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Use of Robust Physical Programming to Design a Network of Closed Loop Supply Chain Considering Multiple Period and Product

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Abstract: Closed loop supply chain has evolved overtime. Therefore, a lot of research have been done to discuss this topic. The majority of these studies considered product demand and/or number of returned product uncertainty. Beside the traditional uncertainties, this paper presents a model to design a closed loop supply chain network considering a novel uncertainty which concerns with product substitution fraction when product substitution is allowed. To solve the problem with multiple objectives, we use physical programming and robust optimization, and to the best of our knowledge, it is the first attempt to use these integrated techniques to solve such a problem. We present a numerical example using a case of network design of an alloy wheel product in Saudi Arabia.

Keywords: Network Design, Uncertainty Set, Multi-Objective, Multi-Period, Multi-Product, Substitution.

1. Introduction

Evolution, in general, is the process of tangible or intangible changes in the characteristics of something over time. Evolution is observed in different fields, for example, manufacturing systems have been evolving among their classes. Those include information technology, production philosophy, production control strategy, inventory control strategy, production layout and machining system configuration [1]. In instance, production philosophy has evolved from lean manufacturing in the 80th of the last century, went through agile manufacturing in the 90th to leagile manufacturing in the late of the 90th from the same century. Similarly, the research evolution in the area of closed loop supply chain (CLSC) has passed over 5 phases until we are able to see its known shape today [2].

The history of the CLSC began from remanufacturing, which was not very familiar in its beginning although customers have demanded it since the early 90th of the last century. The outcomes of this phase, which was outlining the complications related to remanufacturing characteristics, led to the second phase. In the second phase, the entire reverse supply chain was introduced to better understand and solve the listed complications from phase 1. As many optimization models and approaches were introduced in this phase, the path of phase 3 was clear to study and coordinate the reverse supply chain. Phase 3 focused on analyzing the processes of the reverse supply chain and study its economic perspective to support the strategic decisions of product recovery. The evolution has continued to happen as it became mandatory to close the loop of the supply chain. The CLSC was introduced in phase 4, where the profitability of the entire system was studied. Studies on this topic have started and companies, consequently, have started to shift to CLSC in this phase. In the last phase, pricing and marketing issues have been raised as the CLSC is associated with more complications and difficulties [2].

Network design is a major problem in the domain of the CLSC, in which the goal of decision-makers includes, but not limited to, determining the number of facilities to open and the number of products to ship in the CLSC. Although this is a very hot research area, there are still opportunities for future research. In this paper, we propose a model with multiple objectives to design the CLSC network that takes into consideration a novel type of uncertainty which is the substitution fraction that determines the substitution limit in substituting a product at market locations. This is because not all product substitution is accepted, there are some situations when the substitution is rejected.

The rest of this paper is organized as follows: we review the literature available concerning our topic in section 2. We describe the problem of our interest in Section 3. Section 4 demonstrates the methodology to solve the suggested problem. The illustrative example is in section 5 and section 6 presents the result. Conclusion and suggested future work are illustrated in section 7.

2. Literature review

In this section, we review most of the publications in the area of CLSC network design generally. In particular, we investigate publications in the area of single objective and multiple objectives to design CLSC under uncertainties.

2.1 Single objective CLSC network design under uncertainties

An integrated model of robust and stochastic programming with a single time period was presented by Haddadsisakht and Ryan [3]. This model aimed to minimize the total cost of the CLSC network as well as the carbon emission, while the uncertainty in this model was allocated to the demand, rate of returned products and tax per emitted carbon. Jabbarzadeh, Haughton and Khosrojerdi [4] used an extended approach of the stochastic robust optimization to design a real case of the CLSC network considering the uncertainty of distribution. Minimizing the total cost of the network was the objective in this model under multiple period time planning horizon. Four fuzzy programming approaches to design the CLSC network were compared by Wu, Chang and Hsu [5] while the objective was to minimize the total cost. All the four approaches utilized the uncertainty of the demand, fixed costs associate to open facilities and the rate of returned products to be recycled products.

2.2 Multiple objective CLSC network design under uncertainties

In the beginning, we indicate the important review papers in this area. The first review paper is a review of the state of the art conducted by Ilgin and Gupta [6]. In this paper, they covered the period from 1999 to 2010, in which all published papers concerning this topic were collected, classified and summarized. Another review paper was presented by Ilgin, Gupta and Battaïa [7], and it considered all publications between 1996 to 2014. Gupta and Ilgin worked on a book [8], which extended Ilgin, Gupta and Battaïa [7] and covered the rest of the papers published since 2014.

Govindan et al. [9] used a hybrid model that integrated three approaches including fuzzy analytic network process, fuzzy decision-making trial and evaluation laboratory and multi-objective MILP approaches and the objectives were to minimize the total cost and the shortage cost of the CLSC network. They tackled the uncertainty of the demand and the cost parameters on the network. Talaei et al. [10] used another integrated model where robust and fuzzy optimization approaches were integrated and considered the uncertainty of the variable costs and the demand on the CLSC network. In their model, two objectives were considered: minimization of the total cost and the carbon emission of the CLSC network.

Ramezani, Bashiri and Tavakkoli-Moghaddam [11] presented a stochastic programming model to tackle the uncertainty of all costs and price parameters, the demand, as well as the number of returned products. The service level objective in this problem was measured as the proper delivery time of products to customers. A fuzzy goal programming model proposed by Zarandi and Davari [12] under consideration of the aspiration level uncertainty of each objective function. They used the maximal covering location problem, which is a function of coverage level and distance between a distribution center and a retailer, to assign a service level score to each retailer for the service level objective function. In their study, they did not differentiate between the new product demand and the remanufactured product demand, only one demand stream was considered. Similarly, the same demand assumption was used by the study of Pazhani, Ramkumar, Narendran and Ganesh [13] in designing the CLSC network. One of the objective functions in their study was to maximize the service level of hybrid facilities, which work as distribution and collection centers, and the distribution centers. To measure the service coefficient of the hybrid facilities and the distribution centers, they used technique for order preference by similarity to an ideal solution (TOPSIS) to evaluate each hybrid facility and distribution centers according to different criteria. However, this study neglected the impact of uncertainty, except on the aspiration level of the objective functions.

Comparing our work with the available literature on designing the CLSC network, it reveals two main differences. First, to the best of our knowledge, none of the available papers considered the uncertainty of the acceptance of a market location to substitute products in case of inability to satisfy their demand. The nearest study to our work was conducted by Aldoukhi and Gupta [14]–[19] where they considered product substitution in designing the CLSC network. However, it was assumed that the market location always accepted to substitute the product in case of not being able to satisfy the market location demand. Second, we presented a new effective methodology that has not been used in the literature before to solve this problem. Our approach integrates physical programming and robust optimization to tackle the conflict objectives and the uncertainty parameters, respectively.

3. Problem Description

In the CLSC network, manufacturing centers are responsible for producing new products and remanufacturing returned products delivered from collection centers according to their quality levels. The new and remanufactured products are produced and shipped to market locations through distribution centers. The collection centers in the network link the market locations and the manufacturing centers, in which the returned products with different quality levels are collected from the market locations, cleaned, sorted and delivered to the manufacturing centers. In the concerned network, the first generation of the new product is launched at the beginning of the time period. Then, the product demand increases as time passes while the demand for remanufactured products starts to occur later on. Once the second generation of the new product is offered in the market, the demand for the first generation starts to decrease. The demand for the remanufactured product with its second-generation would follow the same pattern. The three objectives considered in this work are economic, environmental and service level objectives. The first objective includes all costs related to the network, the second objective uses the carbon cap-and-trade policy to mitigate the carbon emission resulted from production and transportation activities, and the third objective uses the service level score as illustrated in section 4.3 to maximize the level of service. Our research question, what is the network structure and the amount of product to be shipped within the network under the consideration of different generations of products where the new products from different generations are allowed to substitute each other and similarly with remanufactured produces. Also, when the 1st generation of new products is allowed to substitute the 1st generation of remanufactured products and a similar concept applies to the 2nd generation. This is under consideration of the uncertainty of substitution fraction, the product demand and the number of returned products. Therefore, the goal of this study is to find the optimal selection of facilities to open and the optimal number of products to transport in the network taking into account the above uncertainties and to achieve the above-desired objectives.

4. Methodology

To solve the proposed problem, we integrate physical programming and robust optimization, which is considered as the first attempt to use in this area. We also use TOPSIS to measure the service level score of each market location.

4.1 Linear physical programming

Optimization problems become more difficult to solve when it concerns conflicting objectives. Among the different approaches available, the weighted sum method, ε-constraint method and goal programming method are the most popular approaches used in the literature to solve network design problems with multiple objectives. The reviews conducted by Ilgin, Gupta and Battaïa [7] and Gupta and Ilgin [8] showed how widely these approaches have been utilized not only in the area of network design, they also expand their usage to the different topics under environmentally conscious manufacturing. However, these methods have some issues which might affect the decision made by the decision-makers. For example, the weighted sum approach and the goal programming (preemptive method in goal program) require the user to provide weight for each objective, which is in many cases are meaningless and far from describing the physical preference. Similarly, with the ε-constraint method which requires identifying which objective to minimize first and determine the value of ε.

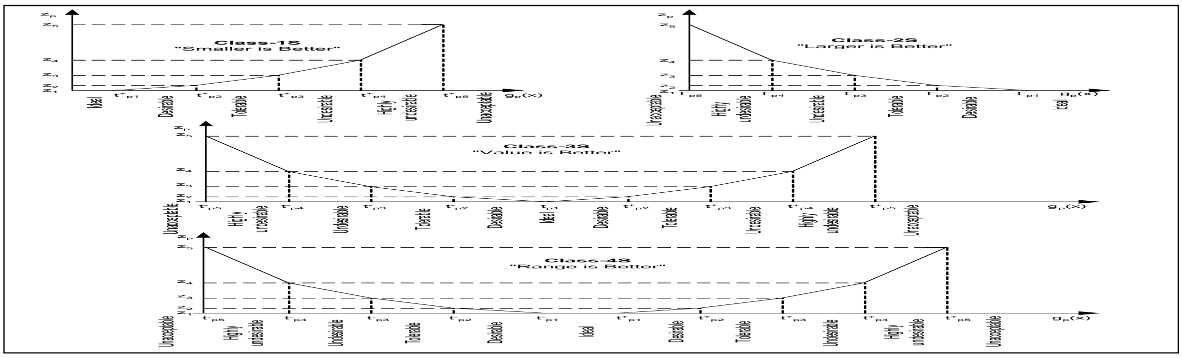

Figure 1: soft class functions for linear physical programming

Linear physical programming (LPP), which was introduced the first time by Messac, Gupta and Akbulut [20], is associated with preference functions that provide the decision-maker with a precise way to express the objectives' preference and give a close representation to real life. The four soft class functions in LPP are: smaller is better (1S), larger is better (2S), value-is-better (3S) and range-is-better (4S). As shown in Fig.1,there are 6 desirability ranges in each class function as follow:

- Ideal
- Desirable
- Tolerable
- Undesirable
- Highly undesirable

- Unacceptable

The general formulation of LPP is as follow:

$$Min\,Z = \sum_{i}\sum_{2}^{5}(wt^{+}_{i,ra}\, d^{+}_{i,ra} + wt^{-}_{i,ra} d^{-}_{i,ra}) \qquad (1)$$

Subjected to:

$$g_i - d^{+}_{i,ra} \leq t^{+}_{i,ra-1} \qquad (2)$$

$$d^{+}_{i,ra} \geq 0 \text{ and } g_i \leq t^{+}_{i5}$$

In LPP formulation, $\boldsymbol{wt^{+}_{i,ra}}$ is the positive weight and $\boldsymbol{wt^{-}_{i,ra}}$is the negative weights for i objective in the $\boldsymbol{ra^{th}}$ range of desirability obtained from Linear Physical Programming Weight LPPW algorithm. We refer the reader to Messac, Gupta and Akbulut [20], Ilgin and Gupta [21] and Kongar and Gupta [22] to understand the procedure of developing LPP model and calculating the LPPW. $\boldsymbol{d^{+}_{i,ra}}$ and $\boldsymbol{d^{-}_{i,ra}}$is the deviations between the value of objective i ($\boldsymbol{g_i}$) and the corresponding target value $\mathbf{t}^{+}_{\mathbf{i,ra}}$ and $\mathbf{t}^{-}_{\mathbf{i,ra}}$, respectively.

4.2 Robust optimization

Physical programming by itself is not enough to tackle a multiple objectives optimization problem associated with uncertainties. Therefore, it is necessary to integrate a methodology that concerns solving uncertainties in optimization problems. Despite different approaches are available to deal with uncertainties; such as stochastic programming, fuzzy set theory and robust optimization, the last approach characterize itself from the others by its capability to deal with the uncertainty of parameters without requiring knowledge of their probability distribution.

In the robust optimization uncertainty set theory, the uncertainty parameter belongs to a convex bounded set that takes different shapes and the set represents all possible realization of the considered uncertainty parameter [23]. In this context, we use abounded box uncertainty set that has been widely used in the literature [3], [24]–[27].

Using uncertainty set theory of robust optimization is formulated as follow:

$$Min\,cx \qquad (6)$$

Subjected to:

$$\bar{A}x + P_A.G_A x \geq \bar{d} + P_d.G_d \qquad (7)$$

$$Hx \geq \bar{r} - P_r.G_r \qquad (8)$$

$$Hx \leq \bar{r} + P_r.G_r \qquad (9)$$

$$x \geq 0$$

This formulation is called a robust counterpart which is a deterministic equivalent format for the robust optimization where it is tractable. It is called a robust feasible solution when it is possible to find a feasible solution to all possible realizations of uncertainty parameters within their set. To better understand the uncertainty set theory in robust optimization, we recommend reading these articles and books [28]–[33]for more details about robust optimization. Our proposed integrated model to design CLSC network is as follows:

$$Min\,Z = \sum_{i}\sum_{ra\geq 2}^{5}(wt^{+}_{i,ra}\, d^{+}_{i,ra} + wt^{-}_{i,ra} d^{-}_{i,ra}) \qquad (10)$$

Subjected to:

$$g_i - d^{+}_{i,ra} \leq t^{+}_{i,ra-1} \qquad (11)$$

$$\bar{A}x + P_A.G_A x \geq \bar{d} + P_d.G_d \qquad (12)$$

$$Hx \geq \bar{r} - P_r.G_r \qquad (13)$$

$$Hx \leq \bar{r} + P_r.G_r \qquad (14)$$

$$x \geq 0,\, d^{+}_{i,ra} \geq 0 \text{ and } g_i \leq t^{+}_{i5}$$

4.3 Technique For order preference by similarity to an ideal solution (TOPSIS)

Pazhani, Ramkumar, Narendran and Ganesh [13] introduced TOPSIS which is a technique to measure the service level score. In general, TOPSIS is a technique to evaluate alternatives based on certain criteria in the multiple criteria decision making (MCDM) environment. In this technique, Euclidean distance is used to measure the distance from each criteria of the alternative to the ideal and worst solution, where they are ranked according to their longest and shortest distance [34]. Then, we find the score of each alternative score which they will be the score of the service level of each market location in our model.

5. Numerical Example

Here, we present a case to design the CLSC network for an alloy wheel product in Saudi Arabia. The motivation for presenting this case is the serious attempts of the Saudi government to open new manufacturing businesses in the region which work parallel with achieving the Saudi Vision 2030. The government of Saudi Arabia encourages investors to develop this business as the Saudi labor force is 5.7 million, nominal GDP is $786 billion, GDP per capital is $23,339 and FDI inward stock is $264 billion. In addition, Saudi Arabia has a perfect location at the crossroads of three continents: Asia, Africa and Europe. It has also 7 seaports and 4 container terminals as well as about 35 industrial cities all around the country with a total area exceeding 198 million square meters [35], [36]. About 50% of the 3.2 million population in Saudi Arabia are under the age of 30 which makes the market of ally wheel part very attractive as this part is a highly replaced part since it enhances the esthetics of vehicles. The demand for the alloy wheel is forecasted to be more than 43 million units in 2029.

In this example, we consider a14 to 19 inches rim which is a typical diameter size for a standard car. It is assumed that customers would return the part when damaged or have it replaced with a second generation (a newer version) of the same part which has an improved shape. Fig. 2 shows how the behavior the product demand as explained in section 3. This table of product demand was also introduced by Almaraj and Trafalis [37]. In table 1, we present the number and locations of potential facilities as well as the markets. The distance between the facility and market locations are measured using google maps. The desirability ranges and the calculated weights using LPPW of each objective function are summarized in table 2 and 3. The amount of carbon emitted resulting from producing alloy wheel are assumed according to Tsai, Chu and Lee [38] and the substitution cost is based on Lang [39]. To determine the service level score of the market locations, we evaluate the market locations according to the following criteria: the population in the region, accessibility of the location and loyalty of location to do future businesses. We use TOPSIS, as introduced previously.

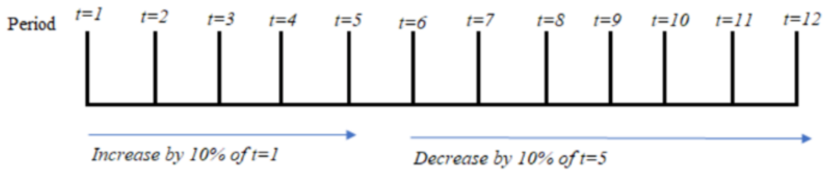

Figure 2: pattern of product demand over the time[37].

Table 1: Number of facilities and locations data

Facility	Location
Manufacturing facility	Riyadh industrial city 3, Dammam industrial city 3, Madinah industrial city
Distribution facility	Suair industrial city, Dammam industrial city 2, Jeddah industrial city 2
Collection facility	Alzulfi industrial city, Dammam industrial city 2, Jeddah industrial city 2
Market locations	Alkharj industrial city, Riyadh industrial city 2, Qassim industrial city 2, Hafr Albatin industrial city, Alahsa industrial city 2, Jeddah industrial city 3, Makkah Almukarrama industrial city, Albaha industrial city 1, Tabuk industrial city, Najran industrial city

Table 2: Desirability ranges

	Objective 1	Objective 2	Objective 3
Ideal	≤ 108,000,000	≤ 12,000,000	200,000 ≥
Desirable	(108,000,000, 112,000,000]	(12,000,000, 13,000,000]	[150,000, 200,000)
Tolerable	(112,000,000, 116,000,000]	(13,000,000, 14,000,000]	[100,000, 150,000)
Undesirable	(116,000,000, 120,000,000]	(14,000,000, 15,000,000]	[50,000, 100,000)
Highly Undersirable	(120,000,000, 124,000,000]	(15,000,000, 16,000,000]	[0, 50,000)
Unacceptable	124,000,000>	16,000,000>	< 0

Table 3: Calculated weights for LPPW

Target	Weights							
i = 1	$W_{1,2}$	0.015	$W_{1,3}$	0.018	$W_{1,4}$	0.0396	$W_{1,5}$	0.08712
i = 2,	$W_{2,2}$	0.06	$W_{2,3}$	0.072	$W_{2,4}$	0.1584	$W_{2,5}$	0.34848
i = 3	$W_{3,2}$	1.2	$W_{3,3}$	1.44	$W_{3,4}$	3.168	$W_{3,5}$	6.9696

6. Results

To conduct this numerical experiment, we used C++ algorithm to find LPPW, Microsoft Office Excel to find the service level score of the market location using TOPSIS and Lingo 18.0 optimization software. We used Microsoft Windows 7 laptop with Intel® Core TM i5-2430M CPU @ 2.4GHz.

We considered .2 uncertainty level of the demand and the number of returned alloy wheels, represented by UL, and the fraction of substituting the alloy wheel, represented by ULFRAC. The results recommend opening the manufacturing facility located at the 3rd industrial city in Riyadh, the distribution facility located at the industrial city in Sudair city and the 2nd industrial city in Jeddah and the collection facility located at the industrial city in Alzulfi city. It was found that the economic objective is in desirable range with $ 111,555,300, the environmental objective is in ideal range with $ 12,000,000 and the service level is in desirable range with 170,989,888 desirable units.

Due to the number of pages limitation, we choose time period 7 to present the quantity of alloy wheels shipped to all market locations that satisfy their demand either directly or indirectly using the concept of substitution. As shown in Fig. 3, among the alloy wheels shipped to satisfy all the market locations, 10,196 units are used to satisfy the demand of the new 1st generation, 7,050 units are used to satisfy the demand of the new 2nd generation, 6,040 units are used to satisfy the demand of the remanufactured 1st generation, 4,935 units are used to satisfy the demand of the remanufactured 2nd generation and 449 units of the remanufactured 2nd generation are used as substitute to satisfy the demand of the remanufactured 1st generation.

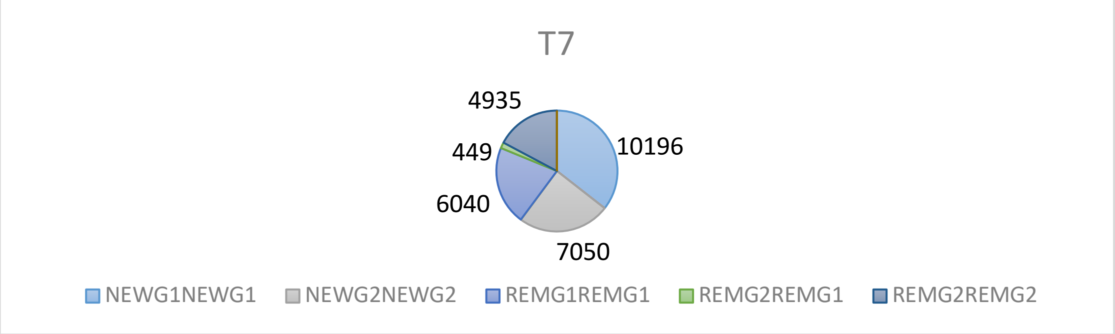

Figure 3: details about the quantity of the alloy wheels shipped to all market location in time period 7.

Table 4 shows the result of varying the UL and ULFRAC to present the impact on the robust optimal solution of each objective function and the number of substituted products. We did not consider uncertainty (ULFRAC = 0) for the last two columns which are the new 1st generation substituting the remanufactured 1st generation and the new 2nd generation substituting the remanufactured 2nd generation. This is because this substitution is always welcomed. However, they also change due to the change on the UL. When we set the UL as 0.9 and ULFRAC as 0.1 for example, the robust optimal solution for the 1st objective is $108,000,000 which is ideal, $12,000,000 for the 2nd objective which is ideal and 200,000for the 3rd objective which is ideal. In addition, the number of the new 2nd generation substituting the new 1st generation is 31,561 units, the number of the new 1st generation substituting the new 2nd generation is 29,816 units, the number of the remanufactured 2nd generation substituting the remanufactured 1st generation is 6,666 units, the number of the remanufactured 1st generation substituting the remanufactured 2nd generation is 4,842 units, the number of the new 1st generation substituting the remanufactured 1st generation is 31,422 units and the number of the new 2nd generation substituting the remanufactured 2nd generation is 11,401 units.

Table 4: impact of varying UL and ULFRAC on quantity of product substituted

UL	***ULFRAC***	TECON	TENVIR	SL	NEWG2 NEWG1	NEWG1 NEWG2	REMG2 REMG1	REMG1REMG2	NEWG1 REMG1	NEWG2 REMG2
0.1	0.9	116,000,000	13,929,640	202,487	-	-	-	-	53,247	28,064
0.2	0.7	112,134,900	12,250,600	179,989	-	-	-	1,816	32,897	6,881
0.3	0.5	100,222,400	12,000,000	200,000	10,287	61,019	-	-	64,924	42,713
0.5	0.3	105,545,100	12,000,000	200,000	41,835	60,965	-	-	63,613	42,675
0.7	0.2	108,000,000	12,000,000	200,000	21,774	50,908	431	12,424	21,680	-
0.9	0.1	108,000,000	12,000,000	200,000	31,561	29,816	6,666	4,842	31,422	11,401

7. Conclusion

As evolution occurs in different sciences and fields, it is interesting to see how CLSC has evolved. Overtime, different topics involved in CLSC has taken researchers' attention due to its wide benefits including economic and environmental benefits.

Beside the traditional uncertainties of the new and remanufactured product demand and the number of returned products, this paper presented a new type of uncertainty in designing multi-period and product CLSC network. The new uncertainty is the substitution fraction that determines the substitution limit in substituting a product at market locations. We used a product substitution policy that allows the two generations of the new products to substitute each other, likewise with the two generations of the remanufactured products. In addition, we allowed the first generation of the new product to substitute the first generation of the remanufactured product. Similarly, with the second generation of the new and remanufactured product. However, we did not consider uncertainty in the substitution fraction when the new product substitutes the remanufactured product from the same generation. This is due to the fact that downward substitution is always welcomed. We studied a case example of alloy wheel CLSC network in Saudi Arabia. When we consider 0.2 uncertainty level of UL and ULFRAC, our results recommend the following:

- Locate the manufacturing facility at the 3rd industrial city in Riyadh.
- Locate the distribution facility at the industrial city in Sudair city and the 2nd industrial city in Jeddah.
- Locate the collection facility at the industrial city in Alzulfi city.

Besides all the benefits obtained from our model, it also helps the supply chain decision makers to take more flexible decisions in terms of determining the quantity of products to ship in the CLSC network including any substituted product to satisfy the market demand.

For future study, we suggest incorporating heuristics to our proposed model to solve a larger problem size. It is also adaptable to use this mathematical model in different industries where product substitution is applicable.

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