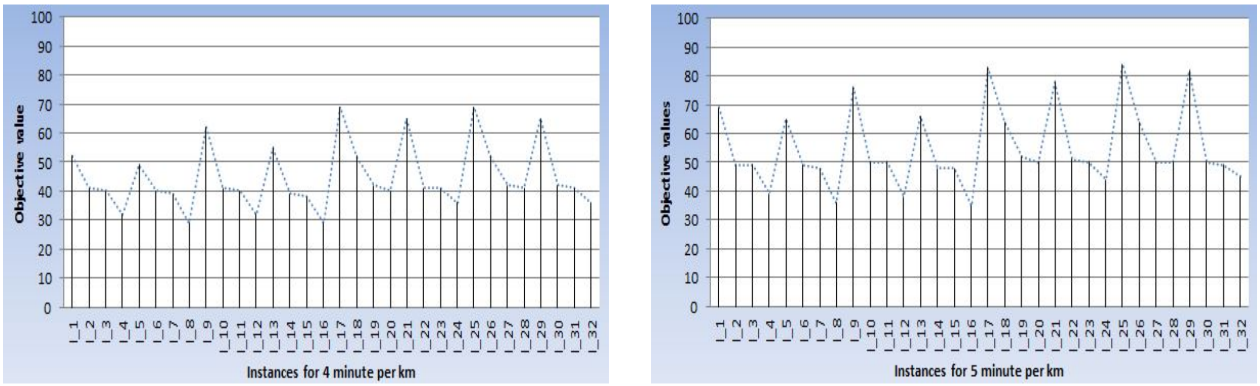

Figure 9: Branch and bound results with varying travel times

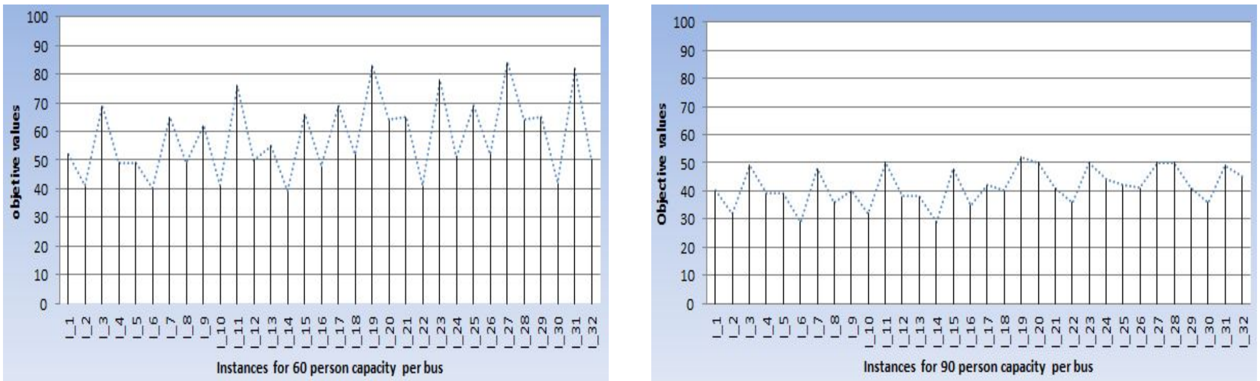

Figure 10: Branch and bound results with varying bus capacity

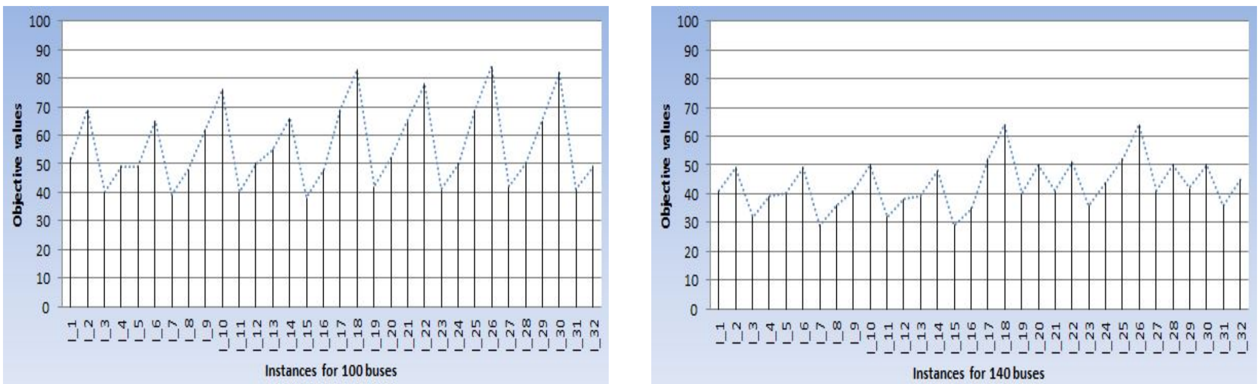

Figure 11: Branch and bound results with varying number of buses

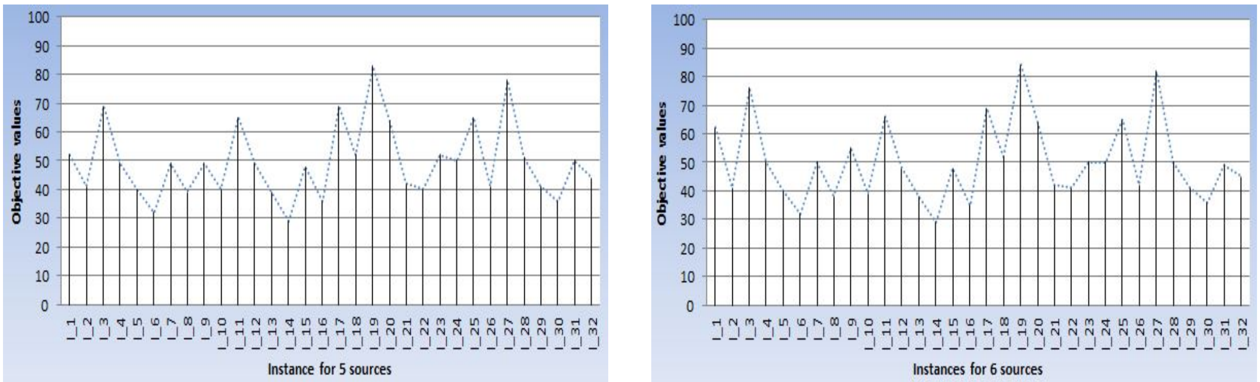

Figure 12: Branch and bound results with varying number of sources

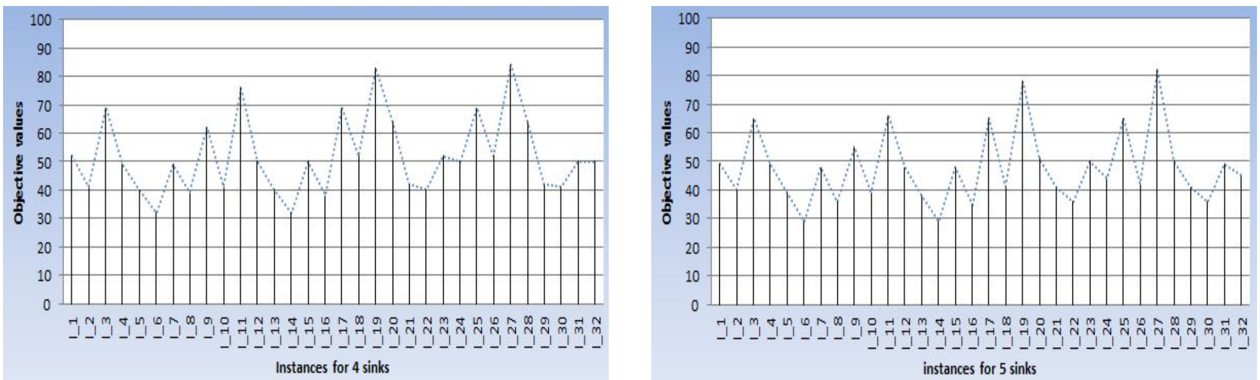

Figure 13: Branch and bound results with varying number of sinks

B.2 Results for RBBEP

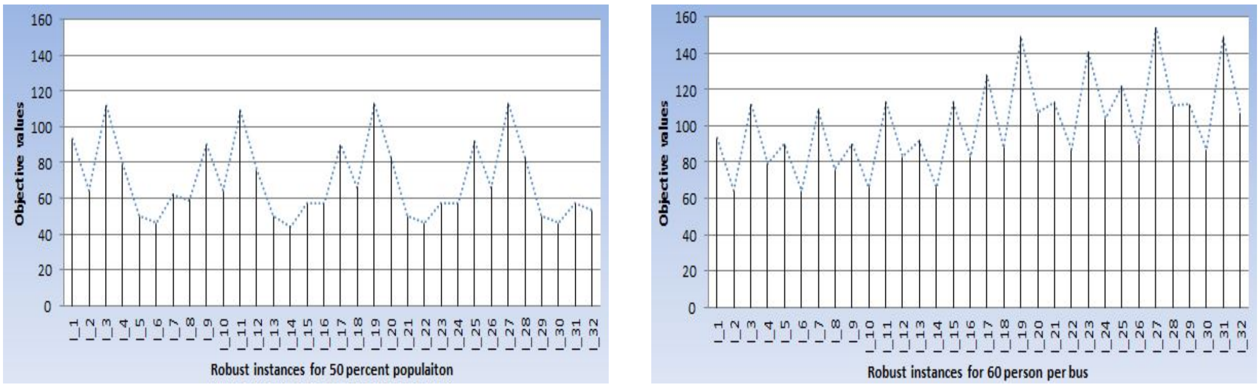

Figure 14: Tabu search results with varying population

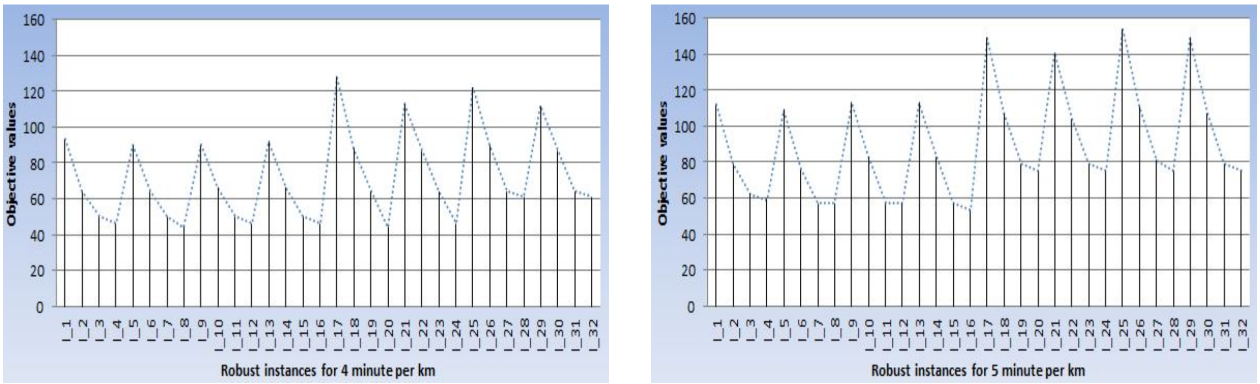

Figure 15: Tabu search results with varying travel times

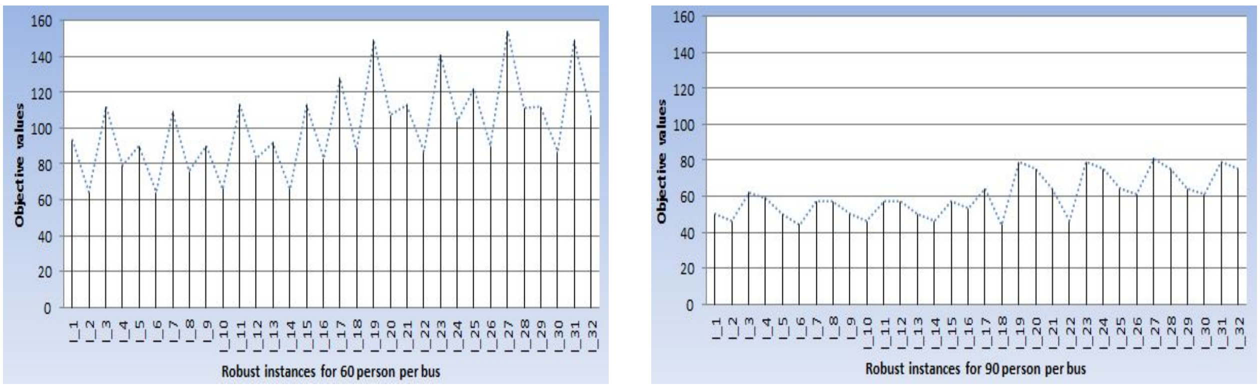

Figure 16: Tabu search results with varying bus capacity

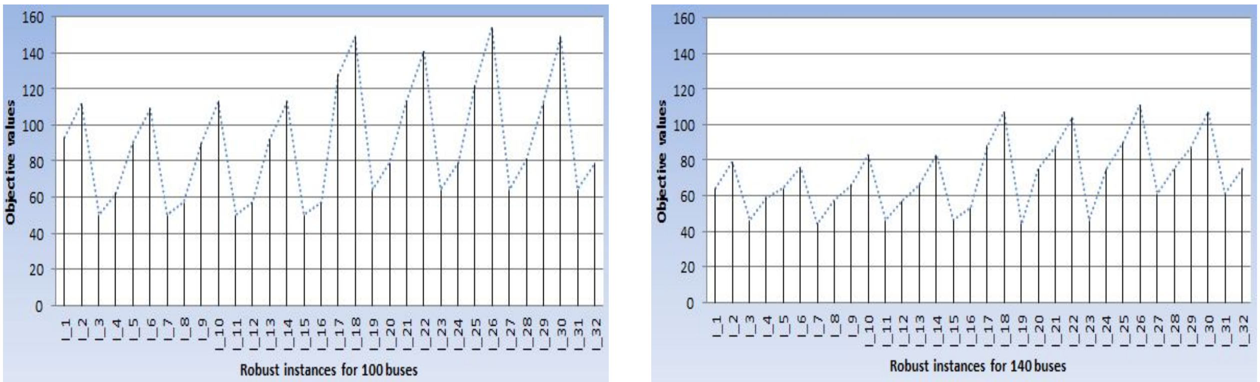

Figure 17: Tabu search results with varying number of buses

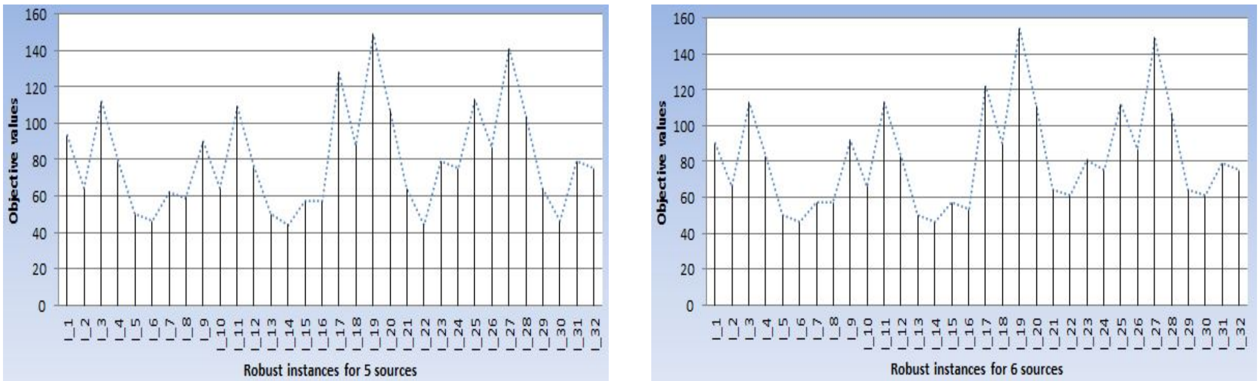

Figure 18: Tabu search results with varying number of sources

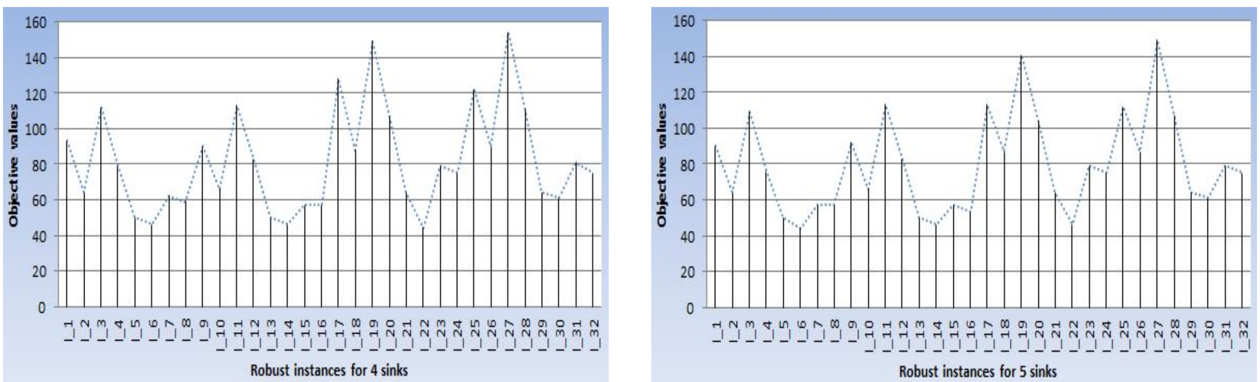

Figure 19: Tabu search results with varying number of sinks