An Adapted NSGA-II Algorithm for Integrated Timetabling and Bus Packing Problems: a Case of Pilgrims Transportation Problem

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Abstract. Every year Saudi Arabia receives millions of Muslims which come from all over the world to perform religious rituals of Hajj (Pilgrimage) during Hajj seasons. Therefore, planning an efficient transportation system is important to facilitate pilgrims / bus movement between holly cities (Makka, Mina, Mozdalifah and Arafa) especially during peak hours. The planning process of a bus network is complicated. Therefore, we divided it into several sub-problem. The first one is Bin Packing Problem with Compatible Categories (BPPCC) which aims to assign a set of pilgrims to the minimum number of bus as possible according to the nationalities. The second one is the Bus Time Tabling Problem (BTT) in which we determine the departure time of each trip. In this case, we adapted a NSGA-II (Non-dominated Sorting Genetic Algorithm) to solve our multi-objective problem in order to converge as possible to the Pareto front and to find a set of varied solutions all along the front. This research suggests better solutions for stakeholder to consider when planning for pilgrims transportation to overcome the long delays and facilitate smooth transition of pilgrims and minimize the number of buses.

Keywords: Pilgrimage, Saudi Arabia, Bin Packing Problem with compatibility categories, Time Tabling, NSGA-II

1 Introduction

Traffic congestion is a situation that occurs on transport networks as use increases especially during peak hours. It has a number of adverse consequences on both economic, social and environmental dimensions, including longer travel times as well as delay, increased fuel consumption which emit a large amount of pollutants, slow speed level and negatively affect travelers experience. Holy cities include one of the largest mass movements in the world, particularly during

S. Krichen et al. (eds.), *Proceedings of International Conference on Decision Aid and Artificial Intelligence (ICODAI 2024)*, Atlantis Highlights in Intelligent Systems 12,
https://doi.org/10.2991/978-94-6463-654-3_7

Hajj period [1]. Therefore, a large number, of solutions have been proposed to solve pilgrims' transport problem which still a challengeable area of interest that need further research to best accommodate the increasing pilgrims flows. The most used public transportation mode in Saudi Arabia is buses. Hajj consists of the set of ordered steps shown in Figure 1 which illustrates pilgrim movements during the Hajj journey.

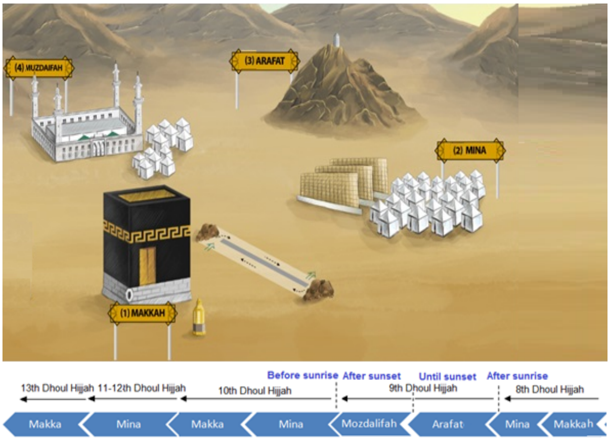

Fig. 1. The most congested area in Hajj and Umra

All pilgrims must start their Hajj journey in Makkah where they perform certain rituals and prayers in the Holy Mosque. Later, most pilgrims move on to stay in pre-assigned camps in the area of Mina from the 8th day until the 9th day of the 12th Hijri month, Dul Hijja. The 9th day is known as the day of Arafat because, on that day, all pilgrims must move from Mina after sunrise to spend the whole day at the holy site of Arafat, also within the Makkah area. After sunset, all pilgrims must move together to the adjacent site of Muzdalifah to spend the night. After sunrise on the 10th day of the Hijri month Dul Hijja, known as the Sacrifice Feast Day, most pilgrims start moving back to their camps in Mina. Three days later they return to Makkah to perform their final rituals and prayers in the Holy Mosque in preparation for their final departure. The collective movement of pilgrims from Arafat to Muzdalifah, and later from Muzdalifah to Mina is called Al-Nafrah phase of the Hajj journey, which are the most congested area. Makkah and the holy sites (Mina, Muzdalifah and Arafat) have fixed surface. They are linked with a limited number of roads. Therefore, severe traffic congestions occur each year between these sites, which result in vehicular trip times that are relatively high. The planning process of a bus network is complicated. Therefore, it is often divided into several subproblems such as line planning, timetable generation, vehicle scheduling. In this paper, we focus on integrating the timetabling (TT) and vehicle scheduling (VS) problems

modeled by a Bus Time tabling problem (BTT) and a Bus scheduling problem (BSc) where the objectives are to maximize the level of service given by the timetable and to minimize the total bus by pilgrims packing and bus scheduling problems. In this case, we adapted a NSGA-II (Non-dominated Sorting Genetic Algorithm) to solve our multi-objective problem in order to converge as possible to the Pareto front and to find a set of varied solutions all along the front. Moreover, we aim to solve this important problem by providing a Decision Support System (DSS) tool for effective decision making in the area of transportation in Saudi Arabia among the airport, Mekkah, Medina, Mina, Muzdulifah and Arafat.
This paper is organized as follows: Firstly, a problem description is presented in Section 2. Secondly, the NSGA-II proposed methodology is introduced in detail in Sections 3. Thirdly, a Decision Support System Architecture is presented in Section 4. Results and Discussion are presented in Section 5 and finally, the conclusion and future work are presented.

2 Related word

Scheduling and timetabling problems have been studied completely but separately. Recently, the problems are combined to solve many real-world applications. Ceder (2001) [2] combined TT and VS problems where the objective is to minimize the fleet size required. The author used headway bounds and an initial frequency in order to avail passenger transfers. The problem is solved by developing a heuristic algorithm and applied to a small examples with up to 4 transfer nodes. An other example of integrating TT and VS is proposed by Chakroborty et al. (2007) [3] which aim to optimize the fleet size using the Genetic algorithm and test results for a 3-line test instance and total scheduling period of 4 hours. In addition, Liu and Shen (2007) [4] proposed an upper level optimizes for the VS problem and a lower level optimizes for TT problem where the first level aims to minimize the fleet size and the second one aims to minimize the total transfer time for passengers. Results are test for up to eight bus lines and three synchronization nodes. In addition, Petersen et al. (2013) [5] proposed a Large Neighborhood Search algorithm to minimize both the costs of vehicles and passenger transfers. A real case of bus service in the Greater Copenhagen area is tested. Moreover, the vital trade-off between the level of service and operating costs is the core issue of PT. Ibarra-Rojas et al. [6] handle this by studying timetabling and vehicle scheduling problems (VSPs). Laporte et al. [7] proposed an approach to timetabling design that addresses the PT network timetabling and scheduling problem. A multi-objective model is formulated by considering the perspectives of users and operators under capacity constraints. Recently, Liu and Ceder (2017) [8] presented a deficit function (DF) based sequential search approach to minimize fleet size and user travel and waiting times. Results are applied to Copenhagen Network data sets with up to 4 unidirectional lines, 4 transfer stops, and one hour of operations. More recently, Fonseca et al. (2018) [9] addressed bi-objective mathematical formulation in order to minimize the passenger transfers and operational costs of the integrated TT and VS. The authors proposed a matheuristic where in each iteration solves the MIP formulation for a sub-problem of TT and VS. The proposed metaheuristic is tested using a realistic case study for the Greater Copenhagen area. Finally, Lubbeche et al. (2019) [10] solved three of public transport planning represented as line planning, timetabling, and vehicle scheduling using an integer linear programming formulation. They used a small size of instances.

3 Problem statement

Planning a bus network system is a complex process, therefore, we have to divide this process into three sub problems: The Problem is defined on a complete multigraph $G = (V, E)$ since there is more than one edge between two nodes where:
- The set of nodes: $V = \{1, \ldots, n\}$ refer to total number of nodes, each node i has a time window $[f_i, l_i]$. For a customer, f_i and l_i are the earliest and latest times to start service.
- The set of edges: $E = \{\{i, j\}\}|i, j \in V\}$ that express the possibility of direct routes between each pair of nodes. Each edge $\{i, j\}$ is weighted by a distance d_{ij}. In this way, bus can flexibly select the travel route to avoid urban congestion. $w_{i,j}$ is the total number of edges between nodes (i, j). For example, $w_{3,5} = 2$ indicates that there are two edges between nodes $(3, 5)$, that is, two existing road connections between them.
1) Bin Packing Problem with Compatible Categories: In this sub problem, the objective is to assign a set of passengers (Pax) to the minimum number of bus as possible while ensuring that the sum of all passengers assigned to a bus does not exceed its capacity C. As result, we try to generate the number of designed bus.
2) Bus Time Tabling (BTT): In this sub problem, Timetabling (TT) is the process of creating a schedule starting from the route network and the desired frequency of service. The result is a set of trips, with the scheduled times at the terminals and major points on the routes.

3.1 The first sub problem: Bin Packing Problem with Compatible Categories

Bin Packing Problem with Compatible Categories is the process of packing a set of items into the minimum number of bin where ensuring that only items from compatible categories are packed together in the same bin without exceeding the bin capacity. The problem is defined as follows:
given a set C=$\{1, 2, \ldots, p\}$ of categories; a set J= $\{1, 2, 3, \ldots, n\}$ of items, each item $j \in J$ weighting $w_j \in \mathbb{Z}^*$ and belonging to a category $G_j \in C$; an infinite number of identical bins of capacity $b \in \mathbb{Z}$; and a compatibility matrix C_p populated with binary elements C^{kt} that equals 1 if category $k \in C$ is compatible with category $l \in C$ and 0 otherwise. Items belonging to categories that are in conflict cannot be assigned to the same bin (i.e. items j and r can't be packed

together if ($C^{G_j G_r} = 0$). We also define subsets $j^k \subset J$, comprising all items $j \in J$ such that $G_j = k, \forall j \in j^k$and assume $b \geqslant w_j \forall j \in J$. The objective of the BPCC is to assign all items to the minimum number of bins while ensuring that the sum of the weights of all items assigned to a bin does not exceed its capacity and that all items assigned to the same bin belong to compatible (i.e., non-conflicting) categories Figure 3 presents a BPCC example solution. The mathematical formulation of the BPP is expressed as follows:

$$Minz \sum_{i=1}^{n} y_i \tag{1}$$

$$\sum_{j \in J} w_j x_{ij} \leqslant b y_i, i = 1, 2, ..., n \tag{2}$$

$$\sum_{i=1}^{n} x_{ij} = 1, j \in J \tag{3}$$

$$y_i, x_{ij}, f_i^k \in \{0, 1\}, \forall i, j \in J, \forall k \in C \tag{4}$$

- The objective function (1) minimizes the total number of the used bins.
- Constraints (2) impose that for each bin and for each time step the total weight of items does not exceed the bin capacity.
- Constraints (3) ensure that each item is packed in exactly one bin.
- Constraints (4) are the binary variables.

3.2 The second sub problem: Timetabling

Timetabling (TT) is the process of creating a schedule starting from the route network and the desired frequency of service. The result is a set of trips, with the scheduled times at the terminals and major points on the routes, the timetable. The TT problem aims at finding "good quality" timetables from the viewpoint of users of the transportation service.

Lines and trips:

Let I represents a set of lines, each line i, ($i \in \{1 \ldots I\}$) is divided into a set of trips denotes by f^i. We will denote by $i(p)$, $p \in \{1, \ldots, f^i\}$, the p^{th} trip of line i. Trip $i(first_s)$ is the first trip of line i in period s. Symmetrically, trip $i(last_s)$ is the last trip of line i in period s.

Nodes

We denote by B a set of all transfer nodes and by B_{ip} a set of nodes from trip p in line i.

Times:

Let S denotes the set of planning periods (morning period , the afternoon period, the night period) and parameter d_s, with $s \in S$, represents the end of planning period s and the beginning of planning period $s+1$. Let f_s^i represents the number of trips of i during period s. Thus, $f^i = \sum_{s \in S} f_s^i$. The travel time of trip $i(p)$ from the initial node (depot) to node b is denoted by t_{ib}^p.

To determine a timetable TT, we need to set the variables X_p^i that correspond to the departure times of each trip $1 \leqslant p \leqslant f^i$ of every line $i \in I$. We define a headway ηs^i the separation between the departure times of consecutive trips of the same line.

Passenger:

We assume that the passenger demand is constant at each planning period for each line and the number of passengers transferring from node bi to line bj are proportional to the bus Capacity C. We would have a given estimated number Pax_s^{bibj} of passengers that transfer from node bi to node bj for each planning period $s \in S$. Based on these assumptions, the actual number of passengers PAX_s^{bibj} that may benefit from a successful transfer of a specific line i (in a planning period s) from node bi to node bj and can be expressed as: $PAX_s^{bibj} = Pax_s^{bibj} + \alpha_s^{bibj}(X_p^i - X_{p-1}^i - \eta s^i)$ where α_s^{bibj} is the number of passengers lost or gained that transfer from node bi to node bj due to headway deviation from the even headway. Since the demand is constant along the planning period, this parameter can be defined as : $\alpha_s^{bibj} = Pax_s^{bibj}/\eta_s^i$. The first objective is to maximize the passenger transfers stated as follows:

$$maximize \quad F_{TT}(X) = \sum_{i \in I} \sum_{bi,bj \in B} \sum_{p=1}^{f^i} PS_{i(p)}^{bibj} \tag{5}$$

subject to

$$\begin{aligned} & d_{s-1} + \tfrac{\eta_s^i}{2} + (p - i(first_s))\eta_s - \delta_s^i \leqslant X_p i \\ & \forall i \in I, S \in S, i(first_s) \leqslant i(last_s) \\ & X_p^i \leqslant d_{s-1} + \tfrac{\eta_s^i}{2} + (p - i(first_s))\eta_s + \delta_s^i \\ & \forall i \in I, S \in S, i(first_s) \leqslant i(last_s) \end{aligned} \tag{6}$$

$$\begin{aligned} & X_p i \geqslant w_p^{ib} - M(1 - Y_{i(p)}^{bibj}) \\ & \forall i \in I, b \in B, 1 \leqslant p \leqslant fi \\ & X_p i \geqslant W_p^{ib} - M(1 - Y_{i(p)}^{bibj}) \\ & \forall i \in I, b \in B, 1 \leqslant p \leqslant fi \end{aligned} \tag{7}$$

$$\begin{aligned} & PAX_s^{bibj} = Pax_s^{bibj} + \alpha_s^{bibj}(X_p^i - X_{p-1}^i - \eta s^i) \\ & \forall i \in I, b \in B, 1 \leqslant p \leqslant fi \end{aligned} \tag{8}$$

$$\begin{aligned} & X_p i \in \mathbb{R}, PAX_s^{bibj} \in \mathbb{R}, \\ & Y_{i(p)}^{bibj} \in \{0, 1\} \forall i \in I, b \in B, 1 \leqslant p \leqslant fi \end{aligned} \tag{9}$$

- The objective function (1) maximizes the level of service given by the timetable.
- Constraints (2) guarantee that each trip is inside its feasible departure time window $[w_p^{ib}, W_p^{ib}]$.
- Constraints (3) allow making a successful transfer $Y_{i(p)}^{bibj} = 1$.
- Constraints (4) represent the passengers that may benefit by the transfer events.

Example:

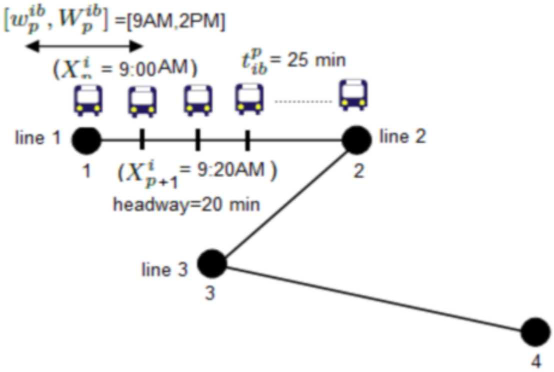

Fig. 2. An example of Time tabling solution

4 The proposed NSGA-II

Genetic Algorithm (GA) is widely applied in solving combinatorial optimization problems especially transportation problems [11] due to its ability to exploit the solution space and to converge to the high quality solutions. Although, most transportation problems has a single-objective function which aims to find a global optimum that always presents the unique solution to be adopted. However, real-life transportation problems requires to be model as a multi-objective function. In this case, we adapted a NSGA-II (Non-dominated Sorting Genetic Algorithm) to solve our multi-objective problem in order to converge as possible to the Pareto front and to find a set of varied solutions all along the front. Indeed, this method is based on dominance in the sense of Pareto as well as the "rank" and "cowding" classification of individuals. The latter presents the order number to classify an individual in relation to others [12]. NSGA-II starts by generating randomly an initial population (Pop) then the population is evaluated using the fitness function (objective functions) and non-dominated rank and crowding distance for each individual are calculated after that genetic operator (Tournament selection, crossover and mutation) are applied to generate the offspring of population ($OPop$) the fitness evaluation is applied again to the set of the $OPop$ and finally an elitist strategy is applied by first combining populations ($Pop + OPop$), second again to the non-dominance and crowding procedure and finally generate new parent population (RPop). The whole process is repeated until reach the maximum number of generation. As result, a set of Pareto optimal solutions (the best non-dominated solutions) are obtained as output. The proposed NSGA-II steps are described in details in the following sub-sections (Algorithm 1).

Algorithm 1 The proposed NSGA-II approach

Begin
for each iteration t **do**
  $R_t = Pop_t \cup Q_t$
  F = fast-non-dominated-sort R_t #
  Calculation of all non-dominated fronts of R_t

  $Pop_t = \varnothing, i = 1$
  while $|Popt + 1| + |F_i| \leqslant N$ **do**
    $t = t + 1$
    Crowding-distance-assignement (F_i) #
    Calculate the crowding distance from the front F_i

    $F_i, \prec n)$ (Sort in descending order using comparison $\prec n$)
    $Pop_{t+1} = Pop_{t+1} \cup F_i[1 : (N - Pop_{t+1}]$ #
    Choose the first $(N - |Pop_{t+1}|)$ best distributed individuals from the front line

    Apply genetic operators (selection, crossover and mutation) to generate a new offspring population Q_{t+1}
  end while
  t=t+1 #
  starting the next generation
end for
END

5 Computational Experiments

Al-Hajj (i.e pilgrimage) is an Islamic event that takes place annually in KSA, where several million pilgrims come to the holy city Makkah and three holy sites for 6 days. The traffic flow in Arabic Saudi during the pilgrimage period is the topic of this study.

5.1 Bus Packing Problem

The number of pilgrims for 2023 is 2.352.122 and 17,000 busses were used to transport pilgrims from Makkah. The capacity of each bus is 50 pilgrims. Pilgrims are assigned to the different available transport buses by countries presented in the Table below: The number of trips needed for each nationality, we observe that we need a total of 47046 trips to transport a total of 2.352.122 pilgrims between holly cities with a total of 17.000 buses. Therefore, the number of trips must be divided into the required interval of time (Time windows) described in the next part.

5.2 Bus Time Tabling Problem

The tests have been performed on 5 real-world bus lines covering 4 major Holly cities (Makkah, Mina, Arafah and Muzdalifah). The 4 Holly cities are connected with more than one edge described in the Figure 9 below. Al-Hajj event in its four holy sites covers around 22 km^2. The traffic density in each road is 5.000

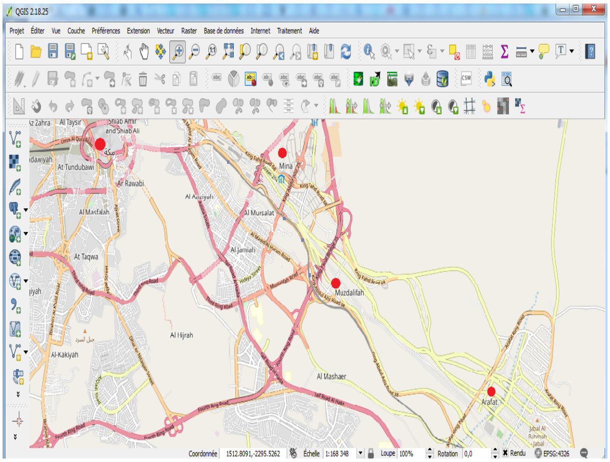

Fig. 3. Holy cities existing roads

veh/h. The transportation between holly cities as seen in Figure 10 must respect the following time window:
- Makkah to Mina $[9am - 11am]$.
- Mina to Arafah $[3:40am - 3pm]$.
- Arafah to Muzdalifah $[4pm - 6pm]$.
- Muzdalifah to Makkah $[2am - 4am]$
- Makkah to Mina $[2am - 4am]$

Table 3, presents the matrix of the average distance between the holy cities (Makkah, Mina, Arafat and Muzdalifah) in more details.

Table 1. Average Distance Matrix between the Holy cities(Km)

$$\begin{pmatrix} & Makkah & Mina & Arafat & Muzdalifah \\ Makkah & 0 & 8 & 14 & 6 \\ Mina & 8 & 0 & 15 & 6.3 \\ Arafat & 14 & 15 & 0 & 10 \\ Mozdalifah & 6 & 6.3 & 10 & 0 \end{pmatrix}$$

Table 4 presents the matrix of the average total travel time between the holy cities (Makkah, Mina, Arafat and Muzdalifah) in more details:

Table 2. Average Total travel time Matrix between the Holy cities(Min)

$$\begin{pmatrix} & Makkah & Mina & Arafat & Muzdalifah \\ Makkah & 0 & 8 & 22 & 11 \\ Mina & 8 & 0 & 21 & 10 \\ Arafat & 23 & 21 & 0 & 13 \\ Mozdalifah & 11 & 10 & 13 & 0 \end{pmatrix}$$

5.3 Results Analyse

The proposed NSGA-II solution approach was implemented using Java Language version 7. All experiments were performed on a PC equipped with Intel (R) Core (TM) i3-4005U CPU with 4 GB (gigabytes) of RAM under Microsoft Windows 7. We generate 10 instances for each instance and a total 40 instances to analyse our solution approach for BTT and BVS. Table 11 details the instance names, types and their parameters. Table 12 reports the computational time (CPU time in seconds) and a number of solutions in the Pareto Frontier (PF) for each one of the proposed instances.

Table 3. Instances types and parameters

Instances	Time Horizon T(hh:mm)	Lines	Nodes	Headway(min)
Hajj1	[9 am - 11 am]	8	2	20 min
Hajj2	[3 : 40am - 3pm]	3	2	60 (1h)
Hajj3	[4pm - 6pm]	3	2	30 min
Hajj4	[2am - 4:05am]	3	2	25 min

Table 4. Computational results obtained by NSGA-II

Instance	**P_1 :[09:00am-11:00am]**		**P_2 :[03:40am-02:40pm]**		**P_3 :[04:00pm-06:00pm]**		**P_4 :[02:00am-04:05am]**	
	CPU	PF	CPU	PF	CPU	PF	CPU	PF
1	284,83	1	9067,68	4	7,83	1	61,98	1
2	123,25	1	4262,78	2	15,53	1	187,531	2
3	192,34	1	5098,78	3	14,35	1	76	1
4	190,79	1	10441,97	**5***	44,46	2	152,495	2
5	132,91	**2***	5081,74	3	133,4	**3***	69,665	1
6	152,74	1	6680,26	3	18,37	1	3742,255	**2***
7	546,61	1	5,084	2	24,51	2	93,15	1
8	560,19	1	4735,76	3	20,81	1	9517,85	2
9	925,59	2	9,021	2	80,98	1	2040,32	2
10	978,84	1	7950,06	3	8,29	1	96,34	1

Based on the results reported in Table 5.12, we conclude that the NSGA-II provides promising results as it could achieve 50% of instance with an optimal solution. Accordingly, the BTT can provide a high level of service using a fixed number of buses. Moreover, our NSGA-II can perform the optimization for the two problems BTT and BBS at the same time.

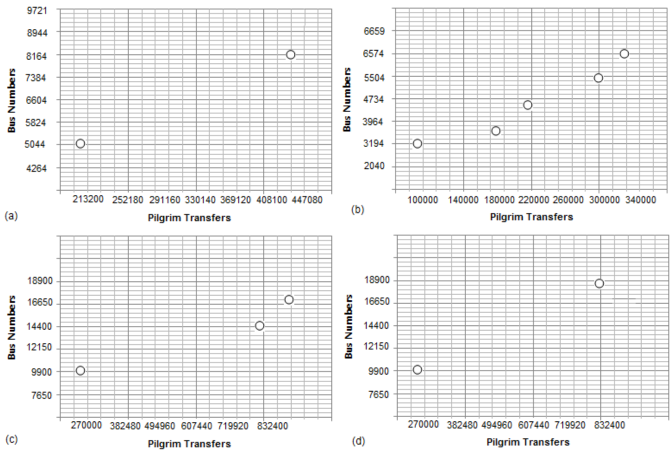

Fig. 4. Pareto Front for each Time Horizon with variant headway time: (a) PF of P_1, (b) PF of P_2, (c) PF of P_3, (d) PF of P_4.

In Table 5.12, we perform numerical results and we mark instances with largest PF with Bold and a star. According to Table 5.12 Figure 14 (a) illustrates the PF of instance with a short headway time of Time Horizon P_1= [9 am - 11 am] equal to 20 min. In this case, we gain more than 200000 pilgrims with 3200 more buses which present 9% of the total number of pilgrims. In addition, Figure 14 (d) presents also a short headway time of Time Horizon P_4= [2am - 4:05am] equal to 25 min. The example shows a good benefit of 600000 with 9000 more buses. Moreover, with a higher headway of 30 min in the Time Horizon P_3= [4pm - 6pm], Figure 14 (c) reports results of instance 6 which perform to three comparable solution. As result, with additional 9000 more buses we can benefit of 600000 more pilgrims. This graphs can be a good support to better decision-making.

Figure 14 (b) gives an illustrative example of instance 4 which plot the higher headway of 60 min (1 h) as result this leads to the best PF equal to five incomparable solutions. These results show clearly that the PF do not convex, thus we can see the performance of our NSGA-II for solving both BTT and BS problems. In fact, the following general results can clearly show the more the headway time increases, the more Pareto optimal points can be generated.

6 Conclusion

In this paper, we study the Bus Time tabling problem (BTT) and Bus Timetabling where the objectives are maximize the level of service given by the timetable and minimise the total bus by packing and scheduling problems.
In this case, we adapted a NSGA-II (Non-dominated Sorting Genetic Algorithm) to solve our multi-objective problem in order to converge as possible to the Pareto front and to find a set of varied solutions all along the front. Furthermore, the proposed solution may be very effective in assisting Hajj authorities to determine the optimal routes with minimum waiting time and minimum total travel time especially when the number of Hajj pilgrims will be increased to rise to 4- 5 million by 2024. For future work, the problem could be extended to cover more operational constraints: such as, cost, number of bus, Time windows, ... We do recommend that a special attention should be given to the transport using bus traveled between the holy cities. In addition, augment the capacity of the read to guarantee the safety of pilgrims during crowded and emergency situations.

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