PLANNING OF EMERGENCY MEDICAL SERVICE STATIONS AND AMBULANCES

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ABSTRACT

In this thesis, we address the Emergency Medical Service (EMS) stations location problem. Firstly, we propose a Backup Double Covering Model (BDCM) as a variant of the well-known Maximal Covering Location Problem where two types of service requests are fulfilled. The objective of the model is to maximize the total population serviced within t_1 and t_2 minutes ($t_1 < t_2$) using two distinct EMS stations where the total number of stations is limited. Our aim in doing so is to provide a backup station in case no ambulance is available in the closer station. Since this problem is intractable for large-scale instances we propose a Tabu Search (TS) approach to find good solutions in reasonable computation time. Three initialization approaches are utilized for comparison: random, a steepest-ascent algorithm, and an LP relaxation-based heuristic. In order to test the effectiveness of the proposed method, we conduct an extensive experimental study on a large number of randomly generated data set with different sizes and number of stations. We observe that the TS algorithm provides good results fast in comparison with the solutions obtained using the optimization software OPL Studio 5.5 equipped with ILOG CPLEX 11.0. Secondly, we propose the multi-period extension of BDCM (MPBDCM). This model requires a given number of stations to be opened in each period where the stations opened in any period cannot be closed in the subsequent periods. To solve this problem efficiently, we adopt a similar TS approach using the same initialization methods as in BDCM. Our extensive experimental study on randomly generated data sets reveal that the TS approach provides good results fast compared to the results obtained by using OPL Studio 5.5. Finally, we apply the TS approaches for planning both the single- and multi-period EMS stations location problem in Istanbul on the data obtained from the Directorate of Instant Relief and Rescue at the Istanbul Metropolitan Municipality.

ÖZET

Bu tezde, acil yadım istasyonlarının planlanması için Yedek Çift Kapsama Modeli (YÇKM) ele alınmıştır. Literatürde kapsamlı bir şekilde ele alınan Enbüyük Kapsama Modeli'ni temel alan bu model, acil yardım konusunda iki tip hizmet gerektirmektedir. Modelde amaç, açılabilecek kısıtlı sayıda acil yardım istasyonları ile t_1 ve t_2 ($t_1 < t_2$) süreleri içinde farklı bölgelerde yer alan en az birer istasyon tarafından kapsanan nüfusun enbüyüklenmesidir. Bu modelin önerilmesindeki hedef, acil yardım hizmetine ihtiyaç duyan talep noktalarına cevap verebilecek yakın bir ambulansın olmaması durumunda daha uzak mesafeden yedek servis sağlamaktır. Büyük boyutlu problemler için modelin çözümü zor olduğundan, anlamlı süre içinde iyi sonuçlar bulabilmek amacıyla Tabu Arama (TA) algoritması önerilmiştir. Karşılaştırma için üç farklı başlangıç çözümü bulma tekniği uygulanmıştır: rassal, miyop ve doğrusal programlama gevşetmeye dayalı sezgisel yöntem. Önerilen yöntemin etkinliğini ölçmek amacıyla rassal üretilen farklı büyüklükteki çok sayıda veri seti ve farklı istasyon sayısı limiti ile deneysel çalışma yapılmıştır. Önerilen TA algortiması, CPLEX 11.0 ile önceki sürümlerine göre çok yüksek performansa sahip OPL Studio 5.5 kullanılarak elde edilen sonuçlar ile kıyaslanmıştır.

Tezde ayrıca, YÇKM'nin uzantısı olarak Çok Dönemli Yedek Çift Kapsama Modeli (ÇDYÇKM) önerilmiştir. Bu modelde, ele alınan her dönemde açılacak istasyon sayısı ile bir dönemde açılan istasyonların sonraki herhangi bir dönemde kapanmaması kısıtları sözkonusudur. ÇDYÇKM'yi etkin bir şekilde çözmek için, YÇKM için tanımlanan başlangıç çözümü bulma teknikleri ile TA algoritması bu modele de uygulanmıştır. Rassal verilere dayalı olarak gerçekleştirilen deneysel çalışma ile YÇKM'de olduğu gibi ÇDYÇKM için de OPL Studio 5.5 ile bulunan çözümlerle kıyaslandığında TA'nın çok kısa sürede iyi sonuçlar bulunduğu görülmüştür.

Sonuç olarak hızlı ve etkin olduğu kanıtlanan TA, İstanbul Büyükşehir Belediyesi, İtfaiye Daire Başkanlığı bünyesindeki Acil Yardım ve Cankurtarma Müdürlüğü aracılığıyla elde edilen gerçek veriler kullanılarak İstanbul'da acil yardım istasyonlarının tek yıllık ve dört yıllık planlanması problemi için uygulanmıştır.

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ABBREVIATIONS

EMS	Emergency Medical Service
BDCM	Backup Double Covering Model
SPBDCM	Single Period Backup Double Covering Model
MPBDCM	Multi Period Backup Double Covering Model
YÇKM	Yedek Çift Kapsama Modeli
TDYÇKM	Tek Dönemli Yedek Çift Kapsama Modeli
ÇDYÇKM	Çok Dönemli Yedek Çift Kapsama Modeli
TS	Tabu Search
OR	Operations Research
FIFO	First in First Out
LP	Linear Programming
IMM	Istanbul Metropolitan Municipality
SCM	Set Covering Model
MCLM	Maximal Covering Location Model
BCM	Backup Coverage Model
TEAM	Tandem Equipment Allocation Model
MMCLM	Modified Maximal Covering Location Model
DCM	Double Coverage Model
DSM	Double Standart Model
MEXCLP	Maximal Expected Covering Location Problem
MALP	Maximal Availability Location Problem
MLSCM	Modified Location Set Covering Model
ACO	Ant Colony Optimization
GA	Genetic Algorithm
LR	Lagrangian Relaxation
HLM	Hypercube Location Model
BDSCM	Backup Double Set Covering Model
TÜİK	Turkish Statistical Institute

CHAPTER 1

INTRODUCTION

The location planning of emergency medical service (EMS) stations is crucial, especially in the populated cities with heavy traffic conditions such as Istanbul since an effective planning of these stations directly affects human life protection. The fatalities and disabilities caused by illnesses, accidents, etc. may be reduced by making the right planning decisions. In recent years, EMS has become more important for countries having a fast growing population such as Turkey (Demirhan, 2003). EMS can be provided in different ways in different countries, e.g. by the help of 112 SOS Alarm company in Sweden (Andersson *et al.*, 2004), 112 Emergency Aid Services in Turkey, Hızır Emergency Aid by Istanbul Metropolitan Municipality, etc.

The aim of this thesis is to propose methods for the location planning of emergency service stations. In the last 30 years, there have been lots of studies in the literature about effective planning both fire brigade and EMS stations. Brotcorne *et al.* (2003) and Goldberg (2004) provide a good review of these studies. Generally, mathematical programming is used as a solution method for these problems. Optimal solutions of several problems described in the literature can be found by means of advancements in computer technology, Operations Research (OR) methods, and software. However, more complicated problems require different heuristic methods, since it is impossible to find the optimal solutions for large-scale problems. The models in the literature generally cover single period planning. However, locating EMS stations is a strategic decision as well. Hence, this thesis addresses both the single- and multi-period planning of EMS stations. We first propose the Single-Period Backup Double Covering Model (SPBDCM) where the objective is to maximize the total population serviced within t_1 and t_2 minutes ($t_1 < t_2$) using two distinct EMS stations, and the total number of stations is limited. The Multi-Period Double Covering Model (MPBDCM) has the same objective aggregated over a set of consecutive time periods. However, the maximum limit on the number of stations is imposed for each period and if a station is opened in any period, it cannot be closed in the subsequent periods. The proposed models are conceptually similar to Maximal Covering Location Model (MCML) in Church and ReVelle (1974), Double

Coverage Model (DCM) in Gendreau *et al*. (1997), and Backup Coverage Model (BCM) in Hogan and ReVelle (1986).

We propose a Tabu Search (TS) for solving these two problems efficiently. TS is a local search technique that was originally developed by Glover (1977). Using an initial feasible solution, TS investigates the neighbors of the existing solution in each iteration in an attempt to improve the best solution obtained so far. Thus, new candidate solutions are generated by using different neighborhood search methods. In order to avoid the repetition of the same solutions, TS forbids a given number of moves by keeping these moves in a tabu list. The moves are removed from the list according to the First in First Out (FIFO) rule, i.e. in each iteration the move at the bottom of the list is removed from the tabu list and instead a new move is included at the top of the list. The moves in the tabu list are not accepted unless they provide solutions better than a pre-determined aspiration level. This level is the threshold value defined as a fixed or varying rate of the best objective function obtained in each iteration. In the TS algorithm, the mechanisms for finding effective initial solutions, i.e. the neighborhood search techniques, tabu list size, and aspiration level criteria are the fundamental components whose values are to be determined effectively to avoid being trapped at a local optimum. In our TS approach, three initialization methods are utilized for comparison: (i) a random method, (ii) a steepest-ascent method, and (iii) a Linear Programming (LP) relaxation method. The performance of the TS approach is tested using on randomly generated data sets. Finally, the approach is applied for planning the EMS stations location problem of the Directorate of Instant Relief and Rescue at the Istanbul Metropolitan Municipality (IMM).

The organization of the thesis is as follows. The literature on the location planning of EMS stations and TS is presented in Chapter 2. Chapter 3 is dedicated to the discussion of and the solution approach to the SPBDCM as well as to the experimental study. MPBDCM and its solution approach are presented in Chapter 4. Chapter 5 discusses the case study in Istanbul. Finally, Chapter 6 concludes the thesis with the discussion of results and future research directions.

CHAPTER 2

LITERATURE REVIEW

Since effective planning of EMS systems is a crucial issue, it has attracted attention from many researchers, and a vast amount of publications exists in the literature. Different OR techniques, heuristics, and meta-heuristics have been proposed for solving different variants of this problem. Thanks to the advancements in the OR methodologies and computer technology, these problems may be efficiently solved using different methods.

We can classify the EMS station planning models in the literature in various ways. One basic classification is the *deterministic* and *probabilistic* cases. In the deterministic models, ambulances are always considered to be available to respond to a service request if they are located within the response zone to the demand points. However, in real life conditions the ambulances may be busy depending on the arrival time to the demand points and service duration. In such cases, same or different busy probabilities are assigned to the service systems and are considered at the time of service request.

The very basic deterministic model is the Set Covering Model (SCM) described by Toregas *et al.* (1971). The objective of this model is to find the minimum number of EMS stations covering all demand points. One of the main characteristics of SCM is to geographically cover all demand points by at least one service station without taking into account the populations of these points. Due to the importance of SCM in the literature, other deterministic models are generally based on this model. However, as stated by Brotcorne *et al.* (2003), there are some circumstances that SCM does not consider. For instance, when an ambulance departs for responding to a service aid, other demand points covered by this ambulance are no longer covered in SCM.

Church and ReVelle (1974) proposed MCLM to plan the EMS stations with a limited number of stations. The aim of this model is to maximize the population or the number of the demand points covered by the stations. By using MCLM, efficiency of the available services (rate of total coverage) can easily be measured. Moreover, extra-cost of locating more stations and extra-coverage of these stations may be compared in strategic decision-making.

Various models based on SCM and MCLM are discussed in the literature. Schilling *et al.* (1979) propose the Tandem Equipment Allocation Model (TEAM) as an extension of

MCLM. In TEAM, the objective is to maximize the population covered with two different service types where the number of stations for each type of service is limited. This model also includes a constraint with respect to the precedence relationship of the two types of services: if a service type is assigned to a demand point, the other service must also be assigned.

SCM, MCLM, and TEAM imply single coverage of demand points by the emergency service systems. In other words, if an ambulance is busy serving a demand point, other demand points covered by this ambulance will no longer be covered, as stated earlier. To overcome this drawback, multiple coverage models have been proposed in the literature, which consider both location planning and ambulance related constraints. The Modified Maximal Covering Location Model (MMCLM) in Daskin and Stern (1981) maximizes the covered population. The model includes a second objective which maximizes the demand points covered multiple times. Two different variants of MMCLM are presented by Hogan and Revelle (1986) DCM. In the first variant of DCM, the population covered at least twice is maximized with a limited number of stations. In the second, given a limited number of stations and ambulances, the demands covered once or multiple times are maximized according to the weights assigned to demand points. As seen, all three types of MMCLM are based on multiple coverage of demand points in a single critical travel time restriction.

Gendeau *et al.* (1997) introduce the Double Standart Model (DSM) which maximizes the demand covered multiple times using two different travel time restrictions. The objective of this model is to maximize the demand covered at least twice in the shorter travel time limit. The constraints include a set covering requirement of all demand points within the longer travel time limit and a given proportion of the population to be covered within the shorter travel time limit. An important difference of DSM from the other deterministic models is the assignment of multiple ambulances to the same station. However, there is an upper bound on the number ambulances to be assigned to each station.

The probabilistic models in the literature vary according to their objective functions and constraints. Daskin (1983) propose the Maximal Expected Covering Location Problem (MEXCLP) which is a stochastic model. In this model, an equal busy probability is assigned to all vehicles. This probability depends on the frequency of calls per day and the total service time needed for these calls. There is a limit on the service provided during a day by the limited number of vehicles. Thus, the expected coverage of demand points is maximized with a given number of ambulances where the objective function increases in a diminishing way as the number of coverage for each demand point increases.

ReVelle and Hogan (1989) develope two different probabilistic models. In the Maximal Availability Location Problem (MALP) there is a reliability factor depending on the busy probability assigned to all ambulances equally, as in MEXCLP. In this case, the probability of having at least one service to respond to the demand point is equal to or greater than this factor. Thus, the least number of ambulances needed by each demand point is determined using the reliability factor and this number is equal for all demand points. As in the other models, MALP restricts the total number of stations and ambulances. The objective of MALP is to maximize the total population or demand points covered with the least number of ambulances. The second type of MALP differs from the first type by diversifying the minimum number of ambulances required by each demand point.

Both MEXCLP and MALP assume that the ambulances are independent from each other while assigning busy probabilities. Batta *et al.* (1989) extended MEXCLP by taking into consideration the dependency of the ambulances to each other assigning different busy probabilities to each demand point.

As an extension to SCM, Ball and Lin (1993) proposed the Modified Location Set Covering Model (MLSCM) which is based on minimization of fixed costs of ambulances. In this model, there is a lower bound on the proportional coverage of demand within the shorter time limit and an upper bound on the number of ambulances assigned to each station. Besides, there is an upper bound on the busy probabilities in order to avoid high probabilities of not responding to the calls.

In addition to all these stochastic models, Marianov and ReVelle (1994) introduced a queueing model as a different extension to SCM. Furthermore, research on the relocation of ambulances dynamically has recently gained momentum in the literature.

By the help of the models proposed in the literature, several applied studies have been conducted for the location planning EMS stations. However, real world instances with large number of demand points and potential locations cannot be solved to optimality using the OR techniques such as branch-and-bound, branch-and-cut or cutting-plane methods. Hence, various heuristic and meta-heuristic methods were developed for efficiently solving these problems. For instance, Gendreau *et al.* (1997) propose a TS algorithm for the location planning of the EMS stations in Montreal. TS provided good results fast in comparison with the solutions obtained by a branch-and-bound algorithm with a limited number of iterations. Harewood (2002) discusses planning EMS in Barbados by the help of simulation techniques. Recently, Doerner *et al.* (2005) have proposed Ant Colony Optimization (ACO) to plan the EMS stations in Austria and compared these results to those obtained by the TS approach of

Gendreau *et al.* (1997). The results reveal that TS finds better results especially for large problems within very short time compared to ACO. Jia *et al.* (2005) have proposed a Genetic Algorithm (GA), a Lagrangian Relaxation (LR) approach, and greedy heuristics for EMS planning in Los Angeles, and then they compare the performance of these methods. In another recent study, Rajagopalan *et al.* (2008) use TS for the Hypercube Location Model (HLM), which is a stochastic model considering the queued calls. In this case, the TS is implemented for the dynamic relocation of ambulances.

TS can give good results fast, and hence, it has become a popular metaheuristic in recent years for solving combinatorial optimization problems. In addition to the applications mentioned above, it has been applied to the Vehicle Routing Problem (Gendreau *et al.*, 1994), scheduling problems (Ferland *et al.*, 1999), the Travelling Salesman Problem (Gendreau *et al.*, 1999), graph theory problems (Osman, 2005), and production planning problems (Bock and Rosenberg, 2000), to name a few. TS has also been implemented to bioinformatics, finance, location and allocation, artificial intelligence, telecommunications problems, etc.

CHAPTER 3

A SINGLE-PERIOD BACKUP DOUBLE COVERING MODEL FOR LOCATION PLANNING OF EMS STATIONS

In this chapter, we discuss the SPBCDM as a variant of the well-known MCLM where two types of service requests are fulfilled. Our aim in using a double covering model is to provide a backup station in case no ambulance is available in the closer station. We will first present a linear mathematical model and introduce a TS approach to solve this NP-hard problem. Then, we will test the performance of the TS approach on randomly generated data set and discuss the results.

3.1. Mathematical Model

In the proposed single period model, the objective is to maximize the total population serviced within t_1 and t_2 time units ($t_1 < t_2$) using two distinct emergency service stations where the total number of stations is limited. If a demand point is covered by any emergency service stations, we assume that the whole population of this demand point is covered. SPBDCM originally proposed by Çatay *et al.* (2007) is as follows:

Notation:

M	set of demand regions ($j \in M$)
N	set of candidate / potential location sites ($i \in N$)
K	the maximum number of EMS stations to be opened
P_j	population of region j

$$a_{ij} = \begin{cases} 1, & \text{if the ambulance in location } i \text{ can reach the region } j \text{ within } t_1 \text{ time units} \\ 0, & \text{otherwise} \end{cases}$$

$$b_{ij} = \begin{cases} 1, & \text{if the ambulance in location } i \text{ can reach the region } j \text{ within } t_2 \text{ time units} \\ 0, & \text{otherwise} \end{cases}$$

Decision Variables:

$$x_i = \begin{cases} 1, & \text{if a station is located in candidate location } i \\ 0, & \text{otherwise} \end{cases}$$

$$y_j = \begin{cases} 1, & \text{if region } j \text{ is double covered} \\ 0, & \text{otherwise} \end{cases}$$

(SPBDCM) Maximize

$$\sum_{j \in M} P_j y_j \tag{3.1}$$

subject to

$$\sum_{i \in N} x_i \le K, \tag{3.2}$$

$$\sum_{i \in N} a_{ij} x_i - y_j \ge 0, \qquad \forall j \in M \tag{3.3}$$

$$\sum_{i \in N} b_{ij} x_i - 2y_j \ge 0, \qquad \forall j \in M \tag{3.4}$$

$$x_i \in \{0,1\} \qquad \forall i \in N \tag{3.5}$$

$$y_j \in \{0,1\} \qquad \forall j \in M \tag{3.6}$$

The objective of the model is to maximize the population which is double covered with a backup station. Constraint (3.2) imposes the total number of stations that can be opened. Constraint (3.3) ensures that any demand point must be covered in t_1 time units in order to be covered multiple times. If a demand point is covered in t_1 time units, it is also covered in t_2 time units by the same station due to $t_1<t_2$. Therefore, constraint (3.4) expresses the requirement of coverage by at least two different stations in t_2 time units. Constraints (3.5) and (3.6) show that all the decision variables are binary. Note that $K \ge 2$ must hold for ensuring a positive coverage.

We can prove that SPBDCM is NP-hard as follows: Consider a special case of SPBDCM where t_2 is sufficiently large such that each potential site i can cover all demand regions in t_2. Then, the problem reduces to a MCLM which is known to be NP-hard (Berman and Krass, 2002).

The main characteristic of SPBDCM that differs from MCLM lies on the decision variables y_j's. When the relaxation of MCLM is solved by relaxing the integrality restriction on variables y_j, y_j's naturally take a value of 0 or 1 in the optimal solution. In other words, making y_j variables continuous does not affect the original problem. However, the same relaxation for SPBDCM may result in y_j variables taking non-binary values. Thus, the upper bound provided by the relaxation of SPBDCM is tighter than the upper bound of the same relaxation of MCLM.

3.2. A Tabu Search Algorithm for SPBDCM

As mentioned earlier, TS is an efficient meta-heuristic that is capable of finding good solutions fast. Thus, we adopt a TS approach for solving the SPBDCM. Since TS necessitates an initial feasible solution, we investigate three initialization approaches, namely a random solution, a steepest-ascent algorithm solution, and an LP relaxation-based solution, and evaluate their contribution to the final solution obtained by the TS procedure.

3.2.1. Initialization Approaches

3.2.1.1. Random Approach

In order to find an initial solution fast, we propose the random method. In this method, we randomly select K stations among N potential location sites using a uniform distribution $U[1, N]$.

3.2.1.2. A Steepest-Ascent Approach

In this method, first a station is opened in the potential location that covers the highest population in t_1 time units. Then, a second station maximizing double covered population along with the available station is opened by considering the coverage in t_2 time units. After this first step, the same method of opening two new stations consecutively is compared to adding another station to the existing solution. The comparison is based on the increase in the objective function value per station opened. The solution which maximizes the per station coverage is accepted. This procedure is repeated until the total number of stations opened reaches K or the whole population is double covered. The steps of the algorithm are described in Figure 1.

Step 1.a: Determine the station covering the largest population in t_1 time units and open it.
Step 1.b: Determine the second station which maximizes the double covered population along with the first station opened and open it.
Step 2.a: Determine the station that increases the double covered population along with the previously opened stations. If there is only one remaining station, open it. Otherwise, go to Step 2.b.
Step 2.b: Determine two new stations by applying the procedure in Steps 1.a and 1.b.
Step 3: Compare the improvements achieved in Step 2.a and 2.b on a per station coverage basis. Select the solution which provides the largest improvement (if there is a tie select the station found in Step 2.a.)
Step 4: If all K stations are opened or the whole population is double covered, stop. Otherwise, return to Step 2.a. by considering only uncovered demand points.

Figure 1. Steps of the steepest-ascent algorithm

3.2.1.3. LP Relaxation-Based Heuristic

In this method, first the LP relaxation of the model is solved by relaxing all the decision variables. If the optimal value of any x_i is 1 in the LP solution, those variables are set equal to 1 since they are expected to be good at maximizing double covered population. Then, the largest non-binary x_i is fixed to 1 and the LP relaxation is solved again. This procedure is repeated until the total number of stations opened reaches K or the whole population is double covered. The steps of the algorithm are described in Figure 2.

Step 1: Solve the LP relaxation of the model.
Step 2: If $x_i = 1$ in the LP solution, fix it to 1.
Step 3: If all stations are opened or the whole population is double covered, stop. Otherwise, fix the largest non-binary x_i in the LP relaxation solution to 1 (ties are broken by selecting the station with the smaller index) and return to Step 1.

Figure 2. Steps of the LP relaxation-based heuristic

3.2.2. Tabu Search Procedure

The most crucial mechanism in the TS is the neighborhood structure since it directly affects the quality of the search and the quality of the final solution as well as the computational complexity of the algorithm. The only feasibility condition of the SPBDCM is the limit on the number of stations. In this thesis, the neighborhood structure is determined as opening and closing same number of stations at each iteration. This structure maintains feasibility of the solution generated. On the other hand, it is obvious that if the neighborhood structure includes multiple stations to close and open at each iteration, the computational burden will increase. Our initial experiments on some randomly generated data showed that closing and opening only one station at each iteration provide good results in less time.

The tabu list is the mechanism in TS to avoid finding the same local optimal solutions during the search procedure. This is achieved by keeping certain moves in a tabu list for a number of iterations so as to prevent the same moves to occur repeatedly. The number of iterations during which a move is kept in the tabu list is determined by the tabu list size. If the tabu list size is too small, cycling may occur since the moves remain forbidden during a small number of iterations. On the other hand, the quality of the solutions obtained can get worse with a too large tabu list size because the moves leading to better solutions may be forbidden for a long time. We refer to the parameter of tabu list size as k_0. Our initial experiments show that $k_0 = 7$ as the magic number works efficiently. We have also investigated the effect of the tabu list size which increases with the problem size because the larger the problem gets the more number of iterations may be needed to forbid the repeating moves. However, we did not observe any relationship between the tabu list size and the problem size.

Another important mechanism in the tabu list is the way a move is kept tabu. We have considered two tabu move types: keeping the list of stations closed and opened separately and keeping closed and opened station pairs in a single list. In the former case, opening a recently closed station or closing a recently opened station is forbidden whereas in the latter case, the exact station pair to be opened and closed simultaneously is forbidden. After an initial experimental study, we have come to the conclusion that using two separate tabu lists, one of which for the station opened and the other for the closed one, gives better results than using a combined tabu list containing opened and closed stations together.

The aspiration level is another parameter in TS. When we generate new candidate solutions at each iteration of TS, one or multiple of these solutions can be in the tabu list, i.e. they are not allowed. However, some solutions can improve the best objective function value despite being in the tabu list. If a tabu move gives the best solution among all the candidate solutions and the objective function value obtained with this tabu move is larger than a pre-determined aspiration level, this move is accepted. Thus, the aspiration level becomes an important parameter in TS. While this parameter can be constant throughout the TS, it can also be dynamic and change at each iteration or only if the objective function value improves. We have experimented several aspiration levels which are set proportional to the best-so-far objective function value (namely 100%, 90%, and 80%) and observed that an aspiration level equal to the best objective function value obtained so far (i.e. 100% case) provides best results. In many cases, the TS may get trapped at a local optimum when it can no longer find a solution better than the best solution obtained so far. In the OR literature, there are lots of different diversification techniques to overcome this undesirable situation. A basic and one of the most applied “diversification” methods to escape from a local optimum in the TS procedure is the random method. When the TS cannot improve the solution quality after a specified number of iterations, a number of open stations can randomly be selected and closed while the same number of randomly selected not-open stations can be opened. In order to determine an appropriate value, we have experimented one, two, three and four stations to be randomly closed and opened. The results showed that the diversification improves the solution quality significantly and closing and opening only one station randomly gives the best results. Hence, we adopted a diversification strategy as follows: If the solution does not improve after k_2 consecutive iterations where $k_2 = 15$ according to our initial experiments, an opened station is randomly closed and a closed station is randomly opened.

The last parameter of the proposed TS is the number of consecutive iterations during which the same current objective function repeats. If the best candidate solution does not improve or deteriorate the current solution for a number of iterations, cycling occurs and the same current objective function repeats. In order to avoid cycling, we use a mechanism to jump to another solution resulting in with the least decrease in the current objective function value instead of accepting the solution which gives the same current objective function value. We refer to this parameter as $k_{1.}$ We have observed that $k_1 = 5$ provided good results in our experiments.

Finally, a stopping criterion with the iteration limit k_3 is imposed to end the TS. The steps of our TS are summarized in Figure 3.

Step 1:	Find an initial feasible solution and set the best-so-far objective function value equal to its objective function value.
Step 2.a:	Determine the station pair whose closing and opening provides the largest objective function value.
Step 2.b:	If both stations are not in the tabu list, replace them. If the best-so-far objective function improves, update its value and go to Step 3. If at least one station is in the tabu list, go to Step 2.c.
Step 2.c:	If the tabu move meets the aspiration criteria accept it, update the best-so-far objective function value if it is improved, and go to Step 3. Otherwise, repeat Step 2.a and 2.b by discarding this station pair.
Step 3:	If the same current objective function does not change during the last “k_1” consecutive iterations replace the station to be closed with the station resulting in the least decrease in the current objective function value to avoid cycling. Go to Step 4.
Step 4:	If the best-so-far objective function value does not improve during the last “k_2” consecutive iterations, perform random diversification. Go to Step 5.
Step 5:	If the total number of iterations reaches the maximum total number of iterations “k_3” stop. Otherwise, return to Step 2.a.

Figure 3. Steps of the TS algorithm for SPBDCM

3.3. Experimental Study

To test the performance of the proposed TS approach we randomly generated 60 problem instances with different sizes in terms of the number of demand regions and potential sites. The values of t_1 and t_2 are set equal to 5 and 8, respectively, in parallel with the requirements determined by the Directorate of Instant Relief and Rescue at Istanbul Metropolitan Municipality.

3.3.1. Random Data Generation

Our data set includes problems with 200, 300, 400, and 500 demand regions. The demands regions are represented by the demand points whose coordinates are uniformly distributed between 0 and 1 within a square area. The square area is divided into four equal zones and an equal number of demand points is placed in each zone to avoid the accumulation in any zone. The total number of potential sites is set equal to 100%, 75%, and 50% of the number of demand points for different problem sizes. These potential sites are randomly selected but the balance among the four zones is preserved. Furthermore, the potential sites are selected in such a way that each demand point can be double covered if a sufficient number of stations exist. For each demand point-location site configuration we have generated 5 problem instances. Thus a total of 60 problem instances (4 demand point configurations * 3 potential site configurations * 5 instances) were generated.

The edge length of the square region is determined according to the number of demand points and then normalized to 1. The reason in doing so is to generate problems with different characteristics. Otherwise, the regions and locations will either get too accumulated to prevent the differention of the problems with respect to their sizes or too dispersed to cause a large number of regions that do not have any means of being double covered at all. Hence, considering an average speed of 40 km/h for the ambulances and Euclidean metric as the distance measure we have adopted the following formulation to calculate the edge length after some analyses: $20*\sqrt{|M|/100}$. Using these data a_{ij} and b_{ij} values are obtained.

The populations of the demand regions were generated randomly as well. Having observed that the populations of the quarters in Istanbul are exponentially distributed we utilized an exponential distribution with mean 1000. The decimal numbers were rounded to the nearest integer. In addition, we made sure that our problem instances were feasible to the Backup Double SCM (BDSCM) with double-coverage in 5 and 8 minutes by the help of the feasibility check before using the coverage data. That is, if any demand point cannot be covered in 5 and 8 minutes by two different stations, we continued generating new random numbers until a feasible data were obtained. Thus, the problems are also feasible to the SCM with single coverage in 5 or 8 minutes. We used the results of SCM in 8 minutes in determining the K value for SPBDCM.

3.3.2. Computational Results

First, we investigate the performance of the initialization heuristics benchmarked against the solution obtained using OPL Studio 5.5 with ILOG Cplex v.11. While the random heuristic gives a gap of 54.89% on the average for all 60 problems, steepest-ascent and LP-relaxation heuristics' performances are similar: 6.95% and 7.18%, respectively. The gap is calculated as (OPL solution/Heuristic solution)-1. Note that the OPL solutions are obtained by running the software using its default setting, i.e. branch-and-bound, branch-and-cut or barrier algorithms.

Table 1. Average gap, standard deviation, and computation times for TS1

	TS1								
	5000 iterations			1000 iterations			250 iterations		
	Average Gap (%)	Standart Deviation	Average Time	Average Gap (%)	Standart Deviation	Average Time	Average Gap (%)	Standart Deviation	Average Time
Close/Open 1 station in diversification	0.31	0.48	447	0.95	0.94	89	2.46	1.72	22
Close/Open 2 station in diversification	0.44	0.54	415	0.95	0.76	83	2.63	1.97	21

Table 2. Average gap, standard deviation and computation times for TS2

	TS2								
	5000 iterations			1000 iterations			250 iterations		
	Average Gap (%)	Standart Deviation	Average Time	Average Gap (%)	Standart Deviation	Average Time	Average Gap (%)	Standart Deviation	Average Time
Close/Open 1 station in diversification	0.30	0.46	427	0.77	0.75	85	1.71	1.32	21
Close/Open 2 station in diversification	0.42	0.52	427	0.94	0.83	85	1.59	1.22	21

Table 3. Average gap, standard deviation and computation times for TS3

	TS3								
	5000 iterations			1000 iterations			250 iterations		
	Average Gap (%)	Standart Deviation	Average Time	Average Gap (%)	Standart Deviation	Average Time	Average Gap (%)	Standart Deviation	Average Time
Close/Open 1 station in diversification	0.24	0.43	612	0.67	0.68	122	0.91	0.75	31
Close/Open 2 station in diversification	0.31	0.48	616	0.77	0.66	123	1.12	0.98	31

In Tables 1-3, we report the average results of all 60 problem instances. The detailed results for each instance are given in Appendix A. In these experiments, OPL Studio 5.5 time limit is set to 600 seconds for the problems having less than 300 potential locations and 1200 seconds for the remaining problems. The parameters are set as discussed earlier: k_0= 7, k_1=5, k_2=15, and k_3=5000. For comparison, we also report the solutions obtained for k_3=250 and k_3=1000. Furthermore, the solutions of 1-station and 2-station diversification strategies are also reported for the same reason. TS1, TS2, and TS3, respectively, refer to the initialization approaches as random, steepest-ascent, and LP-relaxation, respectively.

As seen in Tables 1-3, all three TS approaches provide good results in comparison with the solutions found by OPL Studio 5.5 as a result of only one run of all the problems within the time limit set. We observe that 1-station diversification strategy gives better average gap for TS1, TS2, and TS3 in any number of iterations. Although both TS1 and TS2 have the same average gaps with k_3 = 5000 and 1000 with similar computational times, TS3 requires longer time to arrive at a good solution, as can be expected.

We also observed that OPL Studio 5.5 can solve SPBDCM faster when t_1 and t_2 get bigger.

CHAPTER 4

MULTI-PERIOD BACKUP DOUBLE COVERING MODEL

In this chapter, we extend the model proposed in the previous chapter for multiple periods (MPBDCM). For this strategic planning problem, the appropriate planning horizon may vary for different environments, depending on various factors such as the total population, the planning horizon of the budgets, growth strategies, etc.

4.1. Mathematical Model

In the proposed multi-period model, the objective is to maximize the total population covered in all the periods within t_1 and t_2 time units ($t_1 < t_2$) by two distinct EMS stations where the total number of stations is limited for each period. We assume that if a demand region is double covered; all the population in this region is covered as in SPBDCM. Moreover, if an EMS station is located in a period, it must remain open in the subsequent periods. The mathematical formulation of MPBDCM originally proposed by Çatay *et al.* (2007) is as follows:

Notation:

T set of periods ($t = 1, \ldots, |T|$)

M set of demand regions

N set of location sites

K_t the maximum number of EMS stations to be opened in period t ($K_t \leq K_{t+1}$)

P_{jt} population of region j in period t

$$a_{ij} = \begin{cases} 1, & \text{if the ambulance in location } i \text{ can reach the region } j \text{ within } t_1 \text{ time units} \\ 0, & \text{otherwise} \end{cases}$$

$$b_{ij} = \begin{cases} 1, & \text{if the ambulance in location } i \text{ can reach the region } j \text{ within } t_2 \text{ time units} \\ 0, & \text{otherwise} \end{cases}$$

Decision Variables:

$$x_{it} = \begin{cases} 1, & \text{if a station is located in location } i \text{ in period } t \\ 0, & \text{otherwise} \end{cases}$$

$$y_{jt} = \begin{cases} 1, & \text{if region } j \text{ is double covered in period } t \\ 0, & \text{otherwise} \end{cases}$$

(MPBDCM) Maximize $\sum_{t \in T} \sum_{j \in M} P_{jt} y_{jt}$ (4.1)

subject to

$$\sum_{i \in N} x_{it} \le K_t, \qquad \forall t \in T \qquad (4.2)$$

$$\sum_{i \in N} a_{ij} x_{it} - y_{jt} \ge 0, \qquad \forall j \in M, \forall t \in T \qquad (4.3)$$

$$\sum_{i \in N} b_{ij} x_{it} - 2y_{jt} \ge 0, \qquad \forall j \in M, \forall t \in T \qquad (4.4)$$

$$x_{it} - x_{i,t-1} \ge 0, \qquad \forall i \in N, \forall t \in T \qquad (4.5)$$

$$x_{it} \in \{0,1\} \qquad \forall i \in N, \forall t \in T \qquad (4.6)$$

$$y_{jt} \in \{0,1\} \qquad \forall j \in M, \forall t \in T \qquad (4.7)$$

The objective is to maximize the total population double covered in all the periods. Constraints (4.2)-(4.4) are same as in SPBDCM expressed for each period. Constraints (4.5) make sure that if a station is opened in any period it remains open in the subsequent periods. This constraint is supported by the assumption of unchangeable population and reachability data in 5 and 8 minutes during *T* periods. Thus, the total number of opened stations at each period is bigger than the ones in the previous period(s). Constraints (4.6) and (4.7) ensure that all the decision variables are binary.

4.2. Tabu Search Algorithm for MPBDCM

MPBDCM is an NP-hard problem which is more difficult to solve compared to SPBDCM problems with equal number of demand points and potential locations due to its multi-period nature which imposes more number of binary variables and constraints. Therefore, applying a heuristic and/or a meta-heuristic approach is also required to find a good solution fast. Thus, we apply a similar TS approach by utilizing the same three initialization algorithms hierarchically starting from the first period. The random, steepest-ascent, and LP Relaxation-based heuristics are respectively applied by selecting K_t - K_{t-1}

stations ($K_0 = 0$) among N potential location sites in each time period t in the same way as described in the previous chapter.

In MPBDCM, the TS procedure must satisfy Constraint (4.5). For this purpose, two different multi-period neighborhood search techniques are proposed. In the first, we only perform the search in the last period, i.e. the same TS procedure in the previous chapter is applied to the last period only by updating the open/close stations in the previous periods accordingly. The objective function value spans all periods but not the last period only. In the second neighborhood search strategy, we allow the same moves throughout the whole planning horizon. The open/close stations in the other periods are updated appropriately. The steps of these two TS procedures are summarized in Figures 4 and 5.

Step 1:	Find an initial feasible solution and set the best-so-far objective function value equal to its objective function value.
Step 2.a:	Determine the station pair in the last period whose closing and opening provides the largest objective function value.
Step 2.b:	If both stations are not in the tabu list, replace them by closing the opened and opening the closed station in the related term. Update the opened stations by opening the new and closing the old station in the following period(s) to satisfy Constraints (4.5). If the best-so-far objective function improves, update its value and go to Step 3. If at least one station is in the tabu list, go to Step 2.c.
Step 2.c:	If the tabu move meets the aspiration criteria accept it, update the best-so-far objective function value if it is improved, and go to Step 3. Otherwise, repeat Step 2.a and 2.b by discarding this station pair.
Step 3:	If the same current objective function does not change during the last "k_1" consecutive iterations replace the station to be closed with the station resulting in the least decrease in the current objective function value to avoid cycling. Go to Step 4.
Step 4:	If the best-so-far objective function value does not improve during the last "k_2" consecutive iterations, perform random diversification. Go to Step 5.
Step 5:	If the total number of iterations reaches the maximum total number of iterations "k_3" stop. Otherwise, return to Step 2.a.

Figure 4. Steps of TS algorithm for MPBDCM using neighborhood type 1

Step 1: Find an initial feasible solution and set the best-so-far objective function value equal to its objective function value.

Step 2.a: Determine the station pair by opening each closed station and closing each opened station beginning from the first period until the last period. Thus, any station closed in a period but opened in the subsequent period(s) is considered to be replaced with the mentioned opened station in the previous term(s). Find the station pair providing the largest objective function value.

Step 2.b: If both stations are not in the tabu list and the opened station is closed in the last period, substitute the stations by closing the opened and opening the closed station in the related term and update the opened stations by opening the new and closing the old station in all the following period(s) to ensure Constraints (4.5) in the MPBDCM. However, if the interperiod change of stations occurs between the Xth and Yth periods, update the stations beginning from Xth period through Y-1th period. If the best-so-far objective function improves, update its value and go to Step 3. If at least one station is in the tabu list, go to Step 2.c..

Step 2.c: If the tabu move meets the aspiration criteria accept it, update the best-so-far objective function value if it is improved, and go to Step 3. Otherwise, repeat Step 2.a and 2.b by discarding this station pair.

Step 3: If the same current objective function does not change during the last "k_1" consecutive iterations replace the station to be closed with the station resulting in the least decrease in the current objective function value to avoid cycling. Go to Step 4.

Step 4: If the best-so-far objective function value does not improve during the last "k_2" consecutive iterations, perform random diversification. Go to Step 5.

Step 5: If the total number of iterations reaches the maximum total number of iterations "k_3" stop. Otherwise, return to Step 2.a..

Figure 5. Steps of TS algorithm for MPBDCM using neighborhood type 2

4.3. Experimental Study

To test the performance of the proposed TS approach, we utilized the random data set generated for SPBDCM using a time horizon of 4 periods (T=4). Since there are three different initialization approaches and two different neighborhood search methods we have six different TS implementations as depicted in Table 4.

Table 4. Abbreviations of TS for MPBDCM

Initial Solution Methods	No Interperiod Exchange of Stations	Allowing Interperiod Exchange of Stations
Random	TS1-1	TS1-2
Steepest Ascent	TS2-1	TS2-2
LP Relaxation-based	TS3-1	TS3-2

In Table 5, we report the average results of all 60 problem instances. The detailed results for each instance are given in Appendix B. In these experiments, OPL Studio 5.5 time limit is set to 2400 seconds for the problems having less than 300 potential locations and 4800 seconds for the remaining problems. TS parameters are set as earlier. The number of iterations is 2500. For comparison, we also report the solutions obtained for k_3=1000 and k_3=500.

Table 5. Average gap, standard deviation, and computation times

	2500 iterations			1000 iterations			500 iterations		
	Average Gap (%)	Standard Deviation	Time	Average Gap (%)	Standard Deviation	Time	Average Gap (%)	Standard Deviation	Time
TS1-1	0.99	1.55	1124	1.53	1.52	450	2.34	1.50	225
TS1-2	-0.49	1.29	1006	-0.21	1.19	402	0.22	1.12	201
TS2-1	0.80	1.38	1072	1.19	1.34	429	1.41	1.39	214
TS2-2	-0.48	1.29	978	-0.26	1.24	391	0.08	1.37	196
TS3-1	0.54	1.30	1311	0.72	1.37	524	0.91	1.32	262
TS3-2	-0.50	1.29	1218	-0.32	1.30	487	-0.16	1.26	244

*

We observe that neighborhood type 2 performs better than type 1 with less or similar computational effort for any initialization heuristic. This is in parallel with our expectations since the interperiod exchange of stations allows a better search of the solution space. The negative average gaps indicate that the TS provides better average results than OPL Studio 5.5. This is due to the fact that some instances cannot be solved to optimality in the given time limit. Note that the average computation time of OPL is 3136 seconds whereas the longest TS computation time is 1311 seconds for TS3-1. Similar to our observations in the experiments of SPBDCM, TS with LP relaxation-based initial solution finds better results compared to both TS with random approach and steepest-ascent but at the expense of more computational effort.

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* Since the computer code was revised and became more efficient, the average run times for neighbourhood type 2 appeared to be shorter than type 1, although the opposite is true.

CHAPTER 5

PLANNING THE LOCATIONS OF EMS STATIONS IN ISTANBUL

As we emphasized before, the effective planning of EMS stations is a crucial problem especially in crowded cities having heavy traffic conditions such as Istanbul. In this chapter, we apply our proposed TS algorithm on the real data of Istanbul.

5.1. Data Collection

Since Çatalca and Silivri districts in the European side of Istanbul and Şile in the Asian side are far from all the other districts they require an independent planning and hence, they are excluded from our case study. Since Istanbul is a large and populated city, we agreed on a quarter-wise analysis with the Directorate of Instant Relief and Rescue of IMM. This corresponds to a total of 710 quarters, 243 in the Asian side and 467 in European side. Thus, we needed the population of each quarter and the reachability from one quarter to another in 5 and 8 minutes.

For the population data, we use the data provided by the Turkish Statistical Institute (TÜİK). The most recent data available is the projections for 2007 based on the population figures of 2000. Since the projections were only available for districts, we estimated the populations in the quarters proportional to the figures of 2000.

Data regarding to the quarters are collected by the help of the experienced ambulance drivers of the Directorate of Instant Relief and Rescue at IMM. We assume that each quarter is a potential station site. We also assume that the stations will be located in the center of a quarter and the farthest point in the other quarters must be covered by this station to consider these quarters as the covered demand points. That is, if an ambulance is declared to be able to reach a quarter in 5 or 8 minutes, it can reach all the points in that region in the specified time limit. Furthermore, the response across the two sides of Istanbul via the Bosphorus Bridge and Fatih Sultan Mehmet Bridge is not allowed because of the unpredictable traffic conditions.

5.2. Results of the SPBDCM for Istanbul

The number of stations is assumed as 35 since the Directorate of Instant Relief and Rescue of IMM was planning to operate 35 stations in 2007. OPL Studio solved this problem in 50 seconds. This rather short solution time is, we believe, due to the fact that Istanbul data have certain characteristics that cannot be seen in the random data. Firstly, the Asian and European sides are separated and in fact, the problem can be decomposed into two sub-problems that can be solved independently if the stations are allocated for each side. Secondly, the reachability data is very dense for some zones having many small quarters, e.g. in Beyoğlu, Eminönü, Fatih, and Ümraniye whereas the opposite is true in some zones where the quarters are large and distant from each other, e.g. Büyükçekmece, Sarıyer, and Beykoz. To have a comparable TS solution time, we imposed a stopping criterion in the TS depicted in Section 3.2.2 as follows: if Step 4 is repeated k_4 = 10 times with the same best-so-far objective, the algorithm stops.

Table 6. Comparison of results for SPBDCM

	OPL Studio	TS1	TS2	TS3
Coverage	8,724,151	8,610,610	8,710,099	8,706,795
% Coverage	74.75	73.77	74.63	74.60
Time (s)	50	182	166	193
% Gap	-	1.30	0.16	0.20

The computational results are given in Table 6. The total population of Istanbul is taken as 11,671,710 according to the projections of TÜİK for 2007 based on the population figures of 2000. We used 5 random initial solutions for TS1 to better evaluate the effect of randomness on the solution quality and reported the average. While the average gap is 1.30% the minimum is 0.01% and the maximum is 3.84% optimality. We observe that TS with steepest-ascent heuristic gives the best result in the shortest time; however, TS with LP relaxation-based heuristic has a comparable solution. Note that the steepest-ascent and LP relaxation-based heuristic provide initial solutions with optimality gaps 2.52% and 2.09%, respectively, in 16 and 60 seconds, respectively. As expected, TS3 needs longer computation time because of the initialization that takes time.

Table 7. Comparison of results for SPBDCM with different *K* values

		OPL Studio	TS1	TS2	TS3
***K* = 30**	**Coverage**	8,235,888	8,056,327	8,235,888	8,226,373
	% Coverage	70.56	69.02	70.56	70.48
	Time (s)	41	130.543	142.373	132.370
	% Gap	-	2.18	0.00	0.12
***K* = 40**	**Coverage**	9,142,323	9,137,494	9,136,236	9,111,764
	% Coverage	78.33	78.29	78.28	78.07
	Time (s)	62	230.656	330.335	252.104
	% Gap	-	0.05	0.07	0.33
***K* = 45**	**Coverage**	9,525,754	9,233,325	9,456,463	9,477,891
	% Coverage	81.61	79.11	81.02	81.20
	Time (s)	68	229.921	269.335	195.776
	% Gap	-	3.07	0.73	0.50

In order to observe the sensitivity of the results on different K values, we also solved SPBDCM with K = 30, 40, and 45. The results given in Table 7 show that TS can provide almost near optimal results with different *K* values and initialization approaches.

5.3. Results of MPBDCM for Istanbul

The multi-period planning problem of the EMS stations in Istanbul is performed for 4 years according to the information provided by the Directorate of Instant Relief and Rescue. K_t is taken as 35, 50, 60, and 70 for t from 2007 to 2010. We assumed a constant population throughout the planning horizon. Thus, the results of TS with two different neighborhood described in Section 4.3. are as follows:

Table 8. Comparison of results for MPBDCM

	OPL Studio	TS1-1	TS1-2	TS2-1	TS2-2	T3-1	TS3-2
Coverage	39,525,200	39,020,715	39,102,232	39,165,559	39,437,164	39,343,941	39,363,047
% Coverage	84.66	83.58	83.75	83.89	84.47	84.27	84.31
Time (s)	4800	3754	4815	2651	3252	3743	5046
% Gap	-	1.28	1.07	0.91	0.22	0.46	0.41

Table 8 shows the results of MPBDCM and TS for Istanbul. Similar to the experimental study for SPBDCM, we used 5 random initial solutions for TS1-1 and TS1-2. While the average gap is 1.28% with the neighborhood type 1 and 1.07% with the neighborhood type 2, the minimum gaps are 0.73% and 0.65%, respectively and the maximum gaps are 2.61% and 2.23%, respectively. We observe that TS with steepest-ascent heuristic gives the best result with the neighborhood type 2 and LP relaxation-based heuristic gives the best result with the neighborhood type 1. Also, for all initialization heuristics neighborhood type 2 gives better results than type 1.

Table 9. Comparison of results for MPBDCM with different K_t values

		OPL Studio	**TS1-1**	**TS1-2**	**TS2-1**	**TS2-2**	**T3-1**	**TS3-2**
K_t=30,40,50,60	**Coverage**	37,212,220	36,809,495	36,921,423	37,162,467	37,183,485	37,102,324	37,132,461
	% Coverage	79.71	78.84	79.08	79.60	79.64	79.47	79.54
	Time (s)	4800	3915	3654	3143	3356	3785	3982
	% Gap	-	1.08%	0.78%	0.13%	0.08%	0.30%	0.21%
K_t=40,50,60,70	**Coverage**	39,962,480	39,447,968	39,564,320	39,712,389	39,923,456	39,732,145	39,934,567
	% Coverage	85.60	84.49	84.74	85.06	85.51	85.10	85.54
	Time (s)	4800	3571	3789	4123	3981	4023	4236
	% Gap	-	1.29%	1.00%	0.63%	0.10%	0.58%	0.07%
K_t=45,55,65,75	**Coverage**	40,668,541	39,924,456	39,998,405	40,045,678	40,156,743	40,250,732	40,487,523
	% Coverage	87.11	85.52	85.67	85.78	86.01	86.21	86.72
	Time (s)	4800	3538	3892	3897	4123	3675	4046
	% Gap	-	1.83%	1.65%	1.53%	1.26%	1.03%	0.45%

Similar to the experimental study in Section 5.2., we solved MPBDCM with varying K_t values. As it can be observed in Table 9, neighborhood type 2 gives better results than type 1 for all initialization heuristics and TS can provide good results compared to OPL Studio 5.5.

CHAPTER 6

CONCLUSION AND FUTURE RESEARCH

In this thesis, we present two mathematical models to plan the locations of EMS stations: SPBDCM and MPBDCM. Since both problems are intractable for large-scale cases, we propose a TS solution approach. To obtain an initial solution to TS algorithm, we experiment with three different methods with different computational complexity. We test the performance of the TS with different initialization methods on randomly generated data as well as the data we collected for Istanbul. The results show that our TS approach with either initialization method provide good results compared to the solutions obtained using OPL Studio 5.5 with CPLEX 11.0. Although OPL Studio performs better in the single-period case the performance of TS approach is especially superior in the multi-period case. It should be noted that although OPL provides optimal/near optimal solutions, TS approach may still be preferable since it is an easy to use generic code and accessible to everyone while OPL is a expensive licensed program which requires skills to use.

Further research on this topic may focus on the multi-objective modeling of the problems by considering the investment and operating costs of the stations and ambulances. In this study, we only locate the stations. The number of ambulances at each station can than be determined using the international service standard of 50,000 persons/ambulance. A more robust planning may include the planning of the ambulances as well. Furthermore, our models aim only at maximizing the double covered population. However, a constraint ensuring to cover a specified proportion of all demand by a single station in a given time limit may improve the service quality.

The TS algorithm proposed in the study can be extended in different ways: dynamic or random tabu list size can be considered. In addition, different neighborhood search and diversification strategies may be tested. The structure of the tabu list may also be further investigated.

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APPENDIX A: RESULTS OF SPBDCM FOR RANDOM PROBLEMS

Table A. 1. Comparison of solution for TS1 by closing and opening 1 station in random

						5000 iterations		1000 iterations		250 iterations	
Demand Points	Potential Locations	Data	K	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12	117,299	38.04	0.54	88.02	0.54	17.60	0.54	4.40
		2	12	124,383	13.90	0.60	84.28	0.60	16.86	0.60	4.21
		3	12	116,362	46.56	0.17	88.09	0.18	17.62	2.60	4.40
		4	12	122,749	13.85	0.28	89.33	0.28	17.87	0.95	4.47
		5	13	127,400	42.76	0.17	98.42	0.88	19.68	1.32	4.92
200	150	1	12	114,202	9.39	0.00	63.55	0.63	12.71	2.69	3.18
		2	14	131,223	11.28	0.27	72.97	0.60	14.59	0.60	3.65
		3	13	121,290	7.57	0.00	70.53	0.19	14.11	3.01	3.53
		4	14	132,910	7.00	0.20	72.69	0.20	14.54	2.42	3.63
		5	14	126,775	7.59	0.00	74.03	0.00	14.81	0.00	3.70
200	100	1	12	113,073	6.26	0.26	41.19	1.34	8.24	5.66	2.06
		2	14	131,223	6.53	0.00	46.34	0.12	9.27	0.51	2.32
		3	13	117,316	6.26	0.00	42.23	0.00	8.45	0.00	2.11
		4	14	128,944	5.10	0.00	46.59	0.00	9.32	2.57	2.33
		5	15	130,543	5.37	0.00	49.72	0.00	9.94	0.00	2.49
300	300	1	18	192,288	1200.00	-0.16	326.69	1.10	65.34	1.99	16.33
		2	18	198,448	79.62	0.94	307.91	1.51	61.58	1.74	15.40
		3	17	190,591	1200.00	0.00	264.66	0.63	52.93	2.21	13.23
		4	18	190,326	131.42	0.20	297.06	0.45	59.41	0.45	14.85
		5	17	184,599	179.04	0.00	291.78	0.13	58.36	3.78	14.59
300	225	1	18	185,816	19.26	0.00	223.00	0.00	44.60	0.73	11.15
		2	19	191,668	14.29	0.20	229.69	0.43	45.94	1.28	11.48
		3	18	196,112	18.31	0.00	229.06	0.00	45.81	1.82	11.45
		4	20	197,839	23.25	0.00	248.13	0.93	49.63	3.05	12.41
		5	19	197,213	12.51	0.00	230.53	2.30	46.11	3.32	11.53
300	150	1	20	199,646	8.82	1.34	169.66	1.77	33.93	1.91	8.48
		2	20	198,660	8.31	0.22	163.06	0.74	32.61	2.76	8.15
		3	18	190,428	14.28	0.00	141.58	0.00	28.32	0.02	7.08
		4	20	192,454	11.00	1.11	152.83	2.67	30.57	4.18	7.64
		5	20	196,167	11.01	0.76	156.56	0.76	31.31	2.08	7.83
400	400	1	22	245,930	1200.00	0.38	651.78	1.39	130.36	3.54	32.59
		2	22	251,373	1200.00	0.00	652.70	3.69	130.54	5.62	32.64
		3	23	252,782	1200.00	0.01	654.92	2.06	130.98	6.00	32.75
		4	22	245,944	1200.00	-0.27	655.19	-0.27	131.04	4.40	32.76
		5	22	248,280	1200.00	0.69	613.25	1.26	122.65	5.08	30.66
400	300	1	25	259,988	264.67	0.16	515.36	0.16	103.07	0.52	25.77
		2	24	249,280	481.23	1.20	546.09	1.20	109.22	4.61	27.30
		3	25	254,020	482.90	0.37	515.31	0.37	103.06	1.47	25.77
		4	23	248,581	37.04	0.00	477.56	2.93	95.51	4.44	23.88
		5	24	250,723	19.75	0.00	491.59	0.26	98.32	2.46	24.58
400	200	1	25	257,332	13.75	0.00	303.19	0.28	60.64	0.48	15.16
		2	24	244,917	63.50	0.62	299.86	1.54	59.97	3.12	14.99
		3	25	243,373	24.03	0.43	298.55	0.60	59.71	6.33	14.93
		4	25	246,412	151.10	0.70	322.30	1.18	64.46	2.18	16.11
		5	25	251,909	17.00	0.00	304.84	0.00	60.97	1.17	15.24

500	500	1	28	274,779	1200.00	-0.82	1177.97	-0.62	235.59	4.85	58.90
		2	28	297,297	1200.00	0.22	1204.52	0.91	240.90	1.62	60.23
		3	28	294,185	1200.00	0.36	1168.95	1.02	233.79	2.36	58.45
		4	28	274,779	1200.00	-1.08	1170.86	0.44	234.17	0.49	58.54
		5	28	297,297	1200.00	1.32	1187.77	2.98	237.55	5.86	59.39
500	375	1	30	284,236	1200.00	1.30	996.38	1.30	199.28	2.83	49.82
		2	31	309,925	312.46	0.00	1097.53	1.82	219.51	2.52	54.88
		3	31	305,205	1200.00	0.51	1229.69	0.52	245.94	1.09	61.48
		4	30	284,236	1200.00	1.22	1223.08	1.57	244.62	4.95	61.15
		5	31	309,925	449.50	0.79	1135.45	1.66	227.09	3.72	56.77
500	250	1	30	279,431	227.82	1.07	670.34	2.94	134.07	2.94	33.52
		2	31	304,657	47.20	0.91	822.25	2.30	164.45	2.62	41.11
		3	33	310,639	244.25	0.30	781.88	0.43	156.38	0.57	39.09
		4	30	279,431	231.39	0.58	561.34	2.46	112.27	3.63	28.07
		5	31	304,657	60.07	0.65	594.64	1.31	118.93	1.50	29.73
Average				215,325	364.77	0.31	446.42	0.95	89.28	2.46	22.32

Table A. 2. Comparison of solution for TS1 by closing and opening 2 stations in random

						5000 iterations		1000 iterations		250 iterations	
Demand Points	Potential Locations	Data	K	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12	117,299	38.04	0.42	92.77	0.42	18.55	0.54	4.64
		2	12	124,383	13.90	0.00	88.27	0.00	17.65	1.86	4.41
		3	12	116,362	46.56	0.18	82.42	0.36	16.48	5.48	4.12
		4	12	122,749	13.85	0.33	84.56	0.81	16.91	2.82	4.23
		5	13	127,400	42.76	0.41	102.34	1.09	20.47	2.84	5.12
200	150	1	12	114,202	9.39	0.00	63.22	0.37	12.64	0.38	3.16
		2	14	131,223	11.28	0.00	74.81	0.27	14.96	0.27	3.74
		3	13	121,290	7.57	0.00	70.58	0.19	14.12	1.54	3.53
		4	14	132,910	7.00	0.20	73.94	0.20	14.79	2.04	3.70
		5	14	126,775	7.59	0.00	73.80	0.00	14.76	0.00	3.69
200	100	1	12	113,073	6.26	0.00	41.52	1.56	8.30	5.23	2.08
		2	14	131,223	6.53	0.00	48.02	0.51	9.60	1.11	2.40
		3	13	117,316	6.26	0.00	44.14	0.00	8.83	0.00	2.21
		4	14	128,944	5.10	0.00	49.02	0.00	9.80	1.94	2.45
		5	15	130,543	5.37	0.00	49.89	0.00	9.98	0.00	2.49
300	300	1	18	192,288	1200.00	0.44	283.08	0.74	56.62	1.99	14.15
		2	18	198,448	79.62	1.15	286.84	1.36	57.37	1.42	14.34
		3	17	190,591	1200.00	0.00	261.03	1.40	52.21	1.72	13.05
		4	18	190,326	131.42	0.52	283.33	0.84	56.67	2.40	14.17
		5	17	184,599	179.04	0.13	265.05	2.43	53.01	2.43	13.25
300	225	1	18	185,816	19.26	0.09	206.70	0.09	41.34	0.09	10.34
		2	19	191,668	14.29	0.96	211.11	0.96	42.22	2.03	10.56
		3	18	196,112	18.31	0.26	207.98	0.26	41.60	1.40	10.40
		4	20	197,839	23.25	0.00	232.98	0.00	46.60	0.76	11.65
		5	19	197,213	12.51	0.34	205.63	1.74	41.13	4.23	10.28
300	150	1	20	199,646	8.82	1.32	144.61	1.69	28.92	2.04	7.23
		2	20	198,660	8.31	0.60	139.61	0.74	27.92	2.02	6.98
		3	18	190,428	14.28	0.00	127.34	0.00	25.47	0.00	6.37
		4	20	192,454	11.00	0.87	140.50	1.20	28.10	3.21	7.03
		5	20	196,167	11.01	0.03	139.72	0.03	27.94	4.87	6.99
400	400	1	22	245,930	1200.00	0.04	587.73	1.91	117.55	2.09	29.39
		2	22	251,373	1200.00	2.56	582.30	2.57	116.46	5.36	29.11
		3	23	252,782	1200.00	0.63	633.05	1.01	126.61	2.27	31.65
		4	22	245,944	1200.00	0.34	621.23	1.82	124.25	4.40	31.06
		5	22	248,280	1200.00	0.97	631.54	1.59	126.31	3.13	31.58
400	300	1	25	259,988	264.67	0.81	510.98	1.26	102.20	1.26	25.55
		2	24	249,280	481.23	0.98	479.20	0.98	95.84	1.66	23.96
		3	25	254,020	482.90	0.30	478.47	1.91	95.69	6.85	23.92
		4	23	248,581	37.04	0.13	492.67	0.13	98.53	6.21	24.63
		5	24	250,723	19.75	0.00	495.42	1.02	99.08	5.37	24.77
400	200	1	25	257,332	13.75	0.01	318.58	0.01	63.72	2.31	15.93
		2	24	244,917	63.50	0.60	302.94	0.60	60.59	0.88	15.15
		3	25	243,373	24.03	1.00	298.63	1.58	59.73	6.91	14.93
		4	25	246,412	151.10	0.49	304.20	0.77	60.84	2.13	15.21
		5	25	251,909	17.00	0.27	303.03	1.17	60.61	1.17	15.15

500	500	1	28	274,779	1200.00	-0.68	1157.55	1.30	231.51	2.73	57.88
		2	28	297,297	1200.00	0.64	1163.94	1.30	232.79	2.41	58.20
		3	28	294,185	1200.00	0.67	1154.88	2.22	230.98	8.59	57.74
		4	28	274,779	1200.00	-0.45	1162.20	0.43	232.44	0.84	58.11
		5	28	297,297	1200.00	1.71	1169.13	3.19	233.83	4.49	58.46
500	375	1	30	284,236	1200.00	0.88	913.03	0.88	182.61	0.88	45.65
		2	31	309,925	312.46	0.63	965.39	0.63	193.08	4.59	48.27
		3	31	305,205	1200.00	0.24	958.27	1.57	191.65	4.96	47.91
		4	30	284,236	1200.00	0.92	910.33	0.92	182.07	3.87	45.52
		5	31	309,925	449.50	0.86	1028.36	1.27	205.67	3.96	51.42
500	250	1	30	279,431	227.82	0.90	610.99	0.90	122.20	3.93	30.55
		2	31	304,657	47.20	0.72	657.30	0.89	131.46	2.61	32.86
		3	33	310,639	244.25	0.29	654.05	0.29	130.81	0.70	32.70
		4	30	279,431	231.39	1.57	564.84	2.64	112.97	3.25	28.24
		5	31	304,657	60.07	0.00	601.86	1.08	120.37	1.08	30.09
Average				215,325	364.77	0.44	414.78	0.95	82.96	2.63	20.74

Table A. 3. Comparison of solution for TS2 by closing and opening 1 station in random

						5000 iterations		1000 iterations		250 iterations	
Demand Points	Potential Locations	Data	K	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12	117,299	38.04	0.00	90.04	0.63	18.01	0.63	4.50
		2	12	124,383	13.90	0.56	90.70	3.18	18.14	3.18	4.54
		3	12	116,362	46.56	0.00	87.53	0.34	17.51	0.34	4.38
		4	12	122,749	13.85	0.28	90.16	0.28	18.03	0.28	4.51
		5	13	127,400	42.76	0.41	106.59	0.41	21.32	0.41	5.33
200	150	1	12	114,202	9.39	0.00	66.81	0.37	13.36	0.37	3.34
		2	14	131,223	11.28	0.00	77.78	0.60	15.56	0.60	3.89
		3	13	121,290	7.57	0.00	75.37	0.00	15.07	0.47	3.77
		4	14	132,910	7.00	0.00	75.33	0.00	15.07	2.04	3.77
		5	14	126,775	7.59	0.00	77.81	0.05	15.56	1.83	3.89
200	100	1	12	113,073	6.26	0.00	44.89	1.81	8.98	1.81	2.24
		2	14	131,223	6.53	0.00	50.47	0.00	10.09	0.00	2.52
		3	13	117,316	6.26	0.00	44.52	0.00	8.90	0.00	2.23
		4	14	128,944	5.10	0.00	50.61	0.00	10.12	0.00	2.53
		5	15	130,543	5.37	0.00	53.75	0.00	10.75	0.00	2.69
300	300	1	18	192,288	1200.00	0.12	325.13	0.74	65.03	2.10	16.26
		2	18	198,448	79.62	0.35	297.09	1.56	59.42	1.56	14.85
		3	17	190,591	1200.00	-0.12	274.77	0.90	54.95	1.10	13.74
		4	18	190,326	131.42	0.36	313.88	0.36	62.78	0.36	15.69
		5	17	184,599	179.04	0.13	284.39	0.13	56.88	2.29	14.22
300	225	1	18	185,816	19.26	0.00	220.53	0.00	44.11	0.00	11.03
		2	19	191,668	14.29	1.16	220.21	1.16	44.04	1.47	11.01
		3	18	196,112	18.31	0.00	213.83	1.40	42.77	1.40	10.69
		4	20	197,839	23.25	0.00	253.31	0.00	50.66	0.66	12.67
		5	19	197,213	12.51	0.00	225.34	0.00	45.07	3.79	11.27
300	150	1	20	199,646	8.82	1.34	155.81	1.34	31.16	4.00	7.79
		2	20	198,660	8.31	0.22	161.37	0.38	32.27	1.30	8.07
		3	18	190,428	14.28	0.00	138.58	0.00	27.72	0.00	6.93
		4	20	192,454	11.00	0.87	148.80	1.47	29.76	2.00	7.44
		5	20	196,167	11.01	1.63	150.52	2.08	30.10	2.86	7.53
400	400	1	22	245,930	1200.00	0.34	585.05	0.34	117.01	1.74	29.25
		2	22	251,373	1200.00	0.30	568.37	1.65	113.67	3.52	28.42
		3	23	252,782	1200.00	0.14	624.88	0.14	124.98	2.72	31.24
		4	22	245,944	1200.00	-0.24	574.92	0.01	114.98	0.01	28.75
		5	22	248,280	1200.00	0.14	567.58	0.65	113.52	3.56	28.38
400	300	1	25	259,988	264.67	0.69	469.08	0.69	93.82	3.46	23.45
		2	24	249,280	481.23	0.67	465.17	0.93	93.03	3.45	23.26
		3	25	254,020	482.90	0.98	468.87	2.39	93.77	2.91	23.44
		4	23	248,581	37.04	0.98	438.06	0.98	87.61	2.73	21.90
		5	24	250,723	19.75	0.00	503.52	1.02	100.70	3.30	25.18
400	200	1	25	257,332	13.75	0.15	325.14	0.48	65.03	1.04	16.26
		2	24	244,917	63.50	0.73	323.95	0.78	64.79	1.46	16.20
		3	25	243,373	24.03	0.00	321.84	0.43	64.37	0.90	16.09
		4	25	246,412	151.10	0.36	328.08	0.72	65.62	0.72	16.40
		5	25	251,909	17.00	0.00	325.05	1.52	65.01	2.78	16.25

500	500	1	28	274,779	1200.00	-0.53	1266.22	-0.05	253.24	-0.05	63.31
		2	28	297,297	1200.00	1.04	1258.41	1.04	251.68	2.45	62.92
		3	28	294,185	1200.00	1.03	1256.70	1.03	251.34	2.48	62.84
		4	28	274,779	1200.00	-0.70	1230.33	0.47	246.07	0.47	61.52
		5	28	297,297	1200.00	-0.39	1258.44	-0.39	251.69	0.99	62.92
500	375	1	30	284,236	1200.00	0.70	961.25	0.70	192.25	1.71	48.06
		2	31	309,925	312.46	0.30	1060.73	0.51	212.15	0.51	53.04
		3	31	305,205	1200.00	0.50	1021.42	1.77	204.28	4.41	51.07
		4	30	284,236	1200.00	1.02	979.06	1.73	195.81	2.51	48.95
		5	31	309,925	449.50	0.00	981.16	0.00	196.23	0.96	49.06
500	250	1	30	279,431	227.82	0.60	565.83	2.00	113.17	4.96	28.29
		2	31	304,657	47.20	0.88	604.88	0.88	120.98	1.47	30.24
		3	33	310,639	244.25	0.17	647.73	0.85	129.55	2.13	32.39
		4	30	279,431	231.39	0.41	563.44	2.51	112.69	3.82	28.17
		5	31	304,657	60.07	0.63	601.48	1.02	120.30	2.65	30.07
Average				215,325	364.77	0.30	426.88	0.77	85.38	1.71	21.34

Table A. 4. Comparison of solution for TS2 by closing and opening 2 stations in random

						5000 iterations		1000 iterations		250 iterations	
Demand Points	Potential Locations	Data	K	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12	117,299	38.04	0.00	78.84	0.00	15.77	0.12	3.94
		2	12	124,383	13.90	0.94	82.28	3.21	16.46	3.21	4.11
		3	12	116,362	46.56	0.31	77.95	0.31	15.59	0.46	3.90
		4	12	122,749	13.85	0.28	79.88	0.56	15.98	0.56	3.99
		5	13	127,400	42.76	0.00	91.19	0.17	18.24	0.17	4.56
200	150	1	12	114,202	9.39	0.00	58.22	0.77	11.64	1.54	2.91
		2	14	131,223	11.28	0.00	69.55	0.60	13.91	0.60	3.48
		3	13	121,290	7.57	0.00	66.72	0.47	13.34	0.47	3.34
		4	14	132,910	7.00	0.00	69.77	1.38	13.95	2.04	3.49
		5	14	126,775	7.59	0.00	70.38	0.00	14.08	0.17	3.52
200	100	1	12	113,073	6.26	0.00	39.88	0.85	7.98	1.49	1.99
		2	14	131,223	6.53	0.00	45.20	0.00	9.04	0.00	2.26
		3	13	117,316	6.26	0.00	41.20	0.00	8.24	0.00	2.06
		4	14	128,944	5.10	0.00	45.39	0.00	9.08	0.00	2.27
		5	15	130,543	5.37	0.00	47.20	0.00	9.44	0.16	2.36
300	300	1	18	192,288	1200.00	0.31	262.77	1.77	52.55	1.77	13.14
		2	18	198,448	79.62	1.56	264.91	1.56	52.98	1.56	13.25
		3	17	190,591	1200.00	0.26	244.14	0.34	48.83	1.85	12.21
		4	18	190,326	131.42	0.61	268.17	0.64	53.63	2.56	13.41
		5	17	184,599	179.04	0.76	249.30	2.29	49.86	2.29	12.46
300	225	1	18	185,816	19.26	0.00	195.05	0.00	39.01	0.47	9.75
		2	19	191,668	14.29	0.20	201.11	1.16	40.22	1.16	10.06
		3	18	196,112	18.31	0.00	193.25	0.00	38.65	1.98	9.66
		4	20	197,839	23.25	0.31	217.25	0.63	43.45	0.63	10.86
		5	19	197,213	12.51	0.34	205.78	0.34	41.16	2.47	10.29
300	150	1	20	199,646	8.82	0.00	136.88	1.66	27.38	3.65	6.84
		2	20	198,660	8.31	0.22	141.72	0.77	28.34	2.02	7.09
		3	18	190,428	14.28	0.00	127.31	0.00	25.46	0.00	6.37
		4	20	192,454	11.00	0.84	141.56	1.64	28.31	2.02	7.08
		5	20	196,167	11.01	1.27	142.30	1.27	28.46	2.86	7.11
400	400	1	22	245,930	1200.00	0.79	575.45	0.79	115.09	1.73	28.77
		2	22	251,373	1200.00	1.82	587.66	2.47	117.53	4.21	29.38
		3	23	252,782	1200.00	0.78	615.03	0.78	123.01	2.72	30.75
		4	22	245,944	1200.00	1.45	588.47	1.84	117.69	2.50	29.42
		5	22	248,280	1200.00	0.76	579.83	1.81	115.97	2.27	28.99
400	300	1	25	259,988	264.67	0.11	555.53	1.41	111.11	1.54	27.78
		2	24	249,280	481.23	1.02	535.91	1.29	107.18	3.78	26.80
		3	25	254,020	482.90	0.68	520.61	0.68	104.12	1.80	26.03
		4	23	248,581	37.04	0.00	487.95	0.00	97.59	0.00	24.40
		5	24	250,723	19.75	0.01	525.52	1.05	105.10	1.33	26.28
400	200	1	25	257,332	13.75	0.15	325.09	0.28	65.02	1.08	16.25
		2	24	244,917	63.50	0.00	320.64	0.63	64.13	0.92	16.03
		3	25	243,373	24.03	0.43	308.98	1.21	61.80	5.59	15.45
		4	25	246,412	151.10	0.72	322.30	1.01	64.46	1.40	16.11
		5	25	251,909	17.00	0.00	323.33	0.89	64.67	1.50	16.17

500	500	1	28	274,779	1200.00	0.02	1242.89	0.02	248.58	0.05	62.14
		2	28	297,297	1200.00	0.77	1236.52	1.21	247.30	2.83	61.83
		3	28	294,185	1200.00	0.09	1302.03	0.09	260.41	0.09	65.10
		4	28	274,779	1200.00	-0.56	1273.71	-0.56	254.74	-0.56	63.69
		5	28	297,297	1200.00	1.43	1237.20	2.20	247.44	2.20	61.86
500	375	1	30	284,236	1200.00	0.91	980.34	1.85	196.07	1.96	49.02
		2	31	309,925	312.46	0.00	1032.77	1.32	206.55	1.32	51.64
		3	31	305,205	1200.00	1.55	1014.19	2.21	202.84	2.21	50.71
		4	30	284,236	1200.00	0.77	1106.48	2.18	221.30	2.18	55.32
		5	31	309,925	449.50	0.00	1031.50	0.63	206.30	1.32	51.58
500	250	1	30	279,431	227.82	1.03	589.06	2.71	117.81	3.11	29.45
		2	31	304,657	47.20	0.71	606.31	2.11	121.26	2.96	30.32
		3	33	310,639	244.25	0.17	654.91	0.22	130.98	1.99	32.75
		4	30	279,431	231.39	0.99	570.19	0.99	114.04	1.97	28.51
		5	31	304,657	60.07	0.65	643.55	0.88	128.71	0.88	32.18
Average				215,325	364.77	0.42	427.48	0.94	85.50	1.59	21.37

Table A. 5. Comparison of solution for TS3 by closing and opening 1 station in random

						5000 iterations		1000 iterations		250 iterations	
Demand Points	Potential Locations	Data	K	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12	117,299	38.04	0.42	158.80	0.73	31.76	1.56	7.94
		2	12	124,383	13.90	0.00	136.95	1.12	27.39	1.46	6.85
		3	12	116,362	46.56	0.31	134.61	0.31	26.92	0.78	6.73
		4	12	122,749	13.85	0.28	130.89	0.28	26.18	0.72	6.54
		5	13	127,400	42.76	0.00	145.61	0.00	29.12	0.00	7.28
200	150	1	12	114,202	9.39	0.00	107.36	0.63	21.47	0.81	5.37
		2	14	131,223	11.28	0.00	122.59	0.41	24.52	1.49	6.13
		3	13	121,290	7.57	0.00	130.84	0.00	26.17	1.03	6.54
		4	14	132,910	7.00	0.20	123.22	2.91	24.64	3.60	6.16
		5	14	126,775	7.59	0.00	131.19	0.00	26.24	0.00	6.56
200	100	1	12	113,073	6.26	0.25	80.00	0.66	16.00	0.66	4.00
		2	14	131,223	6.53	0.00	85.23	0.41	17.05	0.41	4.26
		3	13	117,316	6.26	0.00	78.06	0.00	15.61	0.00	3.90
		4	14	128,944	5.10	0.00	87.06	0.00	17.41	1.78	4.35
		5	15	130,543	5.37	0.00	89.36	0.00	17.87	0.00	4.47
300	300	1	18	192,288	1200.00	-0.08	387.13	0.78	77.43	0.78	19.36
		2	18	198,448	79.62	0.34	398.88	1.93	79.78	1.93	19.94
		3	17	190,591	1200.00	-0.12	375.27	-0.12	75.05	0.93	18.76
		4	18	190,326	131.42	0.00	414.02	0.00	82.80	0.00	20.70
		5	17	184,599	179.04	0.03	386.70	0.16	77.34	0.16	19.34
300	225	1	18	185,816	19.26	0.00	296.64	0.60	59.33	0.77	14.83
		2	19	191,668	14.29	0.00	316.42	0.20	63.28	1.16	15.82
		3	18	196,112	18.31	1.02	296.59	1.80	59.32	1.80	14.83
		4	20	197,839	23.25	0.00	344.03	0.52	68.81	0.52	17.20
		5	19	197,213	12.51	0.00	284.31	0.12	56.86	0.34	14.22
300	150	1	20	199,646	8.82	0.00	242.20	1.33	48.44	1.77	12.11
		2	20	198,660	8.31	0.22	216.68	0.22	43.34	0.54	10.83
		3	18	190,428	14.28	0.00	203.58	0.00	40.72	0.17	10.18
		4	20	192,454	11.00	1.20	227.58	1.43	45.52	1.43	11.38
		5	20	196,167	11.01	1.12	224.48	2.02	44.90	2.39	11.22
400	400	1	22	245,930	1200.00	0.28	806.20	0.28	161.24	0.28	40.31
		2	22	251,373	1200.00	0.97	821.34	0.97	164.27	0.97	41.07
		3	23	252,782	1200.00	0.00	982.00	0.37	196.40	0.65	49.10
		4	22	245,944	1200.00	0.01	898.39	0.01	179.68	0.01	44.92
		5	22	248,280	1200.00	0.39	863.16	0.39	172.63	0.57	43.16
400	300	1	25	259,988	264.67	0.16	735.34	1.09	147.07	1.53	36.77
		2	24	249,280	481.23	0.11	692.98	0.11	138.60	0.11	34.65
		3	25	254,020	482.90	0.31	746.20	0.63	149.24	0.63	37.31
		4	23	248,581	37.04	0.00	666.48	1.37	133.30	1.37	33.32
		5	24	250,723	19.75	0.00	710.00	0.73	142.00	0.73	35.50
400	200	1	25	257,332	13.75	0.00	509.53	0.99	101.91	1.00	25.48
		2	24	244,917	63.50	0.75	462.89	1.16	92.58	1.32	23.14
		3	25	243,373	24.03	0.00	468.05	0.95	93.61	0.95	23.40
		4	25	246,412	151.10	0.34	558.89	0.65	111.78	1.03	27.94
		5	25	251,909	17.00	0.62	497.80	1.45	99.56	1.89	24.89

500	500	1	28	274,779	1200.00	-0.91	1589.94	-0.75	317.99	-0.75	79.50
		2	28	297,297	1200.00	0.62	1651.64	0.62	330.33	0.62	82.58
		3	28	294,185	1200.00	1.03	1588.80	1.33	317.76	1.33	79.44
		4	28	274,779	1200.00	-0.75	1587.59	-0.75	317.52	-0.75	79.38
		5	28	297,297	1200.00	0.62	1674.47	0.62	334.89	0.62	83.72
500	375	1	30	284,236	1200.00	0.95	1357.08	0.98	271.42	0.98	67.85
		2	31	309,925	312.46	0.32	1467.64	0.32	293.53	0.81	73.38
		3	31	305,205	1200.00	-0.05	1435.41	0.97	287.08	1.85	71.77
		4	30	284,236	1200.00	0.95	1367.30	0.98	273.46	0.98	68.36
		5	31	309,925	449.50	0.01	1451.36	0.16	290.27	0.84	72.57
500	250	1	30	279,431	227.82	1.16	933.59	1.28	186.72	1.54	46.68
		2	31	304,657	47.20	0.00	972.59	1.81	194.52	1.81	48.63
		3	33	310,639	244.25	0.03	1051.19	0.66	210.24	0.66	52.56
		4	30	279,431	231.39	0.88	899.11	1.64	179.82	1.64	44.96
		5	31	304,657	60.07	0.26	945.27	0.59	189.05	0.59	47.26
Average				215,325	364.77	0.24	612.47	0.67	122.49	0.91	30.62

Table A. 6. Comparison of solution for TS3 by closing and opening 2 stations in random

						5000 iterations		1000 iterations		250 iterations	
Demand Points	Potential Locations	Data	K	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12	117,299	38.04	0.42	165.13	1.56	33.03	1.56	8.26
		2	12	124,383	13.90	0.59	148.95	0.60	29.79	3.88	7.45
		3	12	116,362	46.56	0.17	141.17	0.48	28.23	0.48	7.06
		4	12	122,749	13.85	0.28	137.44	0.28	27.49	0.28	6.87
		5	13	127,400	42.76	0.76	157.63	0.78	31.53	4.84	7.88
200	150	1	12	114,202	9.39	0.00	110.89	0.63	22.18	0.63	5.54
		2	14	131,223	11.28	0.00	129.58	0.27	25.92	0.97	6.48
		3	13	121,290	7.57	0.00	138.41	0.47	27.68	0.47	6.92
		4	14	132,910	7.00	0.20	127.55	1.30	25.51	1.46	6.38
		5	14	126,775	7.59	0.00	135.56	0.00	27.11	0.17	6.78
200	100	1	12	113,073	6.26	0.66	82.84	2.69	16.57	2.98	4.14
		2	14	131,223	6.53	0.00	88.55	0.51	17.71	1.11	4.43
		3	13	117,316	6.26	0.00	81.00	0.00	16.20	0.00	4.05
		4	14	128,944	5.10	0.00	89.78	0.00	17.96	0.00	4.49
		5	15	130,543	5.37	0.00	92.45	0.00	18.49	1.26	4.62
300	300	1	18	192,288	1200.00	0.05	437.05	0.05	87.41	0.80	21.85
		2	18	198,448	79.62	0.00	243.86	1.93	48.77	1.93	12.19
		3	17	190,591	1200.00	-0.12	411.66	0.98	82.33	0.98	20.58
		4	18	190,326	131.42	0.00	434.03	0.00	86.81	0.00	21.70
		5	17	184,599	179.04	0.13	390.39	0.16	78.08	0.16	19.52
300	225	1	18	185,816	19.26	0.00	310.70	0.00	62.14	0.49	15.54
		2	19	191,668	14.29	0.20	324.86	0.96	64.97	0.96	16.24
		3	18	196,112	18.31	0.00	305.61	1.19	61.12	1.80	15.28
		4	20	197,839	23.25	0.00	354.09	1.23	70.82	2.38	17.70
		5	19	197,213	12.51	0.00	309.94	0.34	61.99	0.34	15.50
300	150	1	20	199,646	8.82	0.00	262.77	1.65	52.55	1.77	13.14
		2	20	198,660	8.31	0.00	242.28	1.30	48.46	1.30	12.11
		3	18	190,428	14.28	0.00	219.02	0.73	43.80	0.73	10.95
		4	20	192,454	11.00	0.00	235.39	1.43	47.08	1.43	11.77
		5	20	196,167	11.01	1.77	232.83	1.77	46.57	2.39	11.64
400	400	1	22	245,930	1200.00	0.48	817.50	0.78	163.50	0.95	40.88
		2	22	251,373	1200.00	1.62	847.84	1.62	169.57	1.62	42.39
		3	23	252,782	1200.00	0.17	908.73	0.65	181.75	3.02	45.44
		4	22	245,944	1200.00	0.01	823.11	0.01	164.62	0.01	41.16
		5	22	248,280	1200.00	0.39	813.59	0.57	162.72	0.57	40.68
400	300	1	25	259,988	264.67	0.62	697.67	1.37	139.53	1.49	34.88
		2	24	249,280	481.23	0.41	694.00	0.41	138.80	0.44	34.70
		3	25	254,020	482.90	0.30	684.05	0.85	136.81	0.85	34.20
		4	23	248,581	37.04	0.13	652.33	1.68	130.47	1.79	32.62
		5	24	250,723	19.75	0.00	726.58	1.05	145.32	1.60	36.33
400	200	1	25	257,332	13.75	0.00	479.77	0.00	95.95	1.00	23.99
		2	24	244,917	63.50	0.60	519.77	1.26	103.95	1.56	25.99
		3	25	243,373	24.03	0.43	483.78	0.43	96.76	0.43	24.19
		4	25	246,412	151.10	0.75	530.28	0.99	106.06	0.99	26.51
		5	25	251,909	17.00	0.00	490.55	0.76	98.11	1.13	24.53

500	500	1	28	274,779	1200.00	-0.75	1642.38	-0.75	328.48	-0.75	82.12
		2	28	297,297	1200.00	0.62	1763.11	0.62	352.62	0.62	88.16
		3	28	294,185	1200.00	0.87	1719.63	0.87	343.93	0.87	85.98
		4	28	274,779	1200.00	-0.75	1666.02	-0.75	333.20	-0.75	83.30
		5	28	297,297	1200.00	0.62	1716.80	0.62	343.36	0.62	85.84
500	375	1	30	284,236	1200.00	0.98	1363.09	0.98	272.62	0.98	68.15
		2	31	309,925	312.46	0.00	1471.27	0.36	294.25	1.17	73.56
		3	31	305,205	1200.00	0.57	1435.69	1.62	287.14	1.62	71.78
		4	30	284,236	1200.00	0.98	1357.44	0.98	271.49	0.98	67.87
		5	31	309,925	449.50	0.36	1440.33	0.70	288.07	0.90	72.02
500	250	1	30	279,431	227.82	1.64	845.13	1.64	169.03	1.64	42.26
		2	31	304,657	47.20	1.02	917.89	1.02	183.58	1.81	45.89
		3	33	310,639	244.25	0.41	1112.80	0.85	222.56	0.85	55.64
		4	30	279,431	231.39	0.95	864.02	1.64	172.80	1.64	43.20
		5	31	304,657	60.07	0.00	960.70	0.00	192.14	0.00	48.04
Average				215,325	364.77	0.31	616.45	0.77	123.29	1.12	30.82

APPENDIX B: RESULTS OF MPBDCM FOR RANDOM PROBLEMS

Table B. 1. Comparison of solution for TS1-1 by closing and opening 1 station in random

						2500 iterations		1000 iterations		500 iterations	
Demand Points	Potential Locations	Data	K_1, K_2, K_3, K_4	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12,16,20,24	622,825	2400.00	0.61	223.27	0.61	89.31	1.24	44.65
		2	12,16,20,24	641,252	2400.00	2.03	211.81	2.03	84.72	2.03	42.36
		3	12,16,20,24	620,333	2400.00	0.94	215.72	2.03	86.29	2.03	43.14
		4	12,16,20,24	636,126	2400.00	1.25	213.54	1.40	85.41	2.16	42.71
		5	13,17,21,25	663,241	2400.00	1.99	228.98	1.99	91.59	1.99	45.80
200	150	1	12,16,20,24	609,154	2400.00	1.73	154.67	1.73	61.87	1.88	30.93
		2	14,18,22,26	655,741	2400.00	-0.23	170.60	1.30	68.24	2.32	34.12
		3	13,17,21,25	633,763	1153.15	1.23	163.74	1.23	65.50	4.10	32.75
		4	14,18,22,26	657,909	1558.18	1.09	165.06	1.09	66.02	2.65	33.01
		5	14,18,22,26	654,576	2400.00	0.45	167.08	1.52	66.83	1.65	33.42
200	100	1	12,16,20,24	603,220	356.12	3.01	94.14	3.13	37.66	4.69	18.83
		2	14,18,22,26	653,031	352.34	0.53	103.74	0.53	41.50	1.20	20.75
		3	13,18,23,28	637,486	60.89	1.10	104.22	1.10	41.69	1.71	20.84
		4	14,18,22,26	642,436	327.85	1.12	102.30	1.32	40.92	1.32	20.46
		5	15,19,23,27	658,956	269.26	2.85	111.63	2.85	44.65	2.85	22.33
300	300	1	18,24,30,36	990,429	4800.00	0.21	710.51	1.64	284.20	1.64	142.10
		2	18,24,30,36	1,024,241	4800.00	0.66	709.02	0.66	283.61	2.66	141.80
		3	17,22,27,32	942,404	4800.00	-0.80	629.48	-0.68	251.79	-0.63	125.90
		4	18,23,28,33	959,748	4800.00	0.63	662.89	0.63	265.16	0.63	132.58
		5	17,22,27,32	933,364	4800.00	0.06	630.97	0.06	252.39	2.87	126.19
300	225	1	18,24,30,36	968,258	2400.00	0.59	508.75	0.60	203.50	1.48	101.75
		2	19,25,31,37	994,251	2400.00	1.33	522.59	1.33	209.04	1.44	104.52
		3	18,24,30,36	988,659	2400.00	1.24	507.02	2.37	202.81	3.37	101.40
		4	20,26,32,38	1,014,892	2400.00	0.44	561.46	0.44	224.59	1.88	112.29
		5	19,25,31,37	1,009,938	2400.00	2.09	534.80	2.09	213.92	2.97	106.96
300	150	1	20,26,32,38	997,632	1563.64	1.10	344.18	2.56	137.67	2.69	68.84
		2	20,26,32,38	1,012,396	321.45	1.92	341.37	1.92	136.55	3.52	68.27
		3	18,24,30,36	981,005	2400.00	2.46	321.41	4.01	128.57	4.62	64.28
		4	20,26,32,38	999,337	2203.75	1.75	345.29	2.37	138.12	2.89	69.06
		5	20,26,32,38	1,003,298	2400.00	2.84	342.02	3.25	136.81	3.25	68.40
400	400	1	22,29,36,43	1,291,258	4800.00	1.66	1528.75	1.66	611.50	2.86	305.75
		2	22,30,38,46	1,260,934	4800.00	-2.03	1635.00	-1.11	654.00	-0.43	327.00
		3	23,30,37,44	1,267,927	4800.00	-0.17	1562.84	0.84	625.14	1.77	312.57
		4	22,29,36,43	1,256,179	4800.00	-0.55	1532.08	1.43	612.83	2.52	306.42
		5	22,29,36,43	1,308,762	4800.00	3.08	1528.11	3.08	611.24	3.53	305.62
400	300	1	25,32,39,46	1,320,929	4800.00	1.76	1170.67	2.76	468.27	3.24	234.13
		2	24,33,42,51	1,345,825	4800.00	2.69	1275.55	2.69	510.22	3.93	255.11
		3	25,32,39,46	1,280,708	4800.00	0.44	1173.76	1.33	469.50	1.58	234.75
		4	23,31,39,47	1,289,976	4800.00	1.09	1377.66	1.09	551.06	1.82	275.53
		5	24,32,40,48	1,322,614	4800.00	1.49	1451.33	2.58	580.53	5.06	290.27
400	200	1	25,34,43,52	1,359,595	2400.00	1.91	886.72	1.91	354.69	1.91	177.34
		2	24,33,42,51	1,324,792	2400.00	2.51	854.05	3.61	341.62	4.46	170.81
		3	25,34,43,52	1,317,683	2400.00	2.43	902.72	2.43	361.09	2.43	180.54
		4	25,33,41,49	1,283,177	2400.00	1.74	865.52	2.41	346.21	3.64	173.10
		5	25,33,41,49	1,319,989	2400.00	2.23	888.39	2.29	355.36	2.29	177.68

500	500	1	28,37,46,55	1,441,911	4800.00	-2.80	3350.58	-2.37	1340.23	-0.15	670.12
		2	28,37,46,55	1,488,102	4800.00	-2.93	3228.08	-2.03	1291.23	-1.55	645.62
		3	28,37,46,55	1,466,207	4800.00	-3.04	3405.92	-2.58	1362.37	-0.02	681.18
		4	28,37,46,55	1,441,911	4800.00	-2.32	3365.86	-1.14	1346.34	0.11	673.17
		5	28,37,46,55	1,488,102	4800.00	-3.50	3359.08	-2.31	1343.63	-1.07	671.82
500	375	1	30,40,50,60	1,518,885	4800.00	0.49	2590.42	2.31	1036.17	3.02	518.08
		2	31,41,51,61	1,607,755	4800.00	1.99	2694.02	3.44	1077.61	5.47	538.80
		3	31,41,51,61	1,567,664	4800.00	1.02	2767.14	1.86	1106.86	1.86	553.43
		4	30,40,50,60	1,519,921	4800.00	1.74	2689.98	2.13	1075.99	2.13	538.00
		5	31,41,51,61	1,607,755	4800.00	1.71	2723.72	1.71	1089.49	2.40	544.74
500	250	1	30,40,50,60	1,504,477	2400.00	1.32	1498.75	3.11	599.50	3.55	299.75
		2	31,43,55,67	1,633,786	2400.00	2.70	1718.72	4.39	687.49	5.54	343.74
		3	33,44,55,66	1,611,371	2400.00	2.19	1779.13	2.38	711.65	3.11	355.83
		4	30,40,50,60	1,504,477	2400.00	1.77	1705.58	2.73	682.23	3.06	341.12
		5	31,43,55,67	1,633,786	2400.00	2.37	1804.61	2.37	721.84	3.02	360.92
Average				1,116,606	3136.11	0.99	1123.62	1.53	449.45	2.34	224.72

Table B. 2. Comparison of solution for TS1-2 by closing and opening 1 station in random

						2500 iterations		1000 iterations		500 iterations	
Demand Points	Potential Locations	Data	K_1, K_2, K_3, K_4	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12,16,20,24	622,825	2400.00	-0.19	215.11	-0.19	86.04	-0.19	43.02
		2	12,16,20,24	641,252	2400.00	0.30	214.91	0.54	85.96	1.02	42.98
		3	12,16,20,24	620,333	2400.00	-0.09	216.44	-0.08	86.57	0.19	43.29
		4	12,16,20,24	636,126	2400.00	-0.30	218.73	-0.13	87.49	0.35	43.75
		5	13,17,21,25	663,241	2400.00	-0.23	231.11	-0.23	92.44	0.19	46.22
200	150	1	12,16,20,24	609,154	2400.00	0.16	157.92	0.55	63.17	0.91	31.58
		2	14,18,22,26	655,741	2400.00	-0.23	172.06	-0.12	68.82	0.43	34.41
		3	13,17,21,25	633,763	1153.15	0.14	166.31	0.48	66.52	0.48	33.26
		4	14,18,22,26	657,909	1558.18	0.00	173.89	0.00	69.56	0.00	34.78
		5	14,18,22,26	654,576	2400.00	0.00	176.77	0.51	70.71	0.53	35.35
200	100	1	12,16,20,24	603,220	356.12	0.54	102.61	0.54	41.04	1.15	20.52
		2	14,18,22,26	653,031	352.34	0.02	109.72	0.20	43.89	0.51	21.94
		3	13,18,23,28	637,486	60.89	0.01	110.98	0.01	44.39	0.01	22.20
		4	14,18,22,26	642,436	327.85	0.01	108.78	0.23	43.51	0.47	21.76
		5	15,19,23,27	658,956	269.26	0.00	118.58	0.34	47.43	0.34	23.72
300	300	1	18,24,30,36	990,429	4800.00	-0.66	646.23	0.34	258.49	0.72	129.25
		2	18,24,30,36	1,024,241	4800.00	-0.37	654.84	0.01	261.94	0.01	130.97
		3	17,22,27,32	942,404	4800.00	-1.40	591.47	-1.40	236.59	-1.40	118.29
		4	18,23,28,33	959,748	4800.00	-0.56	600.13	-0.41	240.05	-0.19	120.03
		5	17,22,27,32	933,364	4800.00	-1.25	649.50	-0.46	259.80	-0.07	129.90
300	225	1	18,24,30,36	968,258	2400.00	-0.20	495.84	0.37	198.34	0.46	99.17
		2	19,25,31,37	994,251	2400.00	0.81	529.64	1.05	211.86	1.35	105.93
		3	18,24,30,36	988,659	2400.00	-0.17	487.17	-0.17	194.87	0.19	97.43
		4	20,26,32,38	1,014,892	2400.00	-0.84	541.00	-0.84	216.40	-0.84	108.20
		5	19,25,31,37	1,009,938	2400.00	0.21	547.50	0.21	219.00	0.31	109.50
300	150	1	20,26,32,38	997,632	1563.64	0.17	359.30	0.25	143.72	0.43	71.86
		2	20,26,32,38	1,012,396	321.45	0.53	365.03	0.98	146.01	0.98	73.01
		3	18,24,30,36	981,005	2400.00	0.06	334.11	0.06	133.64	1.08	66.82
		4	20,26,32,38	999,337	2203.75	0.42	358.61	0.95	143.44	0.95	71.72
		5	20,26,32,38	1,003,298	2400.00	0.15	341.88	0.72	136.75	1.61	68.38
400	400	1	22,29,36,43	1,291,258	4800.00	0.01	1381.56	0.01	552.63	0.04	276.31
		2	22,30,38,46	1,260,934	4800.00	-4.27	1521.50	-3.41	608.60	-3.16	304.30
		3	23,30,37,44	1,267,927	4800.00	-2.48	1419.81	-2.00	567.92	-1.37	283.96
		4	22,29,36,43	1,256,179	4800.00	-2.06	1389.59	-1.03	555.84	-0.54	277.92
		5	22,29,36,43	1,308,762	4800.00	0.54	1382.42	0.54	552.97	1.66	276.48
400	300	1	25,32,39,46	1,320,929	4800.00	0.22	1118.41	0.22	447.36	0.39	223.68
		2	24,33,42,51	1,345,825	4800.00	0.69	1176.44	0.69	470.57	2.36	235.29
		3	25,32,39,46	1,280,708	4800.00	-0.87	1092.53	-0.22	437.01	0.58	218.51
		4	23,31,39,47	1,289,976	4800.00	-0.75	1075.61	0.10	430.24	0.88	215.12
		5	24,32,40,48	1,322,614	4800.00	-0.01	1105.77	0.02	442.31	0.60	221.15
400	200	1	25,34,43,52	1,359,595	2400.00	0.05	804.89	0.16	321.96	0.73	160.98
		2	24,33,42,51	1,324,792	2400.00	-0.10	765.77	0.19	306.31	0.47	153.15
		3	25,34,43,52	1,317,683	2400.00	0.15	763.66	0.18	305.46	0.18	152.73
		4	25,33,41,49	1,283,177	2400.00	-0.14	741.56	0.90	296.62	1.48	148.31
		5	25,33,41,49	1,319,989	2400.00	0.35	725.08	0.35	290.03	0.50	145.02

500	500	1	28,37,46,55	1,441,911	4800.00	-3.80	2761.14	-2.86	1104.46	-1.80	552.23
		2	28,37,46,55	1,488,102	4800.00	-3.83	2867.13	-3.74	1146.85	-3.25	573.43
		3	28,37,46,55	1,466,207	4800.00	-4.28	2871.81	-3.19	1148.72	-1.81	574.36
		4	28,37,46,55	1,441,911	4800.00	-3.65	2853.19	-3.32	1141.27	-1.79	570.64
		5	28,37,46,55	1,488,102	4800.00	-3.63	2845.55	-3.63	1138.22	-2.69	569.11
500	375	1	30,40,50,60	1,518,885	4800.00	-0.31	2393.20	-0.31	957.28	0.30	478.64
		2	31,41,51,61	1,607,755	4800.00	0.06	2400.13	0.34	960.05	0.65	480.03
		3	31,41,51,61	1,567,664	4800.00	-0.50	2321.23	-0.26	928.49	0.15	464.25
		4	30,40,50,60	1,519,921	4800.00	-0.22	2466.22	0.37	986.49	1.26	493.24
		5	31,41,51,61	1,607,755	4800.00	0.11	2380.98	0.37	952.39	0.81	476.20
500	250	1	30,40,50,60	1,504,477	2400.00	0.59	1426.81	0.59	570.72	1.42	285.36
		2	31,43,55,67	1,633,786	2400.00	0.62	1624.88	0.62	649.95	0.62	324.98
		3	33,44,55,66	1,611,371	2400.00	0.14	1678.52	0.55	671.41	0.55	335.70
		4	30,40,50,60	1,504,477	2400.00	0.49	1446.47	0.72	578.59	1.09	289.29
		5	31,43,55,67	1,633,786	2400.00	0.35	1554.83	0.35	621.93	1.00	310.97
Average				1,116,606	3136.11	-0.49	1005.88	-0.21	402.35	0.22	201.18

Table B. 3. Comparison of solution for TS2-1 by closing and opening 1 station in random

						2500 iterations		1000 iterations		500 iterations	
Demand Points	Potential Locations	Data	K_1, K_2, K_3, K_4	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12,16,20,24	622,825	2400.00	1.39	221.23	1.39	88.49	2.82	44.25
		2	12,16,20,24	641,252	2400.00	0.54	212.09	0.54	84.84	0.54	42.42
		3	12,16,20,24	620,333	2400.00	1.13	215.89	2.49	86.36	2.49	43.18
		4	12,16,20,24	636,126	2400.00	0.73	220.52	0.73	88.21	0.73	44.10
		5	13,17,21,25	663,241	2400.00	0.98	234.74	1.78	93.90	1.78	46.95
200	150	1	12,16,20,24	609,154	2400.00	2.75	157.22	2.75	62.89	2.89	31.44
		2	14,18,22,26	655,741	2400.00	0.75	171.09	1.45	68.43	1.45	34.22
		3	13,17,21,25	633,763	1153.15	1.84	171.13	2.63	68.45	2.63	34.23
		4	14,18,22,26	657,909	1558.18	1.84	168.52	1.84	67.41	2.03	33.70
		5	14,18,22,26	654,576	2400.00	0.26	172.10	1.06	68.84	1.81	34.42
200	100	1	12,16,20,24	603,220	356.12	1.40	99.38	1.40	39.75	1.40	19.88
		2	14,18,22,26	653,031	352.34	0.47	107.65	0.47	43.06	1.09	21.53
		3	13,18,23,28	637,486	60.89	0.64	107.13	2.39	42.85	2.39	21.43
		4	14,18,22,26	642,436	327.85	0.23	104.62	0.23	41.85	0.23	20.92
		5	15,19,23,27	658,956	269.26	1.24	110.16	1.24	44.06	1.24	22.03
300	300	1	18,24,30,36	990,429	4800.00	0.78	722.97	0.78	289.19	0.78	144.59
		2	18,24,30,36	1,024,241	4800.00	0.81	735.75	2.33	294.30	2.33	147.15
		3	17,22,27,32	942,404	4800.00	-0.18	647.28	-0.18	258.91	0.52	129.46
		4	18,23,28,33	959,748	4800.00	0.28	667.21	0.28	266.88	0.28	133.44
		5	17,22,27,32	933,364	4800.00	0.07	634.42	0.44	253.77	1.57	126.88
300	225	1	18,24,30,36	968,258	2400.00	1.35	549.69	1.35	219.87	1.61	109.94
		2	19,25,31,37	994,251	2400.00	1.63	540.97	2.92	216.39	3.26	108.19
		3	18,24,30,36	988,659	2400.00	0.37	531.01	1.82	212.41	2.14	106.20
		4	20,26,32,38	1,014,892	2400.00	0.73	580.18	0.73	232.07	0.73	116.04
		5	19,25,31,37	1,009,938	2400.00	1.36	529.56	1.36	211.82	1.36	105.91
300	150	1	20,26,32,38	997,632	1563.64	1.35	345.73	1.59	138.29	1.59	69.15
		2	20,26,32,38	1,012,396	321.45	1.42	347.71	1.55	139.08	1.71	69.54
		3	18,24,30,36	981,005	2400.00	1.92	330.42	1.92	132.17	1.92	66.08
		4	20,26,32,38	999,337	2203.75	2.18	352.26	2.66	140.90	2.66	70.45
		5	20,26,32,38	1,003,298	2400.00	1.83	349.02	1.83	139.61	2.10	69.80
400	400	1	22,29,36,43	1,291,258	4800.00	0.49	1500.12	1.13	600.05	1.13	300.02
		2	22,30,38,46	1,260,934	4800.00	-2.57	1669.21	-2.57	667.69	-2.57	333.84
		3	23,30,37,44	1,267,927	4800.00	-1.87	1546.69	-0.77	618.68	1.30	309.34
		4	22,29,36,43	1,256,179	4800.00	0.19	1560.83	0.19	624.33	0.19	312.17
		5	22,29,36,43	1,308,762	4800.00	2.07	1536.58	2.38	614.63	3.35	307.32
400	300	1	25,32,39,46	1,320,929	4800.00	1.59	1164.68	1.93	465.87	2.31	232.94
		2	24,33,42,51	1,345,825	4800.00	1.19	1270.24	1.19	508.10	1.19	254.05
		3	25,32,39,46	1,280,708	4800.00	0.05	1181.44	2.34	472.57	2.34	236.29
		4	23,31,39,47	1,289,976	4800.00	0.38	1212.92	0.38	485.17	0.38	242.58
		5	24,32,40,48	1,322,614	4800.00	1.03	1265.72	1.57	506.29	2.30	253.14
400	200	1	25,34,43,52	1,359,595	2400.00	1.36	794.89	1.59	317.96	1.59	158.98
		2	24,33,42,51	1,324,792	2400.00	2.19	840.74	2.19	336.30	3.20	168.15
		3	25,34,43,52	1,317,683	2400.00	2.59	793.69	2.93	317.48	3.33	158.74
		4	25,33,41,49	1,283,177	2400.00	0.64	788.44	1.20	315.38	1.20	157.69
		5	25,33,41,49	1,319,989	2400.00	2.91	780.89	2.91	312.36	2.91	156.18

500	500	1	28,37,46,55	1,441,911	4800.00	-2.34	3057.90	-2.12	1223.16	-1.82	611.58
		2	28,37,46,55	1,488,102	4800.00	-2.20	3063.03	-0.79	1225.21	-0.79	612.61
		3	28,37,46,55	1,466,207	4800.00	-3.44	3112.23	-2.88	1244.89	-2.88	622.45
		4	28,37,46,55	1,441,911	4800.00	-1.83	3096.14	-1.83	1238.46	-1.83	619.23
		5	28,37,46,55	1,488,102	4800.00	-2.50	3110.04	-1.54	1244.02	-1.54	622.01
500	375	1	30,40,50,60	1,518,885	4800.00	1.35	2445.33	2.41	978.13	3.12	489.07
		2	31,41,51,61	1,607,755	4800.00	0.84	2514.97	1.23	1005.99	1.23	502.99
		3	31,41,51,61	1,567,664	4800.00	0.86	2488.81	1.45	995.52	1.74	497.76
		4	30,40,50,60	1,519,921	4800.00	1.81	2495.48	1.81	998.19	1.81	499.10
		5	31,41,51,61	1,607,755	4800.00	1.24	2490.84	1.24	996.34	1.24	498.17
500	250	1	30,40,50,60	1,504,477	2400.00	1.84	1510.23	1.84	604.09	1.84	302.05
		2	31,43,55,67	1,633,786	2400.00	2.23	1723.15	2.23	689.26	2.23	344.63
		3	33,44,55,66	1,611,371	2400.00	1.86	1692.34	1.86	676.94	1.96	338.47
		4	30,40,50,60	1,504,477	2400.00	1.90	1590.78	1.90	636.31	1.90	318.16
		5	31,43,55,67	1,633,786	2400.00	2.14	1707.19	2.14	682.87	2.14	341.44
Average				1,116,606	3136.11	0.80	1072.39	1.19	428.95	1.41	214.48

Table B. 4. Comparison of solution for TS2-2 by closing and opening 1 station in random

						2500 iterations		1000 iterations		500 iterations	
Demand Points	Potential Locations	Data	K_1, K_2, K_3, K_4	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12,16,20,24	622,825	2400.00	0.04	193.42	0.41	77.37	0.41	38.68
		2	12,16,20,24	641,252	2400.00	-0.04	201.14	0.41	80.46	0.95	40.23
		3	12,16,20,24	620,333	2400.00	-0.61	198.23	-0.61	79.29	-0.11	39.65
		4	12,16,20,24	636,126	2400.00	0.30	200.71	0.30	80.28	0.85	40.14
		5	13,17,21,25	663,241	2400.00	-0.26	209.62	0.01	83.85	0.01	41.92
200	150	1	12,16,20,24	609,154	2400.00	0.04	142.45	1.12	56.98	2.91	28.49
		2	14,18,22,26	655,741	2400.00	-0.18	159.12	-0.18	63.65	-0.18	31.82
		3	13,17,21,25	633,763	1153.15	0.00	152.24	0.00	60.89	1.22	30.45
		4	14,18,22,26	657,909	1558.18	0.00	159.77	0.00	63.91	0.74	31.95
		5	14,18,22,26	654,576	2400.00	0.13	163.35	0.13	65.34	0.13	32.67
200	100	1	12,16,20,24	603,220	356.12	0.71	92.75	0.71	37.10	0.71	18.55
		2	14,18,22,26	653,031	352.34	0.00	101.98	0.02	40.79	0.39	20.40
		3	13,18,23,28	637,486	60.89	0.01	105.32	0.42	42.13	0.93	21.06
		4	14,18,22,26	642,436	327.85	0.00	100.85	0.00	40.34	0.01	20.17
		5	15,19,23,27	658,956	269.26	0.00	103.46	0.00	41.38	0.00	20.69
300	300	1	18,24,30,36	990,429	4800.00	-0.85	675.97	-0.85	270.39	-0.16	135.19
		2	18,24,30,36	1,024,241	4800.00	-0.24	667.25	-0.24	266.90	-0.05	133.45
		3	17,22,27,32	942,404	4800.00	-1.59	615.11	-1.10	246.04	-1.10	123.02
		4	18,23,28,33	959,748	4800.00	-0.72	644.16	-0.32	257.66	-0.32	128.83
		5	17,22,27,32	933,364	4800.00	-1.17	626.31	-0.73	250.52	-0.04	125.26
300	225	1	18,24,30,36	968,258	2400.00	0.08	496.22	0.20	198.49	0.69	99.24
		2	19,25,31,37	994,251	2400.00	0.69	511.89	0.83	204.76	0.99	102.38
		3	18,24,30,36	988,659	2400.00	-0.33	496.14	0.20	198.46	0.20	99.23
		4	20,26,32,38	1,014,892	2400.00	-0.35	524.70	-0.35	209.88	-0.16	104.94
		5	19,25,31,37	1,009,938	2400.00	0.09	508.08	0.33	203.23	0.33	101.62
300	150	1	20,26,32,38	997,632	1563.64	0.22	324.34	0.39	129.74	0.50	64.87
		2	20,26,32,38	1,012,396	321.45	0.79	318.60	0.79	127.44	0.79	63.72
		3	18,24,30,36	981,005	2400.00	0.43	303.53	0.66	121.41	0.67	60.71
		4	20,26,32,38	999,337	2203.75	0.45	323.82	0.45	129.53	0.45	64.76
		5	20,26,32,38	1,003,298	2400.00	0.30	317.94	0.38	127.18	1.25	63.59
400	400	1	22,29,36,43	1,291,258	4800.00	-0.44	1391.46	-0.44	556.58	0.06	278.29
		2	22,30,38,46	1,260,934	4800.00	-3.68	1454.84	-2.94	581.94	-2.94	290.97
		3	23,30,37,44	1,267,927	4800.00	-2.94	1436.93	-2.26	574.77	-2.10	287.39
		4	22,29,36,43	1,256,179	4800.00	-2.08	1395.88	-0.80	558.35	-0.80	279.18
		5	22,29,36,43	1,308,762	4800.00	0.61	1385.78	1.02	554.31	2.63	277.16
400	300	1	25,32,39,46	1,320,929	4800.00	0.11	1090.67	0.11	436.27	0.11	218.13
		2	24,33,42,51	1,345,825	4800.00	-0.11	1154.21	1.03	461.68	1.30	230.84
		3	25,32,39,46	1,280,708	4800.00	-1.05	1076.78	-0.80	430.71	-0.17	215.36
		4	23,31,39,47	1,289,976	4800.00	-1.06	1084.24	-0.79	433.69	-0.47	216.85
		5	24,32,40,48	1,322,614	4800.00	0.09	1121.08	0.09	448.43	0.09	224.22
400	200	1	25,34,43,52	1,359,595	2400.00	0.13	770.26	0.29	308.11	0.29	154.05
		2	24,33,42,51	1,324,792	2400.00	0.14	732.35	0.25	292.94	0.84	146.47
		3	25,34,43,52	1,317,683	2400.00	0.38	775.47	0.49	310.19	1.19	155.09
		4	25,33,41,49	1,283,177	2400.00	0.38	721.21	0.38	288.48	0.80	144.24
		5	25,33,41,49	1,319,989	2400.00	0.26	729.24	0.39	291.69	0.61	145.85

500	500	1	28,37,46,55	1,441,911	4800.00	-3.58	2745.34	-3.05	1098.13	-3.05	549.07
		2	28,37,46,55	1,488,102	4800.00	-3.91	2725.88	-3.91	1090.35	-3.82	545.18
		3	28,37,46,55	1,466,207	4800.00	-4.46	2720.21	-4.46	1088.09	-3.50	544.04
		4	28,37,46,55	1,441,911	4800.00	-3.30	2874.98	-3.30	1149.99	-3.30	575.00
		5	28,37,46,55	1,488,102	4800.00	-3.69	2880.20	-3.33	1152.08	-3.32	576.04
500	375	1	30,40,50,60	1,518,885	4800.00	0.05	2298.97	0.05	919.59	0.74	459.79
		2	31,41,51,61	1,607,755	4800.00	0.10	2399.83	0.10	959.93	0.13	479.97
		3	31,41,51,61	1,567,664	4800.00	-0.29	2337.15	0.37	934.86	1.62	467.43
		4	30,40,50,60	1,519,921	4800.00	-0.07	2219.33	-0.07	887.73	0.75	443.87
		5	31,41,51,61	1,607,755	4800.00	0.15	2231.89	0.31	892.76	0.31	446.38
500	250	1	30,40,50,60	1,504,477	2400.00	-0.03	1379.91	0.70	551.96	1.40	275.98
		2	31,43,55,67	1,633,786	2400.00	0.14	1505.56	0.14	602.22	0.14	301.11
		3	33,44,55,66	1,611,371	2400.00	0.23	1523.48	0.23	609.39	0.23	304.70
		4	30,40,50,60	1,504,477	2400.00	0.57	1395.11	0.63	558.04	1.19	279.02
		5	31,43,55,67	1,633,786	2400.00	0.63	1505.94	0.82	602.37	0.82	301.19
Average				1,116,606	3136.11	-0.48	978.38	-0.26	391.35	0.08	195.68

Table B. 5. Comparison of solution for TS3-1 by closing and opening 1 station in random

						2500 iterations		1000 iterations		500 iterations	
Demand Points	Potential Locations	Data	K_1, K_2, K_3, K_4	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12,16,20,24	622,825	2400.00	0.26	306.15	0.26	122.46	2.34	61.23
		2	12,16,20,24	641,252	2400.00	1.03	290.81	1.03	116.32	1.03	58.16
		3	12,16,20,24	620,333	2400.00	0.40	286.58	1.79	114.63	1.87	57.32
		4	12,16,20,24	636,126	2400.00	0.90	281.77	0.90	112.71	1.77	56.35
		5	13,17,21,25	663,241	2400.00	0.53	296.09	0.53	118.44	0.53	59.22
200	150	1	12,16,20,24	609,154	2400.00	0.49	211.55	0.49	84.62	0.95	42.31
		2	14,18,22,26	655,741	2400.00	0.75	236.77	0.91	94.71	0.91	47.35
		3	13,17,21,25	633,763	1153.15	2.01	240.61	3.66	96.24	3.66	48.12
		4	14,18,22,26	657,909	1558.18	1.07	235.94	1.96	94.37	1.96	47.19
		5	14,18,22,26	654,576	2400.00	0.39	241.03	0.61	96.41	0.61	48.21
200	100	1	12,16,20,24	603,220	356.12	1.71	145.92	2.29	58.37	2.29	29.18
		2	14,18,22,26	653,031	352.34	0.65	153.05	0.65	61.22	0.65	30.61
		3	13,18,23,28	637,486	60.89	0.88	152.41	0.88	60.96	0.88	30.48
		4	14,18,22,26	642,436	327.85	0.28	156.72	0.28	62.69	0.28	31.34
		5	15,19,23,27	658,956	269.26	1.15	163.22	1.15	65.29	1.52	32.64
300	300	1	18,24,30,36	990,429	4800.00	-0.40	875.03	-0.40	350.01	0.63	175.01
		2	18,24,30,36	1,024,241	4800.00	0.82	884.34	0.82	353.74	0.82	176.87
		3	17,22,27,32	942,404	4800.00	-1.03	777.27	-1.03	310.91	-1.03	155.45
		4	18,23,28,33	959,748	4800.00	-0.65	819.94	-0.65	327.97	-0.65	163.99
		5	17,22,27,32	933,364	4800.00	-0.67	785.13	0.76	314.05	0.76	157.03
300	225	1	18,24,30,36	968,258	2400.00	0.89	636.16	0.89	254.46	0.89	127.23
		2	19,25,31,37	994,251	2400.00	1.40	645.35	1.46	258.14	1.46	129.07
		3	18,24,30,36	988,659	2400.00	1.32	626.58	1.32	250.63	1.38	125.32
		4	20,26,32,38	1,014,892	2400.00	0.27	691.89	0.27	276.76	1.46	138.38
		5	19,25,31,37	1,009,938	2400.00	0.81	660.14	0.81	264.06	0.81	132.03
300	150	1	20,26,32,38	997,632	1563.64	1.22	473.61	1.22	189.44	1.22	94.72
		2	20,26,32,38	1,012,396	321.45	1.05	468.28	1.05	187.31	1.05	93.66
		3	18,24,30,36	981,005	2400.00	0.80	434.78	0.80	173.91	0.80	86.96
		4	20,26,32,38	999,337	2203.75	2.25	462.67	2.25	185.07	2.25	92.53
		5	20,26,32,38	1,003,298	2400.00	1.65	456.61	1.65	182.64	1.77	91.32
400	400	1	22,29,36,43	1,291,258	4800.00	0.28	1934.86	0.28	773.94	0.28	386.97
		2	22,30,38,46	1,260,934	4800.00	-2.87	2057.91	-2.87	823.16	-2.87	411.58
		3	23,30,37,44	1,267,927	4800.00	-1.27	2006.38	-1.27	802.55	-1.27	401.28
		4	22,29,36,43	1,256,179	4800.00	-0.18	1876.97	-0.18	750.79	-0.18	375.39
		5	22,29,36,43	1,308,762	4800.00	1.71	1858.75	1.71	743.50	1.71	371.75
400	300	1	25,32,39,46	1,320,929	4800.00	1.08	1458.20	1.40	583.28	1.40	291.64
		2	24,33,42,51	1,345,825	4800.00	1.98	1518.67	1.98	607.47	2.23	303.73
		3	25,32,39,46	1,280,708	4800.00	0.79	1460.66	0.79	584.26	0.79	292.13
		4	23,31,39,47	1,289,976	4800.00	0.27	1479.31	0.41	591.72	0.41	295.86
		5	24,32,40,48	1,322,614	4800.00	1.02	1527.20	1.02	610.88	1.02	305.44
400	200	1	25,34,43,52	1,359,595	2400.00	1.93	1015.75	1.93	406.30	1.93	203.15
		2	24,33,42,51	1,324,792	2400.00	0.97	1001.19	0.97	400.47	2.32	200.24
		3	25,34,43,52	1,317,683	2400.00	1.86	1034.02	1.86	413.61	1.86	206.80
		4	25,33,41,49	1,283,177	2400.00	1.24	1087.92	1.77	435.17	1.77	217.58
		5	25,33,41,49	1,319,989	2400.00	1.55	1041.44	1.55	416.57	1.55	208.29

500	500	1	28,37,46,55	1,441,911	4800.00	-1.75	3708.02	-1.75	1483.21	-0.80	741.60
		2	28,37,46,55	1,488,102	4800.00	-2.97	3753.38	-2.97	1501.35	-2.97	750.68
		3	28,37,46,55	1,466,207	4800.00	-2.94	3714.38	-2.18	1485.75	-0.82	742.88
		4	28,37,46,55	1,441,911	4800.00	-1.99	3686.16	-1.99	1474.46	-1.42	737.23
		5	28,37,46,55	1,488,102	4800.00	-3.15	3681.98	-3.15	1472.79	-3.15	736.40
500	375	1	30,40,50,60	1,518,885	4800.00	1.00	2951.53	1.00	1180.61	1.23	590.31
		2	31,41,51,61	1,607,755	4800.00	1.60	3040.44	1.60	1216.17	1.60	608.09
		3	31,41,51,61	1,567,664	4800.00	0.84	3020.78	1.60	1208.31	1.60	604.16
		4	30,40,50,60	1,519,921	4800.00	1.42	2946.63	1.42	1178.65	1.42	589.33
		5	31,41,51,61	1,607,755	4800.00	1.30	3010.58	1.41	1204.23	1.88	602.12
500	250	1	30,40,50,60	1,504,477	2400.00	1.08	1859.08	1.98	743.63	1.98	371.82
		2	31,43,55,67	1,633,786	2400.00	1.00	1960.77	1.46	784.31	1.46	392.15
		3	33,44,55,66	1,611,371	2400.00	1.21	2013.55	1.21	805.42	1.21	402.71
		4	30,40,50,60	1,504,477	2400.00	2.08	1860.39	2.47	744.16	2.47	372.08
		5	31,43,55,67	1,633,786	2400.00	1.18	2005.58	1.20	802.23	1.37	401.12
Average				1,116,606	3136.11	0.54	1311.15	0.72	524.46	0.91	262.23

Table B. 6. Comparison of solution for TS3-2 by closing and opening 1 station in random

						2500 iterations		1000 iterations		500 iterations	
Demand Points	Potential Locations	Data	K_1, K_2, K_3, K_4	Best Objective Function Value	Time	% Gap	Time	% Gap	Time	% Gap	Time
200	200	1	12,16,20,24	622,825	2400.00	0.09	287.53	0.28	115.01	0.28	57.51
		2	12,16,20,24	641,252	2400.00	0.34	265.14	0.34	106.06	0.78	53.03
		3	12,16,20,24	620,333	2400.00	-0.45	262.02	-0.45	104.81	-0.45	52.40
		4	12,16,20,24	636,126	2400.00	0.15	259.06	0.15	103.62	0.27	51.81
		5	13,17,21,25	663,241	2400.00	-0.26	273.72	0.44	109.49	0.44	54.74
200	150	1	12,16,20,24	609,154	2400.00	0.04	194.31	0.04	77.72	0.04	38.86
		2	14,18,22,26	655,741	2400.00	-0.16	220.92	-0.16	88.37	-0.12	44.18
		3	13,17,21,25	633,763	1153.15	0.14	226.95	1.15	90.78	1.15	45.39
		4	14,18,22,26	657,909	1558.18	0.00	222.33	0.00	88.93	0.00	44.47
		5	14,18,22,26	654,576	2400.00	0.00	233.69	0.21	93.47	0.21	46.74
200	100	1	12,16,20,24	603,220	356.12	0.16	139.94	0.90	55.97	0.90	27.99
		2	14,18,22,26	653,031	352.34	0.00	150.78	0.70	60.31	0.95	30.16
		3	13,18,23,28	637,486	60.89	0.01	150.38	0.01	60.15	0.01	30.08
		4	14,18,22,26	642,436	327.85	0.01	151.60	0.09	60.64	0.09	30.32
		5	15,19,23,27	658,956	269.26	0.00	153.75	0.00	61.50	0.00	30.75
300	300	1	18,24,30,36	990,429	4800.00	0.14	781.88	0.14	312.75	0.14	156.38
		2	18,24,30,36	1,024,241	4800.00	-0.37	800.47	-0.37	320.19	-0.37	160.09
		3	17,22,27,32	942,404	4800.00	-1.30	704.59	-1.18	281.84	-1.18	140.92
		4	18,23,28,33	959,748	4800.00	-0.80	761.13	-0.80	304.45	-0.80	152.23
		5	17,22,27,32	933,364	4800.00	-0.98	732.19	-0.55	292.87	0.11	146.44
300	225	1	18,24,30,36	968,258	2400.00	-0.41	587.48	-0.41	234.99	-0.18	117.50
		2	19,25,31,37	994,251	2400.00	0.67	612.31	0.85	244.92	1.55	122.46
		3	18,24,30,36	988,659	2400.00	-0.19	576.58	-0.19	230.63	-0.19	115.32
		4	20,26,32,38	1,014,892	2400.00	-0.03	636.28	0.12	254.51	0.27	127.26
		5	19,25,31,37	1,009,938	2400.00	0.25	615.16	0.25	246.06	0.25	123.03
300	150	1	20,26,32,38	997,632	1563.64	0.35	453.84	0.37	181.54	0.85	90.77
		2	20,26,32,38	1,012,396	321.45	0.42	435.81	0.42	174.32	0.42	87.16
		3	18,24,30,36	981,005	2400.00	0.15	413.72	0.15	165.49	0.15	82.74
		4	20,26,32,38	999,337	2203.75	0.50	423.75	0.50	169.50	0.50	84.75
		5	20,26,32,38	1,003,298	2400.00	0.22	432.09	0.52	172.84	1.20	86.42
400	400	1	22,29,36,43	1,291,258	4800.00	-0.52	1808.80	-0.52	723.52	-0.52	361.76
		2	22,30,38,46	1,260,934	4800.00	-3.76	1864.55	-3.76	745.82	-3.76	372.91
		3	23,30,37,44	1,267,927	4800.00	-1.90	1824.22	-1.82	729.69	-1.82	364.84
		4	22,29,36,43	1,256,179	4800.00	-2.28	1734.41	-1.54	693.76	-0.83	346.88
		5	22,29,36,43	1,308,762	4800.00	-0.07	1728.14	-0.07	691.26	-0.07	345.63
400	300	1	25,32,39,46	1,320,929	4800.00	0.46	1361.63	0.73	544.65	0.73	272.33
		2	24,33,42,51	1,345,825	4800.00	0.44	1414.16	1.16	565.66	1.16	282.83
		3	25,32,39,46	1,280,708	4800.00	-1.09	1379.14	-0.61	551.66	-0.61	275.83
		4	23,31,39,47	1,289,976	4800.00	-1.03	1352.03	-1.03	540.81	-1.03	270.41
		5	24,32,40,48	1,322,614	4800.00	0.02	1411.09	0.04	564.44	0.04	282.22
400	200	1	25,34,43,52	1,359,595	2400.00	0.16	981.05	0.16	392.42	0.16	196.21
		2	24,33,42,51	1,324,792	2400.00	-0.22	951.78	0.33	380.71	0.69	190.36
		3	25,34,43,52	1,317,683	2400.00	0.17	1004.06	0.17	401.62	0.54	200.81
		4	25,33,41,49	1,283,177	2400.00	-0.06	1036.03	-0.06	414.41	0.64	207.21
		5	25,33,41,49	1,319,989	2400.00	0.08	981.06	0.27	392.42	0.27	196.21

500	500	1	28,37,46,55	1,441,911	4800.00	-3.71	3395.66	-3.22	1358.26	-2.70	679.13
		2	28,37,46,55	1,488,102	4800.00	-4.33	3432.98	-4.03	1373.19	-3.86	686.60
		3	28,37,46,55	1,466,207	4800.00	-4.18	3373.84	-3.95	1349.54	-2.75	674.77
		4	28,37,46,55	1,441,911	4800.00	-3.22	3401.75	-3.09	1360.70	-3.09	680.35
		5	28,37,46,55	1,488,102	4800.00	-4.66	3405.39	-4.66	1362.16	-4.35	681.08
500	375	1	30,40,50,60	1,518,885	4800.00	-0.05	2722.38	0.45	1088.95	0.60	544.48
		2	31,41,51,61	1,607,755	4800.00	0.15	2812.88	0.15	1125.15	0.15	562.58
		3	31,41,51,61	1,567,664	4800.00	-0.22	2785.25	-0.16	1114.10	0.04	557.05
		4	30,40,50,60	1,519,921	4800.00	0.60	2699.84	0.62	1079.94	0.90	539.97
		5	31,41,51,61	1,607,755	4800.00	0.03	2784.81	0.23	1113.92	0.57	556.96
500	250	1	30,40,50,60	1,504,477	2400.00	0.21	1756.48	0.21	702.59	0.60	351.30
		2	31,43,55,67	1,633,786	2400.00	0.35	1879.41	0.35	751.76	0.35	375.88
		3	33,44,55,66	1,611,371	2400.00	0.09	1944.66	0.09	777.86	0.09	388.93
		4	30,40,50,60	1,504,477	2400.00	0.01	1771.08	0.55	708.43	0.88	354.22
		5	31,43,55,67	1,633,786	2400.00	-0.09	1923.98	0.15	769.59	0.15	384.80
Average				1,116,606	3136.11	-0.50	1218.03	-0.32	487.21	-0.16	243.61