Optimal Decision Maker Algorithm for Disaster Response Management with I2Sim Applications

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ABSTRACT

Disaster response management has become an important area of research in recent years, with authorities spending more resources in the area. Infrastructure resource interdependencies are key critical points for a system to operate optimally. After a disaster occurs, infrastructures would have sustained certain degrees of damage, the allocation of limited resources to maximize human survival becomes a top priority. The I2Sim (Infrastructures Interdependencies Simulator) research group at the University of British Columbia (UBC) has developed a software simulation toolbox to help authorities plan for disaster responses. This paper presents an optimization decision algorithm based on Lagrange multipliers, which provides the theoretical basis for I2Sim software decision maker layer. There is a simple scenario of three hospitals constructed with the I2Sim toolbox to illustrate the interdependencies of water and electricity.

Keywords

Optimization algorithm, I2Sim Toolbox, Lagrange Multiplier, Infrastructure interdependency, HRT (Human Readable Table)

1.0 INTRODUCTION

In recent years, governments are spending more resources into research of disaster planning and preparation. Some of the recent major disasters include: 2004 Tsunami in Southeast Asia, 2008 Sichuan Earthquake and 2011 triple Japan disasters (earthquake, tsunami and nuclear power plant meltdown). According to Zimmerman, interdependencies amongst critical infrastructures are key points of vulnerability that can compromise the performance of a system especially during extreme events (Zimmerman, 2004). The series of decisions made after the disaster can mitigate the loss of human lives and the recovery of critical infrastructures (Khouj, Lopez, Sarkaria, Marti, 2011). The I2Sim (Infrastructure Interdependencies Simulator) Research Group at the University of BC (UBC) has been researching this area, after the Government of Canada announced funding support (Government of Canada, 2005).

There are many approaches to disaster resource allocation. According to Li et al., emergency resource scheduling is a key component of Emergency Management System (Li et al., 2011). Their approach is based on the transport path optimization. Based on some statistical uncertainty, how to minimize path from point A to B. Zhou and She presented two solutions of resource allocation. The first solution is how to distribute resources from a single supply source to several disaster areas, based on integer programming model (Zhou and She, 2011). The second solution is how to distribute resources from several supply sources to one disaster area, with the solution based on Topsis method. One of the assumptions of their model is unfettered access to emergency information, which may not always be available after a real disaster. Xiong and Shi built a multi-emergency point schedule model and provided a solution based on a dynamic optimization strategy (Xiong and Shi, 2011).

This paper introduces a method of constrained optimization based on the Lagrange multiplier. This method can be applied to the general problem of resource allocation given constraints. The constraints considered here are limited supply of water and electricity. The decision makers need to decide how to optimally distribute the resources to different facilities based on the level of resources.

2.0 I2SIM TOOLBOX

The I2Sim (Infrastructures Interdependencies Simulation) toolbox was developed at UBC by a research group at UBC (Lee, 2010). The initial objectives of the toolbox are to simulate disaster response scenarios and to help decision makers with efficient allocation of limited resources. But the capabilities of the toolbox are not limited to disaster response. The toolbox is programmed with Matlab/Simulink. The toolbox has a drag-and-use graphical interface and has the advantages of simple to learn and use. The user does not need to know about the inner workings of the blocks. The toolbox is comprised of modular blocks that mimic real life entities such as buildings, pipes, etc. The resources have complex interdependencies.

The I2Sim toolbox has three types of components to model physical entities (Lee, 2010). The first type is a token, which is an entity that circulates in the system. Examples include water, electricity and people. They can represent the resources that are produced at one location and consumed at another. Cell is the second type, which is a component that takes tokens as input and transforms them as output. Examples include hospitals, substations and water stations. Cells may consume two or more types of tokens (resources), which gives rise to the interdependencies. The third type is a channel, which is a conduit that tokens flow through, but transformation does not occur. Examples include electric lines, water pipes and roads. One channel typically carries only one type of token.

At the core of the I2Sim components are Human Readable Tables (HRTs). HRTs describe relationship between input and output at different discrete levels. They enable for a reasonable prediction of real life system. According to the thesis by Lee, HRTs are simplified compared to a previous version to include only discrete levels. There are five discrete levels. For example, a building cell may have 5 discrete levels of Physical Mode (PM). Discrete level is also one of the limitations of I2Sim Toolbox, as they may not represent some situations realistically. But for the sake of computer simulation, it has the advantage of simple implementation.

The operating state of a cell is determined by both Physical Mode (PM) and Resource Mode (RM) (Lee, 2010). Physical Mode is the physical state of a cell, or how intact it is. Resource Mode is how much resources are available for use by the cell. A cell may have the highest level of PM, but it still cannot operate at 100% capacity if the RM is at a low level, and vice versa. Under normal circumstances, both PM and RM are at the highest levels. But after an uncontrollable event such as an earthquake, one or both may be compromised. Each PM is assigned to an HRT.

3.0 METHODOLOGY WITH LAGRANGE MULTIPLIERS

To optimize the decision maker algorithm, the general approach can be thought as a constrained optimization problem. The objective function is to maximize the number of treated patients. In this paper, for instance, the constraints are limited resources of water and electricity. Because the nature of HRT, we are dealing with a discontinuous step function which is non-linear.

The objective function is to maximize the number of treated patients.

$$Max \sum_{i=1}^{n} N_i = N_t \qquad (1)$$

Note N_i is a function of P_i and W_i.

The constraints are shown in Equations 2 and 3:

$$\sum_{i=1}^{n} P_i = P_t \qquad (2)$$

$$\sum_{i=1}^{n} W_i = W_t \qquad (3)$$

Also each P_i and W_i must be non-negative.

P_i – power supplied to a particular cell

P_t – total power available

W_i – water supplied to a particular cell

W_t – total water available

After formulation of the problem we augment the constraints in objective function by using the Lagrange multipliers. A new function is set up by adding two Lagrange multipliers to the original objective function. The augmented function is shown as follows in Equation 4.

$$\mathcal{L} = N_t - \lambda_1\left(P_t - \sum_{i=1}^{n} P_i\right) - \lambda_2\left(W_t - \sum_{i=1}^{n} W_i\right) \qquad (4)$$

Then we take the partial derivatives of the augmented function and set each one equal to zero. That provides the necessary first order conditions to solve the problem. The maximum of this function is found at the point where the partial derivatives of the function to its variables are equal to zero.

From the first order equations, we can infer the following, as shown in Equations 5a and 5b:

$$\frac{\partial \mathcal{L}}{\partial P_1} = \frac{\partial N_1}{\partial P_1} - \lambda_1 = 0, \dots, \frac{\partial \mathcal{L}}{\partial P_n} = \frac{\partial N_n}{\partial P_n} - \lambda_n = 0 \qquad (5a)$$

$$\frac{\partial \mathcal{L}}{\partial W_1} = \frac{\partial N_1}{\partial W_1} - \lambda_2 = 0, \dots, \frac{\partial \mathcal{L}}{\partial W_n} = \frac{\partial N_n}{\partial W_n} - \lambda_n = 0 \quad (5b)$$

After solving for the different distributions of water and electricity, the answers can be plugged into the objective function to find the maximum number of treated patients. At last we can integrate the solution back into the system and check for resource interdependencies.

4.0 CASE STUDY WITH THREE HOSPITALS

We run the algorithm on a simple scenario. The scenario setup in I2Sim blocks is shown in Figure 3. There are three hospitals, and each hospital requires water and electricity to operate. During normal times there are enough resources to supply the hospitals. But after a disaster occurs the resources suddenly become scarce. There is a water pump station and an electricity generation station. The channels are water pipes and transmission lines. The optimal decision making algorithm would be applied at the distributors for electricity and water. Notice the electricity distributor also needs to distribute certain amount of electricity for the pump station to work. The question to answer is how to efficiently distribute the limited resources to the three hospitals. The aggregator calculates the sum of the patient outputs from the three hospitals.

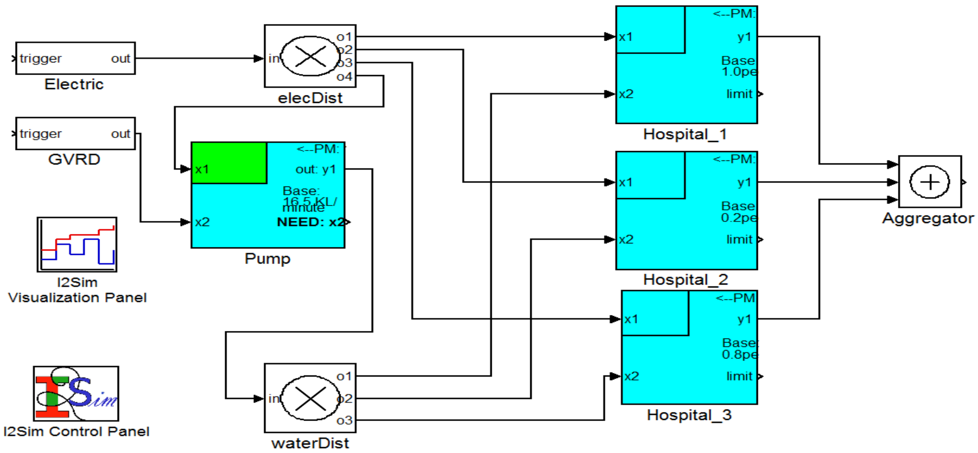

Figure 3: I2Sim Scenario with 3 Hospitals

Table 1 illustrates the HRTs for the three hospitals. The information about the HRTs is assumed to be given conditions. Each row provides a PM of the hospital. The number of treated patients per minute depends on the available amount of electricity and water. If the numbers are plotted, they would be piecewise linear concave curves that flattens out after a certain point (cannot treat more people than there is available). Figure 4 shows the electricity λ for the three hospitals.

Table 1: HRTs for the three hospitals

Hospital 1 HRT				Hospital 2 HRT			Hospital 3 HRT		
Ro	Y1	X1	X2	Y1	X1	X2	Y1	X1	X2

w	(ppl/min)	(MW/min)	(KL/min)	(ppl/min)	(MW/min)	(KL/min)	(ppl/min)	(MW/min)	(KL/min)
1	1	10	6	0.2000	5	4	0.8000	16	16
2	0.9500	7.5000	4.5000	0.1900	3.7500	3	0.7600	12	12
3	0.8000	5	3	0.1600	2.5000	2	0.6600	8	8
4	0.5000	2.5000	1.5000	0.1000	1.2500	1	0.4000	4	4
5	0	0	0	0	0	0	0	0	0

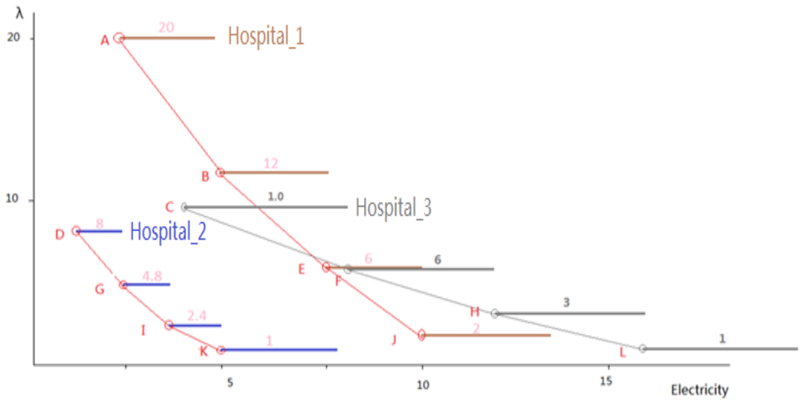

Figure 4: Electricity λ for the Three Hospitals

If the water and electricity distributors operate mutually independent of each other, the distributors know how to distribute the resources. The interesting problem comes in when the two resources are both required for the hospital to function properly. Both the electricity distributor and water distributor know independently what their optimal levels of distribution should be. But what will happen if there is a conflict?

We put the possible optimal dispatch of electricity and water together. The combined solution table is shown in Table 2. The decision maker is faced with resolving conflicts from the two resources. There are three types of resource conflicts, as listed below. The underlying assumption is the PM is at 100% for all hospitals.

Table 2: Combined solution table for electricity and water

Point	Available elec. (MW)	Row (Hosp. 1)	Row (Hosp. 2)	Row (Hosp. 3)	Avail water(KL)	Row (Hosp. 1)	Row (Hosp. 2)	Row (Hosp. 3)
A	2.5	R4	R5	R5	2.5	R4	R5	R5
B	5	R3	R5	R5	3.0	R3	R5	R5
C	9	R3	R5	R4	4.0	R3	R4	R5
D	10.25	R3	R4	R4	8.0	R3	R4	R4
E	12.75	R2	R4	R4	9.5	R2	R4	R4
F	16.75	R2	R4	R3	13.5	R2	R4	R3
G	18	R2	R3	R3	14.5	R2	R3	R3
H	22	R2	R3	R2	16	R1	R3	R3
I	23.25	R2	R2	R2	17	R1	R2	R3
J	25.75	R1	R2	R2	21	R1	R2	R2
K	27	R1	R1	R2	22	R1	R1	R2
L	31	R1	R1	R1	26	R1	R1	R1

Case 1 (Row C in Table 2):

When power is sufficient and water is insufficient, the electricity supplies of the hospitals are more than the water supplies. Then just follow the row of water (R3, R4, R5).

Case 2 (Row E in Table 2):

Water is sufficient and power is insufficient. The water supplies of the hospitals are more than the electricity supplies. Then we follow the row of electricity because it constrains our solution (R2, R4, R4).

Case 3 (Rows H and I in Table 2):

In this case it is difficult to say which resource is sufficient. We have to adjust the Row of either water or power or both. The first question to ask is how many choices do we have? For Hospital 1 we could choose Row 1 or Row 2. For Hospital 2 we could choose Row 2 or Row 3. For Hospital 3 we could choose Row2 or Row3. Therefore, we have $2^3 = 8$ choices.

Some choices are impossible and can be eliminated right away, because when we check the available power or available water, we can see it. In other words, we can get the possible choices by checking HRT. The second question is which choice is the best one? The solution is to run I2Sim and check it out. After eliminating five choices, we are left with three combinations. Their corresponding values are: (R1,R3,R3) = 1.82, (R2,R2,R3) = 1.80, (R2,R3,R3) = 1.77. Therefore we select the highest one, (R1,R3,R3).

5.0 CONCLUSION

This paper presented an algorithm based on Lagrange Multiplier for decision making algorithm. It can be applied to solve interdependency problems involving numerous resources. The I2Sim toolbox can deal with any number of cells with each cell depending on many resources. Resource interdependencies in critical infrastructures may become key vulnerabilities after a disaster occurs. The decision maker is faced with the task of allocating limited resources which interdepend on each other. The objective of this algorithm is to maximize the number of patients treated. The objective function is augmented with Lagrange multipliers and first order conditions taken. The first order conditions are then used to determine the λ values. This algorithm was demonstrated through a simple case study involving three hospitals. The limitation of our approach is the HRT provided needs to be a concave down function. The research is continuing.

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