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RISK ANALYSIS OF SERVICE NETWORKS DISRUPTION

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Abstract: The number and locations of facilities represent the most important decisions when modeling service networks. The facility location problem in the context of service networks is predetermined by the investment costs and/or achieving a certain standard of satisfying users' demand. Systems designed in this way are based on the idea that they will function in regular exploitation conditions, without any interference. However, various adverse events caused by intent, unintentional human activities, technological disasters or natural disasters can lead to a partial or complete cessation of the service networks. For the first time, this paper highlights the importance of the impact assessment of disruption events on the service networks where the r-interdiction median location model is presented as a potential solution approach in a case when these events occur. Also, an extensive overview of the state-of-the-art literature is provided. Finally, a numerical example of the determination of the most vulnerable points of service networks is given to illustrate the effects of potential disruptions, as well as appropriate preventive actions that eliminate or at least mitigate those situations.

Keywords: service networks, facility location, disruptions, r-interdiction median location model.

1. Introduction

The number and locations of facilities represent the most important decisions when modeling service networks from the aspects of timeliness and availability in the provision of services, that is, efficiency in their exploitation. The timeliness of response to user requests and the availability of services mitigates as the number of facilities decreases. This is a consequence of "conflicting" interests between operators and users of service networks. On the one hand, locating a large number of facilities on the service network improves the operator's availability and willingness to respond to user requests on time, while increasing investment and operational costs (i.e. reducing the efficiency of the service network). On the other hand, locating fewer facilities on service networks increases its efficiency, while compromising on service quality (i.e. timeliness and availability decrease).

There are three service network indicators:

- Availability – The service network is available if all users are served within the established quality standard, based on the preferred length/duration of the journey to at least one located facility. This service network indicator is optimized by minimizing the total number of located service facilities that achieve this.

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- Efficiency (of the service network) – Represents the maximum effect in satisfying user demand, the established standard of service quality, which the operator can realize with a limited number of facilities located on the service network. This service network indicator is optimized by maximizing the number of users served.
- Timeliness (reactions to user requests) – Represents the ability of the service network operator to serve users on time. This service network indicator is optimized by minimizing the total weighted distance traveled (travel time) between service facilities and users.

Traditional approaches to facility location are based on the assumption that systems will function as intended and designed, without any interference. However, adverse events caused by intent (e.g. cyber-attacks, strikes, terrorist attacks, and theft), unintentional human activities (e.g. accidental data loss or equipment damage), technological disasters or natural disasters (e.g. earthquakes, hurricanes, landslides, floods, etc.) can make the designed systems non-functional for some time or even result in the loss of life and/or property. Today, the importance of identifying potential harmful events and the risk of their impact on existing systems is increasingly being recognized. Namely, when some disturbing events happen, the services provided by the observed system can be degraded or even destroyed.

The transportation network and the facilities located on it represent the key elements of every production, distribution and service system, and the research on the risk of disruption events and their impact on disruptions in the functioning of these systems belongs to the field of disaster management. The focus of this paper is the investigation of disruption in the functioning of service network facilities as a consequence of the occurrence of unwanted events, whose modeling in location theory is relatively new. In the literature, three main questions need to be answered in the research of malfunctioning objects of different systems (Laporte *et al.,* 2015):

- How destructive can the disruption be to the system, that is, how much damage can it cause? By answering this question, vital objects are found, i.e. objects whose disabling causes the greatest damage to the system.
- Are there ways to protect the system from disruption? By answering this question, we find ways to protect the facilities to prevent disturbances in the functioning of the system. Depending on the unwanted events and disruptions that the system suffers because of them, the protection of facilities can also involve simpler activities such as providing backup power generators or strengthening security and safety systems that will repel potential attackers. On the other hand, such activities could also include planning the relocation of an object to a nearby location that is less susceptible to an unwanted event, such as a flood.
- Is there a possibility to reconfigure the existing system or create new ones that will better respond to the risks of potential disruptions? The answer to this question opens up the possibility of creating completely new systems resistant to the potential effects of disturbances.

The subject of this paper is the analysis of the risk of disruptions in the functioning of service networks such as the postal network, parcel locker network, automated teller machines, etc. through the modeling of the service network in a way that determines the most unfavorable effects of ceasing the functioning of a given number of objects in the observed system by applying the r-interdiction median location model. The goal is to analyze the vital facilities of the service network, i.e. facilities whose disabling causes the greatest damage to the system, which is the first step in the analysis of the risk of disruptions in the functioning of service networks and a prerequisite for creating a strategy aimed at preventing or mitigating the effects of disruptions.

The paper is organized as follows. Section 2 gives an extensive overview of the studies relevant to this research. In the third section, the formulation of the applied location model is shown and explained, while the fourth section contains an illustrative example of a service network on which its application is demonstrated, the results are given, as well as their discussion. In the last section of the paper, concluding considerations and directions for further research are given.

2. Literature Review

Until the beginning of the 21st century, almost all authors who dealt with location analysis ignored the analysis of the risk of disruption in the functioning of the system when optimizing the locations of objects. Due to a very wide range of disruptions that have become occurred in the last twenty years (from natural and technological disasters to strikes and terrorist attacks), interest in modeling the vulnerability of service networks has increased. The papers of Church *et al.* (2004) and Snyder and Daskin (2005) were fundamental papers that dealt with the problem of testing the reliability and resilience of located objects on the network. Church *et al.* (2004) proposed two new location models based on the p-median model and the maximum coverage model. Both models for the observed system identified those locations of facilities that, if they became non-functional, had the greatest impact on the provision of services. Furthermore, the authors upgraded the mentioned models, so in the paper of Snyder and Daskin (2005) a multi-criteria model based on the p-median model was proposed, in which it was assumed that p objects had an equal probability of falling out of the system, and then each of the users was allocated to objects of lower hierarchical level in case all higher-level objects are non-functional. The first objective function represented the total distance traveled by the user to objects of a higher hierarchical level, while the second objective function represented the expected transport costs due to the failure of individual objects at a lower hierarchical level of the system.

Berman *et al.* (2007) looked at the problem of locating objects that explicitly took into account the possibility that some of the objects fall out of the system, which led to users seeking service from functional objects, but this increased transportation costs. The proposed model was a generalization of the p-median model, and the model was applied to the locations of general hospitals in Toronto. The applied model showed that the evaluation of the quality of current hospital locations largely depends on whether the possibility of disruption is taken into account, whereby the current system functions close to optimal if the probability of disruption is high. Church and Scaparra (2007) extended the r-median interdiction model to include the protection of facilities. That resulted in a two-level mathematical programming model that simultaneously took into account both exogenous and endogenous disturbances caused by deliberate attacks on the system.

Azad *et al.* (2013) provided a mixed-integer linear program to model partially and fully disrupted supply chains. Goods-sharing and soft-hardening strategies were adopted to improve the robustness of the framework. Zhu *et al.* (2013) discussed the problem of protecting critical infrastructure in supply systems concerning potential intentional attacks. The authors proposed a probabilistic model of r-median interdiction and developed a greedy heuristic to solve problems of larger dimensions. Maleki and Khanduzi (2015) dealt with the modeling and formulation of r-median interdiction with the protection of objects in a phased environment. Starita *et al.* (2017) proposed a non-linear scenario-based modeling framework for protecting a road transportation system against flooding events. A greedy randomized adaptive search procedure was adopted to generate the best protection plans for road transportation systems in a multi-period planning horizon.

Lei (2019) explored the vulnerability of express delivery systems of perishable goods and high-value commodities. A multi-allocation p-center hub location model is offered to mitigate the degradation of service when losing certain hubs. Bhuiyan *et al.* (2020) introduced a two-stage stochastic program to explore the imperfect effects of protection and disruption under both exogenous and endogenous uncertainty. The accelerated L-shaped decomposition algorithm decided how much protection to invest in the facilities to minimize the expected post-disruption transportation cost. Forghani *et al.* (2020) presented a mixed integer bi-level programming model for minimizing disruption satisfaction costs of customers' demand in hierarchical service systems. A heuristic algorithm was developed to solve the addressed problem under partial interdiction (i.e. limited functionality loss) settings. Hien *et al.* (2020) developed a network fortification model for fortifying transportation networks. They aimed to maximize total demand shortfalls by reallocating defensive resources. The robust stochastic approximation approach was utilized for solving the investigated problem under random demand.

Recently, Zhang *et al.* (2021) extended the r-median interdiction model to include the aspect of protecting objects from potential disruptions in functioning as a consequence of unwanted events caused by intent. The presented model of integer programming took into account the limited resources for the protection of objects. Li *et al.* (2022) provided a two-stage stochastic bi-level program for protecting facilities against attacks with and without considering risk propagation strategies. Also, they utilized a game-theoretic framework for representing network operators (i.e. defenders), attackers, and customers. A hybrid solution approach based on the genetic algorithm was provided to minimize location, protection, and network costs. Finally, an extensive overview of the studies relevant to this research is given in Table 1.

Table 1
Overview of the Studies Relevant to this Research

Author(s) and year	**Research focus**	**Single-multi objectivity**		**Type of objective function(s)**		**Type of parameters**			**Solution approach**		
		Single	Multi	Max	Min	Crisp	Prob.	Fuzzy	Exact	Heuristic	Metaheuristic
Church et al. (2004)	Critical facility asset identification	✓	✗	✓	✗	✓	✗	✗	✓	✗	✗
Snyder and Daskin (2005)	Facility location reliability	✗	✓	✗	✓	✓	✗	✗	✓	✓	✗
Berman et al. (2007)	Unreliable facility centralization and co-location	✓	✗	✗	✓	✓	✓	✗	✓	✓	✗
Church and Scaparra (2007)	Supply facility fortification under intentional strikes	✓	✗	✗	✓	✓	✗	✗	✓	✓	✗
Azad et al. (2013)	Supply chain networks under facility and transportation disruptions	✓	✗	✗	✓	✓	✓	✗	✗	✓	✗
Zhu et al. (2013)	Critical infrastructure protection under intentional attacks	✓	✗	✗	✓	✓	✓	✗	✓	✓	✗
Maleki and Khanduzi (2015)	Infrastructure protection under disruption event	✓	✗	✗	✓	✓	✗	✓	✓	✓	✗
Starita et al. (2017)	Critical infrastructure protection under flooding events	✓	✗	✗	✓	✓	✓	✗	✗	✓	✗
Lei (2019)	Hub-and-spoke networks under disruptions	✓	✗	✓	✗	✓	✗	✗	✓	✗	✗
Bhuiyan al. (2020)	Transportation network design with multiple protection levels	✓	✗	✗	✓	✓	✓	✗	✗	✓	✗
Forghani al. (2020)	Hierarchical systems with partial interdiction	✓	✗	✗	✓	✓	✗	✗	✗	✓	✗
Hien et al. (2020)	Transportation network resilience with defensive resources	✓	✗	✓	✗	✓	✓	✗	✗	✓	✗
Zhang et al. (2021)	Supply chain networks under random and intentional disruptions	✓	✗	✗	✓	✓	✓	✗	✗	✓	✗
Li et al. (2022)	Facility location and protection under non-cooperative attacks	✓	✗	✗	✓	✓	✓	✗	✗	✓	✓
Our study	Service networks under disruption events	✓	✗	✓	✗	✓	✗	✗	✓	✗	✗

3. Service Network Modeling under Disruption

The r-interdiction facility location model considers the existing service network as a median facility location problem, which is the most common situation in practice. It determines the most unfavorable effects of the cessation of functioning of a given number of objects (*r*) on the network, determining the maximum weighted distance between the remaining objects on the network and the users associated with the remaining objects closest to them. Therefore, the inability of one or more facilities to provide services results in a decrease in the quality of services of the observed network through an increase in transport costs, and the locational problem of the r-median interdiction establishes which *r* service facilities, by ceasing to function, would lead to the greatest increase in transport costs in providing services to users.

The following notation was used in the formulation of the location problem of the r-median interdiction:

I – Set of existing locations for the facilities, indexed by *i*
J – set of users, indexed by *j*
i,k – indexes of existing locations of the network's nodes
V_j – demand of user *j*
d_{ij} – the shortest distance between facility *i* and user *j*
r – number of facilities to be interdicted

$T_{ij} = \left\{ k \in I \middle| d_{kj} > d_{ij} \right\}, \forall i \in I, j \in J$ – Sets defined for each facility *i* and customer *j* representing the set of existing sites that are farther than *i* is from demand *j*

Decision variables:

$$X_i = \begin{cases} 1, & \textit{if facility i is disabled} \\ 0, & \textit{otherwise} \end{cases}$$

$$Y_{ij} = \begin{cases} 1, & \textit{if location i serves users in j} \\ 0, & \textit{otherwise} \end{cases}$$

The mathematical formulation of the problem is (Church et al., 2004):

$$\max \sum_{i \in I} \sum_{j \in J} V_j d_{ij} Y_{ij} \qquad (1)$$

s.t.

$$\sum_{i \in I} Y_{ij} = 1, \quad \forall j \in J \qquad (2)$$

$$\sum_{i \in I} X_i = r \qquad (3)$$

$$\sum_{k \in T_{ij}} Y_{kj} \le X_i, \quad \forall i \in I, j \in J \qquad (4)$$

$$X_i = \{0,1\}, \quad \forall i \in I \qquad (5)$$

$$Y_{ij} = \{0,1\}, \quad \forall i \in I, j \in J \qquad (6)$$

The objective function maximizes the demand-weighted total cost after the interdiction of *r* facilities. Constraints (2) ensure that each customer is assigned to a facility after interdiction, while constraints (3) stipulate that exactly *r* facilities are to be interdicted. Constraints (4) force each customer *j* to be assigned to its closest non-interdicted facility. Finally, constraints (5) and (6) represent the binary restrictions on the assignment and interdiction variables, respectively.

3.1. Numerical Example

The proposed model was tested on an illustrative example of the service network consisting of 16 nodes of existing facility locations (*i*=1, ..., 16) and 17 nodes representing users' demands (j=1, ..., 17). Table 2 represents users' demand while Table 3 represents the shortest distances between users and facilities on the network.

Table 2
Users' Demand

j	Number of users	*j*	Number of users
1	213,742	10	57,607
2	183,003	11	56,865
3	177,338	12	51,889
4	174,197	13	46,406
5	168,841	14	45,253
6	165,739	15	35,732
7	108,198	16	26,855
8	86,585	17	19,819
9	72,124		

Table 3
Shortest Distances between Users and Facilities on the Observed Network [km]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	8.0	9.5	11.2	9.4	3.9	1.3	11.4	27.7	34.2	3.3	62.6	52.5	27.2	2.7	3.0	34.1	53.7
2	8.4	14.3	10.6	11.1	1.5	3.7	8.4	31.9	33.6	2.6	59.2	47.9	26.6	4.9	3.5	30.7	49.1
3	2.8	13.8	11.5	1.5	10.3	7.4	13.9	40.8	44.7	9.9	62.9	56.8	20.0	6.3	6.5	34.4	58.0
4	10.0	27.0	2.9	13.9	8.7	10.4	2.2	41.2	30.0	8.3	52.2	57.2	25.9	10.2	9.8	23.7	35.9
5	43.3	51.4	27.8	44.8	33.4	33.4	33.1	64.0	0.9	33.1	40.5	61.1	27.7	33.2	32.0	24.7	45.3
6	77.7	85.8	52.1	79.2	62.3	62.3	52.8	70.9	41.8	62.0	1.1	48.9	63.2	63.3	62.0	35.8	41.3
7	54.5	70.5	54.6	57.4	48.2	50.5	57.1	36.0	79.6	49.1	50.4	0.8	72.7	52.3	50.0	33.7	14.7
8	40.0	36.8	42.2	43	33.7	36.1	42.6	1.0	65.2	34.7	71.4	36.0	58.2	37.9	35.6	38.2	38.5
9	22.6	38.7	12.6	25.6	10.7	11.7	9.0	26.4	47.8	10.3	61.3	42.4	40.8	12.9	11.2	32.8	37.3
10	56.2	72.3	35.2	59.1	49.9	52.2	35.8	37.8	45.7	50.9	43.1	15.2	50.2	54.1	51.7	20.0	0.15
11	34.4	61.6	22.9	37.3	33.1	33.6	23.5	37.6	24.6	32.8	34.3	37.5	37.8	32.9	31.6	0.3	21.7
12	18.5	19.6	43.1	14.9	24.8	24.6	28.4	55.2	48.9	24.3	86.2	71.3	24.2	22.8	23.6	57.7	69.9
13	18.9	27.4	23.1	20.8	25.6	25.4	26.7	56.6	28.9	27.2	66.2	72.1	0.75	23.6	24.8	37.7	49.8
14	25.8	6.9	21.4	20.9	16.0	12.4	21.5	48.7	60.4	14.7	72.8	63.2	35.7	13.0	13.2	44.3	64.4
15	5.5	14.7	9.7	7.2	5.3	3.8	10.1	37.0	32.6	3.7	66.2	53.0	25.9	2.6	2.2	32.4	47.9
16	16.1	32.2	5.8	19.0	14.8	16.5	9.6	45.4	21.9	14.6	55.7	58.5	16.9	14.7	13.4	23.2	35.4

The solver LINGO 19.0 was used to solve the proposed location problem. Figure 1 shows the solutions to the problem regarding the maximum value of the objective function for different values of the parameter r, while Table 4 shows the location indexes of the facilities on the illustrative service network that, for a given r, lead to the greatest disturbances in its functioning, i.e. to the maximum values of the objective function.

In the case when $r=0$, i.e. when all existing objects are functioning, the value of the objective function is 9,817,927. It should be noted that this is also the value of the objective function if this problem were to be solved as a p-median location problem for $p=16$, from where the connection between the r-median of the interdiction and the p-median of the location problem can be observed. In the event of a disruption in the functioning of the system, which implies the loss of the function of one of the service objects ($r=1$), the loss of object 8 (Table 4) would have the greatest negative impact on the system, when the value of the objective function would be 31810520, which is 3, 24 times higher value than when all facilities are in operation, i.e. transport costs of providing services would, in that case, be increased by 324% compared to regular system functioning conditions. When $r=2$, the value of the objective function is 50,698,700, and the two objects whose cessation of functioning would lead to such a value of the criterion function, i.e. have the greatest negative impact on the transport costs of the service network, are 6 and 8 (Table 4) and so on. Therefore, the results from Table 4 provide analysts and system management with information on which facilities are the most disruptive in the functioning of the service network when they fail, which opens up the possibility to determine priorities following the available finances, i.e. the order in which prevention activities for these facilities would be undertaken to reduce the risk of identified potential disorders.

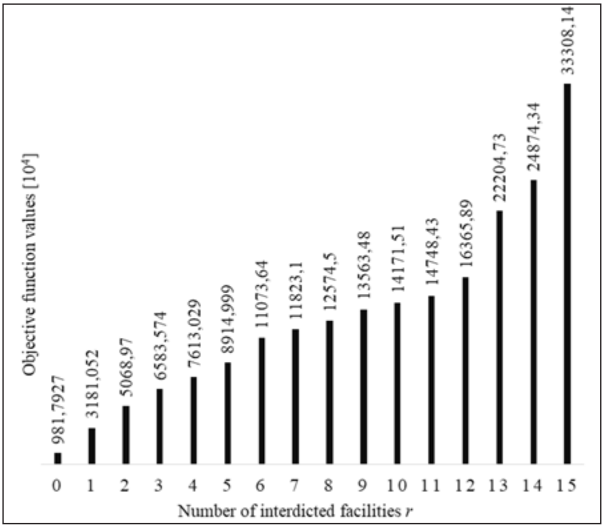

Fig. 1.

Objective Function Values depending on the Number r

Table 4
r Locations that have the most Influence on the System Functioning

r	**Interdicted Locations**
1	8
2	6, 8
3	5, 6, 8
4	5, 6, 8, 11
5	5, 6, 7, 8, 11
6	5, 6, 7, 8, 10, 11
7	5, 6, 7, 8, 10, 11, 13
8	5, 6, 7, 8, 10, 11, 13, 16
9	4, 5, 6, 7, 8, 10, 11, 13, 16
10	4, 5, 6, 7, 8, 9, 10, 11, 13, 16
11	2, 4, 5, 6, 7, 8, 9, 10, 11, 13, 16
12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 15
13	1, 2, 3, 4, 5, 8, 9, 11, 12, 13, 14, 15, 16
14	1, 2, 3, 4, 5, 6, 8, 9, 11, 12, 13, 14, 15, 16
15	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16

4. Conclusions and Implications

This paper emphasizes the importance of conducting a risk analysis of disruptions in the functioning of service networks. The location problem of the *r*-median interdiction was applied to model the considered problem. An extensive overview of the state-of-the-art literature is provided to outline the novelty of the explored topic; i.e., the analysis of service networks under disruption events. A numerical example of determining the most vulnerable points of service networks is presented to analyze in detail the effects of disruptions and determine the order in which prevention activities would be undertaken.

An important direction of future research into the vulnerability of service networks is the extension of the presented r-median interdiction model formulated as a hierarchical location model which enables measurement of interdicted/protected facilities' scenarios. Also, following the concept of sustainable development, for modeling the vulnerability of service networks, in addition, to transport costs that very well represent both the functioning of service networks and the effects of disruptions, it makes sense to include in consideration other representations of disruptions, such as negative ecological effects that disturbances can cause in the environment, etc. In this way, the observed problem would move to the domain of multi-criteria optimization which is another possible future research direction. To solve a multi-criteria optimization model structured like this, in cases where there are a large number of existing locations of service network facilities and user nodes, it is necessary to apply one of the many existing metaheuristics such as the colony predation algorithm (Tu *et al.,* 2021), earthworm optimization algorithm (Wang *et al.,* 2018), elephant herding optimization (Wang *et al.,* 2015), hunger games search (Yang *et al.,* 2021), monarch butterfly optimization

(Wang *et al.,* 2019), slime mould algorithm (Li *et al.,* 2020), etc. In this sense, future research will go in the direction of solving problems of larger dimensions, which would be a service network of realistic dimensions. Future research may utilize some other representative computational intelligence algorithms to solve the investigated problem, like.

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