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A Comprehensive Mathematical Model for Designing an Organ Transplant Supply Chain Network under Uncertainty

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ABSTRACT

One of the most important issues in area of health and hygiene is location-allocation of organ harvesting centers and transplant centers according to coordination between supply and demand. In this paper, a mathematical model is presented for location-allocation of organ harvesting centers and transplant centers. The proposed model does not only minimize the present value of the total system costs, but also minimizes the geographical inequalities. The presented model is a bi-objective nonlinear mathematical programming and some of the problem parameters, such as cost, transport time and the like are associated with uncertainty and considered as fuzzy sets in the mathematical formulation. In this paper, an Organ Transplant Supply Chain (OTSC) has been designed and the ε-constraint method has been used to solve the problem and Iran is considered as a case study. The results show that the patient's family satisfaction rate is more important than the viability rate in the number of transplant operations performed and for a transplant operation to be performed, the minimum satisfaction rate (β_h) should be 0.4 and organ viability rate (UD_o) should be 0.2.

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1. INTRODUCTION

Supply chain management (SCM) problems often manages a dynamic and complex network, composed by organizations and companies that meet the end customer demand. Undoubtedly, management and decision making in the case of such a network requires extensive efforts. The decisions taken in the supply chain area are broadly different. These decisions can be based on the activities of the logistics network or on the basis of the time horizon of decisions [1]. Often, decisions in the supply chain area based on time horizon classified into three levels including (1) strategic decisions, (2) tactical decisions and (3) operational decisions. Strategic decisions have long-term time horizon and could be said to have a time horizon of over five years in the area of health systems [2]. At a lower level, tactical decisions are often scheduled for six to twenty four months [3]. The last level is dedicated to operational level that has a time horizon of a maximum of one week. The most important issue in the strategic design of the supply chain is the location of the facility and then the allocation of flows between the selected facilities [4, 5]. The organ transplant supply chain has all three levels of high decisions. In addition, the allocation policy of donating organs to patients is composed of two main methods (i.e., hierarchical method and central method). In this study, we have used the central method, because this method is more efficient for patients and social justice is established. Other innovation of this paper are summarized as follows:

- Location of organ harvesting centers and transplant centers are determined and allocation of these facilities are specified simultaneously.
- Potential donor satisfaction rate is considered in each hospital.
- An organ viability rate is addressed.
- Dynamic problem situation is generated by assuming different time periods in the problem.
- For the transfer of organ, two modes of land and air transportation is investigated.
- Present value of the total system costs and geographical inequalities are considered simultaneously.

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- A comprehensive mathematical model is presented for organ transplants supply chain network.
- New designing an organ transplant supply chain network.
- Some of the problem parameters such as costs, transport time and so forth are associated with uncertainty and reflected in the model as fuzzy sets.

2. LITERATURE REVIEW

In the following, we review the articles that have the more similarity with the organ transplant supply chain. Paganelli et al. [6] developed an integer linear programming formulation for the aircraft location problem in the Italian territory. They considered different time intervals and service design scenarios and compared performance indexes related to these time intervals and scenarios. Caruso and Daniele [7] presented a mathematical model for OTSC. The main goal of proposed problem was minimizing the total costs related to organ transplants. They found the related optimality conditions and developed the variational inequality formulation.For minimizing and upgrading the efficiency of the Organ Transplant Supply Chain Network (OTSCN), Zahiri et al. [8] presented a multi period location-allocation model for transplant centers in under uncertainty conditions and solved with a robust possibilistic programming method. With numerical experiments and sensitivity analyses they proved applicability of their study. Due to lack of data and uncertain environment in OTSCN, Zahiri et al. [9] proposed a multi period location-allocation model under uncertainty conditions. The proposed model has two objective functions that minimizes the time and cost of the entire supply chain network. Also, the queue M/M/C model used in this study for organ transplant centers. For solving the model, they presented a fuzzy multi objective programming based approach in small and medium size. For large size problem they proposed two meta-heuristic algorithms.

3. PROBLEM DEFINITION AND MATHEMATICAL FORMULATION

Supply chain network of organ transplants includes donors, patients, hospitals, transplant centers, organ harvesting centers and fleets of transportation. The donors in this supply chain are brain dead people that are identified in hospitals and reported to the organ harvesting centers. In this study we presented a Bi-objective model that the first objective function minimizes the present value of the total system costs and the second objective function minimizes geographical inequalities. In fact, we use the second objective function to try to cover all patients and increase social justice. In addition, in some areas, we can integrate organ transplantation and organ harvesting center in order to reduce costs for us that in the mathematical model, we show these areas with *e*. Figure 1 shows the relationships between members of this network. First, a person who is suspected to be brain death is detected by the hospital where it is admitted and reported to one of the organ harvesting centers. Afterwards, harvesting centers sent group of experts to hospital to confirm the brain death, assess the viability of organs and also getting consent from brain death person family (1). If this process has a positive response, the donor for organ harvesting is transferred to the organ harvesting center (2). At the same time, the organ harvesting center reports the donor conditions to the organization allocating organ. The organization identifies the suitable patient from the list of patients waiting transplant operation. The patient goes to the transplant center (3́) and the donation organ is sent by land or air from organ harvesting center to transplant center (3). Finally, organ transplant is done there.

3. 1. Sets

- h index of hospitals, $h=\{1,2,\ldots\ldots H\}$
- k index of candidate transplant centers, $k=\{1,2,\ldots\ldots K\}$
- u index of candidate organ harvesting centers, $u=\{1,2,\ldots\ldots U\}$
- o index of type of organ, $o=\{1,2,\ldots\ldots O\}$
- r index of patients area (recipients), $r=\{1,2,\ldots\ldots R\}$
- t index of time periods, $t=\{1,2,\ldots\ldots T\}$
- e index of candidate locations for establishing integrated facilities, $e=\{1,2,\ldots\ldots E\}$

3. 2. Parameters

- $\tilde{F}_{kt}$ establishing cost of a transplant center in candidate location k in time period t
- $\tilde{F}_{ut}$ establishing cost of an organ harvesting center in candidate location u in time period t
- $\widetilde{CE}_{kot}$ cost of equipping a transplant center k for organ type o in time period t
- $\widetilde{CE}_{uot}$ cost of equipping an organ harvesting center u for organ type o in time period t
- $\tilde{C}_{uht}$ cost of traveling from organ harvesting center u to hospital h in time period t

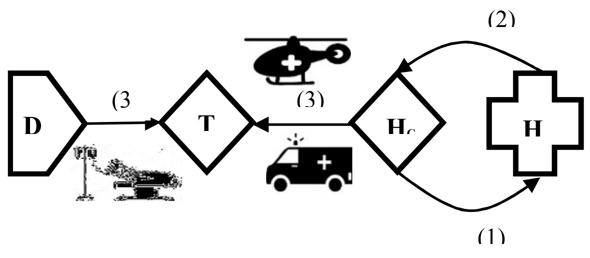

Figure 1. Organ transplant supply chain network

$\widetilde{CM}_{hut}$ cost of moving brain dead person from hospital *h* to organ supply center *u* in time period *t*

$\widetilde{CG}_{ukt}$ cost of moving a unit from organ harvesting center *u* to transplant center *k* in time period *t* by ground mode

$\widetilde{CA}_{ukt}$ cost of moving a unit from organ harvesting center *u* to transplant center *k* in time period *t* by air mode

$\widetilde{CR}_{rkt}$ cost of travel from recipient zone *r* to transplant center *k* in time period *t*

$\tilde{\tilde{f}}_{eot}$ saving cost for integration of facilities in the possible location *e* for organ *o* in time period *t*

$\widetilde{TG}_{uk}$ earthly time distance from organ harvesting center *u* to transplant center *k*

$\tilde{B}_t$ budget in time period *t*

$\tilde{r}$ invest return rate

CD_{ht} number of brain deaths in the hospital *h* in time period *t*

ND_o number of organs obtained for organ *o* from each brain death

D_{rot} number of waiting patients in the area *r* for transplant operation organ *o* in time period *t*

UD_o rate of viability of the organ *o* from each brain death

β_h rate of satisfaction of the organ donation in the hospital *h*

TA_O decisive time threshold for use of air transfer for organ *o*

3. 3. Decision Variables

7 if a transplant center is opened at location *k* in time period *t* 1, otherwise 0

x_{ut} if an organ harvesting center is opened at location *u* in time period *t* 1, otherwise 0

z_{kot} if a transplant center for organ *o* is opened at location *k* in time period *t* 1, otherwise 0

$\acute{z}_{uot}$ if an organ harvesting center for organ *o* is opened at location *u* in time period *t* 1, otherwise 0

q_{hut} if hospital *h* allocated to organ harvesting center *u* in time period *t* 1, otherwise 0

TCN_t total network costs in time period *t*

$\mu_{r\acute{r}ot}$ inequality in the supply of transplantation organ *o* between area *r* and *ŕ*

FL_{uht} flow from organ harvesting center *u* to hospital *h* in time period *t*

FLC_{hut} flow of brain deaths from hospital *h* to organ harvesting center *u* in time period *t*

$FLOG_{ukot}$ ground flow organ *o* from organ harvesting center *u* to transplant center *k* in time period *t*

$FLOA_{ukot}$ air flow organ *o* from organ harvesting center *u* to transplant center *k* in time period *t*

FLR_{rkot} flow from patients area *r* to transplant center *k* for transplant operation organ *o* in time period *t*

3. 4. Model Formulation

$$\mathrm{Min} z_1 = \sum_{t=1}^{T} \frac{TCN_t}{(1+\tilde{r})^{t-1}} \quad (1)$$

$$\mathrm{Min} z_2 = \sum_{r=1}^{R} \sum_{\acute{r}\neq r}^{R} \sum_{o=1}^{O} \sum_{t=1}^{T} |\mu_{r\acute{r}ot}| \quad (2)$$

s.t

$$z_{kot} \ll y_{kt} \quad \forall\, k.o,t \quad (3)$$

$$\acute{z}_{uot} \ll x_{ut} \quad \forall\, u.o,t \quad (4)$$

$$\sum_{u}^{U} \acute{z}_{uot} \gg 1 \quad \forall\, o,t \quad (5)$$

$$\sum_{k}^{K} z_{kot} \gg 1 \quad \forall o,t \quad (6)$$

$$\sum_{t=1}^{T} y_{kt} \ll 1 \quad \forall k \quad (7)$$

$$\sum_{t=1}^{T} x_{ut} \ll 1 \quad \forall u \quad (8)$$

$$\sum_{h=1}^{H} q_{hut} \gg 1 \quad | \sum_{o=1}^{O} \acute{z}_{uot} > 0 \quad \forall u,t \quad (9)$$

$$\sum_{h=1}^{H} q_{hut} = 0 \quad | \sum_{o=1}^{O} \acute{z}_{uot} = 0 \quad \forall u,t \quad (10)$$

$$\sum_{u=1}^{U} q_{hut} = 1 \quad \forall t,h \quad (11)$$

$$FL_{uht} = CD_{ht} . q_{hut} \quad \forall t,h,u \quad (12)$$

$$FLC_{hut} = [CD_{ht} . \beta_h . q_{hut}] \quad \forall t,h,u \quad (13)$$

$$\sum_{k=1}^{K} FLR_{rkot} \ll D_{rot} \quad \forall t,r,o \quad (14)$$

$$\sum_{k=1}^{K} (FLOG_{ukot} + FLOA_{ukot}) = [ND_o . UD_o . \sum_{h=1}^{H} FLC_{hut}] \quad \forall t,u,o \quad (15)$$

$$FLOG_{ukot} + FLOA_{ukot} \ll ND_o . UD_o . z_{kot} . z_{uot} . \sum_{h=1}^{H} FLC_{hut} \quad \forall t,k,u,o \quad (16)$$

$$\sum_{r=1}^{R} FLR_{rkot} = \sum_{u=1}^{U} (FLOG_{ukot} + FLOA_{ukot}) \quad \forall t,k,o \quad (17)$$

$$\frac{\sum_{k=1}^{K} FLR_{rkot}}{D_{rot}} = \frac{\sum_{k=1}^{K} FLR_{\acute{r}kot}}{D_{\acute{r}ot}} + \mu_{r\acute{r}ot} \quad \forall t,r,\acute{r} \neq r,o \quad (18)$$

$$FLOG\_ukot = 0 \;|\; (TG)\tilde{}\_uk > TA\_o \quad \forall t,u,k,o \quad (19)$$

$$TCN_t = \sum_{k=1}^{K} \tilde{F}_{kt} . y_{kt} + \sum_{u=1}^{U} \tilde{F}_{ut} . x_{ut} + \sum_{k=1}^{K} \sum_{o=1}^{O} \widetilde{CE}_{kot} . z_{kot} + \sum_{u=1}^{U} \sum_{o=1}^{O} \widetilde{CE}_{uot} . z_{uot} + \sum_{u=1}^{U} \sum_{h=1}^{H} (\tilde{C}_{uht} . FL_{uht} + \widetilde{CM}_{hut} . FLC_{hut}) + \sum_{u=1}^{U} \sum_{k=1}^{K} \sum_{o=1}^{O} (\widetilde{CG}_{ukt} . FLOG_{ukot} + \widetilde{CA}_{ukt} . FLOA_{ukot}) + \sum_{r=1}^{R} \sum_{k=1}^{K} \sum_{o=1}^{O} \widetilde{CR}_{rkt} . FLR_{rkot} - \sum_{e}^{E} \sum_{o}^{O} \tilde{\tilde{f}}_{eot} . z_{eot} . \acute{z}_{eot} \quad \forall t \quad (20)$$

$$TCN_t \ll \tilde{B}_t \quad \forall t \quad (21)$$

$$\sum_{k}^{K} \sum_{t}^{T} y_{kt} = NK \quad (22)$$

$$\sum_{u}^{U} \sum_{t}^{T} x_{ut} = NU \quad (23)$$

The first objective function minimizes the present value of the total system costs and the second one minimizes geographical inequalities. Constraint 3 ensures that a transplant center can be able for transplant operation if the transplant center is constructed. Identically, Constraint 4 guarantees that an organ harvesting center can be able for donation a particular organ if the organ harvesting center is constructed. Constraint 5 ensures that for each organ in each time period there is at least one harvesting center and constraint 6 ensures that for every organ in each time period there is at least one transplant center. Constraints 7 and 8 guarantee that each transplant center and harvesting center can be constructed in only one period. Constraints 9 and 10 ensures once a hospital is assigned to the organ harvesting center which is able to remove at least one organ. Constraint 11 guarantees that any hospital can only be allocated to a harvesting center. Constraint 12 shows that the flow from each harvesting center in a period Dependents to the number of brain death patient's hospital to which it is assigned. Constraint 13 shows the number of flow from each hospital to the relevant harvesting center in a period the number of brain deaths people have agreed to for donation. Constraint 14 shows that the total flow from each patient area for each transplant organ to the organ transplant centers in a time period less than or equal to the number of applicant patients for the same organ and region during that period. Constraint 15 indicates that the total land and air transport of an organ from an organ harvesting center to a transplant center the number of organs that are the bioavailability necessary for the transplant operation. Constrain 16 indicates that once the flow is established between the harvesting center and transplant center that both are equipped operation of an organ type. Constraint 17 guarantee that patients refer to transplant surgery only the number of organ found in the transplant center. Constraint 18 shows equity and geographical equality in the amount of demand for each area. Constraint 19 shows that if the time interval between the organ harvesting center and the transplant center is greater than the permissible threshold for ground transportation, then transmitted through the airway. Constraint 20 shows the total cost of each period (establishing cost of a transplant center and organ harvesting center, cost of equipping a transplant center and an organ harvesting center, cost of traveling from organ harvesting center to hospital, cost of moving brain dead person from hospital to organ supply center, cost of moving a unit from organ harvesting center to transplant center, cost of moving a unit from organ harvesting center to transplant center, cost of travel from recipient zone to transplant center and saving cost for integration of facilities) [8, 9]. Constraint 21 guarantee that these costs do not exceed of the budget in any period. Constraints 22 and 23 shows the number of constructed facilities (organ harvesting centers and transplant centers).

4. COMPUTATIONAL RESULTS

In this section, we solve proposed the fuzzy mathematical model using the ε-constraint method and consider Iran as a case study to solve this problem. Then, we carry out a sensitivity analysis on some of the problem important parameters. The calculations are done on the core i7 2.5 GHz and GB RAM 12 computer.

4. 1. Epsilon Constraint Method This method was proposed by Chankong and Haimes [10], and then Ehrgott and Ryan [11] developed it. In the ε-constraint method, one of the objective functions is maintained as the main objective function for optimization and other functions with an epsilon limit are limited [12]. To solve the proposed mathematical model with the ε-constraint method, the first objective function of the problem that minimizes the present value of the total system costs is maintained in the objective function and the second objective function is presented as a constraint in the mathematical model. By changing the values of the right of this constraint, Pareto's set of answers is obtained.

4 .2. Case Study and Sensitivity Analysis In this section, the design of Iran's transplant network supply chain for three vital organs of the heart, lung and liver is considered as a case study and data are provided for four periods. The country is divided into 31 provinces, which are considered as areas of patients requiring organ transplant. In addition, according to reports from the Ministry of Health, there are 43 hospitals in these areas that have brain death detection units which are recognized in the mathematical model as organ provider hospitals. Candidate location for organ harvesting centers, transplant centers and establishing integrated facilities according to expert opinion is considered 14, 7 and 2 centers respectively. Figure 2 shows the locations of hospitals, candidate locations for organ harvesting centers, transplant centers and establishing integrated facilities on the map. Other information and data was collected from the Iranian organ transplant unit in the Ministry of Health. By solving the mathematical model using the ε-constraint method, Pareto's solutions are obtained. Table 1 shows the Pareto's obtained with the values of their objective functions. Among the Pareto's solutions in Table 1, the third answer was selected using the TOPSIS method as the optimal answer for a case study in Iran. Figure 3 shows the optimal locations and the way cover the hospital by organ harvesting centers, as well as coverage of organ harvesting centers by transplant centers at the end of four years period. Figures 4, 5 and 6 show the effect of the satisfaction rate on the first objective function, second objective function and the total number of transplant operations performed. Figure 6 shows that for a transplant operation to be performed, the minimum

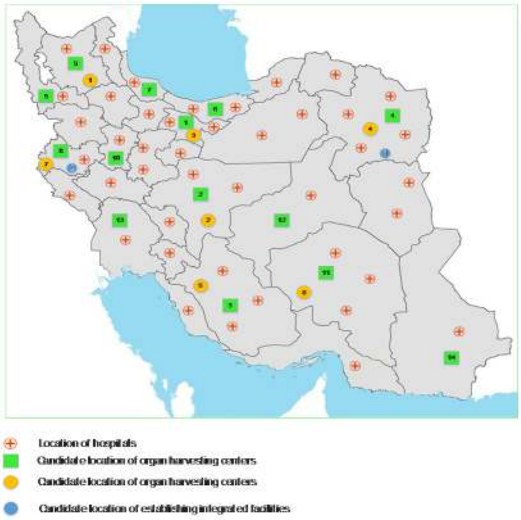

Figure 2. The geographical location of the supply chain centers in Iran

TABLE 1. Pareto solutions for design problem in Iran's supply chain network

The Pareto Answers	OFV_1	OFV_2
1	948612767345	1819.71
2	955022710172	1793.32
3	955905143447	1787.38
4	958748052003	1774.44
5	958998674537	1762.88
6	959177769946	1760.90
7	959437477321	1754.74
8	959862186281	1725.09
9	960311379163	1722.87

patient's family satisfaction rate should be $\beta_h = 0.4$. In addition, when the patient's family satisfaction rate is between 0.4 to 0.6 and 0.7 to 0.9, the number of transplant operations will not change. Figures 7, 8 and 9 show the effect of the viability rate on the first objective function, second objective function, and the total number of transplant operations performed, respectively. Figure 9, shows that for a transplant operation to be performed, the minimum viability rate should be $UD_o = 0.2$. Also, when the organ viability rate is between 0.5 and 0.6 the number of transplant operations will not change. As Figures 6 and 9 show, the patient's family satisfaction rate is more important than the viability rate in the number of transplant operations performed and therefore has a greater impact on the objective function. Figure 10 shows the impact of decisive time threshold for use of air transfer on the first objective function. As it can be seen, system costs decrease as *TA(o)* increases. This indicates that by

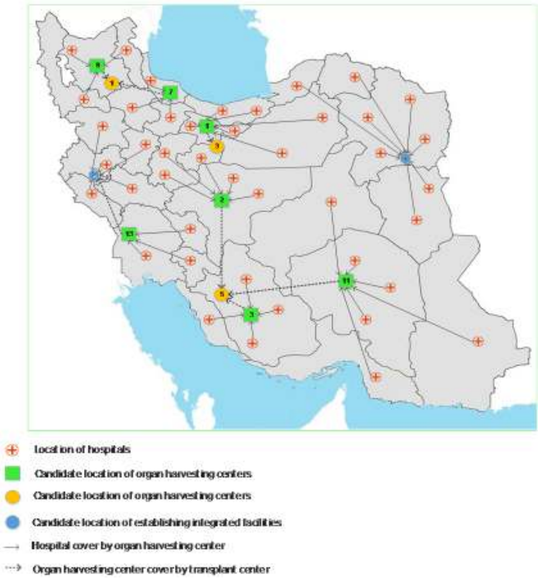

Figure 3. Optimal supply chain network for organ transplant in Iran

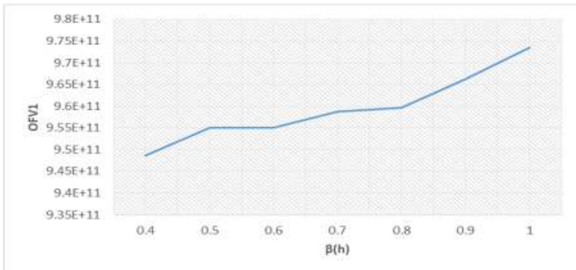

Figure 4. Effect of the satisfaction rate on the first objective function

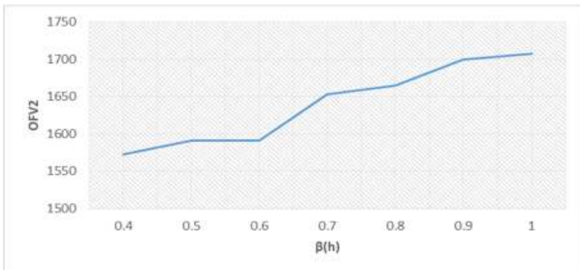

Figure 5. Effect of the satisfaction rate on the second objective function

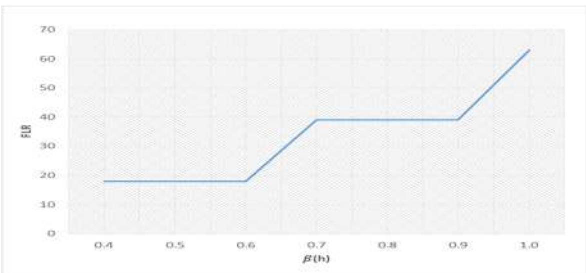

Figure 6. Effect of the satisfaction rate on the FLR

increasing the *TA(o)*, ground transportation increases. Consequently, the system costs decreases. Figure 11 illustrates the impact of the increasing the saving cost for integration of facilities in the potential location on the system costs. It is observed that first objective function has two different trends. First, by increasing the *f (e)*, the systems costs remain constant. After a point, the system costs decrease as *f (e)* increase. It can be concluded that after this point, some facilities are merged. Hence, the related costs to the system decreases as *f (e)* increase.

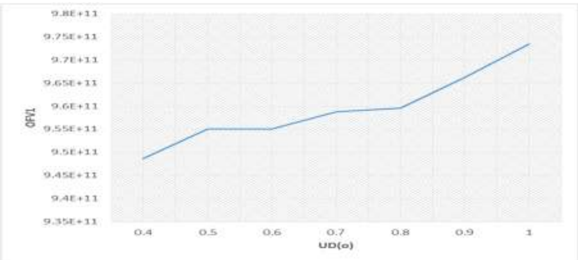

Figure 7. Effect of the viability rate on the first objective function

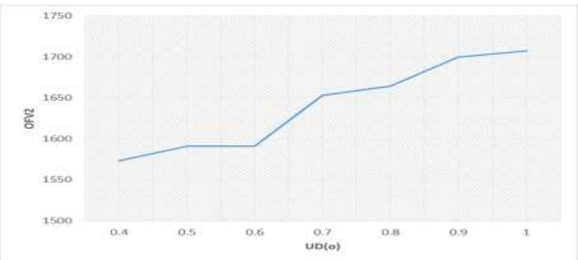

Figure 8. Effect of the viability rate on the second objective function

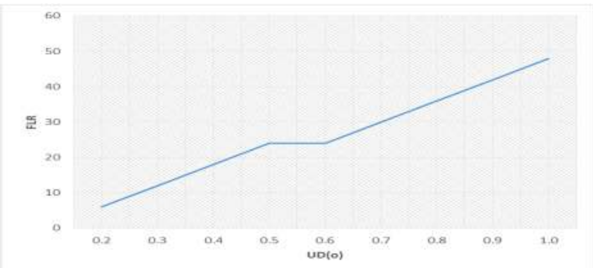

Figure 9. Effect of the viability rate on the FLR

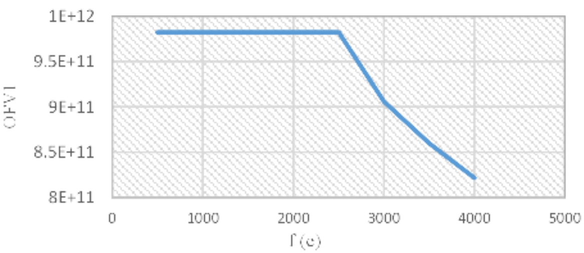

Figure 10. Effect of the TA (o) on the first objective function

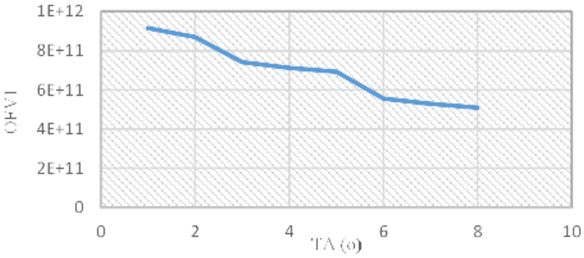

Figure 11. Effect of the f (e) on the first objective function

5. CONCLUSIONS

In this paper, we proposed a new mathematical model for location-allocation of organ harvesting centers and organ transplant centers. It was a bi-objective nonlinear mathematical programming model with uncertain parameters. This model minimized the total cost of construction and handling facilities, as well as the geographical inequalities. The first version of the model was non-linear, so we transform the model to linear one by using some linearization techniques. In this paper, an OTSCN has been designed and the ε-constraint method used to solve the problem in different sizes. Results show that the patient's family satisfaction rate is more important than the viability rate in the number of transplant operations performed and for a transplant operation to be performed, the minimum satisfaction rate β_h and organ viability rate UD_o should be 0.4 and 0.2, respectively. In addition, when the patient's family satisfaction rate is between 0.4 to 0.6 and 0.7 to 0.9, and the organ viability rate is between 0.5 and 0.6 the number of transplant operations will not change. By increasing the *f (e)*, the systems costs remain constant. After a point, the system costs decrease as *f (e)* increase. It can be concluded that after this point, some facilities are merged. Hence, the related costs to the system decreases as *f (e)* increase. For future research, the blood group of patients and donors can be considered or presented as a model for live donors for the kidney organ.

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ε-constraint Method

چکیده

یکی از مهم‌ترین مسائل مربوط به حوزه سلامت و بهداشت، مکان‌یابی و تخصیص محل مراکز برداشت و مراکز پیوند عضو بر اساس هماهنگی عرضه و تقاضا می‌باشد. در این مقاله، یک مدل ریاضی برای مکان‌یابی و تخصیص محل مراکز برداشت و مراکز پیوند عضو ارائه شده است. مدل پیشنهادی نه تنها ارزش فعلی کل هزینه‌های سیستم، بلکه نابرابری‌های جغرافیایی را نیز به حداقل می‌رساند و در برخی از پارامترهای مسئله مانند هزینه، زمان حمل و نقل و غیره با عدم قطعیت همراه هستند. در این مقاله، یک زنجیره تامین پیوند عضو (OTSC) طراحی شده و از روش محدودیت اپسیلون برای حل مسئله استفاده شده است و از ایران به عنوان مطالعه موردی، مورد بررسی قرار گرفته است. نتایج نشان می‌دهند که میزان رضایت خانواده ی بیماران مهم‌تر از نرخ زیست‌پذیری اعضا در تعداد عملیات پیوند و انجام عمل پیوند می‌باشد و حداقل نرخ رضایت‌مندی خانواده‌ها باید ۰/٤ و حداقل میزان نرخ زیست‌پذیری اعضا باید ۰/۲ باشد.

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