A MULTIOBJECTIVE APPROACH FOR SUSTAINABLE AND RESILIENT OPERATIONS NETWORK DESIGN IN SUPPLY CHAIN

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Abstract

Sustainable and resilient operations network design (OND) is a rich area for academic research that is still in its infancy and has potential to affect supply chain performance. Increasing regulations for environmental and social management are forcing firms to consider their operations network from ecological and community objectives. Besides that, facilities and the links connecting them are disrupted from time to time, due to poor weather, natural or manmade disasters or a combination of any other factors, having an extensive effect on return on investment and overall network performance. Therefore, beyond bearing in mind the expected level of network activity, decision makers must evaluate the network exposure to risks.

Recent literature reviews researches showed that there is a gap in works that have considered sustainability and resilient concepts jointly and fully, that is, contemplating, simultaneously, the restorative, adaptative and absorptive capacities, on resilient goal, and the economical, environmental and social pillars of the sustainability.

In this context, this work proposes a novel multi-objective optimization model for designing operations network sustainable and resilient, to a variety of uncertain potential disruptions. The model seeks investment-recovery combinations that minimize the amount invested, the overall network operation cost, the environmental and social impacts of the network and that maximize the distribution network resilience, regarding to the level of service provided to customers in the supply chain. A multi-objective genetic algorithm (MOGA) is used to solve the proposed model for OND problem. A set of numerical experiments illustrates how changes to disruption scenarios probabilities affect the optimal resilient design investments.

Keywords: Operations Network Design, Supply Chain Design, Resilience, Sustainability, Disruption Risks, Multiobjective Genetic Algorithm

1. Introduction

In Supply Chains Management (SCM), developing an efficient operations network design (OND) have the potential to reduce costs related to production, storage and transportation in addition to ensure stakeholders expectations and higher profits [1]. In fact, OND involves strategic long-term decisions, regarding the number, location, capacity, “from-to” flows and type of facilities in the network [2], that have an extensive effect on return on investment and overall supply chains performance [3]. Furthermore, customers have been demanding products to be at the desired place and time, increasing service level expectations [4].

In this context, decision makers must take into account the future level of supply chains activity [5] and the operations exposure to risks, as their impacts depends on the characteristics of both the disruptive event and the network design [6]. Experts have suggested that supply chain disruptions have become more frequent, possibly because of the increasing complexity and vulnerability of the networks due to the internationalization of supply chains [7,8].

Thanks to increasing market pressures, there is a tendency among decision makers to change the generally adopted reactive attitude, and thus incorporate the concept of resilience into SCM [9] as a way to identify alternatives before changes to their operations network or its environment occur [10]. To that end, the system must be embedded with the capacity to absorb, adapt and recover from an adversity or a change in normal operating conditions [11]. These three capacities correspond to the resilience pillars [12] and their incorporation into the system can be accomplished through pre-event investments.

Furthermore, due to increasing global awareness about environment and sustainability, and pressures from various stakeholders, especially government regulators and non-governmental organizations, companies are trying to engage with sustainable practices [13,14]. However, the works above mentioned, that deal with SCM by seeing resilience and sustainability aspects, do not consider all three resilience pillars (absorption, adaptation and recovery) and the sustainability triple bottom line (economical, environment and social aspects) simultaneously.

Then, the main objective of this work is to develop a novel and complete mathematical decision OND model that seeks sustainable and resilient supply chains, including first stage decisions, and second stage decisions, besides the pre-event investment strategies to dampen disruption effects, considering that the supply chain will be exposed to external disruptions. A multi-objective optimization model that incorporates economic, environmental and social aspects as well as resilience assessment is established.

Given the multi-objective approach used, the existence of nonlinear functions and the combinatorial nature of the domain set, a multi-objective genetic algorithm (MOGA) is elaborated to obtain the Pareto set for the problem [15,16], with the construction of specific genetic operators in order to avoid that MOGA evaluates unfeasible solutions. The solutions obtained from MOGA will represent the optimal trade-offs that are inherent to sustainable and resilient OND.

The applicability of the proposed model and the construction of the Pareto Front is showed for an example based from [9] of a garment manufacturing supply chain. The analyzes performed a scenarios that comprise decisions for design and redesign of the network and with or without potential new facilities.

2. 2 Problem definition and formulation of the multi-objective model

Consider a supply chain network, G=(N,A), where N is the set of potential nodes and A is the set of arcs, representing the unimodal routes between the potential nodes. Here, N comprises sets of suppliers (S), manufacturing plants (M), warehouses (W) and clients (C), i.e. $N=S \cup M \cup W \cup$C. Raw materials can be purchased from different suppliers and should be transported to manufacturing plants in order to process them into finished goods. For convenience, the bill-of-material will not be considered, so a single product is distributed from manufacturing plants to warehouses and, hence, to customers, according to their respective demands, like an aggregate planning.

The sets of manufacturing plants and warehouses may be divided into two subsets, {M', M''} and {W', W''}, that comprise the set of facilities that are already open (M' and W') and those that are potentially new (M'' and W''), i.e. M=M'∪M'' and W=W'∪W''. Note that when M'=W'=∅ there is a case of pure design and when M"=W"=∅ we have a redesign of the current operations network. Thus, the model is flexible to evaluate design and redesign cases.

The problem consists in to (re)design the operations network by choosing which manufacturing plants and warehouses are going to participate in the supply network and determining their capacities and locations, besides defining products' flows between facilities. Sets of suppliers and clients (S and C) comprise the totality of potential ones and may or may not have an active connection with their nodes. Therefore, the total demand of clients comprises opportunities, but it must not be necessarily satisfied, and optimum service levels can be chosen.

The network is characterized by a dynamic structure, as manufacturing and warehouse nodes may become unavailable and must be recovered over time. In the meantime, it is possible to define contingent plans such as reconfiguration of products' flow as well as recovery rates plans. The recovery activities consume resources that are previously provided. Thus, the acquisition and maintenance of recovery resources also is a decision that is incorporated in the proposed model.

The assumptions made to build the model is:

• A single type of product is considered (or an aggregate plan);

• Demands of customers are known and constant;

• Facilities can not order more than received orders (storage is not allowed);

• The number of facilities in each echelon as well as their potential sites is restrained by pre-defined values;

• There is no flow between the facilities of the same echelon;

• Suppliers, manufacturing plants and warehouses have limited capacity;

• Manufacturers cannot send production directly to clients;

• Only manufacturing plants and warehouses are affected by disruptive events;

• Disruptive events affect the capacity of facilities;

• Recovering the facility capacity utilizes a portion of the recovery resource which must be acquired previously;

• At the beginning of each period, the total amount of the recovery resource is available even if it was already used in the previous period.

2.3 Sets, parameters and variables

The notations used in the model are presented in Tables 1, 2 and 3.

Table 1 – Problem sets of the proposed model

Sets	Description	Sets	Description
S	Set of suppliers	C	Set of Clients
M	Set of all manufacturing plants	Z	Set of zones/regions where facilities are in
M'	Set of current manufacturing plants	F_z	Set of suppliers, mnufacturers and warehouses located in region z
M''	Set of potential manufacturing plants	C_z	Set of clients located in region z
W	Set of all warehouses	Θ	Set of disruptive scenarios
W'	Set of current warehouses	PR_i	Set of facilities of the previous achelon of the installation i (predecessors)
W''	Set of potential warehouses	SU_i	Set of facilities of the posterior echelon of the installation i (successors)

Table 2 – Decision variables of the proposed model

Decision Variables	Description
of_i	1 if facility i is opened; 0 otherwise
ak_i	Additional initial capacity provided at facility i
ra	Additional initial recovery resource
l_j	Level of service (units of demand) provided/concerted to client j
sf_{ij}	Flow of products from i to j under scenario 0 (no disruptive event)
${f_{ijt}}^{\theta}$	Flow of products from i to j at t^{th} recovery period under scenario θ
${r_{it}}^{\theta}$	Capacity at facility i that is restored at t^{th} recovery period under scenario θ (Recovery Rate)

Table 3 – Parameters of the proposed model

Parameters	Description	Parameters	Description
VNF_i	Value of the investment to open facility i with the minimum projected capacity	CR	Cost of using a recovery resource unit
VAK_i	Value of the investment to increase the capacity of facility i in one unit	CMR	Cost of maintaining a recovery resource unit
VAR	Value of the investment to acquire one unit of recovery resource	RR_i	Required resource for recovering a unit of capacity from facility i
P_0	Probability of scenario 0 (no disruptive event)	EF_k	Embodied carbon footprints of one material purchased from supplier k
P_θ	Probability of scenario θ (disruptive events)	EM_i	Manufacturing carbon emissions of each unit product at plant i
D_j	Total demand (opportunity) of client j per period	ET_{ij}	Per unit carbon emissions of transporting from i to j
LI_j	Minimum level of service that must be provided to client j	LJR_i	Per unit local job requirement of facility i
Π_j	Unit price of the finished product sent to client j	UR_z	Unemployment rate at region z
CF_i	Operating fixed cost of facility i per period	$GDPI_z$	Gross Domestic Produt by Industry at region z
CP_k	Unit cost of purchasing raw material from supplier k	Υ_z	Gross Domestic Produt by client economic sector at region z
CM_i	Unit cost of manufacturing raw material from supplier k	G	Great number
CT_{ij}	Per unit transportation cost from i to j	IK_i	Initial capacity of facility i per period
CH_{ij}	Per unit handling cost from i to j	Γ_i^θ	Impact (% of affected capacity) of disruptive event on facility i in scenario θ
Pen_j	Per unit penalty cost for not reached level of service in client j	IR	Initial available recovery resource
		T	Total number of time periods considered

2.4 Multi-objective proposed model

The proposed OND model is penta-objective, two of them are economic objectives: minimization of initial investment for network design and maximization of network profit rate. There is one environmental objective: minimization of carbon emission rate by operating the network. The social objective comprehends to the maximization of social impacts by operating network. The last concerns to the resilience objective, which aims to minimize the lack in service level, when a disruptive event occurs.

2.4.1 Economic Objective #1: Investment in operations network design (OND)

In our model, investment and operational costs are treated separately, unlike [12] and [9], since they distinctly affect the economy of an organization. That is useful for decision-makers wish to get a good financial performance in their operational routine with minimum investment. Building two distinct economic objective functions allows to analyze this investment-performance relationship. This section deals with investment costs.

Equation (1) models the investment in OND for the proposed problem and accomplishes the set of design-related costs incurred for establishing new facilities (definition of the operations network and adaptive capacity), capacity expansion (absorptive capacity), and additional capability (resources) for restoring capacity after a disruption (restorative capacity).

$$F1 = \sum_{i \in \{M"\cup W"\}} VNF_i \times of_i + \sum_{i \in \{M \cup W\}} VAK_i \times ak_i + VAR \times ar \qquad (1)$$

Note that decisions on expanding capacity is defined to both yet operating facilities and the new ones ($M \cup W$). For operations that are already running, that result embodies, in fact, additional capacity (and enlargement of absorption capacity against disruptive events) for facilities. For new installations, however, that means the statement of the total capacity of that operation, in addition to a minimum value quantified in parameter IK_i (initial capacity).

2.4.2 Economic Objective #2: Network operating profit rate

This objective is concerned with the operational profit of the network incurred over time. It models the mean operating profit rate of the network. In our model the total demand means an opportunity and the level of service can be choice for each customer, therefore seeking the maximization of profit is a more appropriate goal, since the minimum cost would be achieved by minimizing the level of service.

Here, it has been proposed a model that be able to design a network with potential new operations, that results in the definition of capacities and input/output flows for each facility in the network. Thus, understanding that post-event actions, that includes updating flows, are interconnected with pre-event actions (new flows should be defined as variations on normal flows), we are proposing a weighting of pre and post-event operating costs.

Equation (2) shows the network operating profit rate for the problem, where R_0 and C_0 are, respectively, the revenue and the cost of network operating in one period under scenario 0 (no disruptive event), and, $R_\theta(T)$ and $C_\theta(T)$ the revenue and the cost of network operating in T cumulative periods under scenario θ. P_0 and P_θ are the probabilities of the scenarios 0 and $\theta \in \Theta$. Equations (3), (4), (5) and (6) detail R_0, C_0, $R_\theta(T)$ and $C_\theta(T)$. Since fixed costs are equal in all scenarios, C_0 and $C_\theta(T)$ cover only the variable costs and the fixed costs are directly inserted in $F2$, comprising the fixed costs of facility operation and recovery resource maintenance.

$$F2 = P_0 \times (R_0 - C_0) + \sum_{\theta \in \Theta} P_\theta \times \left(\frac{R_\theta(T) - C_\theta(T)}{T}\right) - \sum_{i \in \{M \cup W\}} CF_i \times of_i - CMR \times (IR + ar) \qquad (2)$$

$$R_0 = \sum_{j \in C} \Pi_j \times l_j \qquad (3)$$

$$C_0 = \sum_{i \in S} \sum_{j \in M} CP_i \times sf_{ij} + \sum_{i \in M} \sum_{j \in W} CM_i \times sf_{ij} + \sum_{i \in \{S \cup M \cup W\}} \sum_{j \in SU_i} CT_{ijt} \times sf_{ij} + \sum_{i \in \{S \cup M \cup W\}} \sum_{j \in SU_i} CH_{ij} \times sf_{ij} \qquad (4)$$

$$R_\theta(T) = \sum_{j \in C} \Pi_j \times \sum_{i \in W} \sum_{t=1}^{T} {f_{ijt}}^{\theta} \qquad (5)$$

$$C_\theta(T) = \sum_{i\in S}\sum_{j\in M}\sum_{t=1}^{T} CP_i \times f_{ijt}{}^\theta + \sum_{i\in M}\sum_{j\in W}\sum_{t=1}^{T} CM_i \times f_{ijt}{}^\theta + \sum_{i\in\{S\cup M\cup W\}}\sum_{j\in SU_i}\sum_{t=1}^{T} CT_{ij} \times f_{ijt}{}^\theta + \sum_{i\in\{S\cup M\cup W\}}\sum_{j\in SU_i}\sum_{t=1}^{T} CH_{ij} \times f_{ijt}{}^\theta + \sum_{j\in C} Pen_j \times \left(l_j - \sum_{i\in W}\sum_{t=1}^{T} f_{ijt}{}^\theta\right) + \sum_{i\in\{M\cup W\}}\sum_{t=1}^{T} RR_i \times CR \times r_{it}{}^\theta \tag{6}$$

The cost functions (C_0 and $C_\theta(T)$) are composed of the purchase costs of materials from various suppliers (first summation), the production costs in different manufacturing (second summation), the transportation costs of the whole supply chain (third summation) and the handling costs (fourth summation). The difference among these portions of cost in C_0 and $C_\theta(T)$ is a result of the difference in flow values, as consequence of increased transportation associated with serving some next-echelon operation from secondary facility, that comprises in the post-event efforts to absorb and to adapt the impact of a disruptive event. In addition, the subsequent two terms of $C_\theta(T)$ are the penalty costs for not meeting demand if insufficient capacity remains after the disruption and the costs of recovering the damaged capacity. The latter depict the post-event effort to restore the network provisioning capacity.

2.4.3 Environmental Objective: Total carbon emission rate

In order to propose an environmental-based strategy for the network design and operation, the model will evaluate the environmental impact of the network by assessing CO_2 emission through supply chains. For convenience, CO_2 emissions will be considered as the only environmental influence, which is a very popular environment index and can be measured easily [2].

Like in network operating profit rate model, the total carbon emission rate through supply chains will be modeled as a weighting of pre and post-event emissions, putting an environmental worry in the resilience assessment. Equation (7) show the mathematical model for the total carbon emission rate, with EI_0 and $EI_\theta(T)$ being, respectively, the total carbon emission rates under scenarios 0 and $\theta \in \Theta$. The CO_2 emissions in the embodied footprint left in raw material production (EF_i), the manufacturing process (EM_i) and the transportation among facilities (ET_{ij}) are considered in this model.

$$F3 = P_0 \times EI_0 + \sum_{\theta} P_\theta \times \frac{EI_\theta(T)}{T} \tag{7}$$

$$EI_0 = \sum_{i\in S}\sum_{j\in M} EF_i \times sf_{ij} + \sum_{i\in M}\sum_{j\in W} EM_i \times sf_{ij} + \sum_{i\in\{S\cup M\cup W\}}\sum_{j\in SU_i} ET_{ij} \times sf_{ij} \tag{8}$$

$$EI_\theta(T) = \sum_{i\in S}\sum_{j\in M}\sum_{t=1}^{T} EF_i \times f_{ijt}{}^\theta + \sum_{i\in M}\sum_{j\in W}\sum_{t=1}^{T} EM_i \times f_{ijt}{}^\theta + \sum_{i\in\{S\cup M\cup W\}}\sum_{j\in SU_i}\sum_{t=1}^{T} ET_{ij} \times f_{ijt}{}^\theta \tag{9}$$

2.4.4 Social Objective: Activity in less developed regions

The proposed model of social impact evaluation aims to prioritize less developed zones, in terms of unemployment and sectorial economic activity. The social function (Equation (10)) assess the proportions of local created jobs (LJ_z), the portions of local industrial economic activity (LA_z) and the levels of local demand supply (LD_z). These parts are weighted by local indexes, that represent unemployment rates (UR_z) and participations of economic sector in gross domestic product ($GDPI_z$ and Y_z), in order to allow the model to prioritize product flows from facilities and high level of service to clients located in less developed zones.

That modeling of social impact follows two social subcategories of Global Reporting Initiative's (GRI), *Labor Practices and Decent Work*, where criteria regarding employment are described, and *Society*, where the negative impacts of not having employment on society, the community economic performance and the level of service supplied to community are accounted for.

$$F4 = \sum_{z \in Z} [UR_z \times LJ_z + (1 - GDPI_z) \times LA_z + (1 - Y_z) \times LD_z] \tag{10}$$

$$LJ_z = \frac{\sum_{i \in F_z} \sum_{j \in SU_i} LJR_i \times sf_{ij}}{\sum_{i \in \{S \cup M \cup W\}} \sum_{j \in SU_i} LJR_i \times sf_{ij}} \tag{11}$$

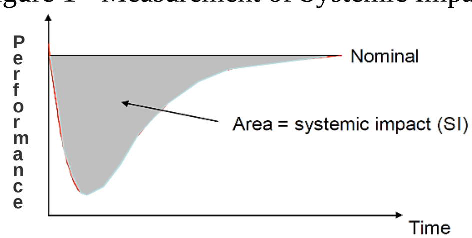
$$LA_z = \frac{\sum_{i \in F_z} \sum_{j \in SU_i} sf_{ij}}{\sum_{i \in \{S \cup M \cup W\}} \sum_{j \in SU_i} sf_{ij}} \tag{12}$$

$$LD_z = \frac{\sum_{j \in C_z} l_j}{\sum_{j \in C_z} D_j} \tag{13}$$

2.4.5 Resilience Objective: Systemic impact on level of service

The resilience of production systems can be defined as its ability to reduce effectively both the magnitude and duration of the deviation from targeted system performance levels due to the occurrence of a disruptive event [17]. The occurrence of an event reduces some performance metric for the system, and through recovery effort this metric returns to its nominal level over time, as shown in Figure . The systemic impact (SI) of that deviation may be defined for the area of the degraded performance [12]. In other words, the greater the system resilience, the less the SI.

Figure 1 - Measurement of Systemic Impact



Source: Vugrin & Turnquist (2012)

Resilient supply chains have a low SI of deviation from targeted level of service when disruptive events occur. In that light, maintaining a high capacity for the network, by opening new facilities and expanding their capacities, reduces the magnitude of event impact, since more capacity keep available to server the customers' demands after disruption (absorption ability). As consequence, spare capacity can be keeping in various operations, allowing serving some next-echelon operation from secondary facility with that spare capacity (adaptation ability), which also reduces the event impact. Finally, the more recovery resource is available, the faster the network returns to its original capacity in serving clients (recovery ability).

In this paper, it is desired maximize the supply chains resilience over the level of service provided to clients of the network. For that, the weighing SI is modeled (Equation (14)), where the level of service provided/concerted to each client (l_j) is the nominal performance value.

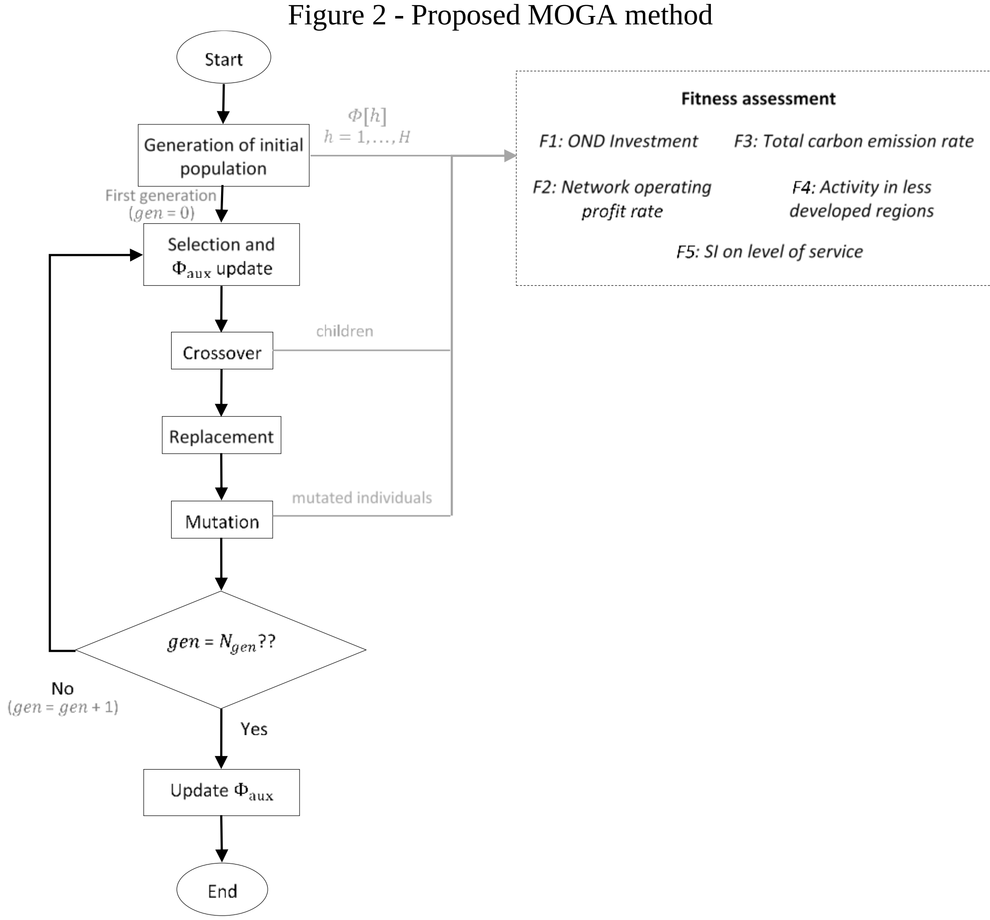
$$F5 = \sum_{\theta} P_\theta \left[\sum_{j\in C} \sum_{t=1}^{T} \left(l_j - \sum_{i\in W} f_{ijt}{}^{\theta} \right) \right] \tag{14}$$

3. A Multi-objective Genetic Algorithm (MOGA) for generating the Pareto-optimal set

For instance, the analysis of a network with 3 suppliers (S), 3 manufacturers (M), 4 warehouses (W) and 5 clients (C), that is a little supply network, with a maximum period to restoration of T=5 and 7 possible disruptive scenarios, there would be a total of almost 2500 decisions variables in which many of them are defined at ranges in order of 10^3. Thus, the use of exhaustive methods to obtain the Pareto-optimal set is prohibitive due to computational time and cost. In addition to the fact that there is a nonlinear function in the model (F4), we propose a Multi-Objective Genetic Algorithm (MOGA), which is described in this section.

An individual generated in MOGA corresponds to a list containing the each type decision variables, $individual \leftarrow$ list[$of_i, ak_i, l_j, ar, sf_{ij}, f_{ijt}{}^{\theta}, r_{it}{}^{\theta}$], in a integer-coded typifying. To obtain a Pareto-optimal set, the dominance relationship is evaluated based on each individual's fitness, which is a five-dimension vector $\underline{F}$=[$F1, F2, F3, F4, F5$] analytically calculated. Our MOGA neither uses elaborated fitness metrics nor transforms multiple objectives into a unique function. Figure details the MOGA method we here propose.

Figure 2 - Proposed MOGA method



Source: This research.

Let H be the fixed size of population Φ, $\Phi[h]$ be the h^{th} individual (that represents a solution) of Φ, and Φ_{aux} be the auxiliary population that stores non-dominated individuals and is updated at each iteration. With exception for the Generation of Initial Population, the steps are repeated for N_{gen} times, where each iteration is a MOGA generation. After this, the Selection and Φ_{aux} update step is performed for the last time and the algorithm provides the nondominated feasible individuals from Φ_{aux}. Table 4 defines the parameters used in the proposed MOGA. Genetic operators are developed to generate only feasible individuals (penalty methods are not used).

Table 4 - Multi-objective GA parameters

MOGA parameter	Description
H	Size of population Φ
p_{cr}	Crossover probability
p_{mt}	Mutation probability
N_{gen}	Number of generations

Source: This research.

4. Application example

In this section, the OND multi-objective model is applied to a case example of a garment manufacturing supply chain, based on data from [10]. The garment manufacturing company is based in Pakistan and a single product (trousers) is taken, having three manufacturing plants (M), three suppliers (S), four warehouses (W) and five clients (C). Data parameters in our model that are not contemplated in [10] were extracted empirically from personal research associated to the local and the type of industry treated in this application example, like Π_j and Pen_j in Table 5 . The solution for OND problem will be performed by application of the MOGA and considering $N = 3$.

Table 5 – Clients' data

Client (j)	**Demand (D_j)**	**Unit Revenue (Π_j)**	**Penalization cost (Pen_j)**	**Zone (Province)**
1	8500	$20	$55	2 (Sindh)
2	8700	$22	$60	1 (Punjab)
3	8600	$19	$52	4 (Balochistan)
4	5500	$21	$57	3 (Khyber Pakhtunkhwa)
5	5000	$22	$60	1 (Punjab)

Source: adapted from [10].

In order to explore how the modelling performs in different situations, the proposed case was designed regarding distinct levels of decisions. To show the outputs obtained, the following analysis brought tables and a chart. The numbers contained in tables are the exact value achieved by the respective objectives, so the performances achieved can be compared. As an alternative to visualize how a Pareto Frontier for those problems are formed, since a five-dimension problem have an inherent representation difficulty, the following cases present a chart for each objective arranged in ascending order. This charts is intended to show how a trending in one objective impacts on the others, and to make the plot easier to analyze, all the results were normalized according to the Equation 15.

$$Xnormalized = \frac{X - Xmin}{Xmax - Xmin} \tag{15}$$

Where (X) is the original number obtained for the objective, $Xmin$ is the lower value obtained and $Xmax$ is the highest value found in the solutions. Applying the normalization, all the results are represented in a 0 to 1 scale, and the relationships between the variables can be visualized.

The case studied comprises a situation which there are a supplier, a manufacture, and a warehouse already existent and the decisions are simultaneously to open new installations and to increase capacity in installations already existent. Table 6 exhibits characteristics of the mono-objective results such as minimum, maximum, medium and standard deviation obtained for each objective.

Table 6 – Mixed Design and Redesing Measures

	Investment $(F1)$	Profit Rate $(F2)$	Environmental $(F3)$	Social $(F4)$	Resilience $(F5)$
Minimum	0	-31657.24	29695.18	2.6200469	0
Medium	0	53829.227	41117.75	2.8228153	0
Maximum	0	114875.22	48868.44	3.0271044	0
SD	0	44123.972	5357.1181	0.1667161	0

Source: This research

Moreover, Table 11 brings the same kind of measures presented in Table 10, but for the multi-objective approach in order to analyze how close they are to the mono-objective solutions by comparing both tables. Assessing all the results, the differences between values found for the profit rate $(F2)$ in both cases draws more attention because the multi-objective did not find a non-negative solution. Also, the results for the social objective $(F4)$ are distant from the reached in the mono-objective approach. Despite that, the resilience $(F5)$ and investment $(F1)$ best results were present in the multi-objective solutions and the $(F3)$ best solution in Table 7 is smaller than the best value from Table 10.

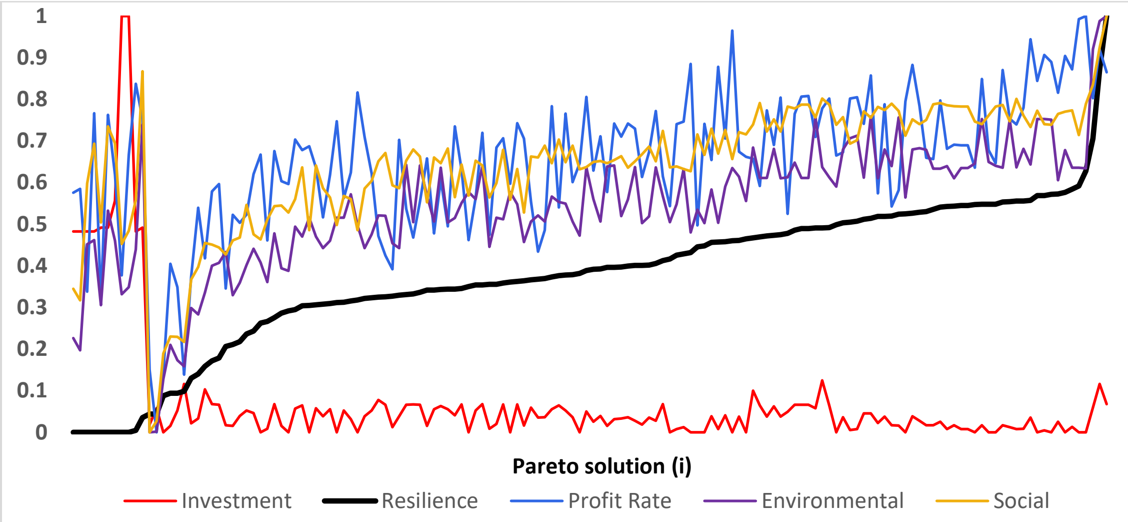
Table 7 – Mixed Design Measures Multi-objective

	Investment $(F1)$	Profit Rate $(F2)$	Environmental $(F3)$	Social $(F4)$	Resilience $(F5)$
Minimum	0	-411332.8	11825.34	0.9643679	0
Medium	21614847	-249872.1	54763.31	1.733073	715.978
Maximum	290000000	-164538	90753.13	2.1635301	1894.677
SD	45158015	41726.102	12204.228	0.1841237	330.57178

Source: This research

In order to compare how the objectives behaves as the resilience $(F5)$ goes from the best solution, which is zero, to the worst result for this objective, Figure 3 displays the lines representing all the five objectives. Examining the chart, is noticeable that the investment function $(F1)$ presented a constant behavior in the biggest part of the results, and only in the best resilience solutions the investment in resilience makes a considerable influence while the other functions presented multiple results. On the other hand, is visible that all the variables' outcomes present an ascending behavior in most of the chart. For the maximization functions, which are the profit rate $(F2)$ and the social $(F4)$, as $(F5)$ grows the better their numbers becomes, while for the minimization environmental function $(F3)$ the results gets worse.

Figure 3 – Ascending F5 for design and redesign case multi-objective solutions



Source: This research

5. Conclusions

This work proposed a multi-objective model to optimize decisions in three different decision levels in cases regarding to OND in a supply chain considering sustainability and resilience. The MOGA developed was capable to (i) consider first and second stage decisions, in order to improve the performance in the proposed case, (ii) incorporate five distinct aspects for the performance analysis and (iii) consider a disruption scenario with respective occurrence probabilities.

With the aim of covering different decision levels, two kinds of outcome were implemented in the model. The first stage representation contemplated the opening of a new facility, while the second stage was represented by the possibility of increase capacity in an existent installation. In order to approach cases where those decisions were manifested in different combinations, the proposed case envolved decisions such as open a new installation and augment the ones already existent. As a result, the proposed case showed better results for the resilience as the investment increases and when the resilience and environmental impact gets worse, the social impact and the profit rate improves and clear trending lines were seen. This result shows how the decision level influenced on the results and demonstrates that the MOGA algorithm was able to approach both decisions, which represents a generalization ability.

Regarding to the resilience the focus was on adopting the concepts of recover, adapt and absorb and the model was able to find solutions that aimed to use those perspectives to deal with the contemplated disrupting events. The sustainability concept adopted was the triple bottom line and each perspective were present in one objective. The social objective deserves a special highlight because this work was able to go further than measuring the social impact with the demand met by complementing this sustainability pillar with the GDPI and the job generation.

Concerning all the objectives, the MOGA was able to bring good solutions in the multi-objective optimization, and it was also capable of reaching solutions close to the ones obtained in the mono-objective optimization and in the environmental objective the performance was even better. However, some limitations and new horizons to explore must be considered. Firstly, the measurement of the environmental and the social objectives. Both could be complemented with other indicators that might be relevant, such as per capita income, political issues and the natural resources utilization's necessity (e. g., water, land).

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