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Simulation analysis of fire truck scheduling strategies for fighting oil fires
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Abstract: Emergency response is an important measure to reduce the loss of any major fire and
prevent its escalation. There may be many fire trucks participating in the fire-fighting at the same time,
and the scheduling of them will affect the fire-fighting efficiency and thus, capacity. This work focuses
on the cycle process of fighting fire and refilling water of fire trucks, and analyzes and compares the
scheduling strategies of the fire trucks. The simulation tool eM-plant is utilized to model the fire-fighting
process. In view of the emergency response in relation to a chemical fire accident and to prevent its
escalation, strategies in the analysis consider the allocation of fire trucks according to the distance of
hydrants, the distribution of fire trucks according to the number of fire hydrants, etc. The results of this
paper show that an even distribution of fire trucks leads to a good performance, but can be further
adjusted to find a more optimal strategy. This study provides guidance for fire truck scheduling in case
of emergency response.

Keywords: fire accident; fire-fighting; scheduling strategy; simulation analysis; eM-plant

1. Introduction

Major industrial fire accidents often result in large number of casualties, large property losses,
environmental pollution and serious social impact. Especially, oil fire accidents in the process industry
may escalate to adjacent installations due to flammable characteristics of chemicals, resulting in a chain
of accidents, that is, a domino effect, with huge losses (Mishra et al., 2013; Reniers & Cozzani, 2013;
Tauseef et al., 2018). The emergency response after an accident occurring is therefore very important to
reduce losses and to prevent it from escalating.

In order to improve the efficiency of an emergency response, many studies have been carried out,
involving the scheduling of emergency resources (Li & Li, 2012; Ren et al., 2012; Hawe et al., 2015; Chi

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et al., 2017), emergency response planning (Calixto & Larouvere, 2010; Khayal et al., 2015), path optimization (Pal & Bose, 2009; Zhang 2011; Chai et al., 2018; Usanov et al., 2020), emergency decision-making (Wang et al., 2013; Tang & Shen, 2015; Nassereddine et al., 2019), collaboration (Kapucu et al., 2010; Wang et al., 2014; Zhou & Reniers, 2016a), and so on. Fire trucks and related resources are important fire-fighting resources, and there are few studies on their scheduling in the literature. Jones et al. (2011) proposed methods to search possible time-extended schedules and allocations of fire truck agents. Tian et al. (2016) introduced a multi-objective scheduling approach for forest fires with limited fire engines. Wu et al. (2018) proposed a bi-objective scheduling approach for multi-point forest fires, aiming to optimize the dispatching of a limited number of fire trucks. These studies focused on how to dispatch fire engines to fight fires, rather than on scheduling during the fighting process.

Time is a key indicator of emergency response efficiency. After an accident occurs, the emergency response process should avoid the waste of time as much as possible, and as soon as possible rescue the wounded and protect property, prevent the accident from expanding and extinguish the accident. The time performance related to emergency responses was the subject of many researches. Kang (2007) analyzed the time-based evacuation of a train fire in a subway station under the situation of the inability of the stairway access. The waiting time for evacuation in crowded transport terminals was studied by Chow and Ng (2008) and a waiting time index (WTI) was proposed to measure the congestion at exits. Park et al. (2016) utilized Geographic Information Systems to analyze fire responders' response times. Bandyopadhyay and Singh (2016) studied the emergency response time of a fire emergency service by analyzing the spatial trajectories coming from GPS data and using agent based simulation. Zhou and Reniers (2016b, 2018) used Petri-net based approaches to analyze the emergency response process in the context of escalation prevention in the process industry.

When a major fire accident occurs, the fire department usually sends many firefighters with fire trucks and other facilities or resources to fight the fire. During the fighting process, the way how these facilities are used has a significant impact on the fire-fighting efficiency. For example, in the fire extinguishing process, the fire trucks will consume a lot of water, and they must replenish water to continue the fire-fighting. The replenishment of fire trucks will impact their working. For instance, in April 2013, a fire and explosion accident occurred in a chemical fertilizer plant in the west of Texas, causing 15 fatalities including 12 emergency responders, and more than 260 injured (U.S. CSB, 2016; Willey, 2017). The blast completely destroyed the fertilizer plant and caused damages to more than 150 buildings around it, also resulting in severe economic losses. During the emergency response, the closest hydrant to the fire scene was 450 meters away. The loss of a lot of time to get water seriously influenced the efficiency of fire-fighting. As another example, on August 29, 2011, a fire occurred in a tank storing more than 800 tons of diesel located in PetroChina Company Limited (“PetroChina”) Dalian branch.
After the fire occurred, the fire brigade of PetroChina Dalian Branch was dispatched immediately and they arrived at the scene first, and several minutes later, 19 other fire squadrons of Dalian City arrived at the scene to fight the fire. A total of 73 fire trucks and 316 firefighters went into the fire-fighting. In the process of extinguishing the fire, in addition to the water supply of fire hydrants near the storage tanks, to transport water, several fireboats were used to pump seawater as well as the municipal sprinkler trucks. Fire trucks need to fill water at various filling points.

This work studies the problem of replenishing water of fire trucks in the process of extinguishing an oil fire, which is rarely involved in previous studies. A modeling tool called eM-plant is used in this study to model the fire-fighting process and perform time analysis.

The predecessor of eM-plant is SIMPLE++ (Simulation in Production Logistics and Engineer, which is programmed in C++), which was jointly developed by Aesop, Tecnomatix and KG in 1992. Although many other modeling and simulation analysis methods or tools were used for simulation analysis of emergency responses, such as Petri nets (Kaakai et al., 2007; Shan et al., 2012; Zhou & Reniers, 2018) and Bayesian networks (Musharraf et al., 2016; Chang et al., 2018), eM-plant has its own characteristics and can be easily used for simulation and analysis. Unlike petri nets and Bayesian networks which have strict mathematical representations and are general mathematical modeling tools, eM-plant focuses on physical modeling and it is mainly developed for modeling of production systems. Using pre-built components, such as work site, production line, buffer, storage station, and vehicle, it can establish 2D or even 3D models for various scale plants or production lines, and carry out performance analysis. A user can quickly build his/her model using graphical modeling, application template and basic modeling objects provided by the system.

The eM-pant simulation tool has been extensively used for research on the simulation of assembly lines, path optimization scheduling of AVGs (Automated Guided Vehicles), scheduling of terminal containers and so on (Zhang & He, 2011; Zhou & Xu, 2017; Viharos & Németh, 2018; Ao et al., 2019), but there are only few researches on the scheduling of fire trucks. Because of its graphical working environment, layer structure, modularization, object-oriented modeling and simple model control, eM-plant deserves better/more application in emergency response analysis.

The rest of this paper is organized as follows. Section 2 briefly describes the problems in fire truck scheduling during fire-fighting. In Section 3, the modeling objects of eM-plant and the modeling approach based on eM-plant are introduced. Both example of fighting to a chemical fire illustrating the proposed approach and scheduling strategies of the replenishment of fire trucks, are analyzed in Section 4. Finally, Section 5 draws the conclusion of this work.
2. Scheduling in Fire-fighting

2.1 Emergency response process

An emergency response to a major fire often includes the actions of alarm, emergency command, emergency protection and rescue, information release, maintaining public security, resettlement of victims, fire-fighting, treatment of toxic and harmful substances, recovery after the accident, and so on. This work studies the emergency response process of fire trucks to tank fire, focusing on the process of fire-fighting that after the arrival of fire trucks, they are put into fire-fighting and driven to water supply points to replenish water, and then driven back to the fire site to fight fire. The process is shown in Fig. 1. The analysis and comparison of the fire extinguishing efficiency of fire trucks in different scheduling strategies are carried out.

![Fire-fighting process of fire trucks](image.png)

**Fig. 1 Fire-fighting process of fire trucks**

2.2 Problems in fire truck scheduling

A tank fire often requires a large number of firefighters, as well as fire trucks and other equipment to extinguish it. If they are not effectively organized, it is easy to throw the fire-fighting site into chaos. The smooth fire-fighting process is a key factor to ensure that the whole accident can be extinguished effectively, and the actual emergency response may not be a good guarantee of this key factor, often with the following problems:

i. Replenishment of fire trucks may not be organized. After fire trucks have run out of the fire-fighting resources (e.g. water or foam), the firefighters usually make their own decision to supplement the fire truck.

ii. Supplementary facilities at the fire site may be inadequate. In the case of limited supplementary facilities (e.g. fire hydrants) at the scene of the accident, the waiting time of fire trucks in the process of replenishing may be long.

iii. The low utilization of some supplementary facilities (e.g. fire hydrants). If the distance between
fire hydrants and the fire site is different, it is possible that a large number of fire trucks will go to the nearest water supply point to add water, while for the farther water supply points, fewer fire trucks will go to replenish water, resulting in a low utilization rate of remote fire hydrants.

iv. The effect of fire truck scheduling may be not good. If the replenishment process of fire trucks is not well scheduled, it may still cause fire trucks to waste a lot of time in the replenishment process, and reduce the number of fire trucks actually involved in the fire extinguishing. This will reduce the fire extinguishing effect and increase the probability of emergency response failure.

3. eM-plant simulation analysis approach

The modeling objects in eM-plant which will be used in this work are shown in Table A.1. Although these objects are not designed for the simulation of processes like emergency response, they can express emergency response activities by giving them new meanings to model emergency response processes.

When a major fire accident occurs, the fire-fighting and rescue process of the firefighters can be modeled and analyzed with eM-plant in the following way.

The Entity object can be used to represent a moving object in an emergency response, such as a fire brigade, a fire truck, etc. The Source object is the object that produces entities and can thus be used to produce entities in an emergency response. DismantleStation represents the dismantling of an entity in eM-plant, this feature can therefore be used to generate multiple other entities from one entity. In an emergency process, it can be expressed such way that after a fire fleet arrives at the fire scene, it breaks down into a certain number of fire trucks.

The Singleproc object can be used to express the locations where emergency response actions are carried out in an emergency response process, and further represent the corresponding emergency response actions, such as the fire extinguishing action of the firefighters at the installation on fire, and the water replenishing action of fire trucks at a hydrant. All these actions take some time and can be reflected by the parameters of the Singleproc object.

In the modeling of the emergency response process, the Line object can be used to represent the path of emergency personnel or resource movement. For example, in the fire-fighting process, the fire truck needs to add water to and from fire hydrants. The round trip process can be represented by the Line object, which represents the road that the fire truck runs on. The length of the Line object indicates the distance, and the velocity of the truck can be set through its parameters.

The TableFile object can be used to record the values or results in the simulation, such as the completion time of an emergency response, and the value of the heat radiation.

The Method object can be used to write functions to control the model, e.g. the repeated execution
of the simulation process, as well as the calculation of the utilization ratio of equipment.

In addition, for emergency response process modeling, variables can be defined with the Variable object for use in other objects like Method.

4. Analysis of fire truck scheduling strategies in fire fighting

4.1 Accident scenario and the emergency response

Whether fire trucks in the process of fire-fighting can replenish the water in time may determine the success or failure of the fire-fighting. Therefore, this work focuses on whether fire hydrants can be well used to replenish fire trucks to extinguish a major fire.

In view of the positions of water supply points in practice, such as the 2013 fertilizer plant fire in western Texas, where the most closest fire hydrant was 450 meters away, and the 2011 PetroChina Dalian branch tank fire, where water supply points were distributed from tens of meters to hundreds of meters to the fire site, the studied scenario is set as follows: an installation of a chemical plant catches fire, and there are three hydrants near the fire scene with distances of 100 meters, 300 meters and 500 meters from the installation on fire, respectively. The fire department sends six fire trucks to fight the fire, each of which could carry 9 tons of water and 3 tons of foam concentrate. All of the fire trucks are filled with water at the beginning. According to the outdoor fire hydrant flow design standard for flammable liquid storage tanks, the water replenishment rate of a fire truck is about 30 L/s. Different fire trucks often have different water consumption velocity. Based on the parameter of the fire monitor flow velocity of a fire truck model of a company, this work determines that the water consumption velocity of the fire trucks is about 25 L/s.

In the process of extinguishing a major fire, it is necessary to monitor the fire. For fires in a chemical plant, one major task of the fire-fighting is to prevent damage of adjacent installations caused by thermal radiation. Therefore, the effect of the fire-fighting is reflected by the thermal radiation measured at a certain distance (e.g., adjacent installations) in this work, and the relationship between the thermal radiation and fire trucks engaged in fire-fighting is determined in a simplified way according to the approach in Zhou and Reniers (2016b). Suppose the fire studied is an oil (e.g. diesel) fire, and foam solution is used to extinguish the fire. The mixing ratio for the foam solution is 3%, and the expansion of the foam solution is 6, thus, one fire truck will produce about 9000L foam solution. Assume the loss rate of foam solution in the fire is 2/3, and the average thickness of the foam solution covering oil is 0.1m, thus, 9000L foam solution can cover about 30 m². This corresponds to 0.1 to 0.2 kW/m² changes of thermal radiation 30 to 45 meters away from the fire center. Thus, a rough formula reflecting the relationship between the number of fire trucks and the change of thermal radiation received by the nearby
installation (about 40m to the fire center) is established, which is shown as follows,

\[
r(t + \Delta t) = \begin{cases} 
    r(t) - 0.2 \times \left( Q - \frac{r(t)}{2} \right) \times \Delta t, & r/2 \neq Q \\
    r(t) - 0.1 \times \Delta t, & r = Q 
\end{cases}
\]

where, \( r(t) \) indicates the radiation at time \( t \); \( Q \) is the number of fire-fighting trucks; \( \Delta t \) is the time increment (minutes).

The relationship reflects the change rate of thermal radiation under fire-fighting. It is based on the following simple estimation. One fire truck may roughly cause 0.2 kW/m\(^2\) changes of thermal radiation 30 to 45 meters away from the fire center (this estimation is based on a pool fire model). So, assume one fire truck can barely control some 2 kW/m\(^2\) of heat radiation in ten minutes, and if the number of fire trucks is increased, thermal radiation will be reduced proportionally, and vice versa.

In the process of fighting a fire, if the fire-fighting capacity such as firefighters and fire-fighting facilities is sufficient, the fire can be controlled and gradually extinguished, and the thermal radiation will gradually decrease. In this study, a fire is extinguished as the thermal radiation received by the determined measuring points is reduced to 0. On the contrary, if the fire-fighting capacity is insufficient, the fire may gradually expand, and the thermal radiation value of the adjacent installation will rise. If the thermal radiation received by adjacent installations exceeds a certain value, adjacent installations may be damaged and a domino effect may occur. This situation is taken as the failure of emergency response in this work and 15kW/m\(^2\) is adopted as the failure threshold value for atmospheric vessels (Reniers & Cozzani, 2013).

**4.2 Fire truck scheduling strategies**

In order to avoid confusion on the fire site and to make better use of fire hydrants to replenish water for fire trucks, five strategies of fire truck scheduling are discussed, which are shown in Table 2.

**Table 2 Scheduling strategies of fire trucks**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy 1</td>
<td>Fire trucks are equally dispatched to fire hydrants, and each hydrant is assigned to fixed fire trucks.</td>
</tr>
<tr>
<td>Strategy 2</td>
<td>The number of fire trucks assigned to hydrants is set in different proportions according to the distance to the hydrants and each hydrant is assigned to fixed fire trucks.</td>
</tr>
<tr>
<td>Strategy 3</td>
<td>Fire trucks are equally dispatched to fire hydrants, but each hydrant is not assigned to fixed fire trucks. Fire trucks give priority to the nearest fire hydrant to add water.</td>
</tr>
</tbody>
</table>
Strategy 4: The number of fire trucks assigned to hydrants is set in different proportions according to the distance to the hydrants and each hydrant is not assigned to fixed fire trucks. Fire trucks give priority to the nearest fire hydrant to add water.

Strategy 5: Fire trucks randomly select hydrants to add water and they have no priority.

Strategy 1: Fire trucks are averagely assigned to hydrants, and fire trucks are fixed to hydrants. When it is determined that the fire trucks are assigned to a certain hydrant, the subsequent circular process of fire-fighting and water replenishing will keep these specific fire trucks going to the designated hydrant to replenish water until completion of the emergency response.

Strategy 2: The closer the fire hydrant is to the fire point, the more fire trucks are allocated to replenish the water. On the basis of Strategy 1, more fire trucks are assigned to the nearer hydrants. Similar to Strategy 1, if a fire truck is assigned to a hydrant, the fire truck will be fixed to the hydrant to replenish water.

Strategy 3: Each hydrant receives the average number of fire trucks, but it does not fix the fire trucks. When a fire truck needs water again, it goes to the nearest hydrant to replenish water, but the total number of fire trucks received by a fire hydrant does not exceed the average number.

Strategy 4: Hydrants closer to the fire point are allocated more fire trucks. Fire trucks are not fixed to hydrants, and they go to the nearest fire hydrant first. But the number of fire trucks received by each hydrant cannot exceed a pre-determined fixed value.

Strategy 5: This strategy reflects the random allocation. When a fire truck runs out of water, it will go to any fire hydrant at random to replenish water.

Time consumption of major actions in the emergency response is shown in Table 3. The water consumption time and the water-filling time are assumed to satisfy normal distributions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Time/Distribution</th>
<th>Object in the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water consumption of fire truck</td>
<td>N(360,15) s</td>
<td>Fighting(i)</td>
</tr>
<tr>
<td>Fire truck time on the road</td>
<td>20s, 60s, 100s</td>
<td>Line(i)</td>
</tr>
<tr>
<td>Load time</td>
<td>N(300,15)s</td>
<td>Assembly(i)</td>
</tr>
<tr>
<td>Time interval</td>
<td>10s</td>
<td>dt</td>
</tr>
</tbody>
</table>
4.3 Simulation analysis and discussion

4.3.1 Modeling and simulation of the strategies

The strategies for fire truck scheduling are modeled using eM-Plant. Fig. 2 shows the model of Strategy 1; the modeling of other strategies is similar.

![Fig. 2 Fire truck scheduling model of Strategy 1](image)

The Source object generates Entity objects, representing the arrival of the fire fleet which is an Entity. The DismantleStation object dismantles the fire fleet Entity into a number of entities of fire trucks, which can carry out fire-fighting actions separately. Fighting(i) indicates the fire-fighting of a fire truck and the time of it represents the water consumption time of the fire-fighting. The replenishing water action of a fire truck is represented by Assembly(i) objects. This study assumes that a hydrant can only replenish a fire truck at a time, and that if multiple fire trucks go to a hydrant to add water at the same time, the Waiting buffer object indicates that they will wait in line. The Counting object in the model plays a role of triggering methods to calculate the heat radiation, judge the number of fire trucks in the fire-fighting state, and determine the state of the system (emergency response success or failure). Line(i) represents the round-trip process of adding water of fire trucks. The table object TableFile records data like the completion time of the emergency response, the value of the heat radiation, to facilitate the subsequent check and analysis.

In the model, variables $AWr(i)$, $n(i)$, $r(i)$, $t(i)$, CS are defined to record the average utilization ratio of hydrants, the number of emergency response successes and failures, the state of fire heat radiation, the emergency response time, and the number of simulations, respectively. The variable $dt$ represents the time interval of the analysis, and the variable $y$ records the number of fire trucks at a certain time in the fire-fighting state.

The model defines several Method objects such as Init, Zero, Formula, and recording(i) for the
initialization of the simulation process, calculation of heat radiation change, calculation of fire hydrant utilization ratio, and recording of fire truck traveling path, etc.

The state of the emergency response process is recorded according to the order of time. Two emergency response processes under Strategy 1 are shown in Fig. 3 (a) and Fig. 3(b), respectively, reflecting the time-dependent changes of heat radiation and fire trucks fighting fire during the emergency response.

Fig. 3 (a) The distribution of fire trucks and the change of heat radiation over time – a success fire-fighting process

Fig. 3 (b) The distribution of fire trucks and the change of heat radiation over time – a failure fire-fighting process

When the time of emergency response actions takes different values according to the corresponding distribution, the result of the emergency response may be ‘success’ or ‘failure’. Fig. 3 (a) shows a success
process, and Fig. 3(b) shows a failure process. It shows that the heat radiation and the number of fire trucks in fire-fighting vary with time during the emergency response. At the beginning, six fire trucks arrive at the same time to fight the fire, the heat radiation value of the fire rapidly decreases, however, after a period of fire-fighting, as the fire trucks use out water resources, they go to hydrants to replenish the water, and the heat radiation value of the fire rises as the number of fire trucks (extinguishing the fire) lowers. In Fig. 3(a), as the number of fire trucks returning to fight the fire again increases in time, the heat radiation of the fire is controlled. If the water replenishing time, together with the waiting time and the traveling time of fire trucks, is too long, e.g., in Fig. 3(b), it will result in an insufficient number of fire trucks fighting the fire, and the heat radiation will gradually rise to exceed the threshold of 15 kW/m$^2$, indicating the failure of the emergency response. On the contrary, if fire trucks can quickly return to fight the fire, the fire will gradually be extinguished. It can also be seen from Fig. 3(a) and Fig. 3(b) that the time of fire trucks being simultaneously in the fire extinguishing process of the success case is longer than that of the failure case, and this result is consistent with the experience of concentrating the emergency response force to extinguish a fire, and the relationship between fire trucks on fighting and the heat radiation mentioned above.

Based on the models of the five strategies, 1000 repeated simulations are carried out for the emergency response to a fire with 7 kW/m$^2$ (approximately equivalent to the heat radiation at a distance of 35 meters from the center of a diesel fire with a radius of 15 meters) and results are obtained as shown in Table 4.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Fire trucks for three hydrants</th>
<th>Success rate</th>
<th>Average time of emergency response (minute)</th>
<th>Utilization of hydrants</th>
</tr>
</thead>
</table>
| Strategy 1 | 2, 2, 2 | 75.4% | Success: 50:53  
Failure: 1:03:11 | 76.49%, 68.56%, 62.39% |
| Strategy 2 | 3, 2, 1 | 5.1% | Success: 1:05:16  
Failure: 49:50 | 87.64%, 68.27%, 32.75% |
| Strategy 3 | 2, 2, 2 | 13.5% | Success: 1:00:34  
Failure: 54:33 | 85.78%, 69.69%, 32.25% |
| Strategy 4 | 3, 2, 1 | 0 | Failure: 38:00 | 84.14%, 60.57%, 13.19% |
| Strategy 5 | randomly | 3.0% | Success: 58:16  
Failure: 43:58 | 59.32%, 58.11%, 57.63% |
In order to compare the sensitivity and effectiveness of different strategies under the situations responding to different fires, the initial fire intensity (thermal radiation value, kW/m²) is adjusted to observe the success rate of the strategies. The simulation results are shown in Fig. 4.

![Success probability of emergency response of different strategies for different intensity fires](image)

**Fig. 4** The success probability of emergency response of different strategies for different intensity fires

In the case of the random allocation of Strategy 5, there is the smallest probability of emergency response success in the face of a smaller fire, whereas in the case of a larger fire, it can be seen that the curve of the success rate of Strategy 5 is above Strategy 4, that is, in the range of this part, the success probability of Strategy 5 is higher than that of Strategy 4. Strategies of Strategy 1, Strategy 2 and Strategy 3 are always better than Strategy 5. Among the fire strategies, Strategy 1 has the best performance.

### 4.3.2 Discussion on strategies

Strategy 5 is an unorganized way of scheduling the fire trucks. The selection of hydrants solely depends on firemen's own random choice. It can be seen from the result that huge waste and defects exist in the scheduling of fire trucks during the fire-fighting.

From the simulation results, the good strategies are Strategy 1, Strategy 3, Strategy 2, Strategy 5 and Strategy 4. Intuitively, it seems that a proportional scheduling based on distance should be better than a uniform scheduling. Because a shorter distance can make the fire truck arrive faster, it seems that fire hydrants closer to fire point should be allocated more fire trucks. But the results show that the average scheduling has a better fire extinguishing effect.

Strategy 1 is simply to divide the fire trucks equally and fix a fire truck to the corresponding hydrant in the subsequent water replenishment process. Strategy 2 and Strategy 3 makes some adjustments on this basis, giving priority to sending fire trucks to the nearer hydrants to replenish water to improve the success rate of the whole emergency response process or reduce the time of extinguishing the fire. But
the results show that Strategy 1 is far better than Strategy 2 and Strategy 3, the success probability of emergency response decreased from 75.4% to 5.1% and 13.5%, respectively, and the effect of Strategy 4 is even worse.

Strategy 2 is to allocate more than the average number of fire trucks to the nearest hydrant to replenish the water, where time is saved and the utilization of the nearest hydrant is increased by from 76.49% to 87.64%, but in this way it increases the waiting time of fire trucks to replenish the water. When a fire truck is filling, other fire trucks have to wait. If there are many fire trucks waiting in the queue, the waiting time is more wasteful than the travel time. At the same time, it reduces fire hydrant utilization rate at the furthest distance, from 62.39% of the average scheduling to 32.75%, which also creates a waste.

Strategy 3 is to give priority to the nearest fire hydrant corresponding to the case of equalization, and to prioritize the dispatch of fire trucks to the nearest fire hydrant until the number of fire trucks reaches the average limit of the hydrant. This strategy increases the use of nearer hydrants by constantly giving them priority, but it decreases the utilization rate of the farthest hydrant from 62.39% to 32.25%. In addition, in observing the moving of fire trucks in the model, the priority scheduling strategy will dispatch the two fire trucks which produce the water replenishing demand one after another to the same fire hydrant, resulting in that fire trucks have to wait a long time while a fire truck is replenishing water.

Strategy 4 combines the distance distribution of Strategy 2, with the priority rule of Strategy 3. According to the above analysis, both Strategy 2 and Strategy 3 want to take full advantage of the nearer fire hydrants, and the combination also combines the disadvantages of them. It greatly reduces the utilization rate of the furthest hydrant, from 62.39% of the average allocation to 13.19%, leading to a low success probability of emergency response (zero in this example).

4.3.3 Further discussion on the average scheduling strategy

In order to explore whether there is a better scheduling strategy, some adjustments are made to the average scheduling strategy (Strategy 1). There are several possible ways:

(i) In view of the problem that the time interval between two fire trucks of a hydrant is small and the waiting time of fire trucks is long in Strategy 3, it may be adjusted in the following way: scheduling fire trucks to hydrants circularly to increase the interval between fire trucks which go to the same hydrant, so that the waiting time may be reduced.

(ii) The first replenishment of all fire trucks is cyclically dispatched to hydrants, after which the fire trucks are fixed to the corresponding hydrant to replenish water. This may also increase the interval between two adjacent fire trucks to replenish water at the same hydrant, and reduce the waiting time.
(iii). According to the analysis of the hydrant utilization rate, if all hydrants have a balanced utilization ratio in the process of replenishing, the emergency response may have better results.

Based on these adjustment ideas, new strategies are determined as shown in Table 5.

Table 5 Adjusted scheduling strategies for the strategy of evenly distribution of fire trucks

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy 1_1</td>
<td>1. Dispatch fire trucks to hydrants circularly and fire trucks are evenly dispatched to hydrants to replenish water.</td>
</tr>
<tr>
<td></td>
<td>2. A fire truck is not fixed to a hydrant to replenish water.</td>
</tr>
<tr>
<td></td>
<td>3. Fire trucks are first dispatched to the nearest fire hydrant.</td>
</tr>
<tr>
<td>Strategy 1_2</td>
<td>1. Dispatch fire trucks to hydrants circularly and fire trucks are evenly dispatched to hydrants to replenish water.</td>
</tr>
<tr>
<td></td>
<td>2. A fire truck is not fixed to a hydrant to replenish water.</td>
</tr>
<tr>
<td></td>
<td>3. Fire trucks are first dispatched to the farthest fire hydrant.</td>
</tr>
<tr>
<td>Strategy 1_3</td>
<td>1. Fire trucks are evenly dispatched to hydrants to replenish water.</td>
</tr>
<tr>
<td></td>
<td>2. Fire trucks go to the hydrants in a circular manner for the first time to replenish water (start with the nearest hydrant), after which the fire trucks are fixed to the corresponding hydrant.</td>
</tr>
<tr>
<td>Strategy 1_4</td>
<td>1. Each hydrant can serve at most the average number of fire trucks.</td>
</tr>
<tr>
<td></td>
<td>2. Fire trucks are given priority to the farthest hydrant, from far to near to meet the service capacity of each hydrant</td>
</tr>
</tbody>
</table>

According to the adjustments, corresponding models are established, and Fig. 5 is the model of Strategy 1_1. Modeling of other strategies is similar.
Fig. 5 Adjusted Scheduling Model of Strategy 1_1

Simulation results of the adjusted models are shown in Table 6. Fire hydrant utilizations are listed from near to far by distance.

### Table 6 Simulation results of adjusted strategies

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Success rate</th>
<th>Average time of emergency response (minute)</th>
<th>Utilization of hydrants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy 1_1</td>
<td>66.5%</td>
<td>Success: 52:24 Failure: 1:03:01</td>
<td>81.83%, 65.34%, 54.28%</td>
</tr>
<tr>
<td>Strategy 1_2</td>
<td>54.8%</td>
<td>Success: 55:30 Failure: 59:26</td>
<td>65.58%, 70.45%, 72.32%</td>
</tr>
<tr>
<td>Strategy 1_3</td>
<td>80.4%</td>
<td>Success: 49:40 Failure: 1:03:35</td>
<td>76.48%, 68.36%, 61.94%</td>
</tr>
<tr>
<td>Strategy 1_4</td>
<td>1.3%</td>
<td>Success: 59:56 Failure: 49:20</td>
<td>44.33%, 64.70%, 78.05%</td>
</tr>
</tbody>
</table>

### 4.3.4 Discussion on the adjusted strategies

Both Strategy 1_1 and Strategy 1_2 dispatch fire trucks to hydrants cyclically, with the difference between a far-to-near cycle and a near-to-far cycle. Strategy 1_1 which starts the cycle from the nearest hydrant has the success rate of 66.5%, and Strategy 1_2 which starts the cycle from the farthest hydrant has the success rate of 54.8%. Comparing with Strategy 3, they both have better results. But they're still worse than Strategy 1.

Strategy 1_3 is based on Strategy 1. Fire trucks are cyclically dispatched to the hydrants for the first time to replenish water, and they are then fixed to the corresponding hydrant. The success rate of
extinguishing the fire increases from 75.4% to 80.4%, indicating that the problem of long waiting times for fire trucks has been improved.

Strategy 1_4 is similar to Strategy 3, except that fire trucks are first sent to the farthest fire hydrant. This idea is to balance the utilization of fire hydrants and see if it can improve the fire-fighting. The results show that although the utilization of fire hydrants is more balanced, the success rate of fire extinguishing is reduced. This suggests that a balanced utilization of fire hydrants does not necessarily lead to a better emergency response. For the deeper analysis of the model, based on the dynamic relationship between the number of fire trucks and the heat radiation, it can be seen that the fire trucks can reduce the heat radiation more quickly when the fire trucks are concentrated to fight the fire. Strategy 1_3 only makes hydrant utilization more balanced, but this balance does not guarantee that more fire trucks will be able to extinguish fire simultaneously in the emergency process.

4.4 Cases where fire trucks cannot be divided equally by hydrants

From the analysis above it can be seen that the emergency response effect is better under the condition of equal distribution of fire trucks to hydrants. If the number of fire trucks cannot be divided equally by fire hydrants, how to allocate the extra fire trucks?

In the preceding analysis, we have come to the conclusion that it is a good strategy to circularly dispatch fire trucks to hydrants (start with the nearest hydrant) when the fire trucks need to refill water for the first time, and then fix the fire trucks to corresponding hydrants. For fire trucks cannot be divided equally by hydrants, redundant fire trucks can be dispatched in turn from the nearest hydrant to the farthest hydrant, or vice versa. This leads to the following two strategies:

Strategy A: Circularly dispatch fire trucks to hydrants (start with the nearest hydrant) when the fire trucks need to refill water for the first time, and then fix the fire trucks to corresponding hydrants.

Strategy B: Circularly dispatch fire trucks to hydrants (start with the farthest hydrant) when the fire trucks need to refill water for the first time, and then fix the fire trucks to corresponding hydrants.

The simulation analysis of the cases where the number of fire trucks is 5, 7, and 8 are carried out, and results are shown in Fig. 6, Fig. 7, and Fig. 8, respectively.

From the results, the two strategies have similar effects, with only a few differences. Strategy A works better with 5 fire trucks, while Strategy B works better with 7 and 8 fire trucks. This is mainly caused by the difference between the travel time and the waiting time at hydrants. When there are fewer fire trucks, the waiting time for replenishment is small, so the travel time has a greater impact on emergency efficiency. For example, for 5 fire trucks, the average waiting time for replenishment is about 25 seconds. Therefore, the first fire truck to refill is preferentially dispatched to the nearest hydrant. The
travel time is shorter, so the effect is a little better. On the contrary, when there are many fire trucks, the waiting time for replenishment is long, and the waiting time has a great influence on the emergency effect. As in the case of 7 fire trucks, the average waiting time is about 103 seconds in Strategy A. When fire trucks are dispatched starting from the farthest hydrant, part of the possible waiting time is shared to the travel time. The average waiting time in Strategy B is about 55 seconds and the total time loss is reduced, so that the effect is better.

The study also analyzed the strategies of fixed average scheduling of fire trucks under the condition that fire trucks cannot be evenly divided by hydrants, and found that if the scheduling of redundant fire trucks is consistent with corresponding strategies of first circular dispatch and then fixed dispatch, the fire-fighting effect is also similar. As in the case of 7 fire trucks, the strategy that the number of fire trucks allocated from near to far is 2, 2, and 3 (a fire truck is fixedly assigned to corresponding hydrant), and the effect is similar to the corresponding Strategy B, which is slightly better than the allocation of (3, 2, 2) mode. This is also true when fire trucks can be evenly divided over the hydrants (e.g., 6 fire trucks in this example).

From the above analysis and discussion, it can be known that to schedule fire trucks when they need to be replenished with water during the fire extinguishing process, they should be evenly distributed to hydrants and each of them should be fixed to an assigned hydrant to replenish water. If the number of fire hydrants near the fire site is small and it may cause a long waiting time, it will have a better effect that after the average allocation, the extra fire trucks are allocated from the farthest fire hydrant to the nearest fire hydrant. Otherwise, the extra fire trucks should be allocated from the nearest hydrant to the farthest hydrant. In any of these cases, fire trucks should be fixed to assigned hydrants.

![Fig. 6 Comparison of Strategy A and Strategy B with 5 tire trucks](image)
5. Conclusions

In view of the situation that fire trucks may be in a chaotic state in the fire emergency response scene and the random mode of scheduling fire trucks to replenish water possibly leading to a very poor emergency response effect, four strategies in addition to the random dispatch are discussed. The tool eM-Plant is adopted to model these strategies and simulations are carried out. The results show that three of the four scheduling strategies have a higher probability of emergency response success than the random scheduling of fire trucks, among which the scheduling strategy of evenly distributing fire trucks to hydrants and fixing fire trucks to corresponding hydrants (Strategy 1) displays very good emergency response performance.

Strategy 1 is further adjusted to find out a more optimal strategy. Several ways of improvement are considered: (1) cyclic dispatch of fire engines to fire hydrants; (2) cyclic dispatch only at the first replenishment of fire engines; and (3) balance the utilization of fire hydrants. In addition, the situation that fire trucks cannot be divided equally by hydrants is also analyzed. Results show that if the number of fire hydrants near the fire site is small, which may cause a long waiting time, it is better that after the average allocation, the extra fire trucks are allocated from the farthest hydrant to the nearest hydrant, and vice versa.

The situation considered in this paper is somewhat simplified, the capacity of the fire trucks is the
same, but in fact, the situation may be more complex in a real emergency response situation. This paper has shown and has proven that an optimal scheduling strategy can be determined by the approach of simulation analysis.

Acknowledgments
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References


Zhang Z., He S., 2011. The research of loading and unloading operation in container terminal based on eM-plant. 4th International Conference on Advanced Computer Theory and Engineering, Chulalongkorn Univ, Dubai, 679-682.


## Appendix

### Table A.1 Simulation objects and their uses of eM-plant

<table>
<thead>
<tr>
<th>Icon</th>
<th>Object name</th>
<th>Classification</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Eventcontroller]</td>
<td>Eventcontroller</td>
<td>Control object</td>
<td>It is used to control the start, interrupt and stop of a simulation, and control the time length of the simulation.</td>
</tr>
<tr>
<td>![Source]</td>
<td>Source</td>
<td>Production object</td>
<td>This is an object producing entities. The MU (moving unit) can be generated by setting the type of entity arrival in this module, as well as the time interval generated.</td>
</tr>
<tr>
<td>![Drain]</td>
<td>Drain</td>
<td>Production object</td>
<td>This is a MU recovery area. An entity passes through a series of processing processes, and finally leaves the system model from this object.</td>
</tr>
<tr>
<td>![Singleproc]</td>
<td>Singleproc</td>
<td>Production object</td>
<td>Single processing station. It can carry on the processing of single object, with the set processing time.</td>
</tr>
<tr>
<td>![DismantleStation]</td>
<td>DismantleStation</td>
<td>Production object</td>
<td>This is a station that can dismantle an entity into parts and components.</td>
</tr>
<tr>
<td>![Buffer]</td>
<td>Buffer</td>
<td>Production object</td>
<td>A buffer can be used to control the waiting of materials and WIP (work in process). Items usually are processed first-in- first-out in a buffer.</td>
</tr>
<tr>
<td>![Line]</td>
<td>Line</td>
<td>Transport object</td>
<td>This object is used to represent the conveyor belt, indicating the flow of entities. Its length and speed can be adjusted.</td>
</tr>
<tr>
<td>![Method]</td>
<td>Method</td>
<td>Information flow object</td>
<td>Users can write their own SimTalk code in this object for the control and scheduling of system details.</td>
</tr>
<tr>
<td>![TableFile]</td>
<td>TableFile</td>
<td>Information flow object</td>
<td>A table which can store all types of system runtime data.</td>
</tr>
<tr>
<td>![Variable]</td>
<td>Variable</td>
<td>Information flow object</td>
<td>This object is used to represent variables which can retrieve the data coming with the system, and can also be used by users when programming.</td>
</tr>
<tr>
<td>![Connector]</td>
<td>Connector</td>
<td>Framework object</td>
<td>It connects objects in a model. The arrow of a connector object indicates the moving direction of the MU.</td>
</tr>
<tr>
<td>![Entity]</td>
<td>Entity</td>
<td>Moving object</td>
<td>It represents the objects processed in a simulation model, e.g. the workpiece processed in an assembly line.</td>
</tr>
</tbody>
</table>