Reactive Operating Schedule in Case of a Disaster: Arrival of Unexpected Victims

I. Nouaouri, J-C. Nicolas, D. Jolly

***Abstract*— Disaster like terrorist attack, earthquake, and hurricane, often affect a high number of people. In this case, hospitals must be able to receive injured persons for medical and surgical treatments. A disaster situation is characterized by different disruptions which perturb largely the execution of the established plans. In hospital and more precisely in operating theatres, the decision-makers have to manage these disruptions in time. In this setting, we propose a reactive approach in order to optimize the operating rooms scheduling taking into account disruptions. In this paper we focus on the insertion of unexpected new victim in the pre-established operating schedule. So, we develop an algorithm consists of several integer linear programs. Empirical study shows that a substantial aid is obtained by using the proposed approach in case of disaster.**

***Index Terms*— Integer programming, Disaster response, Disruptions, Reactive schedule.**

I. Introduction

According to the International Federation of Red Cross and Red Crescent Societies, a disaster is defined as an exceptional event which suddenly kills or injures a large number of people. The Centre of Research on the Epidemiology of Disasters in Brussels, Belgium, uses the following definition: "A disaster is a situation or event which overwhelms local capacity, necessitating a request to a national or international level for external assistance". In fact, in such situation, the need for medical and surgical treatments overwhelms hospitals' capabilities. For that reason, different countries impose that their hospitals have plans for emergency preparation and disaster preparedness. For example, in the USA, the Joint Commission on the Accreditation of Healthcare Organizations requires US hospitals to have a disaster management plan (DMP). In other countries, like in France and in Tunisia, state requirements or laws impose each hospital to have a disaster plan so called white plan [13] [14]. In case of a disaster, this plan is sets in motion (response phase) [11].

Hospital has to treat all victims in time. However, in such situation, disruptions can take place, perturbing so the execution of the established plans [16]. The challenge of the operating rooms scheduling in a disaster situation is to take into account disruptions which occur during scheduling time horizon. In fact, some unexpected victims can arrive to the admitting hospital at any time without being even spent by the advanced medical point (example: AZF disaster in Toulouse, France [15]). Furthermore, state of victims can deteriorate or improve, thus reducing or lengthening the latest start date of their surgical care. These unforeseen events disrupt the established scheduling and need to be considered in a reactive way.

In this paper, we handle only the arrival of a new victim to the hospital.

Some studies published in the literature address emergency problems in hospitals in normal working times. Most of them focus on operating theaters [6] [10] [12] [19] which are considered as a bottleneck in the hospital system.

These last years, some works were interested in disaster situations [5] [8] [9] [17] [18]. The optimization of operating theatres has become an important issue. However, all these works do not consider operating schedule in a reactive way.

Several works treating emergency problem, using reactive approach [6] [7], are inspired from studies achieved on reactive problems in industrial application. Such as (1) the insertion of one or several jobs [20] [22], in the pre-established planning, and (2) the scheduling of activities with uncertain length [1] [23].

Our problem is considered as a flow-shop problem already treated in industrial context [2] [3].

Decision-makers have to be able to react quickly and efficiently in order to take into account a new victim who needs surgical treatments. In this paper, we deal with reactive operating schedule in case of a disaster. Our purpose here is to insert a new victim in the operating schedule. To achieve this, we propose a several-stage model in order to minimize disruption effect caused by the arrival of unexpected victim.

In the rest of this paper we first describe the reactive schedule we address. In Section 3 and 4 we present the proposed approach and the problem modelling. In section 5 we discuss implementation and evaluation issues, while in Section 6 we present our conclusions and possible extensions of this work.

II. Problem Description

In case of a disaster, victims are evacuated to an immediate established pre-hospital triage and dispatching structure which is set up near to the damaged zone. This structure guarantees the first aid emergency cares and routes victims to the available hospitals. The triage allows classifying victims according to the urgency of the medical and/or surgical cares they need.

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In this paper, we consider victims that require surgical cares with predefined processing times and different ready dates in the operating theatre. Each victim is characterized by an emergency level which is defined by the latest start date of its surgical care. Therefore, the surgical care must be planned before the vital prognosis of the victim is being overtaken [4] [14]. The extreme emergencies require some immediate emergency cares in the pre-hospital structure. The victims who have first, second and third emergency level, they are evacuated to the nearby admitting hospital. These emergency cases must be treated in the respective delays: 6 hours, 18 hours and 36 hours.

Pre-hospital and triage structure communicates to the hospital via information system [14] [21]; surgical processing time, ready date and emergency level of each victim before its arrival to the hospital.

In hospital, some human and material resources are available. We consider critical resources: surgeons and operating rooms. Surgeons, their number, and ready dates in the operating theatre are detailed in a pre-established emergency planning. Each surgeon is assigned to an operating room. In such situation, all operating rooms are considered to be polyvalent.

Basing on these data, the admitting hospital achieves its predictive program (operating schedule) at $t = t_0$. However, some disruptions can occur at any moment during the execution of this program.

In reaction to a disturbance at $t = t_p$, hospital must be able to respond quickly and efficiently, in order to minimize the involved consequences.

In case of a disaster, time of arrival of victims is widely variable and depends on type, location, transport capacities and site organization [11]. Furthermore, some victims may arrive at hospitals at any time without passing by the pre-hospital, triage and dispatching structure [15]. In this context, we handle the scheduling operating rooms problem while taking into account the arriving of new victim requiring surgical cares. So, we propose a reactive approach.

III. Proposed Approach

We define P_0 pre-established operating schedule at $t = t_0$ (the predictive program). At $t = t_p$ (date of disruption) a new victim is announced by the pre-hospital, triage and dispatching structure or, arrives directly to the hospital.

In order to minimize disruption effect on P_0, we proceed in several stages.

The first one, model (P_1) is stated as follows: given an operating schedule (P_0), tries to insert the new victim in an untapped (vacant) range. (P_1) has to satisfy some constraints such as ready dates of surgeons and latest start date of its surgical care. Surgical processing time of the new victim has to be lower or more equal to one untapped range.

If the new victim cannot be inserted by (P_1), we compute for every operating room s a free margin Δg_s from elementary margins for each victim i, Δ_i.

We define:
N Number of victims;
SD_i the start date of surgical care of victim i,
FD_i the finish date of surgical care of victim i.

$$\Delta g_s = \sum_{i \in s}^{N} \Delta_i \quad \text{(I)}$$

$$\Delta_i = FD\_l_i - FD\_e_i \quad \text{(II)}$$

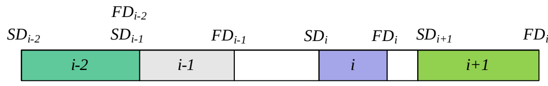

Fig.1. Pre-established schedule.

The latest finish date of surgical care of victim i is given by the equation (III).

$$FD\_l_i = min(dl_i + d_i, SD_{i+1}) \quad \text{(III)}$$

The earliest finish date (date as soon as possible) of surgical care of victim i is given by the equation (IV).

$$FD\_e_i = FD_{i-1} + d_i \quad \text{(IV)}$$

If the new victim cannot be inserted by (P_1), the model (P_2) tries to reschedule, from disruption date, the victims belonging to the operating room which possesses the biggest Δg_s. Current surgical cares won't be interrupted. If the new victim has not been inserted, the model (P_3) tries to reschedule, from disruption date, all surgical cares in all operating rooms. If no solution is found (the new victim has not been inserted) the victim will be reoriented to another hospital.

We present in figure 2, the proposed reactive approach in case of insertion of a new victim in the operating schedule.

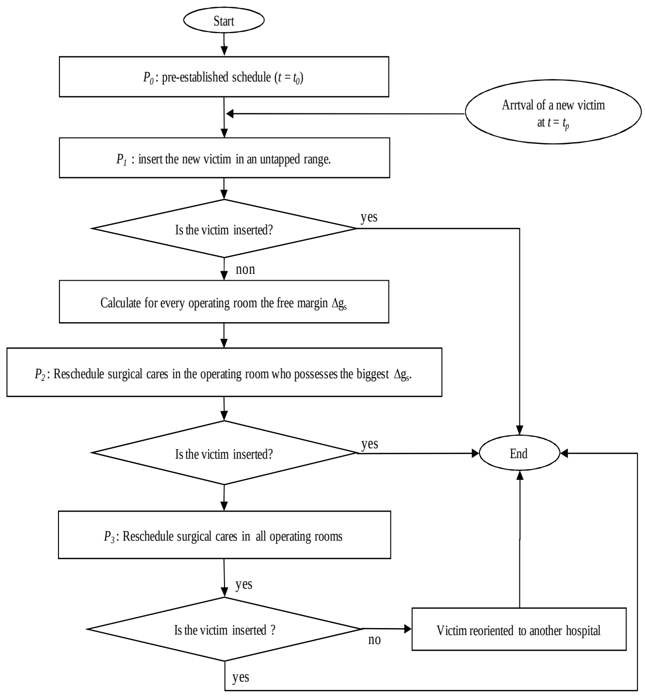

Fig. 2. Reactive approach

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IV. Problem Modelling

We propose a three-stage mathematical model. For each stage, an integer linear programming model is developed using Cplex 6.1 Studio.

Before presenting our models, we will first introduce the following notations:

S Number of operating rooms;
N Number of victims;
H Number of surgeons;
T Time horizon;
d_i Processing time of surgical care of victim i;
dl_i Latest start date of surgical care of victim i;
rv_i Ready date of victim i;
rc_h Ready date of surgeons h with respect to the hospital emergency planning;
M Very big positive number;

We consider in this section, that the number of rooms is equal to the number of surgeons (H=S) and each surgeon is affected to only one operating room.

According to the pre-established schedule, we define:

t_{is} the start date of surgical care of the victim i in the operating rooms s.

y_{ijs} = 1 if the surgical care of the victim j follows the surgical care of the victim i in the same operating room s, 0 otherwise.

t_p Disruption date. It is generated in stochastic way.

NR Number of victims to insert in the operating schedule. In our case, we consider NR = 1.

Besides, we define the following decision variables:

Z_{kts} = 1 if the new victim k is assigned to an operating room s at time t, 0 otherwise.

t_k Start date of surgical care of victim k;

A. Model 1: Insertion of the new victim in an untapped range

In the first stage, we address the optimization problem (P_1). Thus, using the notations listed above, we propose the following integer linear programming:

• The objective function (1) maximizes the number of new victims inserted it in the operating schedule.

$$Maximize \sum_{k}^{NR} \sum_{t_p}^{T} \sum_{s}^{S} Z_{kts} \quad (1)$$

• Constraints (2) ensure that each victim is treated only once during the horizon T.

$$\sum_{t_p}^{T} \sum_{s}^{S} Z_{kts} \leq 1 \qquad \forall k \in \{1..NR\} \quad (2)$$

• Constraints (3) grantee, for every untapped range, one victim is assigned at most at time t.

$$\sum_{t=t_{is}+d_i / t \geq t_p}^{t_{js}} Z_{kts} \leq y_{ijs} \qquad \forall s \in \{1..S\} \ \forall i,j \in \{1..N\} \ \forall k \in \{1..NR\} \quad (3)$$

• Constraints (4) impose to satisfy the emergency level of each new victim.

$$t_k - dl_k \sum_{t_p}^{T} \sum_{s}^{S} Z_{kts} - M(1 - \sum_{t_p}^{T} \sum_{s}^{S} Z_{kts}) \leq 0 \qquad \forall k \in \{1..NR\} \quad (4)$$

• (5) ensures that the duration of surgical care of a new victim is lower or equal to the duration of the untapped range.

$$t_{js} y_{ijs} - (t_{is} + d_i) y_{ijs} \geq d_k \sum_{t_p}^{T} Z_{kts} \qquad \forall s \in \{1..S\} \quad \forall i,j \in \{1..N\} \quad \forall k \in \{1..NR\} \quad (5)$$

• (6) and (7) verify that surgical care can be realized only when victim and surgeon are present in the hospital.

$$t_k + M(1 - \sum_{t_p}^{T} \sum_{s}^{S} Z_{kts}) \geq rv_k \qquad \forall k \in \{1..NR\} \quad (6)$$

$$t_k - rc_s \sum_{t=t_p}^{T} Z_{kts} - M(1 - \sum_{t=t_p}^{T} Z_{kts}) \geq 0 \qquad \forall s \in \{1..S\} \quad \forall k \in \{1..NR\} \quad (7)$$

• (8) ensures that surgical care of the new victim cannot be inserted before disruption date t_p.

$$t_k + M(1 - \sum_{t_p}^{T} \sum_{s}^{S} Z_{kts}) \geq t_p \qquad \forall k \in \{1..NR\} \quad (8)$$

• Constraints (9) ensure that every victim k is assigned to an untapped range.

$$(t_{is} + d_i) y_{ijs} \sum_{t_p}^{T} Z_{kts} \leq t_k \leq t_{js} y_{ijs} \sum_{t_p}^{T} Z_{kts} \qquad \forall s \in \{1..S\} \quad \forall k \in \{1..NR\} \ \forall i,j \in \{1..N\} \quad (9)$$

• Contraints (10) give the start dates of surgical cares.

$$t_k = \sum_{t_p}^{T} \sum_{s}^{S} t.Z_{kts} + (1 - \sum_{t_p}^{T} \sum_{s}^{S} Z_{kts}) M \qquad \forall k \in \{1..NR\} \quad (10)$$

• Constraints (11) ensure the integrality of the variables.

$$Z_{kts} = \{0,1\} \qquad \forall k \in \{1..NR\} \ \forall t \in \{t_p..T\} \ \ \forall s \in \{1..S\} \quad (11)$$

If the new victim has not been inserted, we go to the model (P_2).

B. Model 2: Reschedule surgical cares in the operating room which possesses the biggest free margin Δg_s

Before solving this problem, we have to compute A_s the date from which operating room s (surgeon h) is available after t_p. So it is possible to compute the next availability date of operating room possessing the biggest margin. The room s as well as the surgeon h are known.

The mathematical formulation of this combinatorial optimization problem (P_2) is given by the following linear 0-1 integer program.

W set of waiting victims (including the new victim) for surgical cares.

The decision variables are defined as follow:

X_{its} = 1 if the victim i is assigned to an operating room s at time t, 0 otherwise.

t_i Start date of surgical care of victim i;

- The objective function (12) maximizes the number of treated victims in the operating room s after the disruption date t_p.

$$Maximize \sum_{i}^{W} \sum_{t=t_p}^{T} X_{its} \quad (12)$$

- Constraints (13) ensure that each victim is treated only once during the horizon T

$$\sum_{t=t_p}^{T} X_{its} \leq 1 \qquad \forall i \in W \quad (13)$$

- Constraints (14) grantee that one victim at most is assigned at date t in the operating room s.

$$\sum_{i}^{W} X_{its} \leq 1 \qquad \forall t \in \{t_p..T\} \quad (14)$$

- Constraints (15) impose to satisfy the emergency level of each victim.

$$t_i - dl_i \sum_{t=t_p}^{T} X_{its} - M\,(1 - \sum_{t=t_p}^{T} X_{its}) \leq 0 \qquad \forall i \in W \quad (15)$$

- (16) and (17) verify that surgical care are realized only when victim and surgeon are present in the hospital.

$$t_i + M\,(1 - \sum_{t_p}^{T} X_{its}) \geq rv_i \qquad \forall i \in W \quad (16)$$

$$t_i - rc_s \sum_{t=t_p}^{T} X_{its} - M\,(1 - \sum_{t=t_p}^{T} X_{its}) \geq 0 \qquad \forall i \in W \quad (17)$$

- Constraints (18) verify the availability of the operating room s after the disruption date.

$$t_i \geq A_s . X_{its} - M\,(1 - \sum_{t_p}^{T} X_{its}) \qquad \forall i \in W \quad (18)$$

- Constraints (19a), (19b) and (20) are disjunctive precedence constraints.

$$\sum_{j \neq i}^{W} y_{ijs} \leq 1 \qquad \forall i \in W \quad (19a)$$

$$\sum_{j \neq i}^{W} y_{jis} \leq 1 \qquad \forall i \in W \quad (19b)$$

$$\sum_{i}^{W} \sum_{j \neq i}^{W} y_{jis} = \sum_{i}^{W} \sum_{t=t_p}^{T} X_{its} - 1 \quad (20)$$

- Equations (21) give the start dates of surgical cares.

$$t_i = \sum_{t_p}^{T} t.X_{its} + (1 - \sum_{t_p}^{T} t.X_{its})M \qquad \forall i \in W \quad (21)$$

- Constraints (22) impose no overlapping between two successive cares made in same operating room.

$$t_j \geq t_i + y_{ijs} d_i - M\,(1 - y_{ijs}) \qquad \forall i, j \in W \quad (22)$$

- Constraints (23) and (24) ensure the integrality of the variables.

$$X_{its} = \{0,1\} \qquad \forall i \in W \qquad \forall t \in \{t_p..T\} \quad (23)$$

$$y_{ijs} = \{0,1\} \qquad \forall i, j \in W \quad (24)$$

If the new victim has not been inserted, we go to the model (P_3).

C. Model 3: Reschedule surgical cares in all operating rooms

The objective function (25) maximizes the number of treated victims in all operating rooms.

$$Maximize \sum_{i}^{W} \sum_{t=t_p}^{T} \sum_{s}^{S} X_{its} \quad (25)$$

Under the same constraints used for model 2 taking into account all operating rooms.
For example constraints (2) and (3) become (26) and (27):

$$\sum_{t=tp}^{T} \sum_{s}^{S} X_{its} \leq 1 \qquad \forall i \in W \quad (26)$$

$$\sum_{i}^{W} X_{its} \leq 1 \qquad \forall t \in \{t_p..T\} \quad \forall s \in \{1..S\} \quad (27)$$

V. Computational Experiments

In this section, we present the realized computational experiments using the Cplex solver. We run programs on a Cluster composed of 6 workstations Bixeon® of 3.00 GHz processor and 2-4 Go RAM. We evaluate the performances of the proposed reactive models with different scenarios described on the following.

A. Problem tests

When we consider different scenarios, we take into account uncertain events [6].

Different disaster situations are considered by varying the number of victims (N=25, 50 and 70) and the duration of surgical cares (given between 30 minutes and 2 hours). Moreover 10 staffs are available with different ready dates ($R = (r_1,\ldots r_C)$, C = 10) according to the hospital emergency planning (table 1). The instance label *PN.S.R* means the problem P involves N victims, S operating rooms and ready dates R of staffs.

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Tab. 1. Ready dates of surgical staffs according to hospital emergency planning

R	rc_1(mn)	rc_2(mn)	rc_3(mn)	rc_4(mn)	rc_5(mn)	rc_6(mn)	rc_7(mn)	rc_8(mn)	rc_9(mn)	rc_{10}(mn)
R_1	0	0	0	30	30	30	60	60	120	120
R_2	0	0	0	30	30	30	60	60	60	120
R_3	0	0	0	30	30	60	60	60	120	120
R_4	0	0	30	30	30	60	60	60	120	120
R_5	0	0	30	30	60	60	60	120	120	120

For example *P70.10.R*$_3$ denotes a problem of 70 victims and 10 staffs which ready dates in minutes (mn) are given by R_3, thus $rc_1 = 0$, $rc_2 = 0$, $rc_3 = 0$, $rc_4 = 30$, $rc_5 = 30$, $rc_6 = 60$, $rc_7 = 60$, $rc_8 = 60$, $rc_9 = 120$, $rc_{10} = 120$. In this paper we consider the following instances (table 2).

Tab. 2. Proposed instances

N	Instances
25	P25.4.R$_1$
	P25.6.R$_3$
	P25.6.R$_5$
50	P50.4.R$_1$
	P50.6.R$_3$
	P50.8.R$_3$
70	P70.4.R$_1$
	P70.6.R$_3$
	P70.10.R

For each instance, we generate a predictive program P_0 (pre-established operating schedule) [16]. We apply for every instance 20 scenarios by inserting a new victim requiring surgical cares in the operating schedule. One scenario is characterized by the ready date, the processing time and the emergency level of the new victim. The computational experiments are performed while fixing the time horizon $T = \max_{i=1,\dots,N} (dl_i + d_i)$.

Indeed, after this date, no victim can be treated. T is composed of elementary periods.

B. Results

In order to assess the performance of the proposed approach, we compute for each scenario, the rate of insertion of new victims in the operating schedule (*V.I (%)*).We also compute, the percentage of cases for which disruptions are treated and resolute by the program P_k (*V.I.P*$_k$ *(%)*).

$$V.I(\%) = \frac{\sum_j Inserted \ \ victim \ j}{\sum_i New \ victim \ i} \qquad \text{(V)}$$

$$V.I.P_k(\%) = \frac{\sum_j New \ victim \ j \ inserted \ by \ the \ model \ p_k}{\sum_i New \ victim \ i} \qquad \text{(VI)}$$

Scenarios are generated in a stochastic way. We note Sc_j the scenario j.

The results presented in Tables 3 are obtained by solving Model 1 (P_1), Model 2 (P_2) and Model 3 (P_3). We report for each instance the rate of insertion of new victims in the operating schedule (*V.I (%)*), the percentage of cases for which disruptions are treated and resolved by the program P_k (*V.I.P*$_k$ *(%)*), the minimum CPU time (*Tmin*) and the maximum CPU time (*Tmax*). For each instance, we compute *TM (%)* the mean occupancy rate of operating rooms for pre-established operating schedule.

$$TM(\%) = \frac{\sum_{i=1}^{N} d_i}{C_{max}.S} \qquad \text{(VII)}$$

C_{max} is the Makespan given by the pre-established operating schedule.

Tab. 3. Numerical results

Instances	V.I (%)	V.I.P$_1$(%)	V.I.P$_2$(%)	V.I.P$_3$(%)	CPU time		TM(%)
					Tmin (s)	Tmax (s)	
P25.4.R$_1$	25	5	10	10	26	295	81.25
P25.6.R$_3$	85	10	40	35	47	352	53.17
P25.6.R$_5$	80	10	40	30	43	281	53.33
P50.4.R$_1$	10	0	0	10	524	682	94.82
P50.6.R$_3$	25	0	0	25	609	752	78.73
P50.8.R$_3$	90	15	40	35	43	350	63.79
P70.4.R$_1$	15	0	0	15	869	973	98.30
P70.6.R$_3$	35	0	5	30	826	1239	85.55
P70.10.R$_3$	70	5	25	40	76	1120	59.41

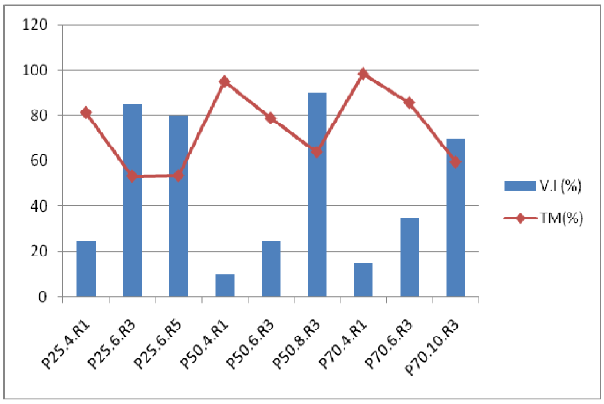

Fig. 3. Percentage of treated cases per instance

The proposed approach has allowed inserting new victims in 48% of cases. The solution is obtained between 26 seconds (minimum) and 21 minutes (maximum).

Table 3 shows that the rate of insertion of new victims varies according to the rate of the mean occupancy rate of operating rooms for pre-established operating schedule (*TM (%)*) (example: *V.I (%)* = 25 for *TM (%)* =81.25 (*P25.4.R*$_1$) beside *V.I (%)* = 85 for *TM (%)* =53.17 (*P25.6.R*$_3$)). In most cases, new victims are inserted by using rescheduling model ((P_2) and (P_3)) (example: in case of *P70.10.R*$_3$, *V.I.P*$_2$(%) = 25 and *V.I.P*$_3$(%) =40). In fact, reschedule models give good results.

Figure 3 shows when the capacity increases (the mean occupancy rate is low) the rate of insertion of new victims is much important.

VI. Conclusion

In this paper, we have addressed a reactive approach in case of a disaster in order to optimize the operating rooms scheduling taking into account disruptions: insertion of a new victim in the established operating schedule. The proposed approach is based on a three-stage integer linear programming model.

The first model tries to insert the new victim in an untapped range. If the victim cannot be inserted, the second model reschedules, from disruption date, the victims belonging to the operating room that possesses the biggest free margin. If the new victim has not been inserted, the third model reschedules all surgical cares in all operating rooms. If no solution is founded the victim will be reoriented to another hospital.

The proposed Heuristic allows hospital to decide in a short time how to take into account a new victim in the operating rooms scheduling, and so to treat a maximum of victims (save the maximum of human life). Another interesting advantage of this approach is that it tries to resolve the problem in three stages in order to minimize disruption effect on operating schedule.

The execution time is relatively long in several cases, which reduces the chance for some victims to be treated in time.

This approach has been tested on different disaster situations with various scenarios. Further research works should focus on decreasing execution time e by improving the proposed approach and dealing with auxiliary services such as hospital beds and analysis laboratory.

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