Towards a cost-effective design of a meat supply chain: A multi-criteria optimization model

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***Abstract*—This paper presents a developed multi-criteria optimization model aiming to obtain a cost-effective design for a meat supply chain network with respect to minimization of total implementation and operational cost, and maximization of customer satisfaction and product quality. Moreover, the aim of this work intends to solve the facility location-allocation problem along with the quantities of products transported between facilities. Two solution approaches were employed to obtain two sets of Pareto solutions and a decision-making algorithm was developed to select the superior solution approach in terms of each of values of the three criteria, respectively. A case study was applied to examine the applicability of the developed model and the performance of the proposed solution approaches. Results are offered and discussed in order to determine a trade-off solution among the considered criteria for solving the meat supply chain network design problem. The developed tri-criteria optimization model can be used as an aided tool by decision makers for designing and optimizing food supply chain networks.**

Keywords—Supply chain; Multi-criteria; Product quality; Solution approach

I. Introduction

Today, the concept of meat supply chains has a methodical connotation in which a meat supply chain generally constitutes four different echelons including farms, abattoirs, retailers and customers to form a network of facilities that supplies and transports livestock to the intermediate retailers providing end products of meat purchased by customers. In recent years, safety and quality of food has been the major issue and consumers require more transparent information relating to food they purchase at the UK supermarkets [1]. The information may contain particular rules that should be maintained throughout the entire supply chain; these rules are also associated with feeding processes and health of livestock at farms, and slaughtering processes at abattoirs [2]. As different commitments may lead to a guide to decision making when purchasing types of meat products. A study by Peattie [3] indicated that consumers spend considerable times and efforts seeking out fresh food by reading food labels to ensure they purchase good quality food. To this aim, the implementation of radio frequency identification (RFID) technology was proposed for enhancing traceability of safety and quality of food products during each process of a supply chain network [4, 5, 6]. Such an RFID-based supply chains can lead to an improvement in monitoring quality and safety of meat products, although it is subjected to additional costs that also need to be considered.

Multi-criteria optimization is an optimization approach that seeks for a set of solutions called "Pareto optimal solutions" based on multi-criteria or objectives, i.e., each of Pareto optimal solutions is a compromised solution among multiple conflicting criteria. During the last few decades, multi-criteria optimization models were applied into supply chain network designs or used for solving distribution problems of a supply chain network [7-9]. These problems can be strategic in such as facility location-allocation problems or tactical in such as flow of products in quantities, along with other criteria of such as costs or profits and so on. For instance, Syam [10], Jayaraman [11] and Yan [12] considered total cost of supply chains as one of important criterion in their research. Altiparmak [13] proposed a genetic algorithm focusing on minimization of inbound and outbound distribution costs and maximization of customer services in terms of delivery time and capacity of distribution centers. Selim [14] presented a multi-criteria optimization model to cope with a production-distribution planning problem of a supply chain. Fuzzy goal programming was used to incorporate decision maker's imprecise aspiration levels. Ferrio [15] formulated a mixed integer linear programming model for configuring and optimizing the design of a multi-product chemical supply chain network which consists of production sites with arbitrary numbers of distribution centers, and customers.

This paper addresses a proposed RFID-based meat supply chain seeking a compromised solution based on three criteria; which include the total cost, customer satisfaction in percentage of demands in product quantity, and numbers of quality meat products to be delivered and received. To this aim, a tri-criteria mixed integer linear programming model was developed and used for optimizing the meat supply chain design with the considered criteria in terms of (i) the number and locations of farms and abattoirs that should be established and (ii) the quantities of livestock transported from farms to abattoirs and meat packets transported from abattoirs to retailers. The compromised programming and weighted Tchebycheff approaches were used to solve the optimization problems of outputs obtained based on the developed model. A decision making algorithm, which includes a two-stage selection, was employed to select the superior solution approach based on the obtained results. The developed model and its solution methodology can be used as a reference tool for decision makers to gain a cost-effective design of food supply chains.

II. The Mathematical Model

In this study, the meat supply chain includes three echelons: farms, abattoirs and retailers. In this chain, livestock is supplied from farms to abattoirs to be slaughtered then transported to retailers where meat products are packed. The RFID technology was proposed for tracing safety and quality of meat products during the transportation process from farms to abattoirs and from abattoirs to retailers [16]. Fig. 1 depicts the investigated meat supply chain.

Sets, parameters and decision variables are as follows:

Sets

I index used for a potential location of farm i , $1 \le i \le I$

J index used for a potential location of abattoir j , $1 \le j \le J$

K index for a fixed location of retailer k , $1 \le k \le K$

Cost parameters:

C_i^{α} cost (£) of RFID equipment and implementation required for farm i

C_j^{β} cost (£) of RFID equipment and implementation required for abattoir j

C_i^t RFID tag cost (£) for each item at farm i

C_j^t RFID tag cost (£) for each item at abattoir j

TC_{ij} unit transportation cost (£) per mile from farm i to abattoir j

TC_{jk} unit transportation cost (£) per mile from abattoir j to retailer k

LC_i^{α} unit labor cost (£) per hour at farm i

LC_j^{β} unit labor cost (£) per hour at abattoir j

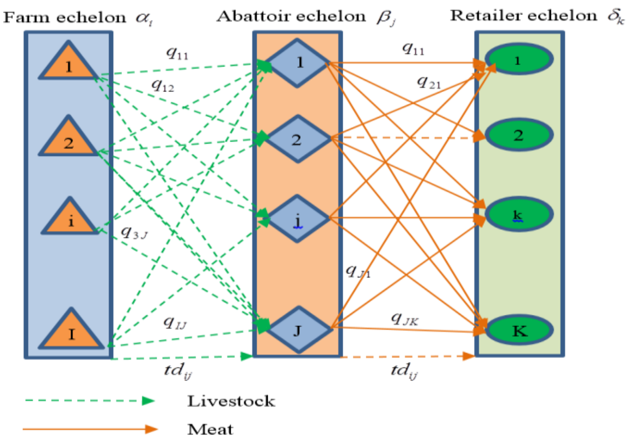

Fig. 1. A sturcture of the meat supply chain of this study.

Parameters of capacity, demand and transportation distance:

S_i^{α} maximum supply capacity (units) of farm i

S_j^{β} maximum supply capacity (units) of abattoir j

W_v transportation capacity (units) per vehicle (v)

D_j^{β} minimum demand (in units) of abattoir j

D_k^{δ} minimum demand (in units) of retailer k

d_{ij} travel distance (mile) from farm i to abattoir j

d_{jk}^n travel distance (mile) from abattoir j to retailer k

Labor parameters:

$R_i^{l\alpha}$ working rate (items) per laborer (l) at farm i

$R_j^{l\beta}$ working rate (items) per laborer (l) at abattoir j

$N_i^{h\alpha}$ minimum required number of working hours (h) for laborer l at farm i

$N_j^{h\beta}$ minimum required number of working hours (h) for laborer l at abattoir j

Other parameters

Q_{ij} healthiness percentage of livestock transported from farm i to abattoir j

F_{jk} freshness percentage of meat pieces transported from abattoir j to retailer k

Decision variables:

q_{ij} quantity of units transported from farm i to abattoir j

q_{jk} quantity of units transported from abattoir j to retailer k

x_i^{α} number of required laborers at farm i

x_j^{β} number of required laborers at abattoir j

Non-negative and binary decision variables:

$$y_i^{\alpha} = \begin{cases} 1: \text{if farm } i \text{ is open} \\ 0: \text{otherwise} \end{cases}$$

$$y_j^{\beta} = \begin{cases} 1: \text{if abattoir } j \text{ is open} \\ 0: \text{otherwise} \end{cases}$$

The criteria functions are formulated as follows:

Minimum total cost F_1 = costs of equipment and implementation for the RFID + RFID tag cost for each item + transportations costs – labor costs saved after the RFID implementation

$$Min\ F_1 = \sum_{i\in I} C_i^{\alpha} y_i^{\alpha} + \sum_{j\in J} C_j^{\beta} y_j^{\beta} + \sum_{i\in I} C_i^{t\alpha} q_{ij} + \sum_{j\in J} C_j^{t\beta} q_{jk} \tag{1}$$
$$+\sum_{i\in I}\sum_{j\in J} TC_{ij} \left\lceil q_{ij} / W_v \right\rceil d_{ij} + \sum_{j\in J}\sum_{k\in K} TC_{jk} \left\lceil q_{jk} / W_v \right\rceil d_{jk}$$
$$-\sum_{i\in I} LC_i^{\alpha} x_i^{\alpha} N_i^{h\alpha} - \sum_{j\in I} LC_j^{\beta} x_i^{\beta} N_j^{h\beta}$$

Maximum customer satisfaction F_2 = the fulfilment of customer' demand in percentage of product quantity as requested by customers.

$$Max\ F_2 = \sum_{k=1}^{K} \left(\sum_{j=1}^{J} q_{ij} \Big/ D_k^{\delta} \right) \tag{2}$$

Maximum product quality F_3 = healthiness of livestock transported from farms to abattoirs + freshness of meat pieces transported from abattoirs to retailers.

$$Max\ F_3 = \sum_{i=1}^{I} Q_{ij} y_i^{\alpha} + \sum_{j=1}^{J} F_{jk} y_j^{\beta} \tag{3}$$

Several constraints are defined after formulating the criteria functions. These constraints are grouped in different categories as follows:

Capacity constraints: ensure the flow balance of products from farms to abattoirs and from abattoirs to retailers.

$$\sum_{i\in I} q_{ij} \le S_i^{\alpha}\ y_i^{\alpha} \qquad \forall\ j \in J \tag{4}$$
$$\sum_{j\in J} q_{jk} \le S_j^{\beta}\ y_j^{\beta} \qquad \forall\ k \in K \tag{5}$$

Demand constraints: ensure that the demands in quantity of products of all abattoirs and retailers are satisfied.

$$\sum_{i\in I} q_{ij} \ge D_j^{\beta} \qquad \forall\ j \in J \tag{6}$$
$$\sum_{j\in J} q_{jk} \ge D_k^{\delta} \qquad \forall\ k \in K \tag{7}$$
$$D_j^{\beta} \ge \sum_{k\in K} q_{jk} \qquad \forall\ j \in J \tag{8}$$

Working rate constraints: determine the required number of laborers at farms and abattoirs.

$$\sum_{j\in J} q_{ij} \le x_i^{\alpha}\ R_i^{l\alpha} \qquad \forall\ i \in I \tag{9}$$
$$\sum_{k\in K} q_{jk} \le x_j^{\beta}\ R_j^{l\beta} \qquad \forall\ j \in J \tag{10}$$

Restriction constraints: restrict the decision variables to binary and non-negative.

$$q_{ij}, q_{jk}\ \ \ge 0,\ \forall i, j, k; \tag{11}$$
$$y_i^{\alpha}, y_j^{\beta}\ \ \in \{0,1\},\ \forall i, j; \tag{12}$$

Finally, $0.75 \le Q_{ij} \le 1$ and $0.75 \le F_{jk} \le 1$ constraints, which limit the healthiness percentage Q and the freshness percentage F to be between 0.75 and 1 based on decision makers' preferences.

III. Multi-criteria optimization methodology

A. Compromised programming approach

The compromise programming approach is its ability to achieve efficient points in a non-convex Pareto curve [17]. This approach based on optimizing one criterion function and shifting the other to the constraint set to be restricted to an assigned value ε. The equivalent solution formula F is presented as follows.

$$Min\ F = \sum_{i\in I} C_i^{\alpha} y_i^{\alpha} + \sum_{j\in J} C_j^{\beta} y_j^{\beta} + \sum_{i\in I} C_i^{t\alpha} q_{ij} + \sum_{j\in J} C_j^{t\beta} q_{jk} \tag{13}$$
$$+\sum_{i\in I}\sum_{j\in J} TC_{ij} \left\lceil q_{ij} / W_v \right\rceil d_{ij} + \sum_{j\in J}\sum_{k\in K} TC_{jk} \left\lceil q_{jk} / W_v \right\rceil d_{jk}$$
$$-\sum_{i\in I} LC_i^{\alpha} x_i^{\alpha} N_i^{h\alpha} - \sum_{j\in I} LC_j^{\beta} x_i^{\beta} N_j^{h\beta}$$

Additional constraints:

$$F_2 \ge \varepsilon_1 \tag{14}$$
$$\left[F_2\right]^{\min} \le \varepsilon_1 \le \left[F_2\right]^{\max} \tag{15}$$
$$F_3 \ge \varepsilon_2 \tag{16}$$
$$\left[F_2\right]^{\min} \le \varepsilon_2 \le \left[F_2\right]^{\max} \tag{17}$$

In this paper, criterion function one is selected to be optimized (Eq.13) and shifting criterion function two and three to be constraints (Eq. 14 and 16, respectively); An increase to the ε value (Eq.15 and 17, respectively) yields Pareto solutions.

B. Weighted Tchebycheff approach

With this approach, the multi-objective model can be transformed into a single-objective model *F*. The purpose of the single-objective model is to minimize the distance between the ideal objective vector *F** and the feasible objective surface [18]. The solution approach function *F* can be formulated as follows:

$$Min\ F = \left(\sum_{n=1}^{3} l_n \left| F_n - F^* \right|^p \right)^{\frac{1}{p}} \tag{18}$$

Subject to constraints defined previously. Noticeably, the values of objective functions vary depending on the value of *p*. Usually, *p* is set as 1 or 2. But, other values of *p* can also be used. In this case study, *p* is set as 1.

C. Decision making algorithm

The next step after deriving the Pareto optimal solutions from the two solution approaches is to select the superior approach. In this paper, the selection algorithm is based onto two stages; the first stage selects the best trade-off solution for each set of solutions. Selecting the superior approach is determined in the subsequent stage. The next two sub-sections present the two stages, respectively.

1) Global criterion approach: From the decision maker's view-point, choosing a solution of Pareto-optimal solutions is called a posteriori method [19]. There are several methods for selecting the most suitable solution in a multi-objective problem. In this case, the global criterion method was used for determining the best solution by minimizing the distance to the ideal objective value [20]. The decision-making formula is expressed as follows:

$$Min\ F = \left(\sum_{n=1}^{3} \left| F_n - F_n^* \right|^{\rho} \right)^{1/\rho};\ \ 1 \le \rho \le \infty \tag{19}$$

In this approach, the solution with the minimum distance is selected as a best solution. Generally, ρ is 1; However, other values of ρ also can be used.

2) The developed technique: The idea of the developed technique for selecting the best approach is based on selecting the solution approach that is closest to the ideal solution. In this technique, S^* denotes the average superiority value for each approach; (i) determine the average mean value for the three criterion functions, (ii) sum the three average mean values, and (iii) select the approach with the lowest superiority value. The selection technique formula is presented as follows:

$$S^* = \sum_{n=1}^{3} \frac{F_n}{F_n^*} \tag{20}$$

Where F_i^* is the ideal value for each criterion. This value is determined by optimizing the criteria functions individually.

IV. Application and comparison: South East London as a case study

A case study is presented to demonstrate the applicability of the developed tri-criteria model and compare the performance of the proposed solution approaches in terms of the criteria values. In the case study, the South-East area of London encompasses 4 farms *i*, 7 retailers *K* and 4 abattoir *j* to suppliers. The given parameters are chosen in a defined range based on assumptions: RFID equipment (e.g. RFID reader and management system) and implementation costs at farm *i* where C_i^{α} = 4400-8800 £, RFID equipment and implementation costs at abattoir *j* where C_j^{β} = 1100-8.7 £, RFID tag cost for each item at farm i and abattoir *j* C_i^{t} = 0.15 £, transportation costs from farm *i* to abattoir *j* and from abattoir *j* to retailer *k* where TC_{jk} = 20 £, supply capacity of farm *I* where S_i^{α} = 2.5K-4.4K, supply capacity of abattoir *j* where S_j^{β} = 1.2K-1.8K, demand of abattoir *j* where D_j^{β} = 800-1.3K, demand of retailer *k* where D_j^{δ} = 100-800K, travel distance from farm i to abattoir j where d_{ij} = 23-400, travel distance from abattoir j to retailer *k* where d_{jk} = 110-162, vehicle capacity W_v = 100, quality percentage of livestock transported from farm i to abattoir *j* Q_{ij} = 0.75-1, freshness percentage of meat pieces transported from abattoir j to retailer *k* F_{jk} = 0.75-1, labor cost per hour at farm *i* and abattoir *j* where ($LC_i^{\alpha}, LC_j^{\beta}$) = 6.5 £, working rate per labor *l* at farm *i* and abattoir *j* where ($R_i^{l\alpha}, R_j^{l\beta}$) = 50 items. Data, which are related to locations of farms, abattoirs and retailers, were collected from the Meat Committee in the UK [21], and the transportation distances between supply chain facilities were estimated using Google-Maps. Also, the demand reported above is the total demand over a one-year period. The prices of RFID equipment and its implementation were based on commercial prices.

Using the above numerical data, the tri-criteria optimization problem described in Section II was solved using two approaches on a computer with corei5-CPU 2.60 GHz, RAM 4.00 GB, using the LINGO[11] software.

Table I elucidates the values for three criteria when optimized individually by using equations 1-3, respectively. This optimization was used for obtaining the ideal solution for each criterion. The total cost can be minimized to 194,180 £ if the criterion function one was only considered, while in this solution the criterion function two and three worsen to 75% and 8,885 items of meat products, respectively. On the antithesis, if the second criterion function F_2 was only considered, customer satisfaction would increase to 100%. However, the total cost was increased to 491,000 £ in this solution. Finally, considering the third criterion F_3 individually, the objective of product quality can be increased to 13,099 items of meat products with an increase in the total cost of 481,390 £ and customer satisfaction equals 99%. In this situation, the contradictory is manifested between these three criteria functions. However, moving toward an enhancement in customer satisfaction and product quality in supply chains requires significantly higher cost investment.

In Table I, it can be easily noticed that no solution is optimal, i.e., it is impossible to obtain an optimal solution for the three criteria when optimizing them individually. To this aim, two solution approaches were employed seeking the Pareto sets derived from co-optimizing the three contradicting criteria functions being considered (simultaneously) as minimizing total cost F_1, maximizing customer satisfaction F_2 and maximizing product quality F_3.

To obtain Pareto optimal solutions using: (i) the compromise programming approach, by altering the incremental epsilon value of 526 between 8,885 to 13,099 for criterion two using Eq.14 and of 0.025 between 0.75 to 1 for criterion three using Eq.16 and (ii) the weighted Tchebycheff

TABLE I. The values of each criterion function when optimized individually

Criterion function	**Min F_1 (£)**	**Max F_2 (%)**	**Max F_3 (Items)**
F_1	194180	0.75	8885

F_2	491000	1	13099
F_3	481390	0.99	13099

approach, the ideal values of the three criteria functions illustrated in Table I were given as ideal values $F_1^{\bullet}, F_2^{\bullet}, F_3^{\bullet}$ for the solution function F using Eq.19. Table II illustrates the obtained two sets of Pareto optimal solutions which were obtained using the two solution approaches. These solutions are associated with the number of farms and abattoirs that should be established.

Shown in Table II**,** the third column represents the obtained values of the first criterion function F_1 in terms of £, obtained values of the second and third criterion functions (F_2 and F_3) in terms of percentage and items are presented in the fourth and fifth columns respectively. The last two columns (right-end) correspond to the number of farms and abattoirs that should be established. For instance, solution 4 for the compromise programming solution approach was obtained by giving an assigning of ε_1 equals 0.825 and ε_2 equals 10,470; accordingly, minimum total cost is equal to 273,171 £ while maximum customer satisfaction is equal to 82.6% and maximum product quality is equal to 10,473 items of meat products. This solution consists an establishment of farms three and four (0 0 1 1) and abattoirs two and four (0 1 0 1).

It can be observed in Table II, the Pareto optimal cannot get better in one criterion except worsening its performance in other criteria.

A. Selecting the superior approach

After solving the tri-criteria optimization problem, to design the meat supply chain network, decision makers have to select the best solution which was obtained using the best approach. As shown in Table II, the criteria values of minimum total cost, maximum customer satisfaction and maximum product quality are slightly different; this makes a direct selection of the best solution impossible. Hence, a decision-making algorithm was used. At the first stage, the global criterion approach was employed to select the best Pareto solution for each solution approach. Pareto solutions 3 and 3 (in Table II) for the two approaches, respectively, were determined as the best solutions for the two solution approaches, where they achieved the minimum distances to their ideal criteria values; these distances are 1.69 and 1.741, respectively. The developed selection technique was then applied to select the superior approach using Eq.20. Accordingly, the obtained superiority values for the two approaches were equal to 2.568 and 2.743, respectively. These values proved the superiority of the compromise programming approach to tackle the considered tri-criteria problem where it obtained the lowest superiority value (2.568); its solution 3 in Table II was obtained by assigning $\boldsymbol{\varepsilon}_1$ equals 0.825 and $\boldsymbol{\varepsilon}_2$ equals 9,937. Based on the determined solution, Fig. 2 illustrates the optimal meat supply chain network design. Subsequently, three farms located in Warwickshire, Leicestershire, and the Yorkshire are determined to be established in addition to two abattoirs located in Birmingham and Warrick shown in such as a google map. The minimum total cost for the selected solution is equal to 248,214 £ while the maximum of both customer satisfaction and product quality is equal to 0.8 % and 9,937 items of meat products respectively. The distribution plan of products was also determined; for instance, 900 livestock are to be transported from farm one (located in Warwickshire) to abattoir four (located in Warrick) and 800 items of meat products are to be transported from abattoir two (located in Birmingham) to retailer one.

V. CONCLUSIONS

In this paper, a tri-criteria mixed integer linear programming model was developed for solving an issue of a three-echelon RFID-based meat supply chain design considering three criteria. The first criterion was total implementations and operational cost, the second criterion was customer satisfaction (%) which includes the fulfillment of customer' demand in product quantities, and product quality in numbers of meat products was considered as a third criterion. To reveal Pareto solutions based on the developed model, two solution approaches were investigated. A numerical case study was studied for examining the applicability of the developed

TABLE II. PARETO SOLUTIONS OBTAINED BY USING TWO DIFFERENT APPROACHES

Solution approach	#	Min (F_2) (£)	Max (F_2) (%)	Max (F_3) (items)	Open farms	Open abattoirs
Compromise programming	1	194180	0.75	8885	1 0 0 1	0 1 0 1
	2	223257	0.776	9411	1 0 1 1	0 1 0 1
	3	248214	0.8	9937	1 0 1 1	0 1 0 1
	4	273171	0.826	10473	0 0 1 1	0 1 0 1
	5	300475	0.85	10989	1 0 1 1	1 0 1 1
	6	345228	0.91	11515	1 1 1 1	1 1 0 1
	7	382940	0.95	12041	1 1 1 1	1 0 1 1
	8	468475	1	13099	1 1 1 1	0 1 1 0
Weighted Tchebycheff	1	194180	0.75	8885	1 0 0 1	0 1 0 1
	2	194180	0.75	8885	1 0 0 1	0 1 0 1
	3	249231	0.78	8920	1 0 1 1	1 1 1 1
	4	288557	0.8	9808	1 1 1 1	1 1 1 1
	5	338858	0.85	10414	1 1 1 1	1 1 1 1
	6	422451	0.91	11094	1 1 1 1	1 1 0 1
	7	539128	0.96	12376	1 1 1 1	1 1 1 1
	8	580471	0.99	13029	1 0 0 1	0 1 0 1

model and to compare the performance of the investigated solution approaches based on their solutions values. However, no solution was ideal as none of these two approaches could reveal an ideal solution for the three criteria functions at a time. To this aim, a developed decision making algorithm was employed that revealed the compromise programming approach as superior. The developed tri-criteria optimization model proved the feasibility of the proposed RFID-enabled meat supply chain in terms of obtaining a compromised solution between economic costs and customer satisfaction.

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