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Presenting a Model for Locating and Allocating Multi-Period Hubs and Comparing It With a Multi-Objective Imperialist Competitive Algorithm

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Abstract. Recently, air pollution has received much attention as a result of reflections on environmental issues. Accordingly, the hub location problem (HLP) seeks to find the optimal location of hub facilities and allocate points for them to meet the demands between source-destination pairs. Thus, in this study, decisions related to location and allocation in a hub network are reviewed and a multi-objective model is proposed for locating and allocating capacity-building facilities at different time periods over a planning horizon. The objective functions of the model presented in this study are to minimize costs, reduce air pollution by diminishing fuel consumption, and maximize job opportunities. In order to solve the given model, the General Algebraic Modeling System (GAMS) along with innovative algorithms are utilized. The results presented a multi-objective sustainable model for full-covering HLP, and provided access to a hub network with minimum transport costs, fuel consumption, and GHG (greenhouse gas) emissions, and maximum job opportunities in each planning horizon utilizing MOICA (multi-objective imperialist competitive algorithm) and GAMS to solve the proposed model. The study also assessed the performance of the proposed algorithms with the aid of the QM, MID, SM, and NSP

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indicators, acquired from comparing the proposed meta-heuristic algorithm based on some indicators, proving the benefit and efficiency of MOICA in all cases.

Keywords: Hub Allocation, Stability, Location, Full Coverage, Flexible Coverage Radius

1. Introduction

The high rate of population growth is one of the driving forces of economic development; therefore, there is a dire need to establish much more efficient transfers between source-destination points. Nevertheless, exploiting a direct connection to transmit the flows of information and goods between such points fails to be economically viable, since it demands much energy and time [1,2]. In order to minimize direct connections and the relevant costs in transport networks, an efficient network is often required. For that reason, the hub location problem (HLP) is always employed to design such networks [3]. This problem is one of the newest and most flourishing areas of location theory. It includes the movement of people, goods, and information between sources and destinations [4, 5].

Hubs and nodes are also among the most influential issues in the fields of transport and supply chain, and approximately 80% of trade is globally accomplished through them, as reported by the International Road Transport Union (IRTU) [4,6]. In addition, hubs have been introduced as special facilities that can act as exchanging (viz. swapping), transferring, and sorting points in numerous transport networks and distribution system services [6,7].

As opposed to connecting each source to a destination within a transport network, the flow of materials is often sent from a source to a destination, and then from a hub to a destination in a hub network. In this way, a transport network derives benefit from economic savings. As the costs of transfers between hubs is not higher compared with that of other nodes, utilizing a hub in a network can definitely save much money. Actually, a hub serves as an intermediary between a source and a destination, and all flows initially stay at a hub, and then redistribute from it [3, 8].

In this regard, hub networks can have a significant impact on reducing transportation costs [9]. Environmental and social concerns have also multiplied in recent years. Likewise, a network of hubs constructed to move a flow between various points can have the least negative impact on the environment. However, the positive effects of hub facilities on communities can be maximized. Ground transport networks can further bring many negative impacts to the environment due to the emission GHGs, such as carbon dioxide (CO2). In addition to paying attention to financial issues to minimize costs or maximize profits in planning hub networks, ecological issues should be taken into account. This is in order to decrease damage to the environment by the vehicles recruited to move the flows. Accordingly, respecting social accountability in designing a network allows for a better assessment of its impact on stakeholders, i.e., employees, customers, and local communities. Considering economic, social, and environmental dimensions in designing a hub network can thus account for sustainable HLP. A new approach to network design, sustainability is regarded as a concept that encompasses all three aspects of economic, environmental, and social aspects [10]. The literature on sustainable issues has so far focused primarily on the economic and environmental dimensions, and little attention has been paid to these dimensions in unison [11].

With regard to the dynamic structure of a transport network, some changes may possibly occur over time. For example, demands for nodes may rise or fall, costs may vary,

there may be no need to build a hub at some point in time, and many problems may even arise in the dynamics of a transport network. Alternatively, a hub has a physical structure, including an airport, a port, and a terminal. The construction of the hub as well as the route between the hub and the nodes also demands much money. On the other hand, organizational budgets are limited, and most organizations are merely allowed to spend only a controlled annual budget to meet the costs of establishing such hubs and routes [8, 12].

Therefore, completing a hub network in a short time seems irrational. The study divides the decision period to complete the final network of a hub into several periods and then decides which hubs and routes are formed in each period. Multi-period hub networks can thus provide several advantages, including applying the dynamics and changes of a transport network to a model and removing organizational budget constraints [9, 12]. In today's highly developed world, managers make decisions based on uncertainty as an integral part of their decision-making process. In other words, most parameters vary over short periods. Therefore, it is not feasible to take decisions for a long period of time; in other words, it seems illogical to do so. As well, failure to take into account uncertainty in the parameters of a model produces poor-quality and not very reliable results. To make the outputs consistent, uncertainty in the parameters of a problem should be observed largely in the model [13].

As hubs are often costly physical facilities, i.e., they take relatively much time and money to be built, it is necessary to consider the time required for their formation. In other words, it may take several periods to build a hub if a decision is made to do so [12]. Despite abundant articles on various hubs, published in recent years, there are still many problems and limitations, so ignoring such constraints, but considering real-world conditions can reduce the quality of outputs and responses [8,14].

Consequently, real-world limitations must be applied to a model in order to augment the quality of its outputs. Transport networks should be designed in a manner that minimizes transportation costs, optimizes fuel consumption, and reduces environmental pollution. It will increase the number of job opportunities and have a positive impact on the community. With its various applications in public transport networks, as well as those for sending postal items, consignments, and information transmission, sustainable HLP has attracted lots of attention in recent years [5,15].

In this line, Contreras et al. [14] presented a new multi-objective mathematical model to solve a single-allocation HLP, reflecting on capacity constraints for hub nodes, and combining it with supply chain management. Accordingly, hubs could be considered as industrial settlements, receiving flows from source points and sending them to destination ones. In this research [11], all four modes of HLPs had been ruminated in the problem model. Some problem parameters, such as cost and capacity, had been further considered indefinitely, and even robust optimization had been exploited to solve the problem. The main purpose of this study was to minimize the costs incurred on start-ups and construction sites, the total time of service, and the total emission of GHGs from different modes of transport and factories operating within the hubs.

Of note, achieving high rates of sustainable economic development and employment necessitates effective and efficient environmental protection, which paves the grounds for social progress, in which all people's needs are met. Most mathematical models used for designing networks are typically to minimize costs or maximize profits, but they pay less attention to environmental issues and their constraints. The growing importance of

environmental issues also drives decision-makers to fully integrate environmental factors into their decision-making process. Reflecting on environmental issues in different networks can accordingly have significant impacts on reducing fuel consumption, GHG emissions, air pollution, and so on [7,15]. Transport networks also play a leading role in the design of sustainable networks because transportation includes a wide range of environmental impacts, such as fuel consumption, resource consumption, acidification, toxic effects on ecosystems and humans, noise pollution, and GHG emissions, especially CO_2, which directly influences human health. In other words, the emissions of large volumes of GHGs has currently turned into a public concern for most core nations, particularly developed countries such as the United Kingdom and the United States. Therefore, the ever-increasing concerns about the devastating effects of transportation systems on human health call for modifying such systems to reduce the negative impacts on the environment. In this regard, social responsibility has been defined as "the continuing commitment by business to behave ethically and contribute to economic development while improving the quality of life of the workforce and their families as well as of the local community and society at large." In this line, Alumur and Kara [13] proposed a linear mathematical model for multiple-cycle HLP in single- and multiple-allocation modes, wherein the capacity of the hub nodes could rise over time. In this research, it was possible to change the hub network in any period over the problem-planning horizon, but it was not feasible to close the formed hubs. As well, the results of solving dynamic and static models had been compared with each other, indicating that the use of static models (here, single-cycle ones) might lead to the selection of incorrect locations for the hubs and additional costs incurred on decision-makers. Teymourian et al. [15] also investigated a multi-period full-covering HLP, in which it was possible to change the coverage radius for the hub nodes in each period over the problem-planning horizon. Besides, it was viable to build new hubs or close the existing ones during each period. The problem model was a single-allocation hub, and no capacity-building hub had been provided for this facility. The main objective of this research is to minimize the costs of constructing and closing the hubs in each period of the problem-planning horizon. Most research conducted in this field has been thus far to minimize the costs of infrastructure networks or maximize their profits to meet the demands of the networks and design sustainable ones, but with little attention to environmental and social factors.

Developed and developing countries have increased their attention to environmental and social issues along with economic ones as a result of population growth in recent years. However, the environmental and particularly the social and economic dimensions of multi-period location problems, including HLPs, have been less examined [16,17]. As a result, different responses can be provided by simultaneously considering the dimensions of stability in multi-period HLPs and the coverage radius of hub facilities, so that decision-makers can compare existing conditions and the different aspects of the problem with a great deal of freedom of action and select the most appropriate alternatives [18-20].

In the multi-period models developed in the related literature on full-covering HLPs, the financial,, environmental, and social dimensions have not been considered all at once in the design of sustainable hub networks. For that reason, the present study deals with the design of a sustainable full-covering network considering all economic, ecological, and social dimensions. Research on full-covering long-term HLPs has to date examined the coverage radius of hub nodes as a constant parameter, while this study is to shed light on coverage radius as a decision-making and flexible variable, given that the problem can vary over any

period of the planning horizon. Thus, the present study intends to design a multi-period, fully covered, and sustainable hub network with flexible coverage radius, and to investigate the impact of sustainable economic, environmental, and social factors on it.

2. Research Methods

This research primarily attempts to offer a mathematical model for the multi-period, full-covering, and sustainable HLP, and reflect on economic, environmental, and social dimensions in creating a hub network.

2.1. Proposed Model

In general, hub location problem holds three main assumptions:

- It is not permitted to establish a direct connection between the source and destination nodes and the transfer merely comes about through an intermediary entitled as a hub.
- A complete network is formed by connecting all pairs of hubs.
- Economic savings are made via shifting the route between each pair of hubs with a discount factor of α as a fixed parameter.

Over the course of this study, all the assumptions of the HLP are taken into account, and a mathematical model is accordingly provided. Regarding that, a multi-objective mathematical model is suggested for the multi-period, full-covering, and sustainable HLP. A primary objective of the model is to minimize the costs associated with designing the infrastructure network, to reduce the total amount of CO2 emitted as a result of hub displacements, and to ensure that the infrastructure network maximizes the positive effects on the community. Diminishing hub network costs also includes that of the three phases of flow transmission in the hub network, the cost of building the hub facility, and the cost of closing the existing hubs in each period. Similarly, decreasing CO2 emissions in this model involves reducing the amount of GHGs emitted in the movement between the nodes as well as enhancing the benefits of building a hub network in the community, including creating a greater number of jobs as a result of establishing a hub network.

2.2. Notions

i: source
k : destination
t: period
$EW+LL$: mass of the vehicles
γ_{kl}: represents a constant value for the arc
β : constant value of fuel consumption
v_{ik}^2 : speed of the vehicles

2.3. Problem Formulation

The proposed model here is a multi-objective (viz. three-objective) one for the full-covering HLP, in which the coverage radius is considered as a decision variable. All demands and hubs are also available in zero time.

$$\min \sum_t \sum_i \sum_k c_{tik}(o_{it} + d_{it})x_{ikt} + \sum_t \sum_i \sum_k \sum_l \alpha c_{klt} y^i_{klt} + \sum_t \sum_k frr_{tk} + \sum_t \sum_k cc_{tk} q_{tk} + \sum_t \sum_k ec_{tk} p_{tk} - \sum_t \sum_k ms_t z_t \tag{1}$$

$$\min(EW + LL)\left\{\sum_t \sum_k \sum_l \sum_i \gamma_{kl} y^i_{klt} d_{kl} + \sum_t \sum_k \sum_i (o_{it} + d_{it}) d_{ik} x_{ikt}\right\} + \beta\left\{\sum_k \sum_i \sum_t v^2_{ik} d_{ik} x_{ikt} + \sum_x \sum_l \sum_t v^2_{kl} d_{kl} W_{klt}\right\} \tag{2}$$

$$\max\left(w_{em}\left(\sum_t \sum_k Fj_{tk} Ur_{tk} p_{tk}\right)\right) + \left(w_{ed}\left(\sum_t \sum_k EV_{tk}(1 - rd_{tk}) p_{tk}\right)\right) \tag{3}$$

The research model is a sustainable hub network. The first objective function accordingly minimizes the costs, the second objective function is to reduce fuel consumption, and the third objective function maximizes job opportunities. The first part of the first objective function correspondingly calculates the costs of transferring the flow from the source *i* to the destination *k* during the period *t*. Likewise, the second part of the first objective function computes the costs of transferring the flow between the hub nodes and the third part calculates the costs of covering each node. Of note, the coverage radius of each hub node is equal to the distance of the hub node to the farthest point covered, respected as a variable in this study. Moreover, the fourth part of the first objective function computes the costs of closing a hub node in the period *t*, and the fifth part calculates the costs of constructing a hub facility over the period *t*. The last part of the first objective function also computes the savings of movable facilities.

As the second objective function calculates the amount of fuel consumption in each route between the hub nodes as well as the source node *i* and the hub, *EW+LL* indicates the mass of the vehicles and γ_{kl} represents a constant value for the arc. The second part of the second objective function also computes fuel consumption by the vehicles, wherein β shows its constant value, and v^2_{ik} refers to the speed of the vehicles.

In addition, the third objective function maximizes the positive effects of the hub network on the community. The first part of this objective function boosts the number of job opportunities created in the infrastructure network and the second part maximizes

economic development in the infrastructure network. In fact, the third objective function examines the issue of social sustainability.

2.4. Solving the Model in CPLEX

To implement the model into CPLEX, the terminal designed by the company can be used. To run it, the DOS prompt environment embedded in the Windows operating system must be exploited.

For parameter-setting purposes in this study, near-field communication (NFC) equals 30,000 for the small-size problems, and 100,000 for the large-size ones. The set parameters of MOICA are illustrated in Table 1.

Table 1: The set algorithm parameters

Factors	Optimal real value	
	S	*L*
n-Pop	193	300
N-imp	5	8
P_A	0.54	0.64
P_C	0.6	0.6
P_R	0.12	0.32
ξ	0.195	0.125
β	1.8	2.15

2.5. Model Input Data Value and Distribution

The problem data are generated by the MATLAB software, whose value and distribution are shown in Table 2.

Table 2: The problem input data value and distribution

	Parameter						
	N	N	*Dij*	*Cij*	*Tij*	*Fi*	*FVk*
Value & distribution	10 15	40 50	U~(10, 20)	Fuzzy(50)	N~(40, 6)	Fuzzy(2000)	Fuzzy(200)
	20	70					
	25	100	*dj*	*sjk*	*wjk*	*Q*	
	30		Fuzzy(100)	N~(12, 4)	N~(8, 2)	Fuzzy(400)	

To produce the fuzzy data, a mean value is first given for the parameter concerned, and then its upper and lower limits are multiplied by a random number that is uniformly between 0.2 and 0.8. For each problem, a certain number of potential locations for the construction of the infrastructure and the predetermined nodes are considered, varying depending on the number of network points. The total number of the problem sets to

evaluate the performance of the proposed algorithm is 67. Each input dataset is also executed four times by the algorithms alone, and then the best response is regarded as the final output of the proposed algorithm. To explicate the numbering of the problems, it is of importance to first write the number of the nodes (viz. customers), then put a # sign, and subsequently add the number of the hub centers (here, distributions) that should be allocated. For example:

50 knots with 4 hubs: 450

2.6. Comparative Indicators to Evaluate the Response Quality

To compare the algorithms, some indicators have been thus far recruited, as briefly described below.

 Quality measure (QM): It is such that all the Pareto responses obtained by each algorithm are considered together, then negation as the logical complement is performed for all responses. Finally, the quality of each algorithm is equal to the share of the new Pareto responses specific to it. In this sense, higher quality implies better algorithm.

 Mean ideal distance (MID): The value of this indicator is equal to the distance of the Pareto points of the algorithm concerned from the ideal point. It is also calculated by the following equation:

$$\mathrm{MID} = \frac{\sum_{i=1}^{n} \sqrt{\left(\frac{f_{1i} - f_1^{best}}{f_{1,total}^{max} - f_{1,total}^{min}}\right)^2 - \left(\frac{f_{2i} - f_2^{best}}{f_{2,total}^{max} - f_{2,total}^{min}}\right)^2}}{n} \tag{4}$$

 Dispersion measure (DM): This indicator, calculated by Eq. 5, shows the amplitude of the Pareto solutions of an algorithm; therefore, the higher the DM, the better the algorithm.

$$\mathrm{DM} = \sqrt{\left(\frac{\max f_{1i} - \min f_{1i}}{f_{1,total}^{max} - f_{1,total}^{min}}\right)^2 + \left(\frac{\max f_{2i} - \min f_{2i}}{f_{2,total}^{max} - f_{2,total}^{min}}\right)^2} \tag{5}$$

 Statute mile (SM): This indicator demonstrates the uniformity of the distribution of the Pareto solutions in the solution environment, and it is calculated via Eq. 6:

$$\mathrm{SM} = \frac{\sum_{i=1}^{n-1} \left|\bar{d} - d_i\right|}{(n-1)d} \tag{6}$$

 Number of Pareto solutions (NPS): The standard value of this indicator refers to the number of Pareto responses found in each algorithm.

 Computing process time (CPU): It is one of the most important indicators in the application of any meta-heuristic algorithm.

3. Results

To compare the performance of the proposed MOICA, 67 datasets created by both algorithms are run, and evaluated using the four indicators mentioned in the preceding section. Before presenting the multi-objective examples, three small-size examples are solved, and subsequently compared via the General Algebraic Modeling System (GAMS) and innovative algorithms. The results show that the proposed model works well for implementing meta-heuristic methods, as given in Table 3.

Table 3: Comparing GAMS output and single-objective genetic algorithm (GA)

Problem no.	GAMS	Time	GA	Time
10#3	575149107098/0026	30.1019	575149107098/0026	112.11
10#4	623941362023/1260	29.1314	623941362023/1260	29.14
15#3	703697126301/1710	10.2615	703697126301/171	44.17

The following are the outputs of solving the model with multi-objective meta-heuristic approaches. The numerical results of the solution are as provided in Table 4.

Table 4: The results of numerical solution of QM and SM for small-size sample problems

Problem no.	MOICA (QM)	MOICA (SM)
10#3	0.765	0.741
10#4	0.895	0.778
15#3	0.750	0.920
15#4	1	0.868
15#5	1	0.634
20#3	1	0.881
20#4	0.765	0.973
20#5	0.565	0.874
20#6	0.434	0.924
25#3	0.900	1.361
25#4	0.727	1.287
25#5	0.708	1.220
25#6	0.809	1.481
30#3	0.750	1.116
30#4	0.647	0.810
30#5	1	0.978
30#6	1	0.980
30#7	0.882	1.041
30#8	1	0.642

In all sample problems, the QM, DM, and SM related to the MOICA are better than the non-dominated sorting GA (NSGA-II). In addition to the above-mentioned indicators, the MID associated with the MOICA is lower in all sample problems (Table 5). Accordingly, it is concluded that the proposed MOICA outperforms the NSGA-II.

Table 5: The results of various indicators and MID for small-size sample problems

Problem no.	MOICA (DM)	MOICA (MID)
10#3	1.574	0.518
10#4	1.414	0.581
15#3	1.414	0.242
15#4	0.664	0.348
15#5	0.444	0.230
20#3	1.087	0.523
20#4	0.896	0.399
20#5	1.169	0.538
20#6	1.161	0.621
25#3	1.381	0.247
25#4	1.297	0.718
25#5	1.314	0.511
25#6	1.414	0.287
30#3	1.279	0.632
30#4	1.178	0.485
30#5	1.478	0.500
30#6	0.010	0.379
30#7	0.947	0.276
30#8	1.184	0.554

Table 6: The numerical solution results for size 40 and 100 of different distribution centers

Problem no.	Size=40	
	MOICA (QM)	MOICA (SM)
40#3	0.928	1.390
40#4	0.364	1.267
40#5	0.642	0.649
40#6	0.500	1.321
40#7	0.630	1.372
40#8	0.958	0.935
40#9	0.760	1.410
40#10	0.778	0.928
Problem no.		
	MOICA	MOICA
40#3	1.267	0.430
40#4	1.175	0.452

40#5	1.176	0.377
40#6	1.179	0.408
40#7	1.064	0.563
40#8	0.827	0.322
40#9	1.132	0.431
40#10	1.350	0.360
Problem no.	Size=40	
	MOICA (QM)	MOICA (SM)
100#3	1	0.653
100#4	0.5	1.364
100#5	1	1.177
100#6	0.750	0.568
100#7	0.583	1.044
100#8	1	0.547
100#9	1	0.454
100#10	1	0.963
100#11	1	0.580
100#12	1	0.711
100#13	1	0.392
100#14	1	1.028
100#15	1	1.355
100#16	1	1.114
100#17	1	0.765
100#18	1	1.036
Problem no.		
	MOICA	MOICA
100#3	0.656	0.243
100#4	1.080	0.440
100#5	1.164	0.099
100#6	0.834	0.397
100#7	1.016	0.230
100#8	0.367	0.147
100#9	0.562	0.027
100#10	0.955	0.275
100#11	0.680	0.275
100#12	1.191	0.340
100#13	0.657	0.175
100#14	0.895	0.218
100#15	1.121	0.482
100#16	1.156	0.392
100#17	0.891	0.179
100#18	0.943	0.280

Table 6 shows the results of all four indicators for the problems with sizes 40 and 100, along with the number of different distribution centers (i.e., hubs). It is concluded that the

proposed MOICA can be a good choice to solve large-size problems as well as small-size ones. As the size of the problems exceeds 20, they enter the phase of difficult cases, and mathematical optimization problem algorithms are not able to solve them in HLPs, so high-performance meta-heuristic algorithms should be employed. It should be noted that the MOICA could be among the most efficient algorithms to solve HLPs.

4. Conclusion

Regarding population growth and increased human activities, the negative effects of these events on the environment and different communities have also been deliberated. This research was thus an attempt to provide a mathematical model for the multi-period, full-covering, and sustainable HLP, and reflect on the economic, environmental, and social dimensions of designing a hub network. In addition, the model presented in this research was solved with GAMS and meta-heuristic algorithms, including the MOICA and the NDSGA-II. A multi-objective sustainable model for full-covering HLP was suggested that provides access to a hub network with minimum transport costs, fuel consumption, and GHG emissions, and maximizes job opportunities at each planning horizon using MOICA and GAMS. Moreover, the study evaluated the performance of the proposed algorithms using the QM, MID, SM, and NSP indicators, obtained from the comparison of the proposed meta-heuristic algorithm based on some indicators, which demonstrated the advantage of MOICA in all cases. As regards future studies, it is recommended that the applications of multi-period HLP in real-case studies, including healthcare systems and crisis management are investigated by scholars.

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