An optimization model for scheduling emergency operations with multiple teams

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Abstract

Post-disaster emergency operations are often chaotic and complex. In most cases, efficiently assigning and scheduling multiple teams of resources are essential for quick and effective disaster relief. Our ongoing research has identified numerous heuristics and mathematical models for resource scheduling, of which only a few incorporate synchronization and optimization of multi-team resource scheduling contexts. This paper presents a novel mixed integer linear programming model to minimize the relief operation completion times required for all incidents by optimally assigning and scheduling various teams of non-expendable resources. Key parameters of the model include: number of incidents, severity level of each incident, number of relief teams of non-expendable resources, type and capability of relief teams, resource requirements at each incident, travel times, process times and release times. Our primary evaluation of the model considered a case study simulation of resource scheduling for some hypothetical fire emergency operations in a central district of the Melbourne metropolitan area. The results are encouraging for practical applications in potential emergency operation management.

Keywords
Emergency operation, Resource scheduling, Optimization, Synchronization

1. Introduction

Emergency operations management during natural or other disasters is often a complex challenge, which involves numerous individuals and organizations as well as diverse chaos, priorities and limitations. Failures to assign relevant resources sufficiently in a timely manner may worsen the disaster impacts and escalate casualties (Rolland, Patterson, Ward, and Dodin, 2010). Our ongoing research revealed that several practices adopt discrete makeshift approaches to coordinate the emergency tasks of recovery responses for disaster impacts. One of the complex decisions in the emergency operation management during the post-disaster response phase is how to swiftly assign and schedule multiple teams of non-expendable resources (e.g. rescue units, and volunteers) to the emergency tasks.
Our literature review revealed an array of studies on emergency operation management (Anaya-Arenas, Renaud, and Ruiz, 2014; Caunhye, Nie, and Pokharel, 2012; Galindo and Batta, 2013; Özdamar and Ertem, 2015). However, there is only limited research on assigning and scheduling various teams of non-expendable resources according to severity levels of emergency disaster relief works. For example, Falasca and Zobel (2012) and Lassiter, Khademi, and Taaffe (2015) introduced cost objective integer programming models for allocating and scheduling volunteers for disaster emergency operations. The time-based objective optimization problem was considered by Felix Wex, Schryen, Feuerriegel, and Neumann (2014), who proposed a non-linear programming model with a set of heuristics to allocate and schedule rescue units to minimize the completion time of incidents as per weighted consideration of

severity levels. Only a few studies have considered that each incident require multiple teams of resources and synchronizing the emergency operations according to their availability. For example, Wex, Schryen, and Neumann (2013) and Schryen, Rauchecker, and Comes (2015) developed non-linear mathematical models for assigning and scheduling rescue units to incidents, which take into account the fact that each incident may require a single rescue unit or a collaboration of rescue units may be needed for each incident. Still, both these models include certain heuristics to solve and compare the solution with some practice outcomes.

This paper presents a novel mixed integer linear programming model to minimize the completion times of emergency relief operations at all incidents/ demand points by optimally synchronizing assignment and scheduling of various teams. This model can be useful for decision makers seeking to optimize the relief operation completion times by:

(1) effectively considering: (a) simultaneous incidents with different severity levels, (b) availability of various teams with different capability; and
(2) efficiently assigning and scheduling multiple teams of non-expendable resources with optimal synchronization to address: (a) diverse demands at different incidents or demand points/ locations, (b) different sources/ base station locations (for teams) and travel times.

2. Model development

Primarily, our model development considered that the problem of the disaster response situation is deterministic/ static. Figure 1 portrays a set of incidents. Furthermore, we examined the disaster response situation with scarce resources in which the incidents that need to be served by multiple teams of non-expendable resources are much higher than the availability of teams. There is a given processing time for each incident once the relief operation for specific point starts. The processing time varies for each incident and depends on each team of non-expendable resources (each team has a unique processing time to process each incident). Similarly, transportation time for teams is varied and depends on each team. When the process for the incident has been completed, the teams are released for the next incident on their route. For the objective function, we try to minimize the total weighted completion times over all incidents. The weighted factor depends on the severity level of damage and the total number of casualties that require relief on each incident. Hence, synchronization of the teams of non-expendable resource during the disaster response is required to lessen the incident's completion time and delay on the releif required on each incident. In addition, the following assumptions are considered:

- Different teams such as medical units, fire brigades, and volunteers (e.g. Victoria State Emergency Service team) are available for emergency operations. The size and capabilities of each team may be different.
- The demand at each incident may be different.
- Each incident may require different teams. However, an incident cannot request more than one team of the same type. If the demand at a demand point/ location is more than the capability of a single available team of a particular type, then simultaneous occurrence of multiple incidents at the same demand point/ location will be suitably considered by the model
- The service starting time is driven by the latest team arrival time.
- The incident processing after commencement will not be interrupted (non-preemption).

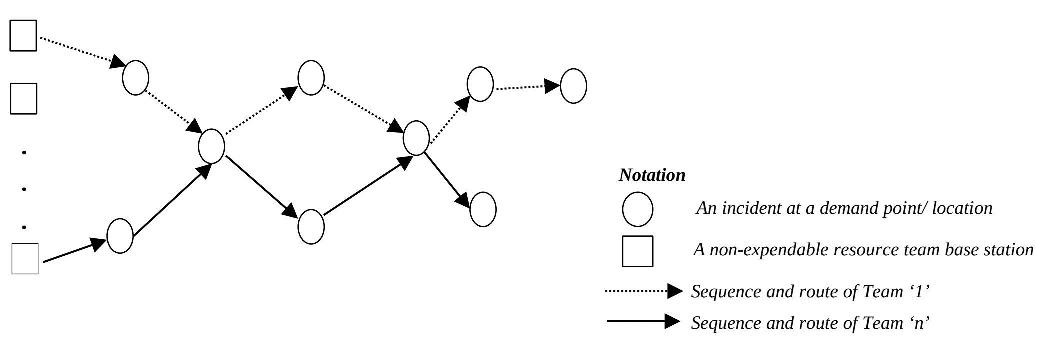

Figure.1 A network conceptualization of emergency relief operations

3. Mathematical formulation

The mixed integer linear programming model described in this paper aims to find the optimal schedule and assignment of resources to incidents. The notations used in this model are consolidated in Table 1.

Table 1. Notations used in the mixed integer linear programming mathematical model

Notation	Description
n	Total number of incidents, with set $i = \{1, \dots, n\}$
t_{ij}^{u}	Travel time required by team u to move from incident i to incident j, for all $i, j \in I, u \in U$
M	Sufficiently large number
U	Total number of teams with set $u = \{1, \dots, U\}$
p_i^u	Time required by each team u to process to process incident i for all $i \in I, u \in U$
r^u	Release time of team u at its depot for all $u \in U$
ω_i	Severity level of incident i
t	Type of team of non-expendable resources (e.g. medical team, fire fighters) with set $t = \{1, \dots, T\}$
α_{it}	Requirement of team type t on each incident, where $\alpha_{it} = 1$ if the incident i requires the team type t; otherwise is zero.
β_{ut}	Capability of team u for skill type t. Where $\beta_{ut} = 1$ if the team u capable for skill type t; otherwise is zero.

The decision variables of the model are:

$X_{ij}^{u} \in \{0,1\}$	Sequence of incidents visit by non-expendable resources. $X_{ij}^{u} = 1$ if incident i is processed by team u immediately before processing incident j;0 otherwise for all $i, j \in I, u \in U$
S_i	Starting time of service at incident i, for all $i \in I$
C_i	Completion time of service at incident i, for all $i \in I$

With these notations and variables, the mathematical model (P1) can be transcribed as below:

$$\text{Min } Z = \sum_{i=1}^{n} \omega_i \times C_i \tag{1}$$

Subject to:

$$\sum_{j=1}^{n+1} \sum_{u=1}^{U} \beta_{ut} \times X_{ij}^{u} = 1 \qquad \forall i \in I;\ \forall t \in T;\ \alpha_{it} \neq 0 \tag{2}$$

$$\sum_{j=1}^{n+1} X_{0(j)}^{u} = 1 \qquad \forall u \in U \tag{3}$$

$$\sum_{u=1}^{U} X_{ij}^{u} + \sum_{u=1}^{U} X_{ji}^{u} \leq 1 \qquad \forall i \in I;\ \forall j \in J \tag{4}$$

$$\sum_{i=0}^{n} X_{il}^{u} - \sum_{j=1}^{n+1} X_{lj}^{u} = 0 \qquad \forall l \in I;\ \forall u \in U \tag{5}$$

$$X_{ij}^{u} = 0 \qquad \forall i \in I;\ \forall j \in J;\ \forall u \in U;\ i = j \tag{6}$$

$$S_i + p_i^u + t_{ij}^u \leq S_j + M \times \left(1 - X_{ij}^{u}\right) \qquad \forall i \in I;\ \forall j \in J;\ \forall u \in U \tag{7}$$

$$C_i \geq S_i + (p_i^u \times X_{ij}^{u}) \qquad \forall i \in I;\ \forall j \in J;\ \forall u \in U \tag{8}$$

$S_i \geq 0 \quad \forall i \in I \quad (9)$

$X_{ij}^u \in \{0,1\} \quad \forall i \in I ; \forall j \in J; \forall u \in U \quad (10)$

In this model, the objective function (1) is to minimize the weighted sum of completion times over all incidents. The constraint sets (2) – (6) relate to finding the optimal sequence of incidents visited by teams of non-expendable resources. For each team, two milestones are considered as the starting and end points (given by 0 for starting point and $n+1$ for ending). The processing time for starting point is equal to release time ($P_0^u = r^u$) and for the ending point is zero ($P_{n+1}^u = 0$).

Regarding the transportation time, each team of non-expendable resource needs a specific t_{0j}^u to arrive to particular incident j from its starting point. For all teams of non-expendable resources, $t_{i\,n+1}^u = 0$. Constraint (2) ensures that one relevant succeeding incident j can be processed after completing the operations of a particular demand point i by a team u. Constraint (3) ensures that each team u starts to process incidents from a base station/ depot (incident 0). Constraint (4) eliminates loop in processing of incidents by each team. Constraint (5) guarantees that if an instant predecessor is available for each incident, it should be an immediate successor for that unless it will be the last incident (incident $n+1$). Constraint (6) eliminates the establishment of any reflection precedence relationship. Constraint (7) ensures that the starting time of processing of each incident cannot be earlier than the earliest arrival time of the teams of non-expendable resources. Constraint (8) calculates the completion time of the entire operation at each incident. Constraints (9) and (10) define the domains of variables C_i, S_i and X_{ij}^u.

4. Illustrative example, results, and discussion

To evaluate the model, a simulated case study of a hypothetical fire emergency scenario in the Melbourne Metropolitan Fire Brigade (MFB) central district has been considered. It aims at demonstrating potential applicability of the model in a practical disaster emergency situation. All information has been randomly generated due to the unavailability of real data. We have considered a simultaneous occurrence of multiple fire emergencies in the case study region. Furthermore, the case study assumed the emergency management has following resources and demand points: (a) two medical teams, (b) two fire fighter teams and (c) 15 simultaneous incidents. Also, we have considered that the Royal Melbourne Hospital and MFB Station No.1 as the primary depot for medical teams and fire brigade teams respectively. The topology and route data such as road network, location of hospital and MFB station have been retrieved from the Victorian Government Open data[1]. Figure 2 illustrates the location of nodes in the Central district of Melbourne. The shortest travel distance between nodes with average speed of 25 km/h is considered as the basis for computing the travel times of resources between nodes. Tables 2 and 3 provide further details of the case. The model was solved by the IBM ILOG CPLEX 12.6 solver and a summary of the obtained solution is portrayed in Figure 2. The results indicate that the model has successfully generated the optimal scheduling plan for assigning and scheduling multiple teams of non-expendable resources for emergency operations. In this case study evaluation, the objective function of the model is 58.53 and the longest path was completed at 3.30 hours. The longest path was completed at incident no.14. The details of starting and completion time of operation in each incident are consolidated in Table 4. For instance, the medical team 1 starts the relief operation from incident 7, then it passes to incident 10 and then finished the relief operation at incident 12. Likewise, the fire fighter team 1 starts the relief operation at incident 15, then passes through incidents 6-12-4-3 and finally finishes the operation at incident 14. The optimal team routes are portrayed in Figure 2.

Table 2. Parameters of case study for evaluationg the model

Input Parameters	Value, range or distribution
The total number of incidents (n)	15
The total number of team of non-expendable resources (u)	4
Processing time of each incident (P_i) (in hours)	Uniform (0,1)
Teams release time from the base (r^u)(in hours)	Uniform (0,1)
Severity level (factor of destruction)incidents (W_i)	Uniform (1,6)

[1] https://www.data.vic.gov.au/

Table 3. Example inputs of case study for model evaluation

No.	Severity level	Medical unit requirement (α_{it})	Fire fighter requirement (α_{it})	Processing time for medical team 1	Processing time for medical team 2	Processing time for fire fighter team 1	Processing time for fire fighter team 2
	Wi	t=1	t=2	Pi1	Pi2	Pi3	Pi4
1	3	1	0	0.4	0.1	0.0	0.0
2	1	1	1	0.4	0.1	0.3	0.2
3	3	0	1	0.0	0.0	0.6	0.7
4	6	1	1	0.8	0.6	0.5	0.9
5	1	0	1	0.0	0.0	0.2	0.0
6	4	0	1	0.0	0.0	0.1	0.7
7	3	1	0	0.1	0.4	0.0	0.0
8	5	0	1	0.0	0.0	1.0	0.9
9	1	0	1	0.0	0.0	0.1	0.1
10	4	1	1	0.2	0.8	0.2	0.1
11	6	1	0	0.7	0.5	0.0	0.0
12	3	1	1	0.1	0.4	0.2	0.6
13	2	1	0	0.4	0.1	0.0	0.0
14	1	0	1	0.0	0.0	0.5	0.6
15	5	0	1	0.0	0.0	0.2	0.4

Table 4. Model solution for the case study scenario

No.	Starting time	Completion time	Weighted completion time
i	S_i	C_i	$W_i C_i$
1	0.86	1.00	3.01
2	2.21	2.43	2.43
3	2.07	2.63	7.88
4	1.36	1.91	11.48
5	1.91	1.92	1.92
6	0.70	0.80	3.19
7	0.17	0.22	0.67
8	0.59	1.51	7.56
9	1.61	1.68	1.68
10	0.40	0.59	2.37
11	0.16	0.68	4.10
12	0.99	1.15	3.45
13	1.17	1.30	2.60
14	2.83	3.30	3.30
15	0.39	0.58	2.90
		Total =	58.53

Our review identified that some ad hoc measures or subjective decisions are being followed in many practices. The optimization model presented in this paper can effectively facilitate optimal scheduling of emergency operations and synchronization of different essential resources for efficient outcomes.

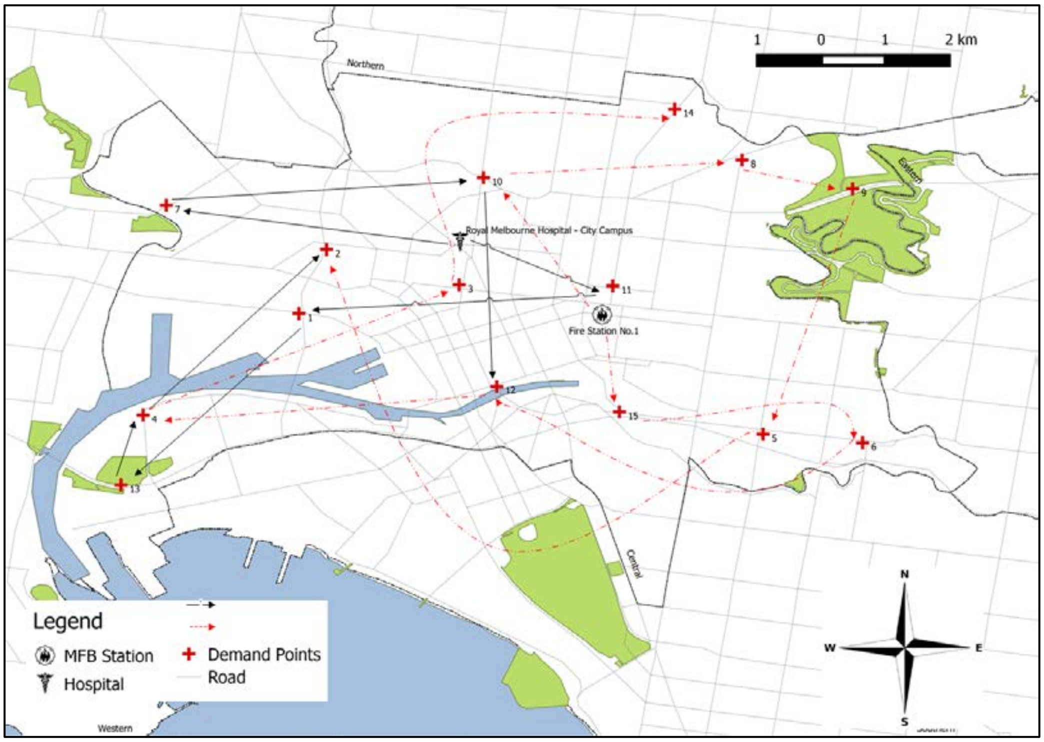

Figure2. Optimal solution of route and sequence for the case study problem

5. Conclusion

This paper presents a novel mixed integer linear programming model is presented to optimally assign and schedule multiple teams of non-expendable resources for emergency operations of disaster response. The proposed model considered the situations that require synchronization of multiple teams. A hypothetically simulated case study in Melbourne's central district area was used for verifying the performance of the model. The results demonstrate the optimal solution with synchronization of resource assignment and scheduling emergency operations. The developed model is capable of potential applications in relevant real emergency operations. Our ongoing research is focused on model constructs including additional aspects such as coordinating various expendable and non-expendable resources, diverse vehicles and capacities. Furthermore, it would be valuable to extend the model with aspects such as uncertainties and dynamic changes of incident resource demands (e.g. emergent/ volatile changes at incidents).

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Biography

Behrooz Bodaghi is currently a full time PhD candidate affiliated with the Centre for Sustainable Infrastructure and the Department of Civil and Construction Engineering at the Swinburne University of Technology, Australia. He earned B.S. in Industrial Engineering from Mazandaran University of Science and Technology, Iran, and a Masters in Industrial Engineering from University Teknologi Malaysia (UTM), Malaysia. His research interests include optimization, scheduling, manufacturing, supply chain management and lean management.

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