



**Modelling and optimization of an RFID-based supply
chain network**

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*“The rare a thing, the more its value increases, except knowledge: the more
diffused it is the more valuable”*

(Imam Ali)

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Abstract

Food supply chains (FSCs) are one of the major sectors in the global economy. Developing efficient and cost-effective food supply chains, provide an opportunity for supply chain and logistics companies to survive in the increasingly competitive market of today. In order to achieve this, one of the methods is to enhance the traceability of food during production, transportation and storage throughout the entire supply chain network in order to improve and maintain the quality and safety of the food provided to customers. Other methods include design and optimization of a supply chain network towards objectives such as the minimization of costs, transportation time and environmental pollution, and the maximization of service level and profits and so on.

This study proposes a radio frequency identification (RFID)-enabled monitoring system for a meat production and supply chains network that ensures the integrity and quality of its meat products. The study also includes the development of three multi-objective optimization models as an aid to solving the facility location and allocation problem and the quantity flow of products travelling throughout the meat supply chain network with respect to trade-off solutions among a number of objectives. To deal with the uncertainty of the input data (e.g., costs, capacity and demands), stochastic programming and fuzzy programming models were also developed. Furthermore, by applying suitable solution approaches, Pareto solutions can be obtained based on the developed multi-objective models. For this a decision-making algorithm was used to select the best Pareto solution. In order to examine feasibility and applicability of the developed approaches, a proposed RFID-enabled automated warehousing system and a proposed RFID-enabled passport tracking system were also used as case studies by applying the developed approaches for the design and optimization of these two systems, respectively.

Research findings demonstrate that the proposed RFID-enabled monitoring system for the meat supply chain is economically feasible as a relatively higher profit can be achieved. The study concludes that the developed mathematical models and optimization approaches can be a useful decision-maker for tackling a number of design and optimization problems for RFID-based supply chains and logistics systems and tracking systems.

Keywords

Supply chains; RFID; Halal; Multi-objective; Fuzzy optimization; Solution approaches; Facility locations; Automated warehouses; Tracking systems.

Table of Contents

Abstract.....	ii
List of Tables	viii
List of Figures.....	x
Acknowledgment.....	xi
Declaration.....	xii
Disseminations.....	xiii
Chapter 1 Introduction	1
1.1 Research background.....	1
1.2 Research aims and objectives.....	4
1.3 Road-map of thesis	6
1.4 Summary.....	9
Chapter 2 Literature review	10
2.1 Traceability of Halal meat products.....	10
2.2 Traceability of food products.....	11
2.3 Multi-objective optimization for food supply chain networks.....	11
2.4 Multi-objective optimization for supply chain networks.....	12
2.5 Multi-objective optimization for supply chain networks under uncertainty.....	13
2.6 Multi-objective optimization for green supply chain networks.....	15
2.7 Mathematical approaches for optimizing automated warehouses.....	15
2.8 Mathematical approaches for optimizing RFID-enabled systems.....	16
2.9 Research gaps.....	17
2.10 Summary.....	18
Chapter 3 Fundamental concepts of multi-objective optimization	19
3.1 Multi-objective optimization.....	19
3.1.1 Methods for multi-objective optimization.....	21
3.1.1.1 ϵ -constraint (compromise programming).....	21
3.1.1.2 Weighted Sum.....	22
3.1.1.3 Goal programming.....	23
3.1.1.4 Weighted Tchebycheff.....	24
3.1.1.6 Global criterion approach.....	24
3.1.1.7 LP-metrics.....	25
3.1.2 Multi-objective optimization for supply chain networks.....	25
3.1.3 Modelling under uncertainty.....	28
3.1.3.1 Approaches to tackle the uncertainty.....	29

3.2 Summary	32
Chapter 4 The RFID-monitoring HMSC	33
4.1 Introduction.....	33
4.2 Halal meat	34
4.2.1 Requirements for Halal meat processing	37
4.3 Food traceability	39
4.3.1 Definition of traceability.....	40
4.3.2 Challenges.....	44
4.4 RFID technology.....	45
4.4.1 RFID History	45
4.4.2 RFID components	46
4.4.3 RFID communication.....	49
4.4.4 Benefits of RFID for supply chain management.....	50
4.4.5 RFID in food supply chains	51
4.5 The proposed 2G-RFID-enabled HMSC	52
4.6 Multi-objective mathematical model	58
4.4 Solution methodology	60
4.4.1 Optimization approach.....	60
4.4.2 Decision-making algorithm.....	62
4.5 Application and evaluation	62
4.7 Summary	67
Chapter 5 A cost-effective decision-making algorithm for an RFID-enabled HMSC network design: A multi-objective approach.....	68
5.1 Introduction.....	68
5.2 The HMSC network model.....	69
5.2.1 The deterministic model.....	69
5.2.2 The stochastic model.....	72
5.3. Solution approaches	74
5.3.1 The ε -constraint approach	74
5.3.2 The developed approach	76
5.3.3 The Max-Min approach	77
5.4 Computational results and analysis.....	78
5.4.1 Results of the deterministic model.....	78
5.4.2 Results of the stochastic model.....	82
5.4.3 The HMSC network design with and without the RFID implementation: a comparison	84
5.5 Conclusions.....	85

Chapter 6 Developing a meat supply chain network design using a multi-objective possibilistic programming approach	86
6.1 Introduction.....	86
6.2 Model description and formulation.....	86
6.3 Optimization methodology	92
6.3.1 Solution method.....	93
6.3.1.1 The LP-metrics method.....	93
6.3.1.2 The ϵ -constraint method.....	94
6.3.1.3 The weighted Tchebycheff method.....	94
6.3.1.4 The TOPSIS method	95
6.4 Case study	96
6.4.1 Results and discussions.....	97
6.5 Conclusions.....	103
Chapter 7 The fuzzy multi-objective distribution planner for a green meat supply chain	104
7.1 Introduction.....	104
7.2 Developing the fuzzy multi-objective distribution planner	105
7.2.1 Modelling the uncertainty	109
7.3 Solution methods	113
7.3.1 LP-metrics.....	113
7.3.2 ϵ -constraint.....	113
7.3.3 Goal programming	114
7.3.4 The Max-Min.....	116
7.4 Application and evaluation of the FMOPM.....	117
7.4.1 Computational results	118
7.5 Conclusions.....	131
Chapter 8 Design and Optimization of an RFID-enabled automated warehousing system under uncertainties: A multi-criterion fuzzy programming approach.....	132
8.1 Introduction.....	132
8.2 Problem description and model formulation.....	132
8.2.1 Notations	133
8.2.2 Formulating the multi-criterion optimization problem	135
8.2.3 Constraints	136
8.3 The proposed optimization methodology	137
8.3.1 Solution procedures	137
8.3.2 Formulating the uncertainty	138

8.3.3 Optimization approach.....	140
8.3.3.1 The developed approach	140
8.3.3.2 SO approach.....	140
8.3.4 The decision-making algorithm	141
8.4 Application and evaluation	142
8.4.1 Results and discussions.....	142
8.5 Conclusions.....	149
Chapter 9 Design and optimization of an RFID-enabled Passport Tracking System....	150
9.1 Introduction.....	150
9.2 Model development	151
9.2.1 Formulating the multi-objective optimization model	155
9.2.2 Constraints	157
9.2.3 Modelling the uncertainty	158
9.3 Optimization methodology	159
9.3.1 Solution approaches	161
9.3.1.1 The ϵ -constraint approach	161
9.3.1.2 The developed approach	162
9.3.2 The decision-making algorithm	162
9.4 Application and evaluation	163
9.4.1 Results.....	164
9.5 Conclusions.....	170
Chapter 10 Conclusions and recommendations for future work.....	171
10.1 Concluding remarks	171
10.2 Research contributions.....	171
10.3 Recommendations for future work	174
10.4 Summary	Error! Bookmark not defined.
Acronyms.....	175
References.....	176

List of Tables

Table 1. List of publications relating to multi-objective optimization problems for supply chains	26
Table 2. List of publications in mathematical modeling for supply chain problems under uncertainty	30
Table 3. Selected definitions of traceability in food supply chain	40
Table 4. A summary of technologies proposed for the traceability of food industry (Aung and Chang, 2014)	42
Table 5. A comparison among the three types of RFID transponders	48
Table 6. Growing history of a livestock in farms	53
Table 7. Information of a packed meat product at abattoirs to be sold at retailers or supermarkets	55
Table 8. The corresponding operations or actions of a HMSC monitoring process shown in Figure 10	57
Table 9. Collected data from the HMC	63
Table 10. Computational results for cases A and B, respectively	64
Table 11. Parameters used for the case study	78
Table 12. Non-inferior solutions obtained using the ϵ -constraint approach	79
Table 13. Non-inferior solutions obtained using the developed approach	79
Table 14. Integrity percentage and probability in integrity percentage for farm 1-5 in varying scenarios	82
Table 15. Results of a set of non-inferior solutions of the stochastic model	83
Table 16. Collected data of the three-echelon meat supply chain	97
Table 17. Optimum values obtained individually by optimizing O_i based on each objective function	98
Table 18. Assignment of weight values for obtaining Pareto solutions using the LP-metrics method and the weighted Tchebycheff method, respectively	98
Table 19. The computational results obtained by assigning the varying α values	99
Table 20. Result of satisfaction degree of each objective function	100
Table 21. Pareto-optimal solutions ranked based on scores using the TOPSIS method	101
Table 22. The result of Pareto solutions in terms of optimum quantity of product flow throughout the three-echelon meat supply chain	102
Table 23. The values of parameters	118
Table 24. Max and Min values in responding to objective Z_1, Z_2, Z_3 and Z_4 , respectively	118
Table 25. Values of Z_1, Z_2, Z_3 and Z_4 obtained by optimizing them individually	120
Table 26. Weights allocation related to the LP-metrics approach	120
Table 27. Computational results of Z_1, Z_2, Z_3 and Z_4 obtained by the LP-metrics	121
Table 28. Assignment of ϵ -value related to the ϵ -constraint approach	122
Table 29. Computational results of Z_1, Z_2, Z_3 and Z_4 obtained by the ϵ -constraint	123
Table 30. Computation results of Z_1, Z_2, Z_3 and Z_4 obtained by the goal programming	125
Table 31. Application data used for the case study	142
Table 32. Assignment of weight values for obtaining Pareto solutions using two approaches	143
Table 33. The results obtained by assigning the varying values to each of the three criterion functions	144
Table 34. The optimal number of storage racks and collection points that should be established	144
Table 35. Result of satisfaction degree of each criterion function	145
Table 36. Pareto-optimal solutions ranked based on scores using the TOPSIS method	145
Table 37. The values of parameters	164
Table 38. Assignment of ϵ -value related to the ϵ -constraint approach	165
Table 39. Results related to F_1, F_2 and F_3 using the ϵ -constraint based on different λ values	166
Table 40. Values of F_1, F_2 and F_3 obtained by optimizing them individually	166

Table 41. Weights allocation related to the developed approach.....	166
Table 42 Results related to F_1 , F_2 and F_3 using the developed approach based on different λ values	167
Table 43. Pareto-optimal solutions ranked based on scores using the developed decision-making algorithm.....	167

List of Figures

Figure 1. Pareto solutions.	21
Figure 2. Halal processes at each stage of the HMSC (Lodhi 2009).	35
Figure 3. The investment size for the RFID technology.	46
Figure 4. A simplified RFID system.	47
Figure 5. Structure of inductive coupling transmission.	49
Figure 6. A simplified structure of the electromagnet wave transmission.	50
Figure 7. Architecture of the proposed RFID-based monitoring HMSC network.	52
Figure 8. The transportation monitoring system.	54
Figure 9. Data flow of the transportation monitoring process.	55
Figure 10. The Halal monitoring process of a HMSC.	56
Figure 11. A Pairwise comparison among the three objectives for case A.	65
Figure 12. Architecture of the proposed RFID-based monitoring HMSC network.	66
Figure 13. The three-echelon HMSC.	69
Figure 14. ROI in relation to the total investment cost using (a) the ϵ -constraint approach, (b) the developed approach, (c) the ϵ -constraint and the developed approaches, respectively.	81
Figure 15. An optimal HMSC network design.	82
Figure 16. The value of OF2 in response to each of the selected integrity scenarios.	83
Figure 17. Comparative results of the total investment cost between the non-RFID-based HMSC and the RFID-based HMSC.	84
Figure 18. The three-echelon meat supply chain network.	87
Figure 19. Locations of candidate facilities in Yorkshire of the UK.	97
Figure 20. The three-echelon meat supply chain network.	105
Figure 21. Membership functions related to the four objectives (a) Z_1 , Z_2 and Z_4 , (b) Z_3	113
Figure 22. Procedures in developing and optimizing the FMOPM.	117
Figure 23. Z_1 , Z_2 , Z_3 and Z_4 values for various α -level.	127
Figure 24. Comparative results obtained based on the three objective functions using the three proposed methods, respectively.	128
Figure 25. The optimal design of the distribution plan for the MSC.	129
Figure 26. Geographical locations of the selected facilities for solution 4.	130
Figure 27. Structure of the proposed RFID-enabled AS/RR (Wang et al., 2010).	133
Figure 28. Flowchart of the optimization methodology.	141
Figure 29. Pareto optimal fronts among the three criterion functions obtained by the two approaches.	147
Figure 30. Structure of the system under study.	152
Figure 31. Membership functions of the objective functions (a) Z_1 and Z_2 , (b) Z_3	161
Figure 32. Flowchart of the FMOM.	163
Figure 33. Pareto fronts for the three objective functions obtained using the two approaches.	169

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Declaration

‘Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award’.



Author's signature

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Disseminations

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4	Mohammed, A., Wang, Q. and Li, X. (2016). A Study in Integrity of an RFID-Monitoring HMSC. <i>International Journal of Food Properties</i> , 5, 1145-1158.	Published
5	Mohammed, A., Wang, Q. and Li, X. (2017). Developing a Meat Supply Chain Network Design Using a Multi-Objective Possibilistic Programming Approach. <i>British Food Journal</i> , 119 (3), 690-706.	Published
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To my parents, my wife and my two children Taym and Jori

Introduction

1.1 Research background

Supply chains encompass different stages participated, directly or indirectly, in satisfying customers' demands. Graneshan and Harrison (1995) defined a supply chain as a network of facilities that jointly perform procurement of materials, transformation of these materials into intermediate or finished products if applicable, and distribution of these materials, intermediate or finished products to customers at the end. Douglas et al. (1998) defined the supply chain as a co-operation of some companies to provide merchandises to markets. In other hand, supply chain management can be defined as *“the systematic and strategic coordination of business functions and the tactics within a particular company within a supply chain”* (Mentzer et al., 2001). Supply chain management is important for incorporating and coordinating activities and operations within different providers aiming to provide the reliable distribution of high quality goods and services to customers in a cost-effective manner (Viaene and Verbeke, 1998).

Food supply chains have traditionally been dominant business in the past centuries (Pullman and Wu, 2012). The global demand of food is expected to double by 2050, this makes food supply chains as one of the key sectors in economy (Accorsi et al., 2016; Mattevi and Jones, 2016; Fritz and Schiefer, 2009). The importance of developing a cost-effective and efficient food supply chain networks is obvious in the increasingly competitive food market (Zhalechian et al., 2016). This partially involves a strategic decision-making process in determination of location and allocation of relevant facilities and a tactical decision in quantity flow of products travelling throughout the supply chain network. However, due to the dynamic nature of supply chain networks, different parameters such as demands, costs and so on may change because of the uncertain circumstances over the market and this may greatly affect the design and performance of the supply chains network (SCD). Therefore, issues of uncertainty need also to be considered in activities of supply chain management (Zhalechian et al., 2016; Fattahi et al., 2015; Davis, 1993). This adds difficulties in seeking

an optimal solution in designing the SCD as this may not be achieved using the linear programming. The latter refers to an important type of optimization in which the objective function and constraints are all linear. Linear programming problems include specialised approaches for their solution and for other types of optimisation problems by solving linear programming problems as sub-problems. Linear programming is heavily used in various management activities, either to maximise the profit or minimise the cost. However, the conventional linear programming deals with certain (crisp) parameters in which the uncertain input parameters that are normally varied in real-life situation (e.g., customers' demands) cannot be handled.

Thus, fuzzy programming can be applied to handle the uncertainty in input parameters of supply chain networks (Alonso-Ayuso et al., 2007; Listes, 2007 and El-Sayed et al., 2010; Wang and Hsu, 2010; Qin and Ji, 2010; Gholamiana et al., 2015). A detailed description on fuzzy programming and design under uncertainty is presented in section 3.1.3.

In recent years, the concern of quality and safety of food is a big issue and customers demand more transparency for real time information on food they purchase in food stores. For Muslim people, Halal meat consumers are increasingly concerned about the integrity of Halal meat products in terms of production, transportation and storage along an entire supply chain network as it is important for Halal meat products, these consumers purchase from supermarkets as truly Halal. Farouk (2016) suggested that the Halal food production needs more transparency about circumstances of livestock throughout the supply chain with the aim of customers can make their decision in purchasing the product. Unlike non-Halal food, Halal food suppliers are required to monitor a Halal Meat Supply Chain (HMSC) network providing adequate information of Halal meat products sold in supermarkets and these information data should also be easily accessed by Halal meat consumers. Research of HMSCs is increasingly important (Pahim et al., 2012), since more and more Halal consumers are not just concerned about Halal products but also Halal logistics and supply chains (Kamaruddin et al., 2012). Khan (2008) supported every stage in the Halal supply chain, which needs to be well considered to preserve the integrity of Halal products. A literature review carried out by authors shows that this area is overlooked by researchers (Lodhi, 2009; Zulfakar, 2012). Also, there are a small number of studies through publications applying fuzzy and stochastic multi-objective optimization methods into FSC design and management. Currently, there are no unified standards of Halal industry worldwide. Every country may have their own standards that need to be followed by the Halal parties. This has led to

confusion, misunderstanding and even abuse in the Halal audit and certification process. The World Halal Forum chairman, Khairy Jamaluddin argued that the absence of a global Halal standard has resulted in the slow growth of Halal industry despite the rising demands for Halal products worldwide (Hassan, 2007; Zulfakar, 2012). In the UK, a committee member needs to visit every abattoir to check the slaughtering process and there is a charge for that service (HMC, 2012). In light of the aforementioned gap, as part of this research work it proposes a monitoring system for Halal meat production from farm to customer that ensures the integrity and quality of Halal meat to customers as it is important to gain the customers trust on Halal products they purchase. To the best knowledge of the author of this thesis, this is the first research that provides the complete system architecture for the HMSC that can be monitored and information on Halal products can be accessed. However, such a monitoring system is subject to an additional cost in investments that should be considered in HMSCs. To this aim, a multi-objective optimization model was developed to examine the economic feasibility of the proposed RFID-enabled monitoring system.

Supply chain designers often encounter difficulties in capturing a trade-off solution due to the optimization of conflicting objectives in such as minimization of costs, and maximization of profits, products quality and service levels. A good plan can also help deliver products timely from manufacturers to retailers through a supply chain network. This process involves a determination of allocations and locations of facilities, material handling capacity, transportation capability, delivery time and other performance measures. Thus, there is a need for optimizing the supply chain network design towards the aforementioned objectives.

This study presents a development of multi-objective optimization models for meat supply chain networks to support a number of strategic and tactical decisions and to obtain compromising solutions among the multiple conflicting objectives. As mentioned previously, issues of uncertainty (e.g., varying costs and demands) need also to be taken into account when designing a supply chain network. To this aim, fuzzy multi-objective optimization models and a stochastic multi-objective optimization model were developed for incorporating the uncertain data (i.e., both fuzzy data and random data). In order to effectively deal with multiple-objective optimization problems, a solution approach was developed to reveal Pareto solutions. Subsequently, a decision-making algorithm was developed as an aid for the decision makers in selecting the best Pareto solution. In order to examine the applicability of the developed optimization approaches in solving similar design and optimization problems, two case studies were applied. These include:

(i) A design and optimization problem of a proposed RFID-enabled automated warehousing system in terms of (1) allocating the optimal number of storage racks and collection points that should be established; and (2) obtaining a trade-off towards the optimization of three objectives: minimization of the total warehouse cost, maximization of the warehouse capacity utilization and minimization of the travel time of products from storage racks to collection points.

(ii) A design and optimization of a proposed RFID-enabled passport tracking system in terms of (1) allocating the optimal number of related offices that should be established; and (2) obtaining a trade-off towards the optimization of three objectives: minimization of the implementation and operational costs, minimization of the RFID reader interference and maximization of the social impact (i.e., number of created career opportunities).

The contribution of this work has the potential in solving the similar optimization problems of a multi-objective model for a food supply chains network design. The developed models can be a useful decision maker to tackle the relevant optimization issues in practice for supply chains network design and logistics. Lastly, the further research work is recommended in this thesis towards a development of a sustainable meat supply chain network design incorporating such as environmental and social considerations and product quality deterioration as objectives.

1.2 Research aims and objectives

This research is aimed at (1) enhancing traceability and confidentiality of meat products in terms of quality and safety throughout its entire supply chain, (2) investigating the economic feasibility of RFID implementation in a HMSC, (3) supporting decision makers in obtaining trade-offs among multiple objectives (e.g. minimum costs, minimum transportation time, maximum service level, minimum environmental impact, maximum confidential products and a compromised management among supply, production and demand), (4) developing a decision-maker to determine the optimal locations and allocations of facilities that should be established in conjunction with the optimal quantity flow of products travelling throughout the supply chain network, and (5) making the study closer to real-life situation by handling the uncertainty in input parameters (e.g. costs and demands). Objectives of this work are as follows:

- 1) To propose a theoretical design in the development of a RFID-enabled monitoring system for a HMSC network design for enhancing traceability and confidentiality of safety, quality and integrity of Halal meat products.
- 2) To develop a multi-objective mathematical model used for investigating the economic feasibility of the proposed RFID-enabled monitoring system for the HMSC. The objectives include minimization of total HMSC cost and maximization of integrity and return of investment (ROI).
- 3) To develop three multi-objective programming models that can be used as decision makers in supporting decision making in strategic (i.e., determine the optimal allocation and location of facilities that should be established) and tactical (i.e., determine the optimal quantity flow of products among facilities) design decisions towards the optimization of several objectives (e.g., maximizing the integrity, ROI and the capacity utilization of facilities and minimizing implementation costs of the RFID-monitoring system, environmental impact and the travel time of products).
- 4) To develop a stochastic programming model to handle the randomness of integrity percentage of products at farms and abattoirs.
- 5) To develop a fuzzy programming model to handle the uncertainty of input parameters such as costs, capacity of related facilities and demands in terms of quantity of products requested by abattoirs and retailers.
- 6) To develop two fuzzy multi-objective programming models aimed at investigating the applicability of the developed optimization approaches in solving two similar design and optimization problems including (i) a proposed RFID-enabled automated warehousing system in terms of the optimal number of storage racks and collection points that should be established; the objectives are minimizing the warehouse total cost, maximizing warehouse capacity utilization and minimizing travel time of products from storage racks to collection points, and (ii) a proposed RFID-enabled passport tracking system to determine the optimal number of offices that should be established; the objectives are minimizing the implementation and operational costs, minimizing the RFID reader interference and maximizing the social impact.
- 7) To develop a solution approach to obtain Pareto solutions based on the developed multi-objective models.
- 8) To develop a decision-making algorithm to support the decision makers in selecting the best Pareto solution.

- 9) To validate the developed models, theories and design approaches based on case studies.

Within the boundary of these research objectives, eight research questions have been highlighted:

- 1) How can the integrity of Halal meat products be traced in HMSCs using a monitoring system?
- 2) Is the potential traceability system feasible in terms of economic cost?
- 3) How to employ the multi-objective approaches as an aid to design a Meat Supply Chain (MSC) network with respect to conflicting objectives?
- 4) How can the uncertainty in the input data be handled regarding the MSC network design?
- 5) How the RFID implementation effect in implementation and operational costs on HMSCs?
- 6) How can accurate Pareto solutions be obtained?
- 7) How can decision makers select the best Pareto solution?
- 8) How can the developed multi-objective approaches be validated?

1.3 Road-map of thesis

This thesis is structured into ten chapters. A brief description of the content of each chapter is presented hereafter.

Chapter one: Introduction

This chapter presents an overall view of the study including background, motivation, aims and objectives of this research work.

Chapter two: Literature review

This chapter presents literature reviews in the fields of (1) traceability of Halal meat and other food products, (2) multi-objective optimization in supply chains including deterministic, fuzzy and stochastic models, (3) mathematical optimization in automated warehouses and network planning, and (4) mathematical optimization in RFID-enabled systems.

Chapter three: Fundamental concepts of multi-objective optimization

This chapter outlines fundamental concepts and methodologies used for the study.

Chapter four: The RFID-monitoring HMSC

This chapter presents a framework in development of an RFID-enabled monitoring system for a HMSC network design for enhancing traceability of integrity of Halal meat products. A multi-objective model was developed and used for investigating an economic feasibility of the proposed RFID-enabled monitoring system. A solution approach was applied to obtain Pareto solutions and a decision-making algorithm was employed to reveal the best Pareto solution.

Chapter five: A cost-effective decision-making algorithm for an RFID-enabled HMSC network design: a multi-objective approach

This chapter is an extension of Chapter three in investigating the economic feasibility of a three-echelon HMSC network that is monitored by a proposed RFID-based management system. The purpose of this study is to seek the maximization of capacity utilization of facilities, the average integrity in numbers of Halal meat products, ROI, and minimization of implementation costs of the RFID-monitoring system. Furthermore, the study aims to examine the effect on the HMSC network design by altering the integrity percentage of Halal meat products.

Chapter six: Developing a meat supply chain network design using a multi-objective possibilistic programming approach

This chapter presents a multi-objective possibilistic mixed integer linear programming model used for seeking trade-off solutions in minimizing the total cost of transportation, the number of transportation vehicles and the delivery time of meat products.

Chapter seven: The fuzzy multi-objective distribution planner for a green meat supply chain

This chapter describes a development of a product distribution planner for a three-echelon green meat supply chain (MSC) design in terms of issues which include numbers and locations of facilities that should be opened in association with the product quantity flows. The problem was formulated into a fuzzy multi-objective programming model (FMOPM) with an aim to minimize the total transportation cost and the impact on environment in particularly CO₂ emissions, and maximize the average delivery rate in satisfying product quantity as requested by abattoirs and retailers. The model was also formulated for handling the uncertainties in input data of the considered MSC.

Chapter eight: Design and optimization of an RFID-enabled automated warehousing system under uncertainties: a multi-criterion fuzzy programming approach

This chapter present a case study by examining the applicability of the above developed solution approach based on a proposed RFID-enabled automated warehousing system. To this aim, a fuzzy tri-criterion programming model is developed seeking the optimal number of storage racks and collection points that should be established, minimizing the warehouse total cost, maximizing warehouse capacity utilization and minimizing travel time of products from storage racks to collection points.

Chapter nine: Design and optimization of an RFID-enabled Passport Tracking System

This chapter examines the performance of the developed solution approach by investigating the design and optimization of a proposed RFID-enabled passport tracking system in numbers of related offices that should be established. It also aims at obtaining trade-offs among three objectives which include minimizing the implementation and operational costs, minimizing the RFID reader interference and maximizing the social impact. To this end, a fuzzy multi-objective model considering economical, performance and social criteria is developed.

Chapter ten: Conclusions and recommendations for future work

This final chapter draws out a summary and conclusions of the study. It also provides the recommendations for the future research work.

1.4 Summary

This chapter presents an overall view of the study including background, motivation, aims and objectives of this research work. It outlines the accomplishments of the proposed research studies by (1) enhancing traceability of meat production and transportation in terms of quality and safety in a meat supply chain network, (2) evaluating the impact of RFID implementation into a HMSC in terms of total implementation and operational cost, (3) obtaining trade-offs among multiple objectives (e.g. minimum costs, minimum transportation time, maximum service level, minimum environmental impact, maximum confidential products and a compromised management among supply, production and demand), (4) developing a decision-maker to determine locations and allocations of facilities and quantity flow of products travelling throughout the supply chain network, and (5) handling the uncertainty in input parameters. The chapter also presents a structure of this thesis including a summary of each chapter that demonstrates the completion of the proposed research studies and outcomes as follows.

Literature review

As reported by Lee and Lings (2008): *“The literature review is where you demonstrate that you understand that which has been done before, and can point to where the existing research is deficient in some way.”* This chapter presents a study in the literature review providing research background and up-to-date developments in the relevant field through publications. It also helps in identifying the research gap that motivates this research work (as outlined in section 1.1).

2.1 Traceability of Halal meat products

Based on the reviewed literature, Halal food is defined as the food that is permissible under the Islamic Shari’ah (laws) for Muslims to eat or drink. It also specifies a number of criteria that direct people as for how food should be prepared in a Halal way. There are a few preliminary studies through publications on traceability of Halal meat products. Junaini and Abdullah (2008) suggested a mobile Halal product verification method on which information of a Halal product can be sent to a customer’s mobile phone using the camera phone barcode scanning technique. Shanahan et al. (2009) proposed an RFID-based framework for improving the traceability of cattles at farms and abattoirs where each cattle’s ear is attached with an RFID tag. Bahrudin et al. (2011) developed a tracking system using RFID technology for enhancing Halal product integrity. Kassim et al. (2012) synthesized a similar system using mobile applications that allow customers to check Halal product information directly on their mobile phones. Mansor et al. (2013) proposed a method for checking meat colors to determine if the slaughtered poultry is handled properly in the Halal way. Feng et al. (2013) developed a traceability system by integrating RFID applications into a personal digital assistant (PDA), which is a handheld PC used by operators at beef segmentation sections to collect data and print out information in a form of barcode label attached with each pack of segmented beef. Similar studies on beef traceability were reported by Bowling et al., 2008; Kang et al., 2010; Lu et al., 2009, 2010; and Shi et al., 2010.

2.2 Traceability of food products

There were many studies using RFID techniques for improving traceability in ensuring safety and/or originality of food products provided in supply chain sectors. Jedermann et al. (2006) developed a smart-container that can monitor the freshness of fruits during transportation using a combination of RFID sensors, sensor networks and software agents. Zhang et al. (2009) introduced an RFID-based system that can improve traceability of frozen foods in terms of food temperatures and arrival times during storage and transportation using RFID sensors, GPS and mobile applications. Wang et al. (2010a) presented a real-time online monitoring decision supporting system which can monitor quality of perishable products providing drivers with suggestions as to how to cope with an abnormality when an alert is triggered during transportation in order to reduce losses of perishable products. Expósito et al. (2013) developed an RFID-based monitoring system used for tracing a wine supply chain. The developed system collects data of the meteorological and botanical information associated with the used grapes using RFID tags that are attached to grape boxes; the system sends collected data to a central server via a GPRS system. These information data can also be accessed online by consumers. In order to identify the origin of agricultural products, Sun et al. (2013) developed an anti-counterfeit RFID-GPS system in which GPS data and encrypted Chinese-sensible codes were applied. The system was used to collect data of location and the weight of the agricultural products and print the anti-counterfeit labels in associated with sold products. The collected data is encrypted/decrypted using AES (Advance Encrypted Standard) algorithm with a different cipher code. Barge et al. (2014) describes an item-level traceability system for cheese products in a dairy factory as each piece of cheese is attached with an RFID tag containing cheese identifications such as cheese type, production date and expiry date. Similar studies were reported by Hsu et al. 2008, 2011; Abada et al. (2009), and Trebar et al. (2011). Chen et al. (2014) proposed a new type of RFID application namely 2G (second-generation RFID) -RFID-Sys using the Internet of Things (IoT) technology with RFID sensor tags (semi-passive tags integrated with sensors) that can monitor food temperatures in a refined smart cold supply chain.

2.3 Multi-objective optimization for food supply chain networks

Findings through a literature review indicate that there are a small number of publications in studying food supply chains using the multi-objective optimization approaches. Rong et al.

(2011) developed a mixed integer linear programming model for solving a production and distribution planning problem of a food supply chain. Paksoy et al. (2012) developed a fuzzy multi objective linear programming model for tackling a problem of a production-distribution network of an edible vegetable oil manufacturer. Sahar et al. (2014) proposed a multi-objective optimization model of a two-layer dairy supply chain aimed at minimizing CO₂ emissions of transportation and the total cost for product distribution. Similar research findings were published by Robinson and Wilcox (2008) and Pagell and Wu (2009). Teimoury et al. (2013) developed a multi-objective model, which was used for identifying the best import quota policy for a supply chain providing fruits and vegetables. Bortolini et al. (2016) proposed a three-objective distribution planner to tackle the tactical optimization issue of a fresh food distribution network. The optimization objectives were to minimize operating cost, carbon footprint and delivery time; the work, however, did not consider other costs and the effect of uncertainty that may occur.

2.4 Multi-objective optimization for supply chain networks

Revelle and Laporte (1996) addressed a number of design issues in supply chains design by seeking compromised solutions known as Pareto solutions (Deb, 2001 and Konak et al., 2006). The concept of Pareto solutions is further described in section 3.1. Amin and Zhang (2013) proposed a mixed integer linear programming model aiming to minimize the total cost for multiple locations in a closed-loop supply chain network. Kannan et al. (2010) developed a genetic algorithm method for seeking a solution in minimization of total costs for a closed-loop supply chain. Sabri and Beamon (2000) developed a multi-objective programming model used for obtaining the optimum performance of a supply chain network considering two conflicting objectives in minimization of the total cost and maximization of volume flexibility of plants. Nozick and Turnquist (2001) developed a mathematical model in location optimization of distribution centers considering costs of facility, inventory, transportation, and service coverage. Cakravastia et al. (2002) provided a mixed integer multi-objective model for determining a selection of suppliers of a supply chain. Chan et al. (2004) presented a hybrid-genetic algorithm for solving the distribution problem of a supply chain network incorporating three objectives (i.e., costs, lead time and capacity). Chen and Lee (2004) developed a multi-objective model of a multi-echelon supply chain network seeking a compromised solution in satisfying all the conflicting objectives, which include fair profit distributions, safe inventory levels, customer service levels, and uncertain demands of

products. Guilléna et al. (2005) formulated a mixed integer multi-objective mathematical model used for optimizing a supply chain design by achieving a maximization of the total profit under uncertainty of financial risk and demand. The similar studies were conducted by Shen (2006); Bojarski et al. (2009); and Chibeles-Martins et al. (2012). Altiparmak et al. (2006) 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 a distribution center. Tzeng et al. (2006) offered a production and distribution model using a multi-objective programming method for maximizing profits of the enterprise and quality of customer services. For the research work of multi-objective approaches, it can refer to a study by Shen et al. (2003). Sourirajan et al. (2009) investigated a two-echelon supply chain for locating distribution centers at a minimal cost using the genetic algorithm by comparing the result using the Lagrangian heuristic approach. Paksoy et al. (2010a) proposed a mixed integer linear programming model used for minimizing costs in holding and ordering goods and transportation of a supply chain. Vahdani et al. (2012) developed a fuzzy bi-objective optimization model in assisting the design of a closed-loop supply chain by minimizing costs of facilities and transportation as objectives. In other studies, Kannan et al. (2012) developed an integrated, multi echelon, multi period, multi-product mixed integer linear programming model used for optimizing the distribution and inventory level of a closed-loop supply chain network using a genetic algorithm. Venkatesan and Kumanan (2012) developed a multi-objective discrete particle swarm algorithm aiming to minimize supply chain costs, lead time and maximize volume flexibility. Shankar et al. (2013) investigated a four-echelon supply chain architecture using the multi-objective evolutionary approach in order to minimize costs of facility location and shipment subject to a requirement that customer demands must be met. Niknamfar (2015) proposed a multi-objective non-linear model used for developing a production-distribution plan in a three-level supply chain.

2.5 Multi-objective optimization for supply chain networks under uncertainty

Vidal and Goetschalckx (1997) and Snyder (2006) reviewed the impact of data uncertainty on supply chain planning-distribution issues. Researchers attempted to tackle the randomness of input data using stochastic programming method (Alonso-Ayuso et al., 2007; Listes, 2007 and El-Sayed *et al.*, 2010). More attention focused on the provision of fuzzy programming techniques in the context of solving supply chain network design and distribution problems

under uncertainty (Wang and Hsu, 2010; Qin and Ji, 2010; Gholamiana et al., 2015). Petrovic et al. (1998) employed a fuzzy approach applied into a simulation model of a supply chain. The approach was developed to assist in decision making on operational supply chain control in an uncertain environment. The objective was to obtain a compromise between a maximization of profit and a maximization of service level. Wang and Shu (2007) developed a fuzzy decision model that helps tackle the issue of uncertainties of a supply chain. Aliev et al. (2007) developed a fuzzy integrated model for solving a production–distribution problem for a supply chain network using the genetic optimization method. Lee and Dong (2009) presented a stochastic model for managing a supply chain with three objectives including costs of facility location, path selection and transportation. Zarandi et al. (2011) proposed an interactive fuzzy goal programming approach to solve a closed-loop supply chain design problem. Saha et al. (2015) developed a multi-item multi-objective supply chain model in a fuzzy-stochastic environment with a potential risk in estimated budgets for long-term contracts.

Shih (1999) addressed the issue in the cement transportation planning by using a fuzzy linear programming approach. Sakawa et al. (2001) developed a fuzzy mathematical programming model used for minimizing cost of production and transportation of products. Liu and Kao (2004) proposed a method to obtain the membership function of the total transport cost as a fuzzy objective value where the cost coefficients and the supply and demand quantities are considered as imprecise parameters. Wang and Shu (2005) investigated a fuzzy decision strategy that helps tackle the issue of uncertainties of a supply chain. Liang (2006) formulated an interactive fuzzy multi-objective linear programming model to solve fuzzy multi-objective transportation problems. The objectives were minimizing the total distribution cost and the total delivery time. Selim et al. (2008) formulated a multi-objective linear programming model aimed at determining the optimum facility location and allocation and the optimum capacity level of a warehouse that satisfies product quantity requested by retailers. Peidro et al. (2009) proposed a fuzzy mono-objective mixed-integer linear programming model used for a supply chain tactical planning in which the total cost was to be minimized. Liu and Papageorgiou (2013) addressed production, distribution and capacity planning of global supply chains by developing a multi-objective mixed-integer linear programming approach considering total cost, total flow time and total lost sales as three objectives.

2.6 Multi-objective optimization for green supply chain networks

Green supply chain management can be defined as the process of purchasing, producing, marketing and performing various packaging and logistical activities while considering the ecological balance. In FSCs context, green food supply chain management is based on considering environmental impacts in addition to other key factors such as travel time of food products throughout the network. It incorporates environmental issues into the organisation's buying decisions and encourages companies to form consistent relationships with green suppliers. In recent years, there has been a growing number of the research in green supply chains. Paksoy et al. (2012a) provided a fuzzy multi-objective model for helping design a green closed-loop supply chain network. The objectives are to minimize all the transportation costs in the forward supply chains and reverse logistics and total CO₂ emissions. Pishvae and Razmi (2012) established a multi-objective fuzzy model for optimizing a green supply chain design in minimizing the total cost and the environmental impact. Kannan et al. (2013) proposed an approach to rank and select the best green suppliers of a supply chain according to economic and environmental criteria and then allocating the optimum order quantities among them. The proposed approach was a combination of the fuzzy multi-attribute utility theory and multi-objective programming. Harris et al. (2014) proposed a multi-objective optimization approach for solving a facility location-allocation problem for a supply chain network where financial costs and CO₂ emissions are considered as objectives. Talaei et al. (2015) presented a bi-objective facility location-allocation model for a closed loop supply chain network design. Robust and fuzzy programming approaches were used to cope with the uncertainties of the variable costs and the demand rate.

2.7 Mathematical approaches for optimizing automated warehouses

There are relatively few historical studies in the area of the optimization of automated warehouse design in terms of several aspects, such as costs, and capacity utilization. Van Der Berg (1999) presented a review on approaches and techniques applied for planning and control of warehouse management. Ma et al. (2015) formulated an automated warehouse as a constrained multi-objective optimization problem aimed at minimizing the scheduling quality effect and the travel distance of products in the warehouse. Huang et al. (2015) proposed a nonlinear mixed integer program with a probabilistic constraint for site selection and space determination for warehouses. The study was aimed at minimizing the total inbound and

outbound transportation costs and the total warehouse operation costs in a two-stage network. Lerher et al. (2013) developed a multi-objective approach to analyze the design and optimization of the automated warehouse. The objectives include travel time, total cost and quality in the number of material handling devices in the warehouse. Lerher et al. (2010) investigated the design and optimization of the automated storage and retrieval system aiming to minimize the initial investment and annual operating cost of the system. Genetic algorithms were used for the optimization process of decision variables. Lerher et al. (2007) proposed a mono-objective optimization approach for automated warehouses. The objective was aimed at minimizing the total cost seeking the best economical design. Lu et al. (2006) presented a methodology, framework and five-step deployment process aimed at developing a holistic approach for implementing RFID enabled manufacturing in manufacturing enterprises. Ashayeri and Gelders (1985) proposed a design model of the automated storage and retrieval systems that enables the determination of the main influential parameters when designing warehouses. The criterion of the model was to minimize investment and operating costs. Karasawa et al. (1980) developed a nonlinear mixed integer programme for an automated warehouse system aimed at minimizing the system cost.

2.8 Mathematical approaches for optimizing RFID-enabled systems

There are relatively few publications in the area of design and optimization of RFID-enabled systems. Of which most previous research focused on criteria related to performance requirements such as tag coverage and reader interference. Chen et al. (2011) proposed an optimization model used for allocating the locations of readers in a RFID-enabled network using the multi-swarm particle swarm approach. Oztekin et al. (2010) presented a study aimed at optimizing the design of an RFID-enabled network in the healthcare service sector for tracking medical assets. Kardasa et al. (2012) investigated a RFID-enabled network planning problem via a development of a multi-objective artificial bee colony algorithm seeking a trade-off among optimal tag coverage, reader interference, and load balance. Mysore et al. (2009) proposed an algorithm for allocating the minimum number of readers required for an efficient coverage when the region is irregular shape. Ma et al. (2014) presented a multi-objective artificial colony algorithm for solving a RFID-enabled network planning problem. Lu and Yu (2014) formulated a k-coverage multi-dimensional optimization model used for evaluating the network performance for an RFID-enabled network.

2.9 Research gaps

Based on the aforementioned literature review, a number of research gaps were identified as follows.

- There were a few preliminary publications in studies on traceability of Halal meat products. None of these studies proposed a monitoring system for Halal meat production from farms to customers to ensure the integrity and quality of Halal meat in order to gain the trust from customers, although there were a few studies focusing on the configuration of HMSC networks. Thus, this area is overlooked by researchers (Lodhi, 2009; Zulfakar, 2012).
- There were no empirical studies in green food supply chains using the fuzzy multi-objective optimization approaches.
- There were no research publications to be found by applying the fuzzy optimization approach into design of the RFID-enabled automated warehousing system. Further, there was a limited research work in studies of multi-objective optimization approaches of automated warehouses (Lerher et al., 2013).
- There were no previous studies which were found in terms of a cost-effective design for an RFID-enabled object tracking system using the multi-objective approach, considering (i) the strategic design decision in numbers of related facilities that should be established, (ii) the total investment cost required for implementing the RFID, (iii) the uncertainties in the input data, and (iv) the economical, performance and social criteria. In other words, the arena of the design and optimization of RFID-enabled object tracking systems that covers all the three aspects (i.e., economical, performance and social aspects) is overlooked.

2.10 Summary

This chapter presents a study in literature review in the relevance to this study. The literature review covers the areas of 1) traceability of Halal meat product, 2) applications of RFID techniques which were used for improving traceability in ensuring safety and/or originality of food products provided in supply chain sectors, and 3) developments in the multi-objective optimization methods to tackle several issues (e.g. supply chain design, facility location problem, etc.) in food supply chains, other types of supply chains, supply chains under uncertainties, automated warehouses and RFID-enabled systems. This chapter also demonstrates that (1) there were a few preliminary publications in studies on traceability of Halal meat products in developing a comprehensive monitoring system for Halal meat production from farms to customers to ensure the integrity and quality of Halal meat to gain the trust of Halal meat customers, (2) there were small number of publications to be found in studying food supply chains using the fuzzy multi-objective optimization approaches, and (3) there were no research studies in applying the fuzzy multi-objective optimization approach into design of an proposed RFID-enabled automated warehousing system and a proposed RFID-enabled passport tracking system as case studies to examine the applicability of the developed approaches.

Fundamental concepts of multi-objective optimization

3.1 Multi-objective optimization

Multi-objective optimization is a multi-criteria decision-making approach used for supporting decision makers in obtaining a trade-off or a compromised solution towards the optimization of several objectives simultaneously. These objectives may also be conflicting in nature such as minimization of total cost and maximization of service level. Problem structuring in multi-objective optimization mainly includes objectives, parameters, decision variables and constraints.

Objectives are the reflection of the desires of decision makers, which indicate the direction to do better.

Parameters are the factors that affect the result variables but are not under the control of decision makers. Either of these factors can be fixed (crisp), in which they are called parameters, or they can vary, variables (fuzzy). These factors are uncontrollable because they are determined by elements of the system environment.

Decision variables are outputs, reflecting the level of effectiveness of the system. The results of decisions are determined by decision makers (value of the decision variables), the factors that cannot be controlled by decision makers, and the relationships among the variables.

Constraints are requirements in which any acceptable solution to the problem must meet. In other words, the constraints describe the set of the feasible solutions of the decision problem.

According to Almaraz, 2014, in a multi-objective problem, it is impossible to obtain a single optimal solution but a trade-off among a number of objectives, since there is a contradictory among antagonist objectives. Also, Messac, 2015, defined the multi-objective optimization as *“a methodical approach to solving problems involving several competing design objectives simultaneously. The fundamental message is that you will almost always have to compromise between your various objectives and find a way to prioritize them somehow”*. For details on

multi-objective optimization, it can be referred to Coello et al., 2007; Miettinen, 1998; Collette and Siarry, 2011; and Rangaiah and Bonilla-Petriciolet, 2013.

The compact multi-objective optimization can be formulated as follows:

$$\max/\min O(x) = (O_1(x), O_2(x), \dots, O_f(x))^T \quad (2.1)$$

subject to

$$g_i(x) \leq 0, i = 1, 2, 3, \dots, a \mid h_j(x) = 0, j = 1, 2, 3, \dots, b. \quad (2.2)$$

Where

O is number of objective functions

a and b is number of constraints

$x \in B^z$ is the decision variable vector

z is number of independent variable x_i

In the multi-objective optimization and unlike the single objective optimization, there is no mono-dominant solution but a set of non-dominant solutions called Pareto (or non-dominant, non-inferior) solutions. Pareto solutions refer to a set of solutions that represent trade-offs between two or more conflicting objectives. In multi-objective optimization, the obtained solution is considered a Pareto solution when it improves one objective and worsens the performance of at least one other objective otherwise it is not a Pareto solution.

Pareto solutions are defined by a set of points that all fit a predefined description for an optimum shown in Figure 1. The predefined concept used for describing an optimal point known as Pareto optimality (Pareto, 1906). Pareto optimality is expressed as a point, $x^* \in X$ is Pareto optimal if there does not exist another point, $x \in X$, such that $O(x) \leq O(x^*)$, and $O_i(x) < O_i(x^*)$ for at least one objective function. The plot of all Pareto in the objective space called Pareto frontier.

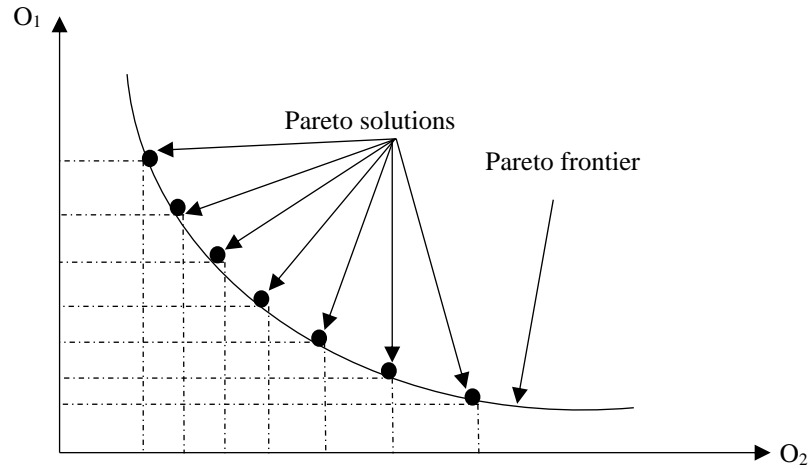


Figure 1. Pareto solutions.

3.1.1 Methods for multi-objective optimization

To solve a multi-objective optimization problem, we need to reveal Pareto solutions on the Pareto frontier which cannot be determined directly. In real optimization problems, the optimization objectives are functions of a number of variables. Thus, solution methods are often employed to combine the multi-objective functions into a mono-objective function so-called Aggregative Objective Function (AOF). The optimization of AOF leads to Pareto solutions. These methods have three main targets (1) present a set of solutions for linear multi-objective problems, (2) approximate the Pareto solutions for non-linear multi-objective problems (some Pareto points are unknown), and (3) approximate the Pareto solutions for discrete multi-objective problems (all Pareto points are unknown) (Caramia and Dell'Olmo, 2008).

There are a number of methods which were used for the multi-objective optimization. Ruzica and Wiecek (2003) and Ehrgott (2005) presented a survey on the optimization methods. Donoso and Fabregat (2007) categorized these methods into classical and metaheuristic methods. In this study the classical methods, which transform the multi-objective problem into a mono-objective problem, were investigated.

3.1.1.1 ϵ -constraint (compromise programming)

This method was introduced by Haimes et al. (1971). The compromise programming approach has its ability to achieve efficient points on a Pareto curve (Chankong and Haimes,

1983). This method keeps the most important objective as an objective function and shift the others to the constraint set to be restricted to an assigned value (ε). The compact solution formula (O) is presented as follow.

$$\max/ \min O_1(x) \tag{2.3}$$

Subject to

$$O_2(x) \leq \varepsilon_1 \tag{2.4}$$

$$O_3(x) \leq \varepsilon_2 \tag{2.5}$$

$$O_f(x) \leq \varepsilon_f \tag{2.6}$$

$$x \in S \tag{2.7}$$

Where S is a set of constraints, ε_f satisfaction level of objective function O_f . A parametric variation of ε_f values leads to Pareto solutions. In case of the objective functions to be maximized, the related constraint re-formulated to of $O_f(x) \geq \varepsilon_f$.

3.1.1.2 Weighted Sum

The Weighted Sum approach is the simplest and the most intuitively meaningful means of solving multi-objective optimization problems. It is also the one that is most widely used.

It aggregates the multi objective functions into a mono scalar function (O) multiplied by an appropriate weight (w_1, w_2, \dots, w_f) for each objective (Ruzika and Wiecek, 2005; and Ehrgott 2005). The weight can be determined by decision makers or applying some approaches like Analytical Hierarchy Process (AHP). The compact solution formula (O) is presented as follow:

$$\min O(x) = \sum_{f \in F} w_f O_f(x) \tag{2.8}$$

Subject to

$$\sum_{f \in F} w_f = 1, w_f \geq 0, f = 1, 2, \dots, F \tag{2.9}$$

$$x \in S \tag{2.10}$$

3.1.1.3 Goal programming

In this approach, undesirable deviations from given goal values are to be minimized. To this aim, each objective is solved individually and its value was given as a goal for the approaching function (Charnes et al., 1955; Colapinto et al., 2015). The compact solution formula (O) is presented as follow:

$$\text{Max / Min } O \tag{2.11}$$

$$\frac{\zeta^1}{G^1} \leq O_1 \tag{2.12}$$

$$\frac{\nu^2}{G^2} \leq O_2 \tag{2.13}$$

$$\frac{\nu^f}{G^f} \leq O_f \tag{2.14}$$

The equivalent objective functions are expressed as follows.

$$\text{Max / Min } O_1 = O_1 + \zeta^1 - \nu^1 = G^1 \tag{2.15}$$

$$\text{Max / Min } O_2 = O_2 + \zeta^2 - \nu^2 = G^2 \tag{2.16}$$

$$\text{Max / Min } O_f = O_f + \zeta^3 - \nu^3 = G^3 \tag{2.17}$$

Where

G^1 goal of the objective 1

G^2 goal of the objective 2

G^f goal of the objective f

ζ^1 negative deviation variable of the objective 1

ζ^2 negative deviation variable of the objective 2

ζ^f negative deviation variable of the objective f

ν^1 positive deviation variable of the objective 1

ν^2 positive deviation variable of the objective 2

v^f positive deviation variable of the objective f

Subject to

$$x \in S \quad (2.18)$$

$$\zeta, v \geq 0 \quad (2.19)$$

3.1.1.4 Weighted Tchebycheff

This approach transforms the multi-objective model into a single-objective model (O). This single-objective model aims to minimize the distance between the ideal objective vector (O^*) and the obtained feasible objective surface (Miettinen, 1998). The compact solution formula (O) is presented as follow:

$$\text{Min } O = \left(\sum_{f \in F} l_f |O_f - O_f^*|^p \right)^{\frac{1}{p}} \quad (2.20)$$

Subject to

$$x \in S \quad (2.21)$$

Generally, ρ is 1; However, other values of ρ also can be used.

3.1.1.5 Global criterion approach

This approach aggregates the multi objective function into a single objective function aiming to minimize the distance to the ideal objective value (O_f^*) (Pandu, 2009). The compact solution formula (O) is presented as follow:

$$\text{Min } F = \left(\sum_{f \in F} |O_f - O_f^*|^\rho \right)^{\frac{1}{\rho}} ; 1 \leq \rho \leq \infty \quad (2.24)$$

Subject to

$$x \in S \quad (2.25)$$

Generally, ρ is 1; However, other values of ρ also can be used.

3.1.1.6 LP-metrics

In the LP-metrics method, each objective function needs to be solved individually aiming to obtain the ideal objective values $(O_1^*, O_2^*, \dots, O_f^*)$ (Al-e-hashem et al., 2011). The compact solution formula (O) is presented as follows:

$$\text{Min } O = \left[w_1 \frac{O_1 - O_1^*}{O_1^*} + w_2 \frac{O_2 - O_2^*}{O_2^*} + \dots, w_f \frac{O_f - O_f^*}{O_f^*} \right] \quad (2.26)$$

Subject to

$$\sum_{f \in F} w_f = 1, w_f \geq 0, f = 1, 2, \dots, F \quad (2.27)$$

$$x \in S \quad (2.28)$$

3.1.2 Multi-objective optimization for supply chain networks

Multi-objective optimization is used by researchers and practitioners for solving supply chain problems in such as selections of suppliers, facility location-allocation, risk mitigation and so on (Gen and Cheng, 1997; Deb, 2001; Barros et al., 1998; Jayaraman et al., 1999; Krikke et al., 1999). In this research, a multi-objective approach was used for solving a facility location-allocation problem and quantity flows of products for supply chain network design.

A supply chain network is a set of suppliers, manufacturers, warehouses and flows of products from suppliers to customers. In general, supply chain network design is involved in a decision-making process in which the strategic decision and the tactical decision need to be made. A strategic decision refers to the number and capacity plants, warehouses, and distribution centers to be established and a tactical decision refers to the flow of products quantity throughout the supply chain network. The selection in numbers and locations of these plants is a significant factor in the success of any supply chain. This factor is usually known as facility location-allocation problem (FLAP) (Bhattacharya and Bandyopadhyay, 2010; Trisnaa et al., 2016). From some decision makers' point of view, the FLAP and flows of product among supply chain facilities dominate 80% of the total costs of the supply chain design (Watson et al., 2012). The determination of the FLAP and the optimal flows of product among facilities called supply chain network design.

In a supply chain network design, minimization of the total cost is one of significant objectives that need to be addressed in the multi-objective optimization problems. Other

objectives, such as travel time, service level, environmental impact, are also important in a supply chain design (Ding et al., 2006; Villegas et al., 2006; Bhattacharya and Bandyopadhyay, 2010; Cheshmehgaz et al., 2013; Hiremath et al., 2013). Normally, the total cost is a sum of product transportation and handling costs, operational costs, inventory costs, equipment and facility establishing costs and labor training costs. Table 1 shows a review of objectives addressed for different supply chain problems based on a review by Trisnaa et al. (2016). These research studies were used to identify one of the research gaps in the literature, in which none of these studies have formulated the combination of objectives that we formulated in this study, in particular, in the context of food supply chains.

Table 1. List of publications relating to multi-objective optimization problems for supply chains

Authors	Objectives
Liang (2008); Xu et al. (2008); Cardona-Valdés et al. (2011); Pourrousta et al. (2012); Shankar et al. (2013); Mastrocinque et al. (2013); Moncayo-Martínez and Zhang (2014); Rad et al. (2014); Nikabadi and Farahmand, (2014); Moncayo-Martínez and Zhang (2013); Nekooghadirli et al. (2014)	Min. total cost Min. delivery lead time
Xu et al. (2008); Farahani and Elahipanah (2008); Benyoucef and Xie (2011); Cardona-Valdés et al. (2011); Liu and Chen (2014); Shankar et al. (2013)	Min. total cost Max. service level
Prasannavenkatesan and Kumanan (2012); Atoeia et al. (2013)	Min. total cost Max. delivery reliability
Pishvae and Razmi (2012); Amin and Zhang (2013)	Min. total cost Min. environment impact
Pishvae and Torabi (2010); Dzipire and Nkansah-gyekye (2014)	Min. total cost Min. delivery tardiness
Zhang and Xu (2014)	Min. total cost Max. average safe inventory levels
Sadeghi, et al (2014)	Min. inventory cost Min. storage space
Wang et al. (2013)	Min. total cost Min. shortage
Shahparvari et al. (2013)	Min. total cost Max. flexibility level

Cheshmehgaz et al. (2013)	Min. total cost Min. response time
Liu and Papageorgiou (2013)	Min. total cost Min. Process time Min. sale losses
Paksoy et al. (2010)	Min. total cost Max. profit Min. gas emission
Al-e-hashem et al. (2011)	Min. total cost Min. variance of cost Max. productivity
You et al. (2012)	Min. total cost Min. gas emission Min. local labor cost
Azaron et al. (2008)	Min. total cost Min. variance of the total cost Min. Financial risk
Altiparmak et al. (2006)	Min. total cost Max. goods delivery Min ratio of plant-DC balance
Selim et al. (2008)	Min. total cost Max. profit
Chen and Lee (2004); Yeh and Chuang (2011); Zhang et al. (2013)	Min. total cost Min. delivery lead time Max. product quality Max. green appraisal score
Liu et al. (2014)	Max. profit Min. gas emission Min. fossil use
Franca et al. (2010)	Max. profit Max. product quality
Ruiz-Femenia et al. (2013)	Max. NPV Min. global warning potential (GWP)

Pasandideh et al. (2015)	Min. total cost Max. the average number of products dispatched to customers
Mansouri (2006)	Min. total set-ups Min. the maximum number of set-ups between the two stages supply chain
Bandyopadhyay and Bhattacharya (2013)	Min. total cost Min. Bullwhip effect
Kamali et al. (2011)	Min. total cost, Min. defective items Min. late delivered items
Özker and Basligil (2013)	Max. satisfaction level of trade Max. satisfaction degrees of customers Max. profit

3.1.3 Modelling under uncertainty

In reality, designing and planning of supply chains is subject to a high degree of uncertainty of input data which may affect the overall performance (Klibi et al. 2010). A summary of different types of uncertainties were presented by Mousazadeh et al., (2014). Ho (1989) categorized uncertainty into environmental and systems uncertainties. Davis (1993) classified the uncertainty into three types: (i) supply uncertainty, (ii) process uncertainty, and (iii) demand uncertainty. Dhoub et al. (2013) proposed categorization for uncertainty: uncertainty in given parameters and elasticity in constraints and targets. Mula et al. 2007 categorized the uncertainty into two types: (i) randomness that results from the random environment in the input data, and (ii) epistemic that arises from scarcity of awareness of the precise value in the input data. While, Klibi et al. (2010) mentioned that uncertainty can be categorized into two types: (i) operational uncertainty such as uncertain demand, and (ii) disruption uncertainty, that occurs due to rare events such as flood or earthquake.

Predominantly, supply uncertainty is caused due to changes in suppliers' performance such as imprecise delivery time and quality of raw materials. Process uncertainty comes as a result of faults happening in manufacturing and/or delivery processes. Demand uncertainty is the most common uncertainty in real industry; it normally refers to the uncertain demand of customers regarding a particular product, fashion style, a particular season of the year and so on.

3.1.3.1 Approaches to tackle the uncertainty

Three main approaches, which are generally used to handle the uncertainty in the context of mathematical formulation for the supply chain, are emphasized through a literature review. These approaches are fuzzy programming, robust programming, and stochastic programming. Each approach has particular features. Thus, employing the right approach is dependent on pre-known criteria such as the type of uncertainty, nature and structure of the supply chain and the level of scarcity in the input data. Concisely, descriptions of these approaches are presented in the next sub-sections.

3.1.3.1.1 Fuzzy programming

Fuzzy programming is used to deal with the fuzziness of given parameters. This approach is applied by (i) modelling the uncertain parameters into appropriate possibilistic distributions in the form of fuzzy numbers, and (ii) presenting the soft targets and/or constraints in the form of particular fuzzy membership functions which is normally based on decision makers' preferences.

Fuzzy programming can be categorized into two main groups: (i) flexible programming, and (ii) possibilistic programming (Inuiguchi and Ramík 2000; Mula et al. 2006; Torabi and Hassini 2008; and Mousazadeh et al., 2014). Flexible programming is employed to handle the elasticity in value of targets and/or constraints. Regarding the possibilistic programming, it is employed to handle the insufficient information about exact values of given parameters as a result of deficiency of needed data. Accordingly, suitable possibilistic distributions based upon both available objective data and subjective opinions of decision makers are introduced for modeling imprecise data in the form of fuzzy numbers.

Notwithstanding, when a particular supply chain problem has a diverse of aforesaid categories of uncertainties, both the possibilistic and flexible programming approaches could be concurrently employed.

3.1.3.1.2 Robust programming

Robust programming is used to handle the uncertainty when the exact values of parameters are rarely known. Pishvae et al. (2012a), “*a solution to an optimization problem is said to be robust if it has both feasibility and optimality robustness. Feasibility robustness means that the solution should remain feasible for (almost) all possible values of uncertain parameters and optimality robustness means that the value of objective function should*

remain close to optimal value or have minimum (undesirable) deviation from the optimal value for (almost) all possible values of uncertain parameters”.

3.1.3.1.3 Stochastic programming

Stochastic programming is used in a mathematical model associated with uncertain parameters which are assumed to be random (Coello et al., 2007). These random parameters follow a pre-defined probability distribution. Nonetheless, in more advanced configurations, this distribution is insufficiently defined (Ben-Tal et al., 2009). According to Birge and Louveaux (1997); and Sahinidis (2004), stochastic programming can be categorized into two main groups: (i) Programming with recourse, and (ii) Probabilistic programming. Programming with recourse (e.g., two-stage programming), when the decision variables are separated into two stages. The first stage and second stage decisions need to be defined prior to and after the awareness of the uncertain input data, respectively. On the other hand, probabilistic programming is frequently employed. Consequently, this approach concentrates on the minimization of expected recourse objectives. Table 2 shows a list of reviewed papers from the literature on multi-objective optimization in supply chains under uncertainty. The reviewed research studies presented in Table 2, identify that no research work yet, has coped with the uncertainty in the input parameters using the fuzzy programming and stochastic programming to obtain a cost-effective design for a food supply chain.

Table 2. List of publications in mathematical modeling for supply chain problems under uncertainty

Author	Approach
Petrovic et al. (1998); Shih (1999); Sakawa et al. (2001); Liu and Kao (2004); Chen and Lee (2004); Wang and Shu (2005); Aliev et al. (2007); Xu et al. (2008); Liang (2008); Peidro et al. (2009); Tsai and Hung (2009); Qin and Ji (2010); Wang and Hsu (2010); Zarandi et al. (2011); Pourrousta et al. (2012); Pishvae and Razmi (2012); Kannan et al. (2013); Díaz-Madroñero et al.(2014); Gholamiana et al. (2015); Saffar et al. (2015); Subulan et al. (2015); Azadeh et al. (2016); Uygun and Dede (2016); Govindan et al. (2016);	Fuzzy
Azaron et al. (2008); Pishvae et al. (2009); Chen et al. (2010); Franca et al. (2010); Rodrigo et al. (2010); Cardona-Valdés et al. (2011); Al-e-Hashem et al. (2011); Cardoso et al. (2013); Ruiz-Femenia et al. (2013); Nekooghadirli et al. (2014); Santibañez-Aguilar et al. (2016); Shabani and Sowlati (2016); Jalali et al. (2016); Keyvanshokoo et al. (2016)	Stochastic

Pishvae and Torabi (2010); Bandyopadhyay and Bhattacharya (2013); Vahdani et al. (2013); Zhang and Xu (2014); Ozgen and Gulsun (2014)	Fuzzy Possibilistic
Pishvae et al. (2011); Kisomi et al. (2016); Aalaei and Davoudpour (2016)	Robust
Vahdani et al. (2012); Talaei et al. (2015)	Fuzzy robust
Saha et al. (2015); Afrouzy et al. (2016)	Fuzzy stochastic
Vahdani and Mohammadi (2015); Keyvanshokoh et al. (2016)	Stochastic robust

3.2 Summary

This chapter presents an overview of the multi-objective optimization including its definitions, solution methods and applications to solve several problems in supply chains. The chapter also presents a study in identifying three approaches (e.g. fuzzy programming, robust programming, and stochastic programming) that are used to handle the uncertainty in mathematical formulation of the supply chains. The above chapters also form the background and foundation of this research work.

The RFID-monitoring HMSC

4.1 Introduction

In recent years, businesses of Halal food have been spreading at a rapid pace. Meantime, Halal food consumers are increasingly concerned about the integrity of Halal-food related products in terms of production, transportation and storage along an entire supply chain network as it is important for Halal food products these consumers purchase from supermarkets is truly Halal. Unlike non-Halal food, this requires Halal food suppliers who are able to monitor a Halal food supply chain network providing adequate information of Halal food sold in supermarkets and these information data can also be easily accessed by Halal food consumers. Consumption of Halal food is a well-known diet among Muslim and many non-Muslim people. Production and supply of Halal meat products is one of fast-growing businesses around the world. If a specific process of HMSCs is not handled properly in a Halal way, retailers or consumers may regard these products as non-Halal. As a result of this, there is a desire for Halal meat consumers who increasingly demand more transparent information relating to the integrity of Halal meat products they purchase in supermarkets. Nevertheless, a survey by authors indicates that there are a number of concerns from Halal food consumers about the integrity of Halal meat products sold in supermarkets. These include periodic records in livestock feeding and growing history in farms, slaughtering processes at abattoirs and Halal meat transportation from abattoirs to retailers. However, these issues are often overlooked by researchers (Lodhi, 2009; Zulfakar, 2012).

To cope with the increasing demand for the Halal meat products that are produced according to the Islamic Law, a HMSC monitoring system is needed for improving the traceability of Halal meat integrity. This study presents a framework in development of an RFID-enabled HMSC network for enhancing traceability in terms of integrity of Halal meat products to be sold in supermarkets. Nevertheless, such an integrated system is subject to additional costs for RFID system implementation and ROI, which also need to be investigated. To this aim, a multi-objective mathematical model was developed and used for examining the economic

feasibility of the proposed RFID-enabled HMSC network in order to obtain a trade-off decision within three conflicting objectives.

4.2 Halal meat

Halal is an Arabic word which means “permissible” in English translation and it is often used in association with food, i.e., food that is permissible under the Islamic Shari’ah (laws) for Muslims to eat or drink. It also specifies a number of criteria that direct people as for how food should be prepared in a Halal way. For instance, production and transportation of Halal meat products need to comply with the Islamic Shari’ah, and this should be applied to all sessions including each process of livestock feeding, slaughtering, transporting, packing and storing before being sold in supermarkets. It is noted that Muslims consume Halal food as part of their worship that is an order from Allah.

Halal integrity refers to a food product that remains Halal from upstream to downstream of a food supply chain free from any activities that might breach the Halal status intentionally or unintentionally (Zulfakar et al. 2012). In other words, Halal integrity is to assure the products are being sourced, produced, processed, stored and disseminated parallel with the Islamic values of high quality and safety. Production and supply of Halal meat products is one of fast-growing businesses in the world (Fuseini et al., 2016; Lada et al., 2009; Ali, 1996). For instance, the Malaysia Investment Development Authority estimated global Halal food industry in 2013 was between 453 billion GBP to 1.73 trillion GBP and it is forecasted to be worth 4.8 trillion GBP by 2030. Moreover, the Halal industry in Europe is estimated by 51 billion GBP, with an increasing demand from countries such as the United Kingdom, France and Germany (Talib et al., 2015). Also, in the United Kingdom, Muslims purchase around 20 % of British livestock (UK Government Statistics, 2006; BBC, 2005). In the same line, Halal food customers intend to pay extra money for high integrity Halal food (Kamaruddin et al., 2012; Tieman et al., 2013). This also refers to the growing demand on Halal food industry.

In general, the main difference in producing Halal meats from any other type of foods is manifested in ensuring Halal feeding of livestock (e.g., good quality, clean foods and free from prohibited elements such as Pork enzyme) and monitoring the livestock health at farms in addition to ensuring the Halal slaughtering process at abattoirs. If a specific process of HMSCs is not handled properly in a Halal way, retailers or consumers may regard these

products as non-Halal (Tieman, 2011). Figure 2 shows the processes at every stage of the HMSC (Lodhi, 2009).

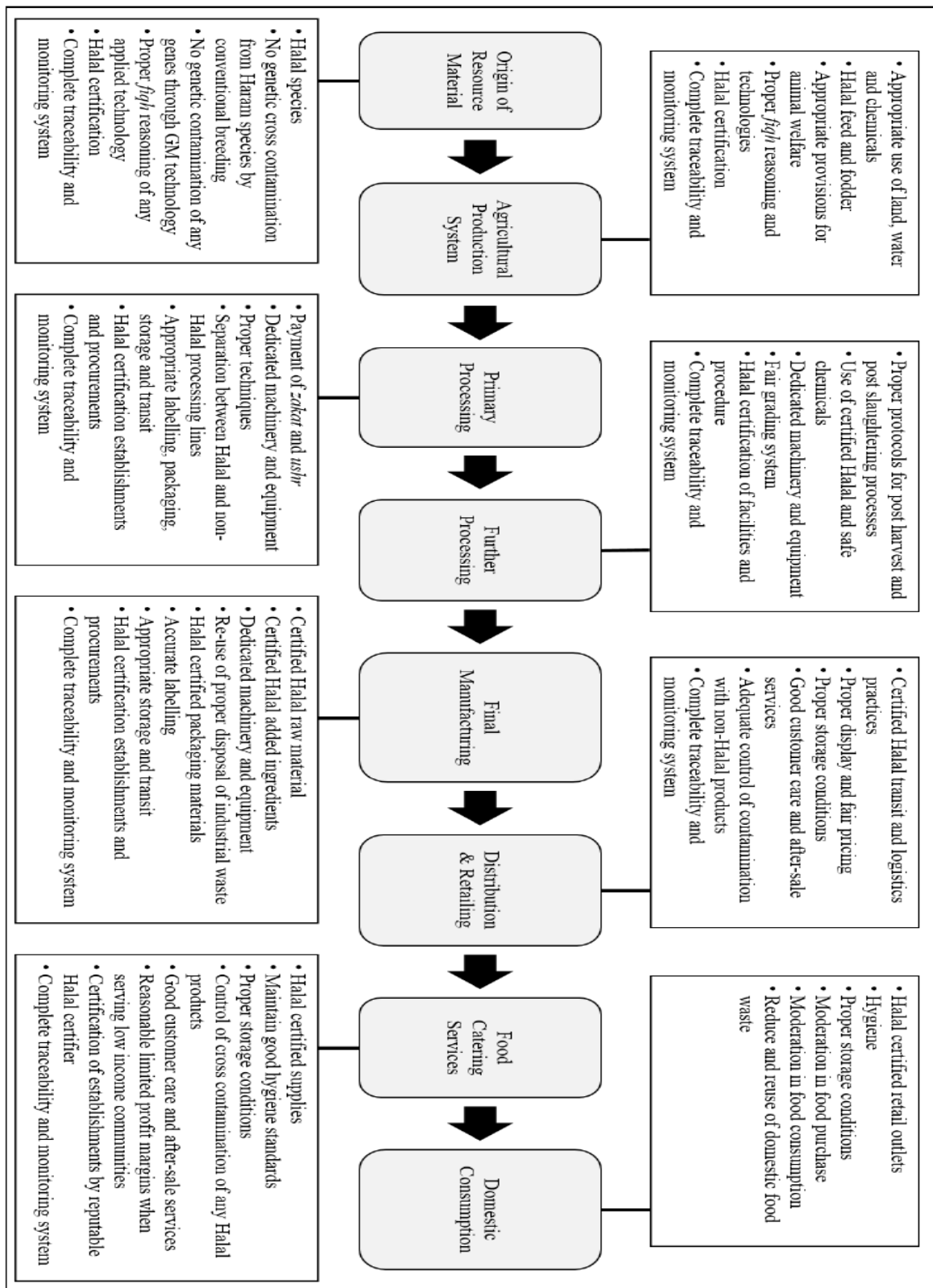


Figure 2. Halal processes at each stage of the HMSC (Lodhi 2009).

It is noteworthy in Figure 2, that Halal products are not only required at consumption but at every stage and activity along the HMSC. In this Figure, Lodhi (2009) specified that the integral elements of halal supply chain are halal control, halal certification and halal monitoring systems. The author also has classified the key stages involved in the Halal food supply chain which starts with the origin of resource material, followed by agricultural production system, primary processing, further processing, final processing, distribution, retail, food service industry and ended with domestic/end use. In each of this key stage of Halal supply chain, he also has identified the basic control points needed to maintain halal integrity. The three most common Halal critical points identified by the author in the food supply chain are Halal certification, Halal traceability and appropriate storage, transit and equipment.

As a result of this, there is a desire for Halal meat consumers who increasingly demand more transparent information relating to integrity of Halal meat products they purchase in supermarkets (Abdul-Talib and Abd-Razak, 2013; Mohayidin and Kamarulzaman, 2014; Smith, 2009). Integrity of Halal meat products is particularly an issue for those Halal meat consumers who live in non-Muslim countries. In the UK as an example, British Muslims are increasingly looking for Halal-labeled meat (Knot, 2009). Besides, Jamal and Sharifuddin (2015) presented a study about the effect of the perceived value and perceived usefulness of a Halal-labeled product. Thus, most Halal meat consumers can only purchase Halal meat products in local Muslim shops rather than primary supermarkets due to a lack of traceability of Halal meat integrity; as a study findings by Ahmed (2008) concluded that the majority of UK Muslims do not trust big supermarkets when buying Halal meats which leads to a tremendous inconvenience for Halal meat consumers. A similar study by Verbeke et al., 2013 showed that majority of Belgian Muslim consumers are willing to pay extra for certified Halal meat at the Halal shop than at the supermarket. This hinders the opportunity in business expansion of Halal meat products that can also be sold in any supermarket chains.

Based on the reviewed research works, Halal meat integrity represents the backbone for the Halal meat industry. The absence of integrity concept leads to hurdle Halal industry (Evans, 2007). Thus, it is essential to maintain the Halal meat integrity throughout its entire supply chain. Notwithstanding, this is a huge challenge for decision makers since “*cross contamination can happen in various stages of the supply chain movements particularly in these three areas which are warehousing and storage, transportation, and terminal interchange*” (Tieman, 2007). For instance, cross contamination may happen during the

transportation activity in which one of the meat product get a pH value higher or lower the normal level due to bad temperature calibration. Also, it may happen due to bad storage at abattoirs and long waiting time at retailers.

In the same line, traceability and quality control of Halal meat integrity is highly recommended from decision makers and customers as one of main key factors to advocate integrity of HMSCs (Tieman, 2007). Therefore, the HMSC parties (e.g. retailers and customers) push to implement a robust traceability system and a better integrity guarantee (Zulfakar et al. 2012). Farouk (2016) suggested the implementation of closed-circuit television (CCTV) and related technologies in farms and abattoirs aiming to zero-tolerance for any practice of livestock abuse in the meat supply chain. Bahrudin et al. (2011) and Anir et al. (2008) suggested for decision makers of HMSC to implement information and communication technologies (ICT) for Halal transportation such as internet real-time tracking and tracing using global positioning system (GPS), transportation management system (TMS), electronic data interchange (EDI) and RFID to monitor Halal transportation activities. However, the ability of tracing the integrity of Halal meat products at every stage throughout its supply chain is the main challenge for all parties of HMSCs (Zailani et al., 2010; and Lodhi, 2009).

4.2.1 Requirements for Halal meat processing

As mentioned before, Halal meat must follow the rules of the Shari'ah. The Shari'ah imposes that the livestock must have been produced according to environments conducive to express normal behavior, and that the slaughter of such livestock must be implemented kindly (Fuseini et al., 2016). The Shari'ah is based on the Holy Qur'an and sayings of the prophet Mohammed (the Prophet of Islam). The following verse addresses what is measured Halal and what is prohibited (Haram) for Muslims to eat.

حُرِّمَتْ عَلَيْكُمْ الْمَيْتَةُ وَالْدَّمُ وَلَحْمُ الْخِنْزِيرِ وَمَا أُهْلَ لِغَيْرِ اللَّهِ بِهِ، وَالْمُنْخَنِقَةُ وَالْمَوْقُوذَةُ
وَالْمُتَرَدِّيَةُ وَالنَّطِيحَةُ وَمَا أَكَلَ السَّبُعُ إِلَّا مَا ذَكَّيْتُمْ وَمَا ذُبِحَ عَلَى النُّصُبِ وَأَنْ
تَسْتَقْسِمُوا بِالْأَزْلَمِ ذَٰلِكُمْ فِسْقٌ الْيَوْمَ يَبْسُ الَّذِينَ كَفَرُوا مِنْ دِينِكُمْ فَلَا تَخْشَوْهُمْ
وَإَخْشَوْنَ الْيَوْمَ أَكْمَلْتُ لَكُمْ دِينَكُمْ وَأَتَمَمْتُ عَلَيْكُمْ نِعْمَتِي وَرَضِيْتُ لَكُمُ الْإِسْلَامَ
دِينًا فَمَنِ اضْطُرَّ فِي مَخْصَصَةٍ غَيْرِ مُتَجَانِفٍ لِإِثْمٍ فَإِنَّ اللَّهَ غَفُورٌ رَحِيمٌ ﴿٣﴾

It may be translated to:

“Forbidden for you (to eat) are (unslaughtered) dead animals, blood, the flesh of swine and animals slaughtered in the name of beings other than Allah. (Also forbidden are) animals that die as a result of strangulation, violent blows or fall from a height, as well as animals gored to death or (partially) eaten by wild beasts unless you salvage (and slaughter) them (before they die). Also forbidden are animals slaughtered before idols, altars and monuments (dedicated to beings other than Allah) as well as meat distributed by resorting to raffle. These are sins. Today, the unbelievers have given up hope about (wishing) your faith (away). Do not fear them; fear me! I have this day perfected your way of life for you, and I have completed my favor upon you. I have chosen Islam (submission) to be your religion. If one is compelled by hunger (to eat the forbidden food) and not by a desire to deviate and debauch – then of course Allah is the most Forgiving and the most Merciful” (Qur’an, Chapter Al-Maeda 5, Verse 3).

Furthermore, several sayings have focused on the protection of the benevolence of livestock along the slaughtering process. For instance:

“Verily Allah has prescribed ihsan (proficiency, perfection) in all things. So if you kill then kill well; and if you slaughter, then slaughter well. Let each one of you sharpen his blade and let him spare suffering to the animal he slaughters.” (Sahih Muslim).

In accordance to the Shari’ah, the slaughtering process must comply with following conditions:

- The livestock to be slaughtered must be from the types that are allowed for Muslims to consume.
- The livestock must be alive at the time of being slaughtered.
- The livestock must not be suffering from any ailments or any lacerations.
- Each livestock must be slaughtered individually in which not to see each other during slaughtering.
- All livestock must be shielded from the sight of blood before slaughtering.
- Whetting the knife must be out of sight of the livestock.
- Livestock must be oriented toward Qibla (Mecca).
- Water should be offered to the animal before slaughter, and it should not be slaughtered when hungry.

- At the time of slaughtering, the slaughterer must pronounce “Bismillah; Allahu Akbar” (In the Name of Allah; Allah is the Greatest).
- Slaughtered animal must leave without the head to be cut off until the contaminated blood drained out of the carcass.

4.3 Food traceability

The concerns about food safety have risen over the past decade; since customers have increasingly demanded a verified proof of traceability of quality and safety of food as a major goal for their food selection (Beulens et al., 2005; Bertolini et al., 2006; Regattieri et al., 2007; Trienekens and Zuurbier, 2008). Opara (2003) highlighted three main reasons that raised these concerns: (i) modern customers ask for food that is fresh, palatable, nutritious and safe, (ii) growing demands for foods that offer particular health and nutraceutical benefits, and (iii) varying routines and increasing revenue in countries for growing quantity of foods that are eaten outside the home as restaurant meals. Greger (2007) argued that there is a long distance between livestock production and livestock distribution which may increase the chance in infection and spread of diseases.

Moreover, due to the eruption of the mad-cow disease in the United Kingdom in 1985, the Euro-Retailer Produce Working Group (EUREP) and a private party consisting of several European supermarket chains and their major suppliers created GLOBALGAP (Good Agricultural Practice; formerly EurepGAP) to define controlled principles for the warranty of food products around the world (GLOBALGAP, 2009). Besides, a number of European vendors countered the occurrences of food hazards such as mad-cow disease by developing new strategies in trades of food throughout Europe. Saltini and Akkerman (2012) highlighted that only in Europe food borne disease affects about 1% of population (approximately seven million people) each year. Only in 2011, approximately 16.7% of population (47.8 million people) were sick in America in relation to food related illness (Resende-Filho and Hurley, 2012). Further, there were increasing anxieties after the scandals of the contaminated infant formula in China (The New York Times, 2008).

These concerns resulted in developments in the traceability of food products as part of food supply chains management. Traceability is an approach to enforce the legislation to be implemented to assure the food safety and quality requirements (Aung and Chang, 2014). An effective safety and quality-monitoring system can be useful to maintain food safety

throughout its supply chain to increase customer sureness (Kher et al., 2010) and to link manufacturers and customers (Regattieri et al., 2007). Apart from that, McKean (2001) and Meuwissen et al., (2003) proposed that a traceability system improves transparency and information flow in food supply chain.

4.3.1 Definition of traceability

Definitions of traceability can vary based on different criteria (Golan et al., 2004). According to the definition of ISO 9000 (2005) standards, traceability is “*the ability to trace the history, application or location of that which is under consideration*”. This extended their previous definition in ISO 8402, that defined traceability as “*the ability to trace the history, application or location of an entity by means of recorded identifications*” (Bertolini et al., 2006; Kelepouris et al., 2007; Canavari et al., 2010; Olsen and Aschan, 2010; Karlson et al., 2013). This definition further considers the food history in terms of the source of food, the production history, and the delivery and place of the product after distribution (Aung and Chang, 2014). Bosona and Gebresenbet (2013) defined food traceability as “*a part of logistics management that capture, store, and transmit adequate information associated with food, feed, food-producing or substance at all stages in a food supply chain so that the product can be checked for safety and quality control, traced upward, and tracked downward at any time*”. Tables 3 shows a number of selected definitions of traceability.

Table 3. Selected definitions of traceability in food supply chain

Author	Definition of traceability in FSC
Wilson and Clarke (1998)	Information about food from the source to the end user
Schwägele (2005)	<i>“The ability to trace food products up and down the production chain through all stages of production”</i>
Dalvit et al. (2007); McKean (2001)	The ability of a system to keep information about products from farms to retailers
Olsen and Borit (2013)	The ability to access any or all information of food
Resende-Filho and Hurley (2012)	<i>“The probability of finding the source of a problem”</i>
Manos and Manikas (2010)	<i>“The ability to trace the history of product through the supply chain to or from the place and time of production, including the identification of the inputs</i>

	<i>used and production operations undertaken”</i>
Bertolini et al. (2006); Olsen and Aschan (2010); Karlson et al. (2013); Kelepouris et al. (2007)	<i>“The ability to trace the history, application or location of an entity by means of recorded identifications”</i>

Based on the reviewed definitions, it can be concluded that most of these definitions attempted to describe traceability as the aptitude to trace the movement of food products throughout the supply chain. A reliable traceability system can lead to reduction of production and delivery of low quality food, thus decrease the probability for poor marketing and recalls of food products.

Opara (2003) mentioned that there are six types of traceability that may improve the overall performance of the food supply chain. These types are:

1. Product traceability: refers to the product’s location at any level in the supply chain. This may improve product recall, distribution of information data to customers and other parties, and logistics and inventory management.
2. Process traceability: determines the category of operations activities that may affect the product throughout through its supply chain. These activities are involved in interactions which lead to changes of the natural resources into end products through physical, mechanical, chemical processes or environmental and atmospheric factors.
3. Genetic traceability: determines the genetic constitution of the product. This includes information on the type and origin (source, supplier) of genetically modified organisms/materials or ingredients as well as information on planting materials (such seeds, stem cuttings, tuber, sperm, and embryo) used to create the raw product.
4. Inputs traceability: refers to category and origin of inputs such as manure, irrigation water, food, and the use of chemicals for the conservation and/or changing of the natural resources into processed food products.
5. Disease and pest traceability: chases the epidemiology of pests, and biotic hazards such as bacteria, viruses and other emerging pathogens that may contaminate food and other ingested biological products derived from natural resources.
6. Measurement traceability: relates individual measurement results through an unbroken chain of calibrations to accepted reference standards (Gardner and Rasberry, 1993). To achieve this, measuring and test equipment and measurement

standards are calibrated utilizing a reference standard whose calibration is certified as being traceable to a national or international standard (Cameron, 1975).

Manos and Manikas (2010) reported that the selection of appropriate and effective traceability system should be associated with main five criteria: (i) construction of the food supply chain under investigation, (ii) association between supply chain parties, (iii) capacity of technologies and human resources for handling activities, (iv) quality and production operations, and (v) packaging materials and methods. However, implementing a traceability system needs a cooperation and integration of all parties of the food supply chain. This cooperation and integration could result in a maximum advantage on the overall supply chain than improving traceability partially. On the contrary, lack of cooperation may lead to inefficiency of food supply chain management (Rábade and Alfaro, 2006).

Several researchers addressed the necessity of technologies in food supply chain management for tracing quality and safety of products, identifying products, capturing, analyzing and transmitting information data (Opara, 2003; Aarnisalo et al., 2007; Regattieri et al., 2007; Smith et al., 2008; Aung and Chang, 2014). Table 4 summarizes a number of proposed technologies in the context of improving the traceability in food industry.

Table 4. A summary of technologies proposed for the traceability of food industry (Aung and Chang, 2014)

Technology	Description	Strengths	Weaknesses
Alphanumeric codes	Label which includes a sequence of numbers and letters of various sizes, replaced by bar code	Simple to use and economic	Code read/write not automatic Poor performance High data integrity corruption No standards defined Lack of tie between different actors Cannot collect environmental information (no sensing capability)
Bar codes	Optical machine readable representation of data. Encodes alphanumeric characters and consist of vertical bars, spaces, squares and dots	Simple, more economical and exact traceability	Reading needs line of sight Unreadable for damaged labels Can read one at a time by scanner Cannot collect

			environmental information (no sensing capability)
RFID	Detect presence of tagged objects, identify or track using radio waves	No line of sight in reading can read and write tags Higher data rate and larger memory size Reversible tags Can read many tags simultaneously	Rely on RFID reader for data collection, No cooperation among the devices Can read data within one hop Cost still a burden Limited capability for environmental sensing
Wireless Sensor Network (WSN)	Collect sensing data from physical or environmental conditions Variety of sensors available for sensing and monitoring	Multi-hop networking In-network processing Can deploy different network topologies Secure communication among nodes Longer reading ranges Sensor-actuator networking	Not suitable for identification purpose Need energy saving techniques for continuous Sensing

Alphanumeric codes are not commonly implemented since they (i) need human intervention and budgets, (ii) do not provide automatic reading, and (iii) suffer from deficiency in data reliability. In the past decade, the implementation of RFID technology, however, has been becoming an ever-increasing popularity in the traceability of supply chain as one of the most cutting edge technologies (Chrysochou et al., 2009; Manos and Manikas, 2010; Zailani et al., 2010; McEntire et al., 2010; Azuara et al., 2012). RFID is an automatic identification technology which was proposed by industry to identify items and gather real-time data without human involvement (Mousavi, 2002).

4.3.2 Challenges

Due to the growing demands by consumers for improving safety and quality of food, some of food producers are forced to implement traceability systems from suppliers to end-customers throughout the supply chains. Even though, this implementation faces several hurdles from different perspectives, which can be categorized into three main categories:

- **Economic:** implementing a new traceability system is associated with extra costs in investment which considers as a barrier for decision makers particularly for small-size manufactures and low developed countries. From different point of view, Karippacheril et al. (2011) argued that reducing cost of new traceability technologies such as cheaper bar codes and RFID tags leads to promote better food supply chains. The reducing costs and efficient performant is expected to encourage (i) decision makers to heavily contribute in the development and implementation of food traceability systems, and (ii) developed countries like China to implement food traceability systems aiming to develop their competitiveness in the global food industry (Xiao-hui et al., 2007; Smith et al., 2008; Xiaoshuan et al., 2010).
- **Technological:** improved traceability systems need efficient and complex technologies which do not encourage the decision makers because of the complexity of the technologies and absence of high-skilled staff for managing the new traceability system (Schwägele, 2005; Engelseth, 2009; Xiaoshuan et al., 2010; Bosona and Gebresenbet, 2013).
- **Standardization:** traceability of food industry is frequently multifaceted because of the differences in data collection, fluctuation in sorts of collected data, differences in sharing data within a facility and among food supply chain parties (McEntire et al., 2010). There is a major issue in traceability of food supply chain due to the absence of global standardization. This results in incompatibility among variant solutions proposed by variant parties in a supply chain (Regattieri et al., 2007; Salampasis et al., 2012). Global and unified standards could improve the existing traceability systems (Kher et al., 2010). Ackerley et la. (2010) reported that there is a lack in information about the traceability of pollution/losses of food during distribution.

4.4 RFID technology

RFID is an automatic identification technology using wireless radio frequency signals. It can identify objects within a given radio frequency range through radio waves without human intervention or data entry (Muller-Seitz et al., 2009). RFID provides identification codes that can be related to human, livestock and objects for tracing purposes (Mats et al., 2008). The implementation of RFID has rapidly been spreading into supply chain management (Nath et al., 2006), object (e.g, livestock) tracking, inventory and access control ((Nemmaluri et al., 2008, Finkenzeller, 2010), vehicle security (Seshagiri et al., 2005), military and medical sciences (Finkenzeller, 2010), and production and delivery of products (Cardiel et al., 2012; Lin and Ho, 2009).

4.4.1 RFID History

RFID was originally invented in 1935, by physicist Sir Robert Alexander Watson-Watt (RFID Journal, 2005). The preliminary usage of radio frequency communication was in World War II by the Germans, Japanese, Americans and British for identifying aircrafts. The issue was that the system could not recognize between enemy and friendly aircrafts. Later, the British army developed the "Identification Friend or Foe" system (IFF) for identifying the friendly aircrafts (Wizard Wars, 2016). They installed a transmitter on British aircrafts individually. When the transmitter sends broadcast signals and once the aircraft receives a signal from radar stations on the ground, the sent signal identifies the aircraft as friendly. In 1970, United States government employed RFID for tracking nuclear and hazardous materials.

In later 1970s, RFID technology was used as a theft prevention system namely the "Electronic Article Surveillance" (EAS). The EAS was built based on tags that can store one-bit data. That bit was read when the customer left the store and the system generates an alarm when the bit was not unset. In 1980, RFID tags were used for the agriculture for tracking livestock when the Dutch Government required the individual identification of around 75 million pigs (Ollivier, 1996). In the early 1990s, IBM company improved the RFID in terms of read range and data transfer speed. In 1999, RFID technology were boosted by establishing the Auto-ID Center at the Massachusetts Institute of Technology funded by the Uniform Code Council, EAN International, Procter and Gamble and Gillette. The tasks were to develop a global standard for item-level tagging as well as the ability of attaching low-cost RFID tags on all products made for tracking purposes. In the last decade, the RFID

implementation has been increasingly becoming popular in retailers such as Albertsons, Metro, Target, Tesco, Wal-Mart. Figure 3 shows the investment size for the RFID from 2010 to 2012, and an estimated investment in 2020 (Statista, 2015).

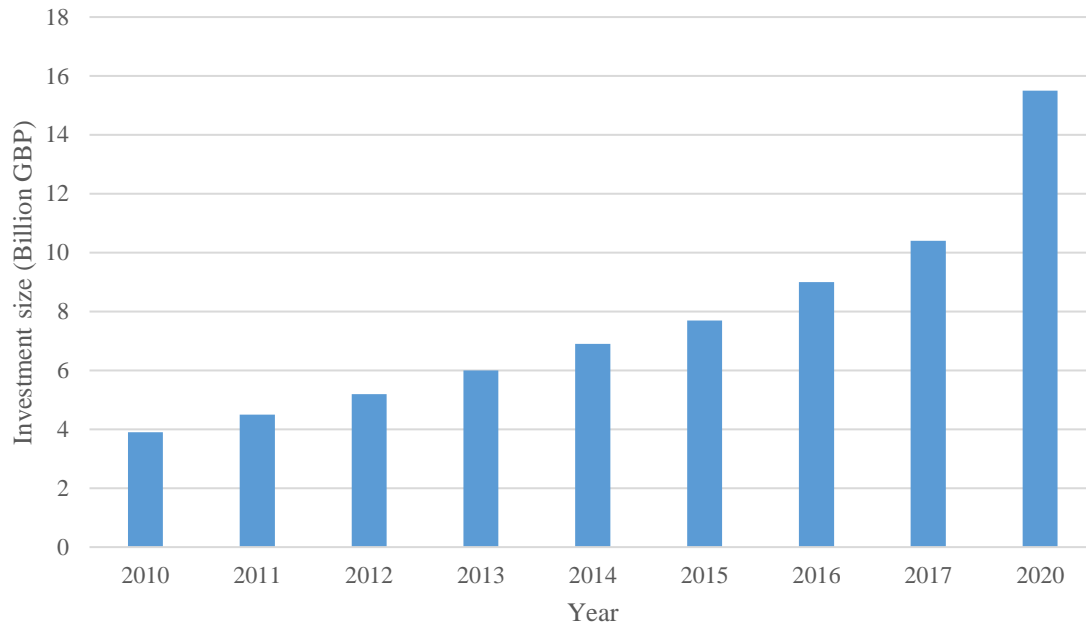


Figure 3. The investment size for the RFID technology.

4.4.2 RFID components

A typical RFID system consists of three main components (shown in Figure 4):

1. RFID tag or transponder: which is attached on an item to be tracked where it carries an Identification code that can be recovered by RFID readers. A RFID tag consists of a microchip, an antenna, and a battery (for active RFID tag only). The microchip is used to store information and the antenna is used to transmit and receive the information.
2. RFID reader or transceiver: which is responsible for both reading data from and writing data to a RFID tag. It consists of a radio frequency module, a control unit, and an antenna to interrogate RFID tags via radio frequency signals.
3. Data processing sub-system: which is used for analyzing and presenting data in a useful manner obtained from the RFID reader. Also, several RFID readers are equipped with an interface that let them to transfer their received data to a data processing subsystem.

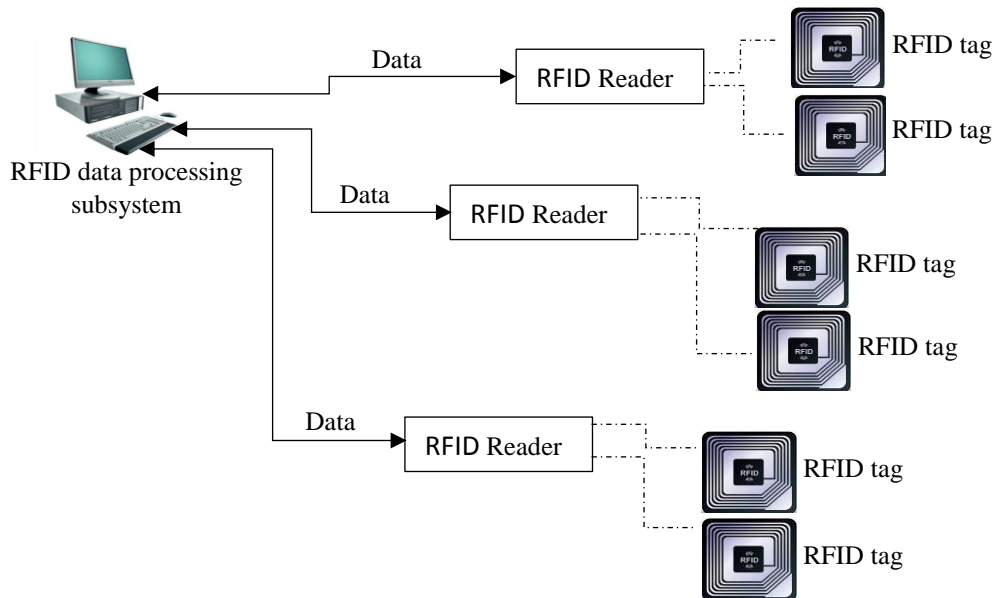


Figure 4. A simplified RFID system.

RFID tags or transponders are classified into three types according to their power source:

1. Passive: which do not have an internal power source. Passive tags are powered from the received radio frequency signal of the RFID transceiver and either reflect or load modulate the transceiver's signal for communication. For that reason, the RFID transceiver must be keep its field active until the transmission is completed. A RFID passive tag is the cheapest and the smallest RFID tag with an acceptable performance for several applications. On the other hand, it has relatively poorer reading range between 2mm and one meter.
2. Semi-passive: which has an internal power source that keeps the microchip activated at all times. It has two main advantages: it has a faster respond rate, therefore maximizing the quantity of RFID transponders that can be scanned per second. Furthermore, it has a wider reading range than a passive transponder.
3. Active: which has an on-tag power supply. Unlike semi-passive, it sends a radio frequency signal to communicate with the RFID transceiver. In other words, it can send a radio frequency signal without being called by a RFID transceiver. Its range can be tens of meters. Table 5 shows further comparison among the three types of RFID transponders.

Table 5. A comparison among the three types of RFID transponders

Attribute	Passive	Semi-passive	Active
Energy source	Induction	Battery	Battery
Cost	0.1 GBP – 5GBP	0.2 GBP – 15 GBP	20 GBP – 50 GBP
Reading range	< ~1m	<~ 20m	<~ 100 m
Memory size	128b-2Kb	128b-8Kb	64Kb-228Kb
Life time	Up to 10 years	1-5 years	1-5 years

Furthermore, RFID tags or transponders can also be classified to three main groups according to their operating frequency.

1. Low-frequency (LF, 30 - 500kHz): which is the cheapest tag type. It is less affected by the existence of metal or fluids. The weaknesses of this tag are their short reading range, low transmission rate and it must be within the reading range of readers during the transmission process. The most popular frequencies used from this band are 125 - 134.2 kHz and 140 - 148.5 kHz.
2. High-frequency (HF, 10 – 15MHz): which is the most common used tag. It has a higher transmission rate and reading range but it is more expensive than the low frequency tag. The most popular frequency used from this band is 13.56MHz.
3. Ultra-high frequency (UHF, 850 - 950MHz, 2.4 - 2.5GHz, 5.8GHz): which has the highest transmission rate and reading range. This increases the number of RFID tags to be read at a time. On the other hand, UHF tag can be expensive and affected by the existence of metal or fluids. UHF frequencies are 868MHz (Europe), 915MHz (USA), 950MHz (Japan), and 2.45GHz.

Globally, the operation of RFID systems is controlled by local governmental schemes which regulate the electromagnetic spectrum in a district. The majority of RFID systems work in bands known as Industrial-Scientific-Medical (ISM) which are regulated by the International Telecommunications Union (ITU). These bands are un-licensed to be used by low-power, short-range systems. For RFID systems, the most popular ISM frequencies are 13.56 MHz and 902-928 MHz (in the US only). In addition, the low frequency band 9kHz-135 kHz is freely available for use in most countries, and the 868MHz-870MHz band is available for use by nonspecific short-range devices in Europe. Further details about frequency bands can be found in Scharfeld, 2001.

Lastly, in the last few years there was an increasing interest in the integration of sensors into RFID tags which is so-called 2G-RFID sensor tags or RFID sensor tags. The 2G-RFID sensor tag is capable of transmitting information data of relevance to not merely each item's unique identification code but also each item's physical parameter (e.g. heartbeats and temperatures). Recently, this type of tag has been applied into applications in such as cold supply chains to provide a temperature profile of fruits or vegetables throughout the chain; valuable fragile items to provide proofs of shocks during its distribution by sensing the acceleration; electronic seal tags to provide tamper evidence of any transported item or product package even without visual inspection (Ruhanen et al., 2008). Normally, the 2G-RFID sensor tags are categorized according to their sensing feature which includes sensing of temperature, accelerating, light, pressure, gas and chemical.

4.4.3 RFID communication

Generally, the transmission of data in RFID systems has two main methods:

- Inductive coupling (<30MHz): the magnetic field is generated by RFID readers and by the inductive coupling; RFID tags are powered to receive from and send data to RFID readers via a coiled antenna. This transmission has a lack in transmission range since tags must stay within the transmitting range of readers during the data transmission. Figure 5 illustrates a structure of the inductive coupling transmission.

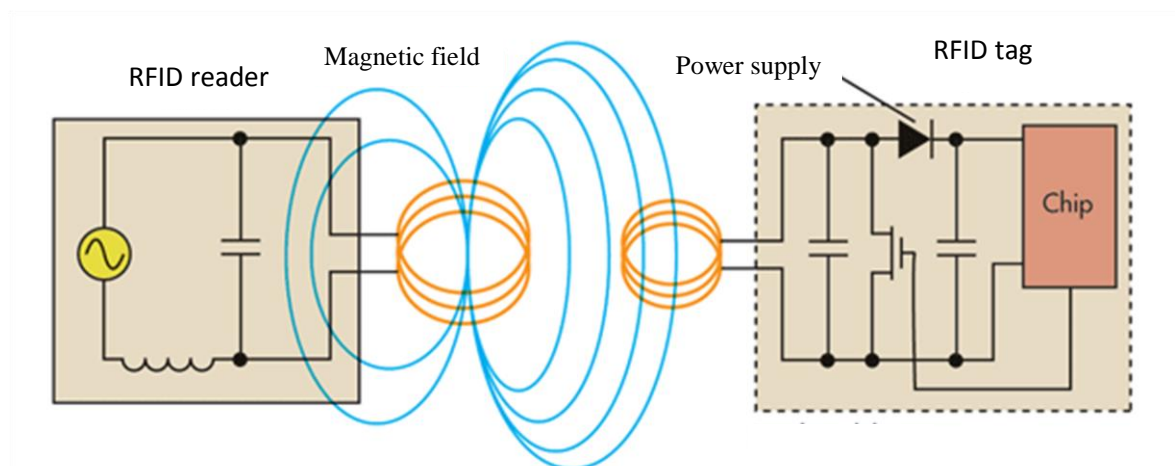


Figure 5. Structure of inductive coupling transmission.

- Electromagnetic wave (>30MHz): RFID tags have an internal power supply (e.g., a battery) and actively send a radio frequency signal for communication with RFID readers. Its transmission range is longer than the inductive coupling. Figure 6

illustrates a simplified structure of the electromagnetic wave transmission. Both methods, communicate when transponders are interrogated by readers.

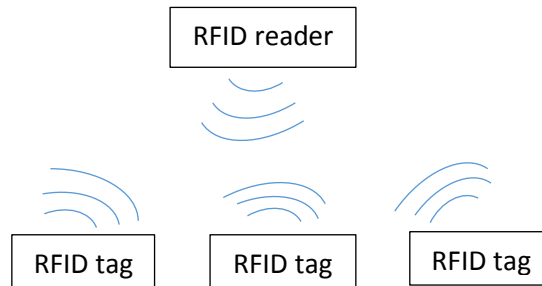


Figure 6. A simplified structure of the electromagnetic wave transmission.

4.4.4 Benefits of RFID for supply chain management

RFID has a number of technical benefits such as non-line of sight communication, unique identification of items and real-time information (Zeimpekis et al., 2007; Zhang et al., 2012). These advantages support several aspects of the supply chain (e.g., distribution center management, distribution management, operations scheduling, and inventory management) (Bourlakis et al., 2011). RFID has a saved resource of information related to the supply chain activities that can be analyzed for managing and developing supply chain operations (Ngai et al., 2010). A review study by Sarac et al. (2010) concluded that the RFID highlights three main sorts of issues in supply chain management:

- Inventory incorrectness: notwithstanding the development in the automatic inventory management, firms frequently address a disparity between collected and real inventory levels (Dai and Tseng, 2012). DeHoratius and Raman (2008) addressed that 65% of the inventory archives in retailers were imprecise which led to higher inventory costs, missing auctions, and reduced revenues. RFID implementation can provide real-time data for inventory management (Dai and Tseng, 2012; Xu et al., 2012).
- Bullwhip influence: which is a phenomenon arises when the demand inconsistency is grown in the supply chain (Forrester, 1958). This phenomenon is caused as a result of the demand prediction, order batching, price variations, lead time, market sensitivity, resource allocations, poor information sharing, and lack of supply chain visibility and transparency (Vlachos, 2014). For further details about bullwhip effect studies refer to

Geary et al., 2006. Thus, RFID aims at minimizing the bullwhip influence by enhancing inventory visibility and reducing safety stock levels (Zhou, 2011).

- Suboptimal replenishment: Replenishment is an important key factor in protecting customer service with the lowest inventory holding costs. The RFID implementation helps the firms in emerging cutting-edge replenishment strategies that is outperformed manual or barcode-based systems (Vlachos, 2014). It is expected that the RFID implementation in developing firms' strategies can lead to improve cost efficacy and service levels (Condea et al., 2012).

Other benefits may be found in Tajima, 2007.

4.4.5 RFID in food supply chains

In the last two decades, RFID has generated a lot of interest in the food supply chain. Azuara et al., 2012; Regattieri et al., 2007; and Salampasis et al., 2012 argued that RFID tags are effective tools for food traceability due to the small-size of tags with food compatible.

Primarily, RFID tags were attached with cases and pallets that contain items/products for enhancing inventory management. Today, RFID tags are attached individually with items for tracking items. For instance, in Ireland, traceability of meat products is presently managed by a number of policies such as EU 178/2002, which sets overall ethics and necessities of food laws, EC 1760/2000 which creates a system for the documentation of livestock; and EC 911/2004 which manages ear-tags, passports and holding registers. All livestock in Ireland have a RFID ear-tag attached individually with an identification number. The owner of the livestock then sends a National Calf Birth Registration form to the National Calf Birth Registration Centre to be registered in a central database. This leads to a National Bovine Administrative Document and a livestock Identity Card/Passport being issued for livestock individually (Carthy et al., 2011). This central database is governed by Department of Agriculture, Fisheries and Food (DAFF). It was established to register all births, movements, deaths and disposals of livestock (DAFF, 2003). Carthy et al. (2011) argued that the RFID implementation in the entire food supply chain (from farm to plate or fork) enables automation, improves product quality and safety, saves cost, provides a central database of information, monitors products' condition through the transportation process, and allows internal traceability.

4.5 The proposed 2G-RFID-enabled HMSC

Figure 7 illustrates the architecture of a simplified RFID-enabled HMSC for monitoring each process of Halal meat production and transportation. The proposed RFID-enabled monitoring HMSC consists of farms, abattoirs, transporters, retailers and consumers as described below:

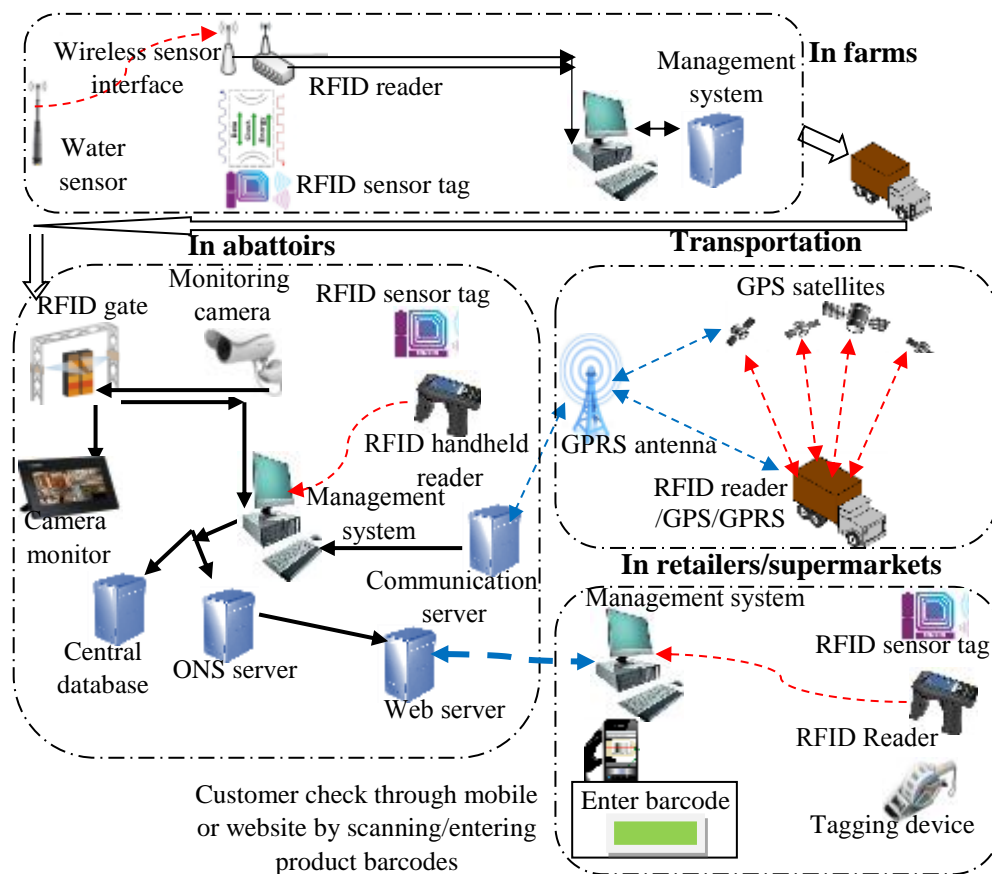


Figure 7. Architecture of the proposed RFID-based monitoring HMSC network.

In farms: Each livestock is attached with a 2G-RFID sensor tag which can store both passive and active information. The 2G-RFID sensor tag is capable of transmitting information data in the relevance to not merely a unique identification code of an attach livestock but also its health status such as heartbeats and body temperatures. Information data are collected by wireless RFID readers that interrogate RFID-sensor tags by emitting radio signals and subsequently RFID sensor tags respond by sending information data to RFID readers. The gathered information data by RFID readers are sent to a host computer management system. Water supply for each livestock is monitored by a water sensor mounted on a water basin. When contaminated water is detected by a water sensor, it sends an alert to the computer

management system for records and farmers ought to isolate those contaminated livestock immediately from others. Periodically, farmers should also take a medical record of livestock relating to illnesses, medical treatments and treatment results during the growing period. The record should include information of given medical treatments and vaccination that do not contain pork enzymes which make livestock as non-Halal. The growing history of each livestock needs to be input into the computer management system manually. All the collected information data will be analyzed and displayed as shown in Table 6 allowing traders and consumers to check relevant information in terms of the integrity of Halal meat products they purchase in farms or supermarkets by either entering product codes online or scan them using their smart mobile phones.

Table 6. Growing history of a livestock in farms

Info category	Info details
Category	Beef
Feeding methods	Halal
Types of diseases /symptoms	Bovine Ephemeral Fever
Treatment duration	4 days
Treatment results	Healed
Growing History/Kg	10Kg/8mth
Enzyme History	None
Last Update of Info	11/02/15

In abattoirs: Because each livestock is attached with a 2G-RFID tag, once these transported livestock from farms enter into abattoirs through an RFID-reader mounted gate, information data of each livestock will be collected and stored automatically in an abattoir database. To comply with the Halal slaughtering process (see chapter 2. Academy, 1997), slaughtering places must be monitored by abattoir operators through installed cameras. If a livestock is not slaughtered according to the Halal way, this livestock needs to be isolated and marked as non-Halal. At the end of the slaughtering process, each segmented meat is packed and tagged with a new 2G-RFID sensor tag that is used for monitoring its pH values; a typical pH value for meats ranges from 4.8 to 5.8 (Lomiwe et al., 2010). The information data can be collected by an RFID handheld reader and the collected information data are subsequently sent back to the abattoir database.

In transportation: Figure 8 illustrates the architecture of the proposed monitoring system during transportation of Halal meat products from abattoirs to retailers. Each container of a lorry is equipped with an RFID reader, a temperature sensor, a GPS and a GPRS system.

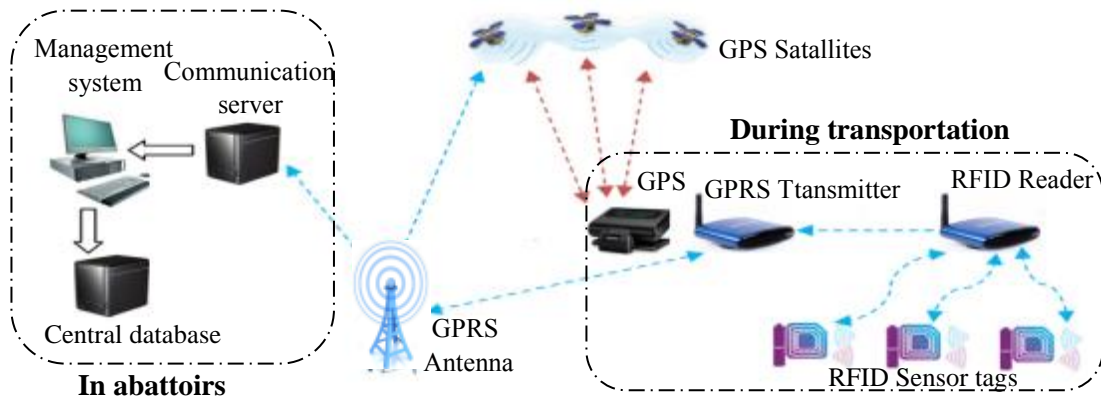


Figure 8. The transportation monitoring system.

The RFID reader is used for collecting identification information as well as pH values from 2G-RFID sensor tags, which are attached with each of packed Halal meat products in the lorry. The GPS is used for tracking locations of the lorry sporadically providing an estimated arrival time to retailers. A temperature sensor continuously detects container's temperatures and sends an alert to notify drivers if the temperature reaches the upper limit. Information data collected by an RFID reader and a GPS are sent back to the abattoir management system over a GPRS network that consists of a GPRS transmitter, an antenna and a receiver. These data can be retrieved by retailers. GPRS rather than GSM (global system for mobile) was selected as its active transmission can share available resources. Also, it uses a packet switch technique allowing an allocation of resources when needed; furthermore, it provides a data transfer rate up to 172 kbps. Figure 9 shows data transmission flow throughout the transportation monitoring process.

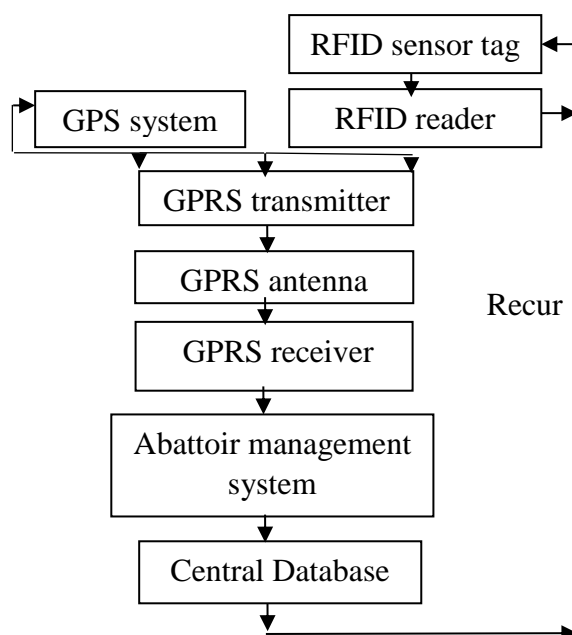


Figure 9. Data flow of the transportation monitoring process.

In retailers or supermarkets: Once packed meats from abattoirs arrive at a retailer or a supermarket, each packed meat is scanned by a handheld RFID reader to collect information data that are subsequently uploaded into an inventory management system at the retailer or the supermarket. Meat in each package may then be sliced and repacked in smaller sizes and each re-packed meat is tagged with a barcode label that contains relevant information of the packed meat product as shown in Table 7 which can be accessed by consumers entering barcodes online or using a mobile scanner.

Table 7. Information of a packed meat product at abattoirs to be sold at retailers or supermarkets

Info category	Info details
Meat type	Beef
Origin of meat	Scotland
Slaughtering date	12/08/14
Slaughterer Name	Omar
Arrival date to the shop	13/08/14

Figure 10 shows a flowchart that illustrates a complete monitoring process during Halal meat production (at farms and abattoirs), transportation and in retailers. Table 8 shows the

Table 8. The corresponding operations or actions of a HMSC monitoring process shown in Figure 10

Operations	Description
Fx	Farms
F1	Each livestock is attached with an RFID tag.
F2	A water sensor is installed at each water basin to detect water contamination; the water sensor sends an alert to the management system if water is contaminated at the water basin.
F3	Identify and separate the livestock watered by the contaminated water basin.
LHx	
LH1	Record any disease of a livestock by entering medical information data into the computer management system.
LH2	Identify and separate the infected livestock.
LH3	Update the management system by entering types of diseases and results of treatments of the infected livestock.
Ax	Abattoirs
A1	Receive inventory data of RFID-tagged livestock through an RFID-reader mounted gate at an abattoir.
A2	Monitor the Halal slaughtering process by operators through cameras to ensure that each livestock is slaughtered with absence of other livestock at a slaughtering station.
A3	Knife must be invisible to each slaughtered livestock.
A4	Each slaughtered livestock's head is held at a certain position for 25 seconds to allow draining contaminated blood.
A5	Separate and mark each slaughtered livestock as non-Halal if the slaughtering process does not follow steps A2-4.
A6	Attach each slaughtered livestock with an RFID sensor tag for monitoring meat quality during transportation; collect its information data by an RFID handheld reader.
Tx	Transportation
T1	Monitor container temperatures and products' pH values by a temperature sensor and RFID sensor tags respectively and send an alert to notify drivers if any of these values reach above the upper limit.
T2	Transmit data collected from GPS and RFID readers to the abattoir management system via a GPRS system.
T3	Identify, separate and return any stale meat to the abattoir.
Rx	Retailers
R1	Operators unload arrived meats into stores of a retailer, scan RFID tags by a handheld RFID reader for acquisition of inventory data.
R2	Segment and repack meats in small packages tagged with barcode labels ready for sales.
R3	Consumers can check information of Halal meat integrity by scanning product barcodes using a mobile scanner or entering barcodes online.
R3a	Retailers return non-Halal meat products to abattoirs.

4.6 Multi-objective mathematical model

In this study, a mathematical model with three conflicting objectives was developed for investigating the economic feasibility of the proposed RFID-enabled HMSC in order to obtain a cost-effective decision. The first objective Z_1 is aimed at minimizing the total investment cost. The second objective Z_2 is aimed at maximizing the Halal meat integrity in the number of Halal meat products. And the third objective Z_3 is aimed at maximizing ROI. Sets, parameters, variables and notations are described as follows:

Sets:

I	set of farms $i \in I$
J	set of abattoirs $j \in J$
K	set of retailers $k \in K$

Parameters:

$C_i^{E,\alpha}$	RFID equipment (E) cost (GBP) required for farm i
$C_j^{E,\beta}$	RFID equipment (E) cost (GBP) required for abattoir j
$C_i^{I,\alpha}$	RFID implementation (I) cost (GBP) required for farm i
$C_j^{I,\beta}$	RFID implementation (I) cost (GBP) required for abattoir j
$C_{ij}^{T,u}$	unit transportation (T) cost (GBP) per mile from farm i to abattoir j
$C_{jk}^{T,v}$	unit transportation (T) cost (GBP) per mile from abattoir j to retailer k
d_{ij}^u	travel distance (mile) from farm i to abattoir j
d_{jk}^v	travel distance (mile) from abattoir j to retailer k
W	transportation capacity (units) per vehicle
S_i^α	maximum supply capacity (units) of farm i
S_j^β	maximum supply capacity (units) of abattoir j

D_j^β	minimum demand (in units) of abattoir j
D_k	minimum demand (in units) of retailer k
P_{ij}^u	integrity percentage through first transportation link u from farm i to abattoir j
P_{jk}^v	integrity percentage through second transportation link v from abattoir j to retailer k
R_i^α	return of investment (GBP) per item for farm i
R_j^β	return of investment (GBP) per item for abattoir j

Variables:

x_{ij}^u	quantity of units transported through the first transportation link u from farm i to abattoir j
x_{jk}^v	quantity of units transported through the second transportation link v from abattoir j to retailer k
y_i^α	$\begin{cases} 1: \text{if farm } i \text{ is open} \\ 0: \text{otherwise} \end{cases}$
y_j^β	$\begin{cases} 1: \text{if abattoir } j \text{ is open} \\ 0: \text{otherwise} \end{cases}$

To minimize the total investment cost Z_1 , which consists of equipment costs, implementation costs and transportation costs, it is given by:

$$\begin{aligned} \text{Min } Z_1 = & \sum_{i \in I} (C_i^{E,\alpha} + C_i^{I,\alpha}) y_i^\alpha + \sum_{j \in J} (C_j^{E,\beta} + C_j^{I,\beta}) y_j^\beta \\ & + \sum_{i \in I} \sum_{j \in J} C_{ij}^{T,u} [x_{ij}^u / W] d_{ij}^u + \sum_{j \in J} \sum_{k \in K} C_{jk}^{T,v} [x_{jk}^v / W] d_{jk}^v \end{aligned} \quad (4.1)$$

To maximize integrity of Halal meat products Z_2 is the main objective of the RFID-based monitoring HMSC network, it is given by:

$$\text{Max } Z_2 = \sum_{i \in I} \sum_{j \in J} P_{ij}^u x_{ij}^u + \sum_{j \in J} \sum_{k \in K} P_{jk}^v x_{jk}^v \quad (4.2)$$

ROI Z_3 is the third objective that need to be considered. ROI is based on profits of each livestock sold to abattoirs and each meat product sold to retailers, it is given by:

$$\text{Max } Z_3 = \sum_{i \in I} \sum_{j \in J} R_i^\alpha x_{ij}^u + \sum_{j \in J} \sum_{k \in K} R_j^\beta x_{jk}^v \quad (4.3)$$

Subject to

$$\sum_{i \in I} x_{ij}^u \leq S_i^\alpha y_i^\alpha \quad \forall j \in J \quad (4.4)$$

$$\sum_{k \in K} x_{jk}^v \leq S_j^\beta y_j^\beta \quad \forall j \in J \quad (4.5)$$

$$\sum_{i \in I} x_{ij}^u \geq D_j^\beta \quad \forall j \in J \quad (4.6)$$

$$\sum_{j \in J} x_{jk}^v \geq D_k^\gamma \quad \forall k \in K \quad (4.7)$$

$$D_j^\beta \geq \sum_{k \in K} x_{jk}^v \quad \forall j \in J \quad (4.8)$$

$$x_{ij}^u - \text{integer} \quad (4.9)$$

$$x_{jk}^v - \text{integer} \quad (4.10)$$

$$y_i^\alpha - \text{binary} \quad (4.11)$$

$$y_j^\beta - \text{binary} \quad (4.12)$$

Where constraints 4-5 are supply constraints in quantity and constraints 6-8 are demand constraints in quantity.

4.4 Solution methodology

4.4.1 Optimization approach

In order to obtain Pareto optimal solution, a solution approach was developed. This approach transforms the multi-objective model into a single-objective model Z_s which is formulated by

considering each objective individually. This single-objective model aims to minimize the scalarized differences between each objective and its optimal value. Undesired deviations Z_d are proposed to be subtracted from Z_s with the aim to achieve more accurate objective values. These values are close enough to non-inferior optimal solutions which lead to a clear insight of a compromise solution between conflicting objectives for decision makers. The solution approach function Z can be formulated as follows:

$$\text{Min } Z = Z_s - Z_d \quad (4.13)$$

Where

$$Z_s = \left[(w_1 \mu_1) - (w_2 \mu_2) - (w_3 \mu_3) \right] \quad (4.14)$$

$$\text{s.t. } \begin{cases} \mu_1 = \left[\frac{Z_1 - Z_1^*}{Z_1^*} \right] \\ \mu_2 = \left[\frac{Z_2 - Z_2^*}{Z_2^*} \right] \\ \mu_3 = \left[\frac{Z_3 - Z_3^*}{Z_3^*} \right] \\ 0 \geq w_n \geq 1 \quad n = (1, 2, 3) \\ \sum_{n=1}^3 w_n = 1 \end{cases} \quad (4.15)$$

Set $w_n^* = \frac{w_n Z_n^*}{Z_n^* - Z_n}$, then

$$\begin{aligned} Z_d &= w_1^* Z_1 + w_2^* Z_2 + w_3^* Z_3 \\ &= \frac{w_1 Z_1^*}{Z_1^* - Z_1} Z_1 + \frac{w_2 Z_2^*}{Z_2^* - Z_2} Z_2 + \frac{w_3 Z_3^*}{Z_3^* - Z_3} Z_3 \end{aligned} \quad (4.16)$$

Finally, based on the aforementioned procedures the solution objective function can be written as follows.

$$\begin{aligned} \text{Min } Z &= (w_1\mu_1 - w_2\mu_2 - w_3\mu_3) \\ &- \left(\frac{w_1 Z_1^*}{Z_1^* - Z_1} Z_1 + \frac{w_2 Z_2^*}{Z_2^* - Z_2} Z_2 + \frac{w_3 Z_3^*}{Z_3^* - Z_3} Z_3 \right) \end{aligned} \quad (4.17)$$

The constraints contain equations 4.4-4.10 and 4.15. Utilizing this approach yields a mono objective function, mixed integer linear programming model which can be solved using a linear programming solver i.e., LINGO or Xpress.

LINGO and Xpress are software used for modeling and solving linear, nonlinear, and mixed-integer optimization problems.

4.4.2 Decision-making algorithm

Once the Pareto optimal solutions are obtained, it needs to determine one optimal solution used for implementation. The selected solution can be made by decision makers with the highest degree of preference of the related objectives. So far, several approaches have been employed aiming to select the best trade-off decision in a multi-objective problem. In this study, a decision-making algorithm was developed and used to select the best solution from the derived Pareto set. The selected solution is subject to the highest superiority value S which is determined by a subtraction of the minimum distance to the ideal solution Z^+ and the maximum distance to the worst solution Z^- . The selection formula can be expressed as follow:

$$S = \sum_{i=1}^I |Z_i^+ - Z_i| - \sum_{i=1}^I |Z_i - Z_i^-| \quad (4.18)$$

4.5 Application and evaluation

In order to examine the applicability of the developed mathematical model as well as the usefulness of the developed solution methodology, two case studies were applied based on data shown in Table 9. The data were collected from farms, abattoirs and retailers by the Halal Meat Committee in the UK (HMC, 2012). Travel distances were estimated between farms and abattoirs and between abattoirs and retailers using the Google map. In case study A, London-South West area was considered, it includes five farms, six abattoirs and eleven retailers. In case study B, London-South East area was considered. It includes five farms, six abattoirs and three retailers.

Table 9. Collected data from the HMC

Case A / London – South West			
$I = 5$	$C_j^{E,\beta} = 4K-7.5K$	$D_k^\gamma = 50-100$	$d_{ij}^u = 23- 410$
$J = 6$	$C_j^{I,\beta} = 700-1.2K$	$P_{ij}^u = 0.85-0.98$	$d_{jk}^v = 110 -174$
$K = 11$	$S_i^\alpha = 1.2K-2.5K$	$P_{jk}^v = 0.85-100$	$W = 100$
$C_i^{E,\alpha} = 4K-8K$	$S_j^\beta = 1K-1.8K$	$R_i^\alpha = 30-100$	
$C_i^{I,\alpha} = 400-800$	$D_j^\beta = 300-1.5K$	$R_i^\beta = 15-100$	
Case B / London – South East			
$I = 5$	$C_j^{E,\beta} = 4K-7.5K$	$D_k^\gamma = 100-200$	$d_{ij}^u = 23- 400$
$J = 6$	$C_j^{I,\beta} = 700-1.2K$	$P_{ij}^u = 0.90-0.98$	$d_{jk}^v = 110 - 162$
$K = 3$	$S_i^\alpha = 1.2K-2.5K$	$P_{jk}^v = 0.85-100$	$W = 100$
$C_i^{E,\alpha} = 4K-8K$	$S_j^\beta = 1K-1.8K$	$R_i^\alpha = 60$	
$C_i^{I,\alpha} = 400-800$	$D_j^\beta = 600-1.5K$	$R_i^\beta = 40$	

In this work, LINGO¹¹ was used for computing results aiming to seek optimization solutions. Table 10 shows outputs of Pareto solutions which were obtained by assigning varying weight values to each objective for case study A and B, respectively. These solutions are associated with allocations of farms, abattoirs and retailers that need to be opened for a specified supply chain network. These results, however, were obtained by assigning seven sets of three varying values in weights to the three objectives.

Table 10. Computational results for cases A and B, respectively

Solution number	Weights of objectives (Z_1, Z_2, Z_3)	Min Z_1 (GBP)	Max Z_2 (Items)	Max Z_3 (GBP)	Farms open	Abattoirs open	Iterations number
Case A							
1	1,0,0	279922	137952	559000	1, 3, 4, 5	1, 3, 4, 5, 6	2543
2	0.9,0.05,0.05	279922	137952	559000	1, 3, 4, 5	1, 3, 4, 5, 6	2611
3	0.8,0.1,0.1	279922	137952	559000	1, 3, 5	1, 3, 4, 5, 6	2344
4	0.7,0.15,0.15	305260	296576	559000	1, 3, 4, 5	1, 2, 3, 5, 6	6911
5	0.6,0.2,0.2	308076	307475	559000	2, 3, 4, 5	2, 3, 5, 6	1712
6	0.5,0.25,0.25	494596	309232	679960	2, 3, 4, 5	2, 3, 5, 6	136
7	0.4,0.3,0.3	459858	311230	690260	1, 2, 4, 5	1, 2, 3, 4, 5	130
Case B							
1	1,0,0	90480	93151	210000	1, 5	4, 6	819
2	0.9,0.05,0.05	90480	93151	210000	1, 5	4, 6	2459
3	0.8,0.1,0.1	103290	212015	210000	1, 5	5, 6	28223
4	0.7,0.15,0.15	121770	253107	306000	1, 5	5, 6	616
5	0.6,0.2,0.2	127352	109776	272280	1, 4, 5	4, 5	2415
6	0.5,0.25,0.25	128253	4506	252000	1, 4	1	2070
7	0.4,0.3,0.3	383029	74206	436500	1, 2, 3, 5	1, 2, 5, 6	5865

By analyzing the obtained solutions, the objectives (by minimizing the total investment cost, maximizing the Halal meat integrity and maximizing ROI) are conflicting objectives, i.e., maximizing or minimizing one objective value may lead to an increase of undesired values of other one or two objectives. As an example, a maximal integrity number of Halal meat products and a maximal ROI may result in an increase of the undesired value which is total investment cost. A pairwise comparison among the three conflicting objectives for case A is illustrated in Figure 11. The result shown in Figure 11 (a) indicates that decision makers do not need to invest more than 305,076 GBP on the RFID-based monitoring HMSC network as it will only lead to a slight increase the number of Halal meat products. By comparison, the computed result shown in Figure 11 (b) indicates that decision makers need not to invest more than 459,858 GBP to achieve a maximal ROI of 690,260 GBP, i.e., a further increase in the total investment cost from 459,858 GBP to 494,596 GBP will not lead to an increase but a slight decrease of ROI. This result proves that the maximum total investment cost does not necessarily lead to a maximal ROI. The result shown in Figure 11 (c) indicates a maximal number of Halal meat products (311,230 items) that yields a maximal ROI of 690,260 GBP.

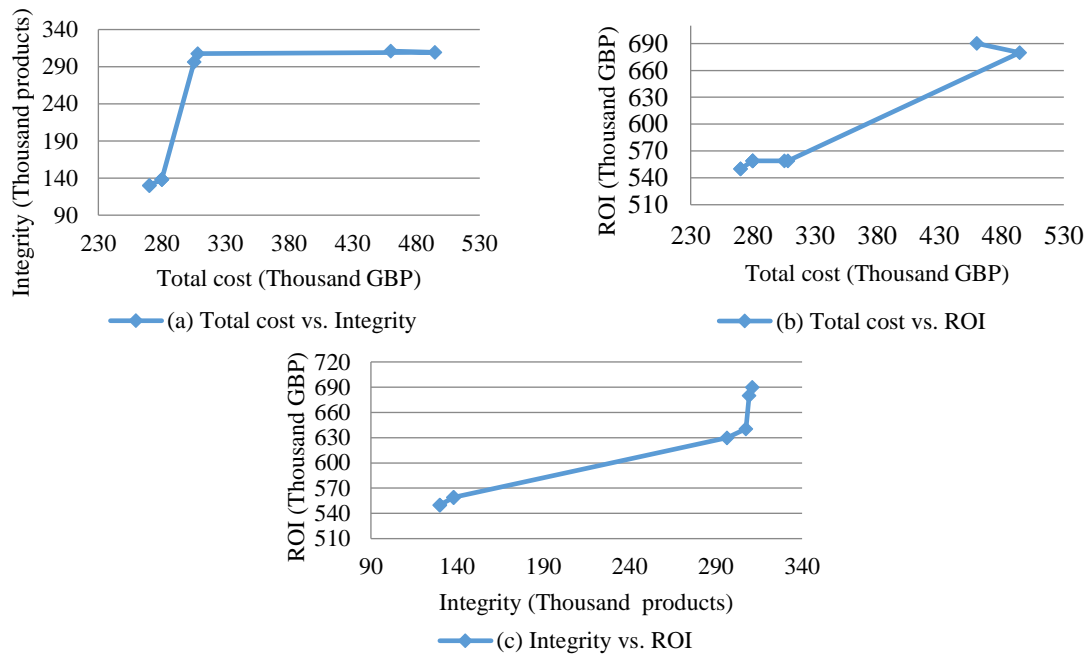


Figure 11. A Pairwise comparison among the three objectives for case A.

In practice, one of these solutions must be selected by preferences of decision makers or using a decision-making algorithm. To this aim, the developed decision making algorithm was utilized. Accordingly, solution three is the best solution for case A and solution two is the best solution for case B. It is noted that solution three for case study A generates a maximal ROI of 559,000 GBP, a maximal integrity number of 137,952 items and a minimal total investment cost of 279,922 GBP; it gives three farms and five abattoirs that need to be opened for the specified HMSC network. The result for solution two for case study B gives a maximal ROI of 210,000 GBP, a maximal integrity number of 93,151 items and a minimal total investment cost of 90,480 GBP, which suggests two farms and two abattoirs that need to be opened for the specified HMSC network.

Finally, Figure 12 shows the selected optimal design of HMSC networks that were obtained by setting up weight values (0.8, 0.1, 0.1) for case study A (solution three in Tables 10) and (0.9, 0.05, 0.05) for case study B (solution two in Tables 10). The geographic configuration shows locations of farms, abattoirs and retailers which need to be established for the proposed RFID-based HMSC network design. For instance, solution three for case study A suggests that the HMSC network needs three farms located in Warwickshire, Leicestershire and Yorkshire, respectively, and five abattoirs located in Birmingham, Balham, West Midland, Warwick and Norfolk, respectively. These abattoirs supply Halal meat products to eleven retailers. Solution two for case study B suggests the HMSC network needs two farms

located in Lancashire and Warwickshire, respectively, and two abattoirs located in Balham and West Midland, respectively. These abattoirs supply Halal meat products to three retailers.

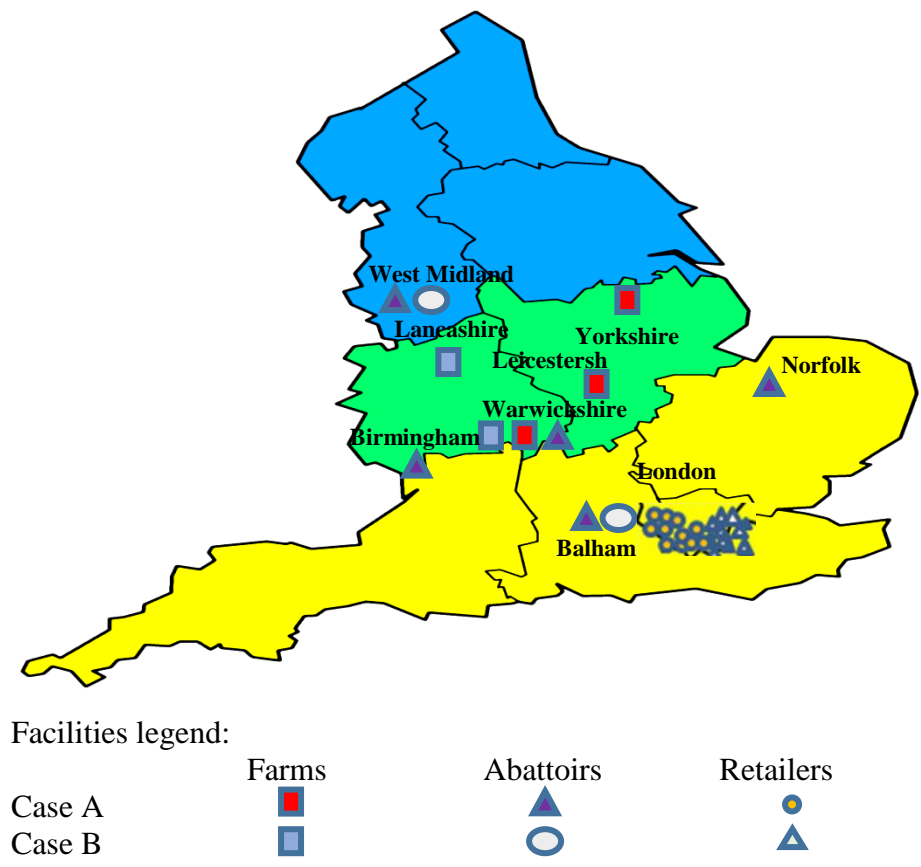


Figure 12. Architecture of the proposed RFID-based monitoring HMSC network.

4.7 Summary

This chapter presents a feasibility study by examining a proposed RFID-based monitoring process that enhances the integrity of HMSCs. Firstly, it defines the Halal meat followed by the requirements for halal meat processing. It shows that traceability of Halal meat integrity is highly recommended from decision makers and customers as a main key factor to advocate integrity of HMSCs. Secondly, it defines the traceability in the context of food supply chain and the technologies used for that purpose. In this line, it identifies the main key factors of traceability that could improve the overall performance of the food supply chain; in contrast, it shows its main application challenges in terms of economic, technological and standardization. Thirdly, it presents the RFID technology including its history, components, communication fields and applications in food supply chain. Lastly, it presents a framework of an RFID-based monitoring system that collects relatively accurate and real-time information data in order to improve traceability of Halal meat products in each process in production and transportation sectors. Retailers and consumers can also check information of Halal meat products in terms of Halal meat integrity online or using mobile phones. A multi-objective mathematical model was developed as an aid for a trade-off decision making process in design of the proposed RFID-enabled HMSC network. Subsequently, a solution methodology was developed including a solution approach to obtain Pareto solutions and a decision-making algorithm to select the best Pareto solution. Based on the computed results, the proposed system is economically feasible as a relatively high profit can be possibly obtained.

A cost-effective decision-making algorithm for an RFID-enabled HMSC network design: A multi-objective approach

5.1 Introduction

Today, a cost-effective design of efficient food supply chain networks is crucial for retailers to maintain a share in the increasingly competitive market. The design of a food supply chain network, however, often involves a trade-off decision making process by minimizing its total cost and transportation time, whilst maintaining quality of food to be delivered to customers. In practice, such a trade-off decision may also vary over time due to the consistent change in conditions of the unpredictable market. Thus, the performance of a supply chain network needs also to be evaluated consistently providing a timely and right decision based on alternative solutions (Shen, 2007; Shankar *et al.*, 2013).

As mentioned previously, safety and quality of food has been the major issue on which consumers require more transparent information relating to food they purchase at supermarkets. Based on the aforementioned argument (refer to section 4.1), for Muslim communities in the UK, integrity of Halal food is essential. Nevertheless, this field is overlooked by researchers, although there were a few studies focusing on various configurations rather than optimizations of HMSC networks (Lodhi, 2009; Zulfakar, 2012).

In this thesis, the author presented a cost-effective design of a three-echelon HMSC network that is monitored by implementing a RFID-based system to improve the integrity traceability of Halal meat products. To help design a cost-effective RFID-based system, first, a deterministic four-objective mixed integer linear programming model was developed and used for investigating the proposed RFID-based HMSC network in terms of (1) number of facilities to open to the HMSC network, (2) locations of facilities, (3) optimal quantity flow of Halal meat product, (4) a comparison in the total investment and operational cost using the RFID-based HMSC and the non-RFID-based HMSC, and (5) a compromised solution based on four conflicting objectives: minimizing the total investment cost of the HMSC network, maximizing the average integrity number of Halal meat products, maximizing the ROI, and maximizing the capacity utilization (%) of facilities (i.e., farms and abattoirs). To obtain non-

inferior solutions based on the developed multi-objective model, two approaches were used. Subsequently one of these optimal solutions can be selected using the Max-Min approach. Second, a stochastic programming model was developed and used for examining the effect on the HMSC network design by altering the integrity percentage of Halal meat products. The study shows that the proposed method can be a useful tool as a decision maker for HMSC supply chains network design.

5.2 The HMSC network model

Figure 13 illustrates a three-echelon HMSC network, which consists of farms, abattoirs and retailers. To ensure the integrity of Halal meat products, an RFID-based monitoring system was proposed to monitor the process in production at farms and abattoirs and distribution through the transportation (Mohammed et al., 2016). In order to help designers, determine a cost-effective HMSC design, a multi-objective mathematical model was developed as an aid for quantifying the investment cost, the ROI, the integrity number of Halal meat products and capacity utilization (%) of the HMSC-related facilities.

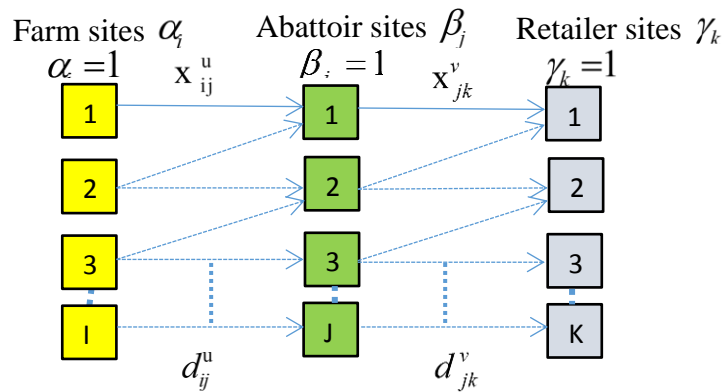


Figure 13. The three-echelon HMSC.

5.2.1 The deterministic model

The following notations were used:

Sets:

- I set of farms $i \in I$
- J set of abattoirs $j \in J$
- K set of retailers $k \in K$

Given parameters:

$C_i^{E,\alpha}$	RFID equipment (E) cost required for farm i
$C_j^{E,\beta}$	RFID equipment (E) cost required for abattoir j
$C_i^{I,\alpha}$	RFID implementation (I) cost required for farm i
$C_j^{I,\beta}$	RFID implementation (I) cost required for abattoir j
C_i^t	RFID tag cost per item at farm i
C_j^t	RFID tag cost per item at abattoir j
$C_{ij}^{T,u}$	unit transportation (T) cost per mile from farm i to abattoir j
$C_{jk}^{T,v}$	unit transportation (T) cost per mile from abattoir j to retailer k
$C_i^{h,\alpha}$	handling cost per item at farms i
$C_j^{h,\beta}$	handling cost per item at abattoir j
d_{ij}^u	travel distance of livestock from farm i to abattoir j
d_{jk}^v	travel distance of Halal meat products from abattoir j to retailer k
W	transportation capacity per vehicle
S_i^α	maximum supply capacity of farm i
S_j^β	maximum supply capacity of abattoir j
D_j^β	minimum demand of abattoir j
D_k^γ	minimum demand of retailer k
P_{ij}^u	integrity percentage of livestock through first transportation link u from farm i to abattoir j
P_{jk}^v	integrity percentage of meat products through second transportation link v from abattoir j to retailer k
R_i^α	return of investment for farm i
R_j^β	return of investment per item for abattoir j

Decision variables:

x_{ij}^u	quantity of units transported through the first transportation link u from farm i to abattoir j
x_{jk}^v	quantity of units transported through second transportation link v from abattoir j to retailer k
y_i^a	$\begin{cases} 1: \text{if farm } i \text{ is open} \\ 0: \text{otherwise} \end{cases}$
y_j^b	$\begin{cases} 1: \text{if abattoir } j \text{ is open} \\ 0: \text{otherwise} \end{cases}$

Thus, the RFID-based HMSC multi-objective model can be formulated as follows:

$$\begin{aligned}
Min \ OF_1 = & \sum_{i \in I} (C_i^{E,\alpha} + C_i^{I,\alpha}) y_i^a + \sum_{j \in J} (C_j^{E,\beta} + C_j^{I,\beta}) y_j^b + \sum_{i \in I} \sum_{j \in J} C_i^t x_{ij}^u \\
& + \sum_{j \in J} \sum_{k \in K} C_j^t x_{jk}^v + \sum_{i \in I} \sum_{j \in J} C_i^{h,\alpha} x_{ij}^u + \sum_{j \in J} \sum_{k \in K} C_j^{h,\beta} x_{jk}^v + \sum_{i \in I} \sum_{j \in J} C_{ij}^{T,u} \left[\frac{x_{ij}^u}{W} \right] d_{ij}^u \\
& + \sum_{j \in J} \sum_{k \in K} C_{jk}^{T,v} \left[\frac{x_{jk}^v}{W} \right] d_{jk}^v - \sum_{i \in I} C_i^{h,\alpha} x_{ij}^u + \sum_{j \in J} C_j^{h,\beta} x_{jk}^v
\end{aligned} \tag{5.1}$$

Where, OF_1 refers to the minimization of the total cost.

$$Max \ OF_2 = \sum_{i \in I} \sum_{j \in J} P_{ij}^u x_{ij}^u + \sum_{j \in J} \sum_{k \in K} P_{jk}^v x_{jk}^v \tag{5.2}$$

Where, OF_2 refers to the maximization of integrity number of Halal meat products.

$$Max \ OF_3 = \sum_{i \in I} \sum_{i \in J} R_i^\alpha x_{ij}^u + \sum_{j \in J} \sum_{k \in K} R_j^\beta x_{jk}^v \tag{5.3}$$

Where, OF_3 refers to the maximization of the ROI.

$$Max \ OF_4 = \sum_{i \in I} \sum_{j \in J} \frac{x_{ij}^u}{S^\alpha} + \sum_{j \in J} \sum_{k \in K} \frac{x_{jk}^v}{S^\beta} \tag{5.4}$$

Where, OF_4 refers to the maximization of capacity utilization (%) of HMSC facilities.

By minimizing objective OF_1 based on the non RFID-based HMSC model, it is given as follows:

$$\begin{aligned}
Min OF_1^{non} = & \sum_{i \in I} \sum_{j \in J} C_{ij}^{T,u} \left[\frac{x_{ij}^u}{W} \right] d_{ij}^u + \sum_{j \in J} \sum_{k \in K} C_{jk}^{T,v} \left[\frac{x_{jk}^v}{W} \right] d_{jk}^v \\
& + \sum_{i \in I} C_i^{h,\alpha} x_{ij}^u + \sum_{j \in I} C_i^{h,\beta} x_{jk}^v
\end{aligned} \tag{5.5}$$

Subject to the following constraints:

$$\sum_{i \in I} x_{ij}^u \leq S_i^\alpha y_i^\alpha \quad \forall j \in J \tag{5.6}$$

$$\sum_{j \in J} x_{jk}^v \leq S_j^\beta y_j^\beta \quad \forall k \in K \tag{5.7}$$

$$\sum_{i \in I} x_{ij}^u \geq D_j^\beta \quad \forall j \in J \tag{5.8}$$

$$\sum_{j \in J} x_{jk}^v \geq D_k^\gamma \quad \forall k \in K \tag{5.9}$$

$$D_j^\beta \geq \sum_{k \in K} x_{jk}^v \quad \forall j \in J \tag{5.10}$$

$$x_{ij}^u, x_{jk}^v \geq 0, \quad \forall i, j, k; \tag{5.11}$$

$$y_i^\alpha, y_j^\beta \in \{0,1\}, \quad \forall i, j; \tag{5.12}$$

For Eq. 5.1, it minimizes the total investment cost of the RFID-based HMSC. The total investment cost includes costs of RFID-related equipment and implementation, and transportation and material handling of Halal meat products. For Eq. 5.2, it maximizes the integrity number of Halal meat products. For equation 5.3, it maximizes the ROI. For Eq. 5.4, it maximizes the capacity utilization (%) of HMSC facilities. For equation 5.5, it determines the minimum total cost for the non-RFID based HMSC; the cost includes the transportation cost and the material handling cost. Eq. 5.6 and Eq. 5.7 are capacity constraints of farms and abattoirs respectively. For Eq. 5.8-5.10, respectively, it ensures that all demands in product quantity are satisfied as requested by abattoirs and retailers. For Eq. 5.11 and 5.12, respectively, it limits the decision variables to be binary and non-negative.

5.2.2 The stochastic model

The stochastic programming model is often used for dealing with uncertain parameters that may affect a scenario of a system or entity (Coello *et al.*, 2007; Birge and Louveaux, 1997; Al-Othman *et al.*, 2008). Considering a decision y , which is influenced by scenario s of

element r , the result of decision y is defined by $z(y, r)$. Assuming a set of scenarios S , i.e., $\{r^s, s = 1, \dots, S\}$ and P_s is the probability of r^s . By minimizing objective OF, it can be described as follows:

$$\text{Min OF} = \sum_{s=1}^S P_s z(y, r^s) \quad (5.13)$$

The following notations are used:

Sets:

Ω set of scenarios $\xi \in \Omega$

Given parameters:

$P_{ij\xi}^u$ integrity percentage of livestock through the first transportation link u from farm i to abattoir j in scenario ξ

$P_{jk\xi}^v$ integrity percentage of meat products through the second transportation link v from abattoir j to retailer k in scenario ξ

Prob_ξ Probability of scenario ξ

Decision variables:

$x_{ij\xi}^u$ quantity of units transported through the first transportation link u from farm i to abattoir j in scenario ξ

$x_{jk\xi}^v$ quantity of units transported through the second transportation link v from abattoir j to retailer k in scenario ξ

$y_{i\xi}^\alpha$ $\left\{ \begin{array}{l} 1: \text{if farm } i \text{ in scenario } \xi \text{ is open} \\ 0: \text{otherwise} \end{array} \right.$

$y_{j\xi}^\beta$ $\left\{ \begin{array}{l} 1: \text{if abattoir } j \text{ in scenario } \xi \text{ is open} \\ 0: \text{otherwise} \end{array} \right.$

By minimizing objective OF₂ based on the stochastic objective function, it is given in the following formula:

$$Max OF_2 = \sum_{\xi \in \Omega} \sum_{i \in I} \sum_{j \in J} P_{ij\xi}^u x_{ij\xi}^u Prob_{\xi} + \sum_{\xi \in \Omega} \sum_{j \in J} \sum_{k \in K} P_{jk\xi}^v x_{jk\xi}^v Prob_{\xi} \quad (5.14)$$

Where, OF₂ refers to the maximization of integrity number of Halal meat products by altering the value of integrity percentage, subject to:

$$\sum_{i \in I} x_{ij\xi}^u \leq S_i^{\alpha} y_{i\xi}^{\alpha} \quad \forall (j \in J; \xi \in \Omega) \quad (5.15)$$

$$\sum_{j \in J} x_{jk\xi}^v \leq S_j^{\beta} y_{j\xi}^{\beta} \quad \forall (k \in K; \xi \in \Omega) \quad (5.16)$$

$$\sum_{i \in I} x_{ij\xi}^u \geq D_j^{\beta} \quad \forall (j \in J; \xi \in \Omega) \quad (5.17)$$

$$\sum_{j \in J} x_{jk\xi}^v \geq D_k^{\gamma} \quad \forall (k \in K; \xi \in \Omega) \quad (5.18)$$

$$D_j^{\beta} \geq \sum_{k \in K} x_{jk\xi}^v \quad \forall (j \in J; \xi \in \Omega) \quad (5.19)$$

$$x_{ij\xi}^u, x_{jk\xi}^v \geq 0, \quad \forall i, j, k, \xi; \quad (5.20)$$

$$y_{i\xi}^{\alpha}, y_{j\xi}^{\beta} \in \{0,1\}, \quad \forall i, j, \xi; \quad (5.21)$$

5.3. Solution approaches

In order to obtain non-inferior solutions based on a multi-objective model, a number of solution approaches were found through a literature review. In this work, the ε -constraint method and the developed approach were utilized as described below:

5.3.1 The ε -constraint approach

Based on this approach (see section 3.1.1.1), by minimizing objective OF, the equivalent objective function can be formulated as follows:

$$\begin{aligned}
\text{Min OF} &= \sum_{i \in I} (C_i^{E,\alpha} + C_i^{I,\alpha}) y_i^\alpha + \sum_{j \in J} (C_j^{E,\beta} + C_j^{I,\beta}) y_j^\beta + \sum_{i \in I} \sum_{j \in J} C_i^t x_{ij}^u \\
&+ \sum_{j \in J} \sum_{k \in K} C_j^t x_{jk}^v + \sum_{i \in I} \sum_{j \in J} C_i^{h,\alpha} x_{ij}^u + \sum_{j \in J} \sum_{k \in K} C_j^{h,\beta} x_{jk}^v + \sum_{i \in I} \sum_{j \in J} C_{ij}^{T,u} \left[\frac{x_{ij}^u}{W} \right] d_{ij}^u \\
&+ \sum_{j \in J} \sum_{k \in K} C_{jk}^{T,v} \left[\frac{x_{jk}^v}{W} \right] d_{jk}^v - \sum_{i \in I} C_i^{h,\alpha} x_{ij}^u + \sum_{j \in I} C_i^{h,\beta} x_{jk}^v
\end{aligned} \tag{5.22}$$

Eq. 5.22 is subject to the following constraints:

$$\left(\sum_{i \in I} \sum_{j \in J} P_{ij}^u x_{ij}^u + \sum_{j \in J} \sum_{k \in K} P_{jk}^v x_{jk}^v \right) \geq \varepsilon_1 \tag{5.23}$$

$$\left(\sum_{i \in I} \sum_{j \in J} P_{ij}^u x_{ij}^u + \sum_{j \in J} \sum_{k \in K} P_{jk}^v x_{jk}^v \right)^{\min} \leq \varepsilon_1 \leq \left(\sum_{i \in I} \sum_{j \in J} P_{ij}^u x_{ij}^u + \sum_{j \in J} \sum_{k \in K} P_{jk}^v x_{jk}^v \right)^{\max} \tag{5.24}$$

$$\left(\sum_{i \in I} \sum_{j \in J} R_i^\alpha x_{ij}^u + \sum_{j \in J} \sum_{k \in K} R_j^\beta x_{jk}^v \right) \geq \varepsilon_2 \tag{5.25}$$

$$\left(\sum_{i \in I} \sum_{j \in J} R_i^\alpha x_{ij}^u + \sum_{j \in J} \sum_{k \in K} R_j^\beta x_{jk}^v \right)^{\min} \leq \varepsilon_2 \leq \left(\sum_{i \in I} \sum_{j \in J} R_i^\alpha x_{ij}^u + \sum_{j \in J} \sum_{k \in K} R_j^\beta x_{jk}^v \right)^{\max} \tag{5.26}$$

$$\left(\sum_{i \in I} \sum_{j \in J} \frac{x_{ij}^u}{S^\alpha} + \sum_{j \in J} \sum_{k \in K} \frac{x_{jk}^v}{S^\beta} \right) \geq \varepsilon_3 \tag{5.27}$$

$$\left(\sum_{i \in I} \sum_{j \in J} \frac{x_{ij}^u}{S^\alpha} + \sum_{j \in J} \sum_{k \in K} \frac{x_{jk}^v}{S^\beta} \right)^{\min} \leq \varepsilon_3 \leq \left(\sum_{i \in I} \sum_{j \in J} \frac{x_{ij}^u}{S^\alpha} + \sum_{j \in J} \sum_{k \in K} \frac{x_{jk}^v}{S^\beta} \right)^{\max} \tag{5.28}$$

Additional constraints include equations 5.6-5.12.

In the above model, the first objective is retained as an objective function in Eq. 5.22, and objective function two, three and four were considered as constraints; i.e. equation 5.23 restricts the value of the second objective function to be greater than or equal to ε_1 that varies between a minimum value and a maximum value for objective two as Eq. 5.24. Equation 5.25 restricts the value of the third objective function to be greater than or equal to ε_2 that varies between a minimum value and a maximum value for objective three in Eq. 5.26. Equation 5.27 restricts the value of the fourth objective function to be greater than or equal to ε_3 that varies between a minimum value and a maximum value for objective four in Eq. 5.28.

5.3.2 The developed approach

With the developed approach previously described (see section 4.4.1) approach, Z can be minimized by the formula as follows:

$$\text{Min } Z = Z_s - Z_d \quad (5.29)$$

Where, Z refers to the solution function. We know:

$$Z_s = \left[(w_1 \mu_1) - (w_2 \mu_2) - (w_3 \mu_3) - (w_4 \mu_4) \right] \quad (5.30)$$

$$\text{s.t. } \begin{cases} \mu_1 = \left[\frac{OF_1 - OF_1^*}{OF_1^*} \right] \\ \mu_2 = \left[\frac{OF_2 - OF_2^*}{OF_2^*} \right] \\ \mu_3 = \left[\frac{OF_3 - OF_3^*}{OF_3^*} \right] \\ \mu_4 = \left[\frac{OF_4 - OF_4^*}{OF_4^*} \right] \\ 0 \geq w_n \geq 1 \quad n = (1, 2, 3, 4) \\ \sum_{n=1}^4 w_n = 1 \end{cases} \quad (5.31)$$

$$\text{Set } w_n^* = \frac{w_n OF_n^*}{OF_n^* - OF_n}, \text{ then}$$

$$\begin{aligned}
Z_d &= w_1^* OF_1 + w_2^* OF_2 + w_3^* OF_3 + w_4^* OF_4 \\
&= \frac{w_1 OF_1^*}{OF_1^* - OF_1} OF_1 + \frac{w_2 OF_2^*}{OF_2^* - OF_2} OF_2 + \frac{w_3 OF_3^*}{OF_3^* - OF_3} OF_3 + \frac{w_4 OF_4^*}{OF_4^* - OF_4} OF_4
\end{aligned} \tag{5.32}$$

Thus, Z can be minimized using the following equation:

$$\begin{aligned}
Min Z &= (w_1 \mu_1 - w_2 \mu_2 - w_3 \mu_3 - w_4 \mu_4) \\
&- \left(\frac{w_1 OF_1^*}{OF_1^* - OF_1} OF_1 + \frac{w_2 OF_2^*}{OF_2^* - OF_2} OF_2 + \frac{w_3 OF_3^*}{OF_3^* - OF_3} OF_3 + \frac{w_4 OF_4^*}{OF_4^* - OF_4} OF_4 \right)
\end{aligned} \tag{5.33}$$

The constraints contain equations 5.6-12 and 5.31.

5.3.3 The Max-Min approach

In this case, the Max-Min approach was applied for selecting a trade-off solution among the non-inferior set of solutions obtained from the objective function OF based on a satisfaction value \mathcal{G}_{OF_x} . For the detail about this approach, it refers to Lai and Hwang (1992) and Basu (2004). The formula of using the Max-Min approach is given below:

$$\begin{aligned}
&Max_x \left\{ \min \left\{ \mathcal{G}_{OF_x} - \mathcal{G}_{OF_x}^{ref} \right\} \right\} \\
&= Max_x \left\{ \min \left\{ \left(\frac{OF_x^{\max} - OF(x)}{OF_x^{\max} - OF_x^{\min}} \right) - \mathcal{G}_{OF_x}^{ref} \right\} \right\}
\end{aligned} \tag{5.34}$$

$$\text{s.t.} \left\{ \mathcal{G}_{OF_x} = \begin{cases} 1 & OF(x) \leq OF_x^{\min} \\ \left(\frac{OF_x^{\max} - OF(x)}{OF_x^{\max} - OF_x^{\min}} \right) & OF_x^{\min} \leq OF(x) \leq OF_x^{\max} \\ 0 & OF(x) \geq OF_x^{\max} \end{cases} \right. \tag{5.35}$$

Where, OF_x^{\max} and OF_x^{\min} are the maximum value and the minimum value of the objective function OF_x , respectively. Within the non-inferior set $\mathcal{G}_{OF_x}^{ref}$ which is a minimal satisfaction value accepted for objective function OF_x . The minimal satisfaction is assigned by decision makers in consonance to their preferences.

5.4 Computational results and analysis

Table 11 shows the collected data over a year period in London-South East area from the UK Halal Meat Committee (HMC, 2014). These data were used for generating the computational results as a case study, which comprises 5 farms, 11 retailers and 6 abattoirs. The travel distances between farms and abattoirs or between abattoirs and retailers were estimated using the Google map. The case study was investigated based on assumptions that (1) there are no restrictions for sharing the HMSC network resources, i.e. any farm can supply the Halal meat products to any abattoir, and any abattoir can supply the Halal meat products to any retailer, and (2) There is a steady demand from retailers.

Table 11. Parameters used for the case study

$I = 5$	$C_j^{E,\beta} = 4K-7.5K$ (GBP)	$D_k^\gamma = 100-500$	$d_{ij}^u = 23- 400$
$J = 6$	$C_j^{I,\beta} = 700-1.2K$ (GBP)	$P_{ij}^u = 0.90-0.95$	$d_{jk}^v = 110 - 162$
$K = 11$	$S_i^\alpha = 2.5K-4.4K$	$P_{jk}^v = 0.91-95$	$W = 100$
$C_i^{E,\alpha} = 4K-8K$ (GBP)	$S_j^\beta = 1.2K-1.8K$	$R_i^\alpha = 60$	$C_i^{h,\alpha} = 4$ (GBP)
$C_i^{I,\alpha} = 400-800$ (GBP)	$D_j^\beta = 800-1.3K$	$R_j^\beta = 40$	$C_j^{h,\alpha} = 4$ (GBP)
$C_i^t = 0.15$ (GBP)	$C_j^t = 0.15$ (GBP)		

In this study, the deterministic model was developed using the LINGO¹¹ software and the stochastic programming model was developed using the Xpress IVE software on a personal laptop Corei5 2.5GHz with a 4GB RAM.

5.4.1 Results of the deterministic model

To obtain the non-inferior solutions, two solution approaches were used as described in section 5.3. Table 12 shows a list of results of twelve non-inferior solutions obtained using the ϵ -constraint approach by altering the incremental epsilon value of 1,124 between 6,771 and 19,137 for objective two, of 67,672 between 397,600 and 1,141,992 for objective three and of 0.025 between 0.65 to 0.95 for objective four, respectively. Table 13 shows the results of eleven non-inferior solutions obtained using the developed approach where each objective was individually optimized as an optimal value of OF_1^* , OF_2^* , OF_3^* , OF_4^* , respectively by altering the scalarization values (w_1, w_2, w_3, w_4) in Eq. 5.33.

Table 12. Non-inferior solutions obtained using the ϵ -constraint approach

#	Assigned \mathcal{E} values			Objective function solutions				Facilities to open	
	\mathcal{E}_1	\mathcal{E}_2	\mathcal{E}_3	Cost (OF_1) (GBP)	Integrity (OF_2) (items)	ROI (OF_3) (GBP)	Capacity (OF_4) (%)	Farms	Abattoirs
1	6771	397600	0.65	131051	6876	397600	0.65	1,5	1,4,5
2	7895	465272	0.69	152574	7937	465280	0.695	1,5	1,4,5
3	9019	532944	0.715	185735	9019	532960	0.72	1,5	1,4,5
4	10143	600616	0.74	217252	10147	607800	0.75	1,4,5	3,4,5
5	11251	668288	0.765	249371	11267	671680	0.77	1,4	1,2,5
6	12391	735960	0.79	294938	12638	735960	0.8	1,4,5	1,2,3,4,5
7	13515	803632	0.815	348498	13868	803640	0.815	1,3,4,5	1,2,4,5
8	14639	871304	0.84	401008	14939	871340	0.85	1,2,4,5	1,2,3,4,5
9	15763	938976	0.865	484449	15989	938980	0.87	1,2,3,4,5	1,2,3,4,5
10	16887	1006648	0.89	563408	17038	1006660	0.905	1,2,3,4,5	1,2,3,4,5
11	18011	1074320	0.915	642321	18087	1074320	0.92	1,2,3,4,5	1,2,3,4,5
12	19135	1141992	0.95	721281	19137	1142000	0.96	1,2,3,4,5	1,2,3,4,5

Table 13. Non-inferior solutions obtained using the developed approach

#	Assigned Weights	Objective function solutions				Facilities to open	
	W_1, W_2, W_3, W_4	Cost (OF_1) (GBP)	Integrity (OF_2) (items)	ROI (OF_3) (GBP)	Capacity (OF_4) (%)	Farms	Abattoirs
1	0.9,0.025,0.025,0.05	131051	6876	397600	0.65	1,2	1,4,5
2	0.8,0.1,0.05,0.05	131051	6876	397600	0.695	1,2	1,4,5
3	0.7,0.1,0.1,0.1	131251	6974	398000	0.72	1,2	1,4,5
4	0.64,0.2,0.13,0.13	219704	8079	433680	0.75	1,2,4,5	1,2,3,4,5
5	0.6,0.13,0.13,0.14	257170	9911	563600	0.77	1,5	1,5
6	0.5,0.25,0.125,0.125	297025	11296	590120	0.8	1,3,4,5	2,3,4,5
7	0.4,0.2,0.2,0.2	645100	14654	845480	0.815	1,2,3,4,5	1,2,3,4,5
8	0.34,0.44,0.11,0.11	681255	14954	895480	0.85	1,2,3,4,5	1,2,3,4,5
9	0.3,0.4,0.15,0.15	701255	15038	990860	0.89	1,2,3,4,5	1,2,3,4,5
10	0.2,0.5,0.15,0.15	-	-	-	-	-	-
11	0.1,0.3,0.3,0.3	-	-	-	-	-	-

It can be seen in Table 13 that there is no feasible solution if the weights for the first objective are assigned less than 0.3. This implies that decision makers may not ignore the importance of this result for the HMSC network design. Also, shown in Table 13, the non-inferior solutions can be obtained by opening the less number of abattoirs, compared to the results shown in Table 12. For instance, the result for solution 5 shown in Table 12, it requires three abattoirs, compared to the result for solution 5 shown in Table 13 that it requires two abattoirs at weights $w_1 = 0.6$, $w_2 = 0.13$, $w_3 = 0.13$ and $w_4 = 0.14$. With this solution, it leads to a maximal ROI of 563,600 GBP, a maximal integrity number of 9,911 items of Halal meat products and a maximal capacity utilization of 77% under the total investment cost of 257,170 GBP. The result shows that the developed approach is more effective than the ϵ -constraint method for gaining a better solution.

Figure 14 explains the computational results of solutions in a relation between the total minimal investment cost and the maximal ROI. These solutions are divided into three bands shown in Figure 14(b) according to the assigned weight values. In band 1, by adjusting the varying weight values in a range at 0.9, 0.025, 0.025, 0.05 and 0.64, 0.12, 0.12, 0.12, respectively; it gives the value of OF_1 moderately increases from 131,051 GBP to 220,000

GBP and the value of OF_3 increases from 397,600 GBP to 433,680 GBP, respectively. This implies that the HMSC may be configured with the lower cost investment. In contrast, by adjusting the weight values in a range at 0.64, 0.12, 0.12, 0.12 and 0.5, 0.25, 0.125, 0.125, respectively; it gives the value of OF_1 a moderate increase from 220,000 GBP to 645,000 GBP and the value of OF_3 increases from 433,680 GBP to 845,480 GBP, respectively; this implies that the HMSC is configured with a compromised solution (e.g., solution 5 in Table 13). Similarly, shown in band 3, the HMSC is configured with the higher ROI. A number of solutions were also identified and these results are placed in the middle of the non-inferior frontier shown in Figure 14(a). For instance, by giving an assigning of $\varepsilon_1 = 11,267$ and $\varepsilon_2 = 668,288$, it yields a total investment cost of 249,938 GBP and a ROI of 735,930 GBP. Figure 14(c) shows comparative results obtained under the same constraints using the ε -constraint and the MWS approaches, respectively. It gives non-linear results of the ROI in response to the total investment cost. Figure 14(c) shows the total investment cost of 131,000 GBP leading to the ROI of 397,600 GBP using both approaches. After this point, the ROI increases over the increase of the total investment cost. Nevertheless, the ROI does not increase significantly if the total investment cost increases up to 220,000 GBP, but it increases sharply after the total investment cost increases more 220,000 GBP using the MWS approach. By comparison, the ROI increases significantly over the increase of the total investment cost using the ε -constraint approach. Overall, the comparative result shows that the developed approach outperforms the ε -constraint approach in providing the better solution result.

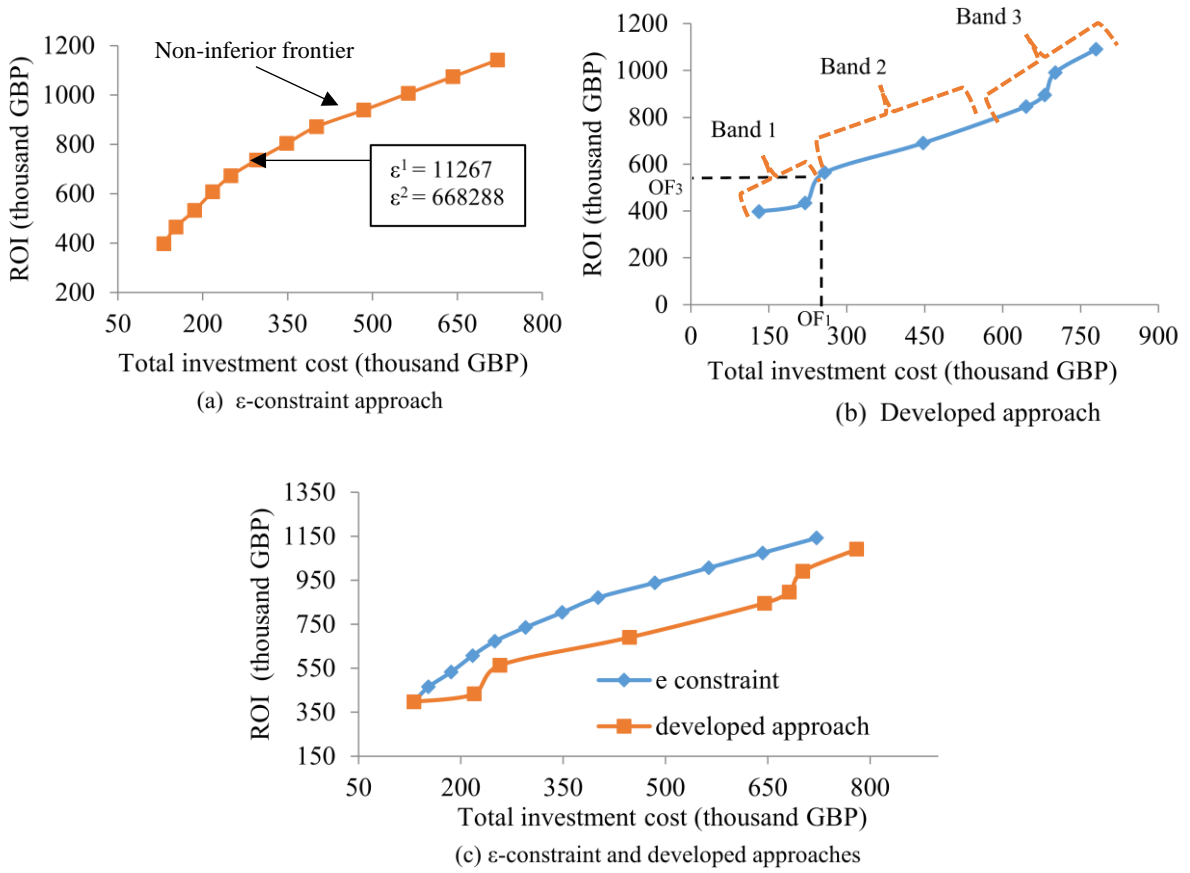


Figure 14. ROI in relation to the total investment cost using (a) the ϵ -constraint approach, (b) the developed approach, (c) the ϵ -constraint and the developed approaches, respectively.

To design the HMSC network, decision makers often need to find a solution based on a number of alternative possibilities using a decision-making approach. To this aim, the Max-Min approach was applied. Based on this approach, solution 1 (shown in Table 13) is determined as the best solution, where $g_{OF_1}^{ref} = 0.5$, $g_{OF_2}^{ref} = 0.5$, $g_{OF_3}^{ref} = 0$, and $g_{OF_4}^{ref} = 0$, i.e. in this case the decision maker seeks a compromised solution based on a cost/integrity-oriented HMSC network design. Figure 15 demonstrates an example of the established HMSC network design based on solution 1 which was obtained with $w_1 = 0.9$, $w_2 = 0.025$, $w_3 = 0.025$, and $w_4 = 0.05$. This network design includes an establishment of two farms which are located in Warwickshire and Leicestershire and three abattoirs which are located in Warwick, Birmingham and Norfolk, respectively. Figure 15 also illustrates the optimal quantity flow of Halal meat products from farms to abattoirs and from abattoirs to retailers. It shows that farm 1 is requested to supply 1000 livestock to abattoir 5 which supplies 500 Halal meat products to retailer 7; 188 Halal meat products to retailer 8; 100 Halal meat products to retailer 9; and 10 Halal meat products to retailer 10, respectively.

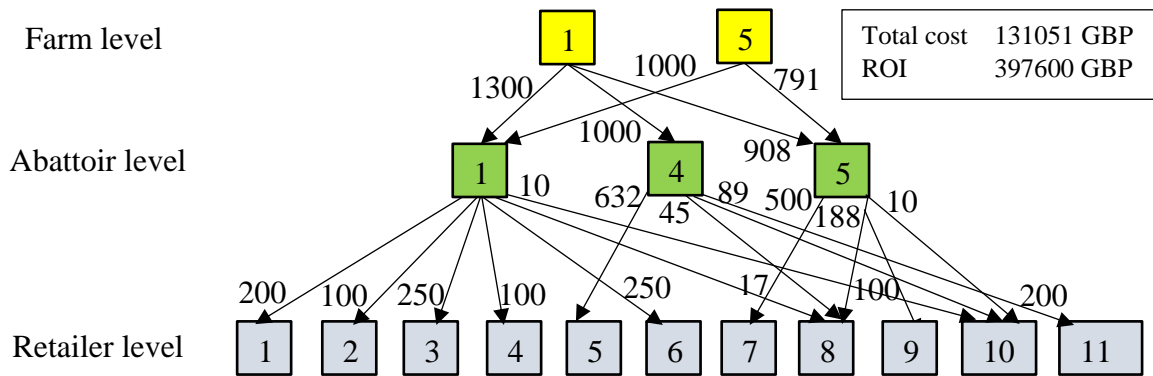


Figure 15. An optimal HMSC network design.

5.4.2 Results of the stochastic model

Table 14 shows a sample of varying integrity percentages and probability in response to each of integrity percentage by assigning a value from low to high levels associated with five farms based on 243 scenarios (3^5) as a case study.

Table 14. Integrity percentage and probability in integrity percentage for farm 1-5 in varying scenarios

Farm	$P_{ij}^H(\%)$			$Pro_{ij}^H(\%)$		
	Low	Mid	High	Low	Mid	High
1	85	92	95	0.25	0.50	0.25
2	90	93	99	0.25	0.50	0.25
3	88	95	98	0.25	0.50	0.25
4	86	90	96	0.30	0.40	0.30
5	90	93	98	0.30	0.40	0.30

Table 15 shows the results of a set of non-inferior solutions based on the stochastic model using the ϵ -constraint approach. It shows that solution one has a maximal ROI of 397,611 GBP, a maximal integrity number of 7,634 Halal meat products, a maximal capacity utilization of 65% and a minimal total investment cost of 147,094 GBP; it gives two farms and three abattoirs that need to be opened for the specified HMSC network.

Table 15. Results of a set of non-inferior solutions of the stochastic model

#	Assigned ϵ values			Values of objective function				Facilities open	
	ϵ_1	ϵ_2	ϵ_3	Cost (OF_1) (GBP)	Integrity (OF_2) (items)	ROI (OF_3) (GBP)	Capacity (OF_4) (%)	Farm	Abattoir
1	6771	397600	0.65	147094	7634	397611	0.65	1,5	1,4,5
2	7895	465272	0.69	178104	8682	465291	0.7	1,4,5	1,4,5
3	9019	532944	0.715	206143	9717	532971	0.71	1,4,5	1,4,5
4	10143	600616	0.74	236143	10750	600651	0.755	1,4,5	1,4,5
5	11251	668288	0.765	293004	11791	668315	0.775	1,3,4,5	1,4,5
6	12391	735960	0.79	356042	12914	735961	0.855	1,2,3,4,5	1,4,5
7	13515	803632	0.815	356042	12914	735961	0.815	1,3,4,5	1,3,5
8	14639	871304	0.84	513414	15057	871332	0.9	1,2,3,4,5	1,3,4
9	15763	938976	0.865	596544	15882	938983	0.95	1,2,3,4,5	1,2,3

Figure 16 shows the values of objective function seeking for maximization of the integrity number of Halal meat products based on solution 5 which has the twelve selected scenarios. As shown in Figure 16, in scenario 12, it yields the highest value of $OF_2 = 12,698$ Halal meat products. By contrast, in scenario 1, it yields the lowest value of $OF_2 = 10,984$ Halal meat products. It is noted in Figure 16 that by altering the integrity percentage of Halal meat products, the capacity utilization (%) varies. As an example, with a decrease of the average integrity percentage by 5% in scenario 1, the integrity number of Halal meat products decreases by 3.3% only. In scenario 12, with an increase of the average integrity percentage to 5%, it leads to 2.2% increase in the integrity number of Halal meat products. This is because the result was obtained by optimizing four conflicting objectives at a time as a compromised solution.

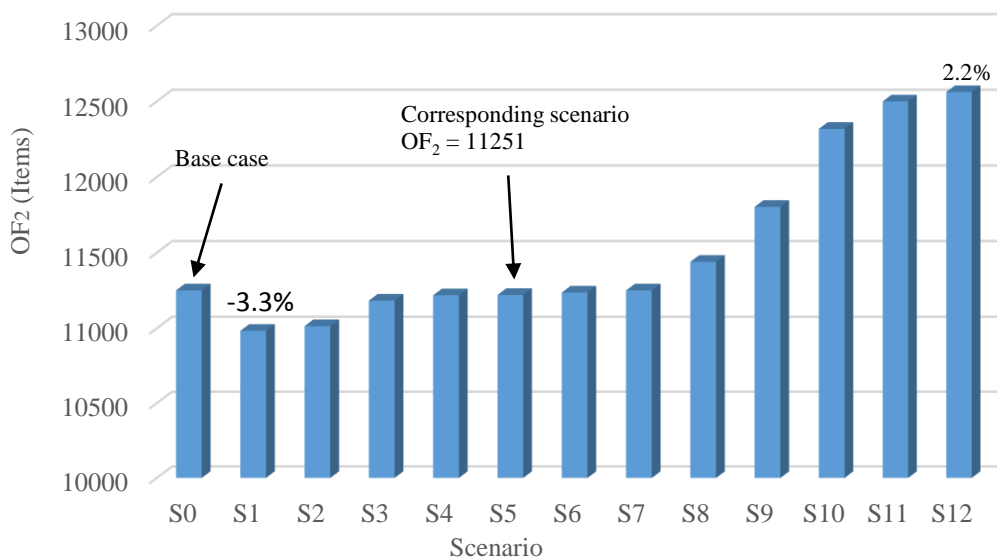


Figure 16. The value of OF_2 in response to each of the selected integrity scenarios.

5.4.3 The HMSC network design with and without the RFID implementation: a comparison

Figure 17 shows the comparative result of the total investment cost of the HMSC network with or without the RFID implementation based on the eight non-inferior solutions obtained from the RFID-based HMSC multi-objective model and the non-RFID-based HMSC model. It can be seen in Figure 17 that it leads to a decrease in the total investment cost of an average 50,552 GBP after a year period of the RFID implementation into the HMSC network, compared to the same HMSC network without the RFID implementation. As shown in Figure 17, for solution 1, it yields a total investment cost of 158,555 GBP of the non-RFID-based HMSC network compared to a total investment cost of 131,051 GBP of the RFID-based HMSC network. For solution 5, it yields an average decrease in difference in the total investment cost of 45,068 GBP after the RFID implementation. The result shows that the RFID implementation for the HMSC network is economically feasible.

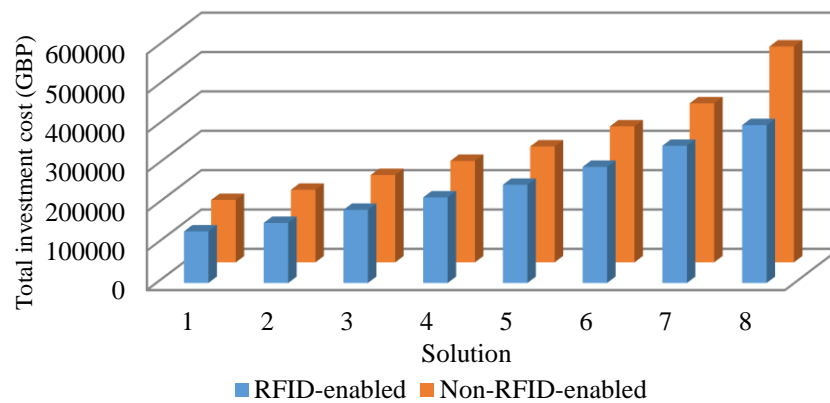


Figure 17. Comparative results of the total investment cost between the non-RFID-based HMSC and the RFID-based HMSC.

5.5 Conclusions

In this study, a deterministic model using the multi-objective approach was developed and used for examining the economic feasibility of a proposed RFID-based HMSC network with respect to minimizing the total investment cost, maximizing the average integrity of Halal meat products, the ROI and the capacity utilization of farms and abattoirs. Furthermore, a stochastic programming model was also developed for investigating the effect of varying integrity percentage that affects the number of Halal meat products of the HMSC network. Two solution approaches, which are the ϵ -constraint method and the developed method, were applied and two sets of non-inferior solutions were generated and compared based on the developed multi-objective model. The Max-Min approach was proposed to select the best non-inferior solution. A case study was used for demonstrating the applicability of the developed models and a comparison of computational results based on the deterministic model and the stochastic model are presented in the chapter. The conclusion shows that the proposed RFID-based HMSC is economically feasible and it leads to a decrease in the total investment cost of an average 50,552 GBP after a year period. The developed models can also be useful for determining a cost-effective design of a HMSC network.

Developing a meat supply chain network design using a multi-objective possibilistic programming approach

6.1 Introduction

A network of food supply chains covers a number of sectors involved in production, distribution and consumption of food products. For delivering a high quality of food products with minimum costs and maximum profits, different tactics can be employed (Simchi et al., 2001 and Shankar et al., 2013); of which supply chains network design plays a key role on product quality, service levels, material flow, customer satisfaction and profitable return (Meier et al., 2012). Nevertheless, supply chain designers often encounter difficulties in making a trade-off solution due to optimization of conflicting objectives such as minimization of costs, and maximization of profits and service levels. A good plan can also help deliver products timely from manufacturers to retailers through a supply chain network. This process involves a determination of allocations and locations of facilities, material handling capacity, transportation capability, delivery time and other performance measures.

This study presents a study in developing a multi-objective possibilistic model of a meat supply chain with an aim to minimizing the total transportation cost, the number of transportation vehicles and the delivery time of meat products from farms to abattoirs and from abattoirs to retailers. The research outcome shows that the developed model can reveal Pareto solutions towards the optimization of three objectives. For this, it can be used as an aided tool to achieve a compromised solution for supply chain designers when developing a similar supply chain network in its optimal objectives.

6.2 Model description and formulation

Figure 18 illustrates a three-echelon meat supply chain network consisting of farms, abattoirs and retailers. A RFID-based transportation system was proposed for monitoring safety and quality of meat products during the transportation process from farms to abattoirs and from abattoirs to retailers (Mohammed et al., 2016). RFID-based logistics and supply chains are a

trend for future generation automated warehouses where customers place their orders on line and ordered goods are delivered directly to door steps of these customers (Wang et al., 2010). In this study, the key components of the RFID-based transportation monitoring system include an RFID reader, a GPS transmitter and a GPRS transmitter, which are attached to a lorry container. In order to minimize (1) the total transportation cost (2) the number of required vehicles for transportation (3) the delivery time. A three-objective mathematical model was developed and used for making a design decision; this also includes a determination of numbers of farms and abattoirs in response to flow of quantity of meat products between farms and abattoirs and between abattoirs and retailers.

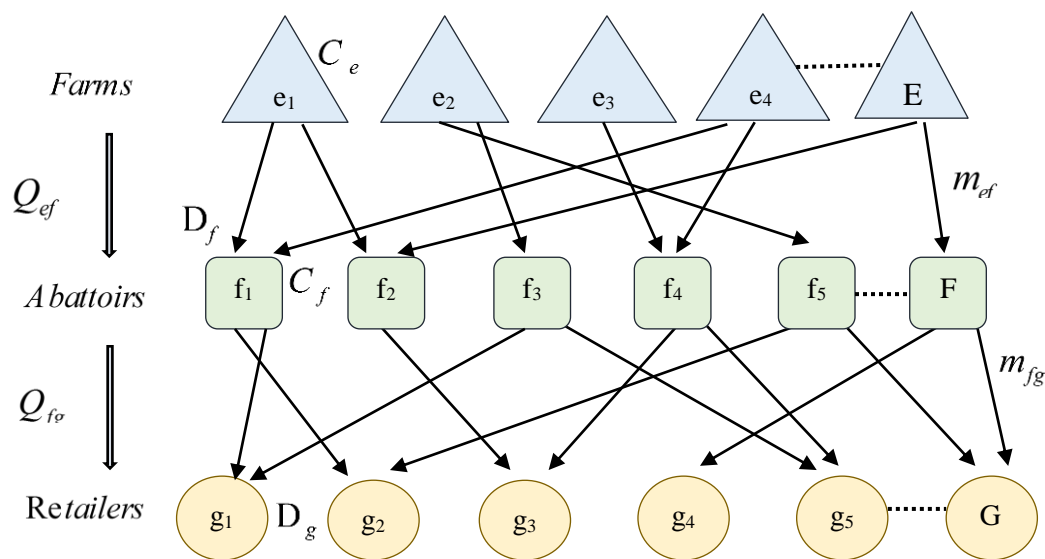


Figure 18. The three-echelon meat supply chain network.

Notations and decision variables are described as follows:

sets

E set of farms (1... e ... E)

F set abattoirs (1... f ... F)

G set retailers (1... g ... G)

Parameters

C_{ef}^t RFID tag cost (GBP) per item transported from farm e to abattoir f

C_{fg}^t RFID tag cost (GBP) per item transported from abattoir f to retailer g

$C_{ef}^{m/l}$ RFID reader cost (GBP) required per lorry l travelling from farm e to abattoir f

$C_{fg}^{m/l}$ RFID reader cost (GBP) required per lorry l travelling from abattoir f to retailer g

TC_{ef} unit transportation cost (GBP) per mile from farm e to abattoir f

TC_{fg} unit transportation cost (GBP) per mile from abattoir f to retailer g

d_{ef} transportation distance (miles) of livestock from farm e to abattoir f

d_{fg} transportation distance (miles) of processed meats from abattoir f to retailer g

C_l transportation capacity (units) per lorry l

S^l speed (m/h) of lorry l

C_e maximum supply capacity (units) of farm e

C_f maximum supply capacity (units) of abattoir f

D_f minimum demand (in units) of abattoir f

D_g minimum demand (in units) of retailer g

Decision variables

m_{ef} quantity of livestock transported from farm e to abattoir f

m_{fg} quantity of processed meats transported from abattoir f to retailer g

Q_{ef} number of expected required vehicles to transport livestock from farm e to abattoir f

Q_{fg} number of expected required vehicles to transport processed meats from abattoir f to retailer g

Binary decision variables

$u_e = \begin{cases} 1: & \text{if farm } e \text{ is open} \\ 0: & \text{otherwise} \end{cases}$

$$v_f = \begin{cases} 1: & \text{if abattoir } f \text{ is open} \\ 0: & \text{otherwise} \end{cases}$$

The aim of the developed three-objective model of the meat supply chain network is to minimize the total transportation cost O_1 , which includes (a) unit transportation cost per mile (b) RFID tag cost per unit and (c) RFID reader per vehicle, is given in Eq. 6.1.

$$\begin{aligned} \text{Min } O_1 = & \sum_{e \in E} \sum_{f \in F} TC_{ef} m_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} m_{fg} + \sum_{e \in E} \sum_{f \in F} C_{ef}^t m_{ef} + \sum_{f \in F} \sum_{g \in G} C_{fg}^t m_{fg} \\ & + \sum_{e \in E} \sum_{f \in F} C_{ef}^{m/l} Q_{ef} + \sum_{f \in F} \sum_{g \in G} C_{fg}^{m/l} Q_{fg} \end{aligned} \quad (6.1)$$

By minimizing the number of required transportation vehicles O_2 , it is given in Eq. 6.2.

$$\text{Min } O_2 = \sum_{e \in E} \sum_{f \in F} TC_{ef} Q_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} Q_{fg} \quad (6.2)$$

By minimizing the delivery time O_3 , it is given in Eq. 6.3.

$$\text{Min } O_3 = \sum_{e \in E} \sum_{f \in F} \frac{d_{ef}}{S^l} m_{ef} + \sum_{f \in F} \sum_{g \in G} \frac{d_{fg}}{S^l} m_{fg} \quad (6.3)$$

Subject to:

$$\sum_{e \in E} m_{ef} \leq C_e u_e \quad \forall f \in F \quad (6.4)$$

$$\sum_{f \in F} m_{fg} \leq C_f v_f \quad \forall g \in G \quad (6.5)$$

$$\sum_{e \in E} m_{ef} \geq D_f \quad \forall f \in F \quad (6.6)$$

$$\sum_{f \in F} m_{fg} \geq D_g \quad \forall g \in G \quad (6.7)$$

$$D_f \geq \sum_{g \in G} m_{fg} \quad \forall f \in F \quad (6.8)$$

$$\sum_{e \in E} Q_{ef} = m_{ef} / C_1 \quad \forall f \in F \quad (6.9)$$

$$\sum_{f \in F} Q_{fg} = m_{fg} / C_1 \quad \forall g \in G \quad (6.10)$$

$$Q_{ef}, Q_{fg} \text{ integer} \quad (6.11)$$

$$m_{ef}, m_{fg} \geq 0 \quad \forall e, f \quad (6.12)$$

$$u_e, v_f \in \{1, 0\}, \quad \forall e, f \quad (6.13)$$

Eq. 6.4-6.5 are the constraints of capacity at farms and abattoirs in which Eq. 6.4 ensures the number of livestock transported from farms to abattoirs do not exceed the supply capacity of farms; also, Eq. 6.5 ensures the number of meat products transported from abattoirs to retailers do not exceed the supply capacity of abattoirs. Eq. 6.6-6.8 ensure that all the demands of abattoirs and retailers must be satisfied. Eq. 6.9-6.10 give the estimated number of vehicles for objective function two. Eq. 6.11-6.13 prohibit decision variables used from the non-binary and non-negativity.

The possibilistic programming is a mathematical optimization approach that can be used for tackling optimization problems under uncertainty when parameters are not clearly defined (i.e., fuzzy parameters), or an exact value is not critical to the problem. Thus, the multi-objective model as described above was transformed further into an equivalent crisp model using the possibilistic programming proposed by Jiménez et al. 2007 as follows:

To minimize the total transportation cost O_1 , it is given:

$$\begin{aligned} \text{Min } O_1 = & \sum_{e \in E} \sum_{f \in F} TC_{ef} m_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} m_{fg} + \sum_{e \in E} \sum_{f \in F} C_{ef}^t u_e + \sum_{f \in F} \sum_{g \in G} C_{fg}^t v_f \\ & + \sum_{e \in E} \sum_{f \in F} C_{ef}^m Q_{ef} + \sum_{f \in F} \sum_{g \in G} C_{fg}^m Q_{fg} \end{aligned} \quad (6.14)$$

To minimize the number of transportation vehicles O_2 , it is given:

$$\text{Min } O_2 = \sum_{e \in E} \sum_{f \in F} \left(\frac{Q_{ef1} + Q_{ef2} + Q_{ef3} + Q_{ef4}}{4} \cdot TC_{ef} \right) + \sum_{f \in F} \sum_{g \in G} \left(\frac{Q_{fg1} + Q_{fg2} + Q_{fg3} + Q_{fg4}}{4} \cdot TC_{fg} \right) \quad (6.15)$$

To minimize the delivery time O_3 , it is given: (6.16)

$$\text{Min } O_3 = \sum_{e \in E} \sum_{f \in F} tt_{ef}^l m_{ef} + \sum_{f \in F} \sum_{g \in G} tt_{fg}^l m_{fg}$$

Subject to:

$$\sum_{e \in E} m_{ef} \leq C_e u_e, \quad \forall f \in F \quad (6.17)$$

$$\sum_{f \in F} m_{ef} \leq C_f v_f, \quad \forall g \in G \quad (6.18)$$

$$\sum_{e \in E} \frac{d_{ef}}{S^l} \quad \forall f \in F \quad (6.19)$$

$$\sum_{f \in F} \frac{d_{fg}}{S^l} \quad \forall g \in G \quad (6.20)$$

$$\sum_{e \in E} m_{ef} \geq \left[\frac{\alpha}{2} \cdot \frac{D_{f1} + D_{f2}}{2} + \left(1 - \frac{\alpha}{2}\right) \frac{D_{f3} + D_{f4}}{2} \right], \quad \forall f \in F \quad (6.21)$$

$$\sum_{f \in F} m_{fg} \geq \left[\frac{\alpha}{2} \cdot \frac{D_{g1} + D_{g2}}{2} + \left(1 - \frac{\alpha}{2}\right) \frac{D_{g3} + D_{g4}}{2} \right], \quad \forall g \in G \quad (6.22)$$

$$\left[\frac{\alpha}{2} \cdot \frac{D_{f1} + D_{f2}}{2} + \left(1 - \frac{\alpha}{2}\right) \frac{D_{f3} + D_{f4}}{2} \right] \geq \sum_{g \in G} m_{fg}, \quad \forall f \in F \quad (6.23)$$

$$\sum_{e \in E} \left[\frac{\alpha}{2} \cdot \frac{Q_{ef1} + Q_{ef2}}{2} + \left(1 - \frac{\alpha}{2}\right) \frac{Q_{ef3} + Q_{ef4}}{2} \right] = m_{ef} / C_l, \quad \forall f \in F \quad (6.24)$$

$$\sum_{f \in F} \left[\frac{\alpha}{2} \cdot \frac{Q_{fg1} + Q_{fg2}}{2} + \left(1 - \frac{\alpha}{2}\right) \frac{Q_{fg3} + Q_{fg4}}{2} \right] = m_{fg} / C, \quad \forall k \in K \quad (6.25)$$

$$Q_{ef}, Q_{fg} \text{ integer} \quad (6.26)$$

$$m_{ef}, m_{fg} \geq 0 \quad \forall e, f \quad (6.27)$$

$$u_e, v_f, \alpha \in \{1, 0\}, \quad \forall e, f \quad (6.28)$$

Knowing that constraints with uncertain parameters must be formed at least with a satisfaction level of α .

6.3 Optimization methodology

In order to obtain the Pareto-optimal solutions, the following steps were carried out:

- (1) Find the upper and lower bound (U, L) solution for each objective function. This can be obtained by:

The upper bound solution is:

$$Max O_1(U_1) = \sum_{e \in E} \sum_{f \in F} TC_{ef} m_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} m_{fg} + \sum_{e \in E} \sum_{f \in F} C_{ef}^t u_e \quad (6.29)$$

$$+ \sum_{f \in F} \sum_{g \in G} C_{fg}^t v_f + \sum_{e \in E} \sum_{f \in F} C_{ef}^m Q_{ef} + \sum_{f \in F} \sum_{g \in G} C_{fg}^m Q_{fg}$$

$$Max O_2(U_2) = \sum_{e \in E} \sum_{f \in F} TC_{ef} Q_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} Q_{fg} \quad (6.30)$$

$$Max O_3(U_3) = \sum_{e \in E} \sum_{f \in F} tt_{ef}^l m_{ef} + \sum_{f \in F} \sum_{g \in G} tt_{fg}^l m_{fg} \quad (6.31)$$

The lower bound solution is:

$$Min O_1(L_1) = \sum_{e \in E} \sum_{f \in F} TC_{ef} m_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} m_{fg} + \sum_{e \in E} \sum_{f \in F} C_{ef}^t u_e \quad (6.32)$$

$$+ \sum_{f \in F} \sum_{g \in G} C_{fg}^t v_f + \sum_{e \in E} \sum_{f \in F} C_{ef}^m Q_{ef} + \sum_{f \in F} \sum_{g \in G} C_{fg}^m Q_{fg}$$

$$Min O_2(L_2) = \sum_{e \in E} \sum_{f \in F} TC_{ef} Q_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} Q_{fg} \quad (6.33)$$

$$Min O_3 = \sum_{e \in E} \sum_{f \in F} tt_{ef}^l m_{ef} + \sum_{f \in F} \sum_{g \in G} tt_{fg}^l m_{fg} \quad (6.34)$$

- (2) Find the respective satisfaction degree $\mu(x_i)$ for each objective function, this can be obtained by:

$$\mu_1(O_1(x)) = \begin{cases} 1 & \text{if } O_1(x) \geq U_1 \\ \frac{O_1(x) - L_1}{U_1 - L_1} & \text{if } L_1 \leq O_1(x) \leq U_1 \\ 0 & \text{if } O_1(x) \leq L_1 \end{cases} \quad (6.35)$$

$$\mu_2(O_2(x)) = \begin{cases} 1 & \text{if } O_2(x) \geq U_2 \\ \frac{O_2(x) - L_2}{U_2 - L_2} & \text{if } L_2 \leq O_2(x) \leq U_2 \\ 0 & \text{if } O_2(x) \leq L_2 \end{cases} \quad (6.36)$$

$$\mu_3(O_3(x)) = \begin{cases} 1 & \text{if } O_3(x) \geq U_3 \\ \frac{O_3(x) - L_3}{U_3 - L_3} & \text{if } L_3 \leq O_3(x) \leq U_3 \\ 0 & \text{if } O_3(x) \leq L_3 \end{cases} \quad (6.37)$$

- (3) Transform the crisp model obtained from section 6.2.2 to a single objective function using the three proposed solution methods in Eq. 6.38, 6.40 and 6.45.
- (4) Select the best Pareto-optimal solution from the three Pareto sets using the Technique For Order Preference By Similarity To Ideal Solution (TOPSIS) method.

6.3.1 Solution method

In this work, three sets of Pareto-optimal solutions were obtained using the three solution methods, which are the LP-metrics method, the ϵ -constraint method and the weighted Tchebycheff method.

6.3.1.1 The LP-metrics method

The LP-metrics method is described as follows:

1. Based on the developed multi-objective model, each of the three objectives is optimized individually to obtain the optimal objective values O_1^* , O_2^* and O_3^* , respectively.
2. Convert the three-objective model into a modular-objective function using the following function.

$$\text{Min } O = \left[w_1 \frac{O_1 - O_1^*}{O_1^*} + w_2 \frac{O_2 - O_2^*}{O_2^*} + w_3 \frac{O_3 - O_3^*}{O_3^*} \right] \quad (6.38)$$

Subject to Eq. 17-28.

3. Determine the importance of objectives based on decision makers' preferences and the weight formula for the three objective functions is given as follows:

$$\sum_{x=1}^3 w_x, \quad w_x \geq 0 \quad (x = 1, 2, 3) \quad (6.39)$$

6.3.1.2 The ε -constraint method

With this approach (see section 3.1.1.1), the equivalent solution formula O can be minimized as follow:

$$\begin{aligned} \text{Min } O = & \sum_{e \in E} \sum_{f \in F} TC_{ef} m_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} m_{fg} + \sum_{e \in E} \sum_{f \in F} C_{ef}^t u_e + \sum_{f \in F} \sum_{g \in G} C_{fg}^t v_f \\ & + \sum_{e \in E} \sum_{f \in F} C_{ef}^m Q_{ef} + \sum_{f \in F} \sum_{g \in G} C_{fg}^m Q_{fg} \end{aligned} \quad (6.40)$$

Subject to:

$$\sum_{e \in E} \sum_{f \in F} \left(\frac{Q_{ef1} + Q_{ef2} + Q_{ef3} + Q_{ef4}}{4} \cdot TC_{ef} \right) + \sum_{f \in F} \sum_{g \in G} \left(\frac{Q_{fg1} + Q_{fg2} + Q_{fg3} + Q_{fg4}}{4} \cdot TC_{fg} \right) \leq \varepsilon_1 \quad (6.41)$$

$$\left[\sum_{e \in E} \sum_{f \in F} \left(\frac{Q_{ef1} + Q_{ef2} + Q_{ef3} + Q_{ef4}}{4} \cdot TC_{ef} \right) + \sum_{f \in F} \sum_{g \in G} \left(\frac{Q_{fg1} + Q_{fg2} + Q_{fg3} + Q_{fg4}}{4} \cdot TC_{fg} \right) \right]^{\min} \leq \varepsilon_1 \leq \left[\sum_{e \in E} \sum_{f \in F} \left(\frac{Q_{ef1} + Q_{ef2} + Q_{ef3} + Q_{ef4}}{4} \cdot TC_{ef} \right) + \sum_{f \in F} \sum_{g \in G} \left(\frac{Q_{fg1} + Q_{fg2} + Q_{fg3} + Q_{fg4}}{4} \cdot TC_{fg} \right) \right]^{\max} \quad (6.42)$$

$$\sum_{e \in E} \sum_{f \in F} tt_{ef}^l m_{ef} + \sum_{f \in F} \sum_{g \in G} tt_{fg}^l m_{fg} \leq \varepsilon_2 \quad (6.43)$$

$$\left[\sum_{e \in E} \sum_{f \in F} tt_{ef}^l m_{ef} + \sum_{f \in F} \sum_{g \in G} tt_{fg}^l m_{fg} \right]^{\min} \leq \varepsilon_2 \leq \left[\sum_{e \in E} \sum_{f \in F} tt_{ef}^l m_{ef} + \sum_{f \in F} \sum_{g \in G} tt_{fg}^l m_{fg} \right]^{\max} \quad (6.44)$$

And Eq. 6.17-6.28.

In this research, objective one is optimized in Eq. 6.41 and objective two and three are constraints in Eq. 6.42 and 6.44 respectively. An increase to the ε value in Eq. 6.43 and 6.45 yields a Pareto set of solutions.

6.3.1.3 The weighted Tchebycheff method

With this approach (see 3.1.1.4), the solution approach function O can be formulated as follows:

$$\text{Min } O = \left(\sum_{i=1}^3 l_i |O_i - O_i^*|^p \right)^{\frac{1}{p}} \quad (6.45)$$

Subject to Eq. 6.17-6.28. It is noticed, 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 was set as 1.

6.3.1.4 The TOPSIS method

After revealing the Pareto solutions using solution approaches, a final trade-off solution needs to be determined. At present, a number of approaches can be utilized to determine the best solution based on the obtained Pareto solutions. This can be achieved based on preferences of decision makers, using a decision maker or an optimization algorithm. In this work, the TOPSIS method was employed to support decision makers in selecting the final Pareto solution from a set of Pareto solutions derived from the multi-objective model by using solution approaches. This approach is a decision-making approach which can be used for selecting a solution nearest to the ideal solution, but also the farthest from the negative ideal solution (Ramesh et al., 2012). Assuming that $PR = \{PR_{op} | o=1,2,\dots,x \text{ (number of pareto solutions); } p=1,2,\dots,y \text{ (number of objectives)}\}$ refers to the $x * y$ decision matrix, where PR is a performance rating of one of alternative Pareto solutions with respect to values of objective function. Thus, the normalized selection procedure can be formulated as follows:

$$NPR = \frac{PR_{op}}{\sum_{p=1}^o PR_{ap}} \quad (6.46)$$

The amount of decision information can be measured by the entropy value as:

$$E_p = \frac{-1}{\ln x} \sum_{o=1}^x PR_{op} \ln(PR_{op}) \quad (6.47)$$

The degree of divergence D_p of the average intrinsic information contained for $p = 1, 2, 3, 4$ can be calculated as:

$$D_p = 1 - E_p \quad (6.48)$$

The weight value for each objective function is given by:

$$w_p = \frac{D_p}{\sum_{k=1}^y D_k} \quad (6.49)$$

Thus, the normalized value of the weighted objective is given by:

$$v_{op} = w_o PR_{op} \quad (6.50)$$

A distance between alternative solutions can be measured by the n-dimensional Euclidean distance. Thus, the distance of each alternative from the positive and negative ideal solutions is given as:

$$D_p^+ = \sqrt{\left\{ \sum_{o=1}^y (v_{po} - v_o^+)^2 \right\}} \quad , \quad p = 1, 2, \dots, x \quad (6.51)$$

$$D_p^- = \sqrt{\left\{ \sum_{o=1}^y (v_{po} - v_o^-)^2 \right\}} \quad , \quad p = 1, 2, \dots, x \quad (6.52)$$

The relative closeness of (values of) alternative solutions to (the value of) the ideal solution is expressed as follows:

$$rc_p = \frac{D_p^-}{D_p^+ + D_p^-} \quad , \quad p = 1, 2, \dots, x \quad (6.53)$$

Where $D_p^- \geq 0$ and $D_p^+ \geq 0$, then, clearly, $rc_p \in [1, 0]$

The trade-off solution can be selected with the maximum rc_p or listed in descending order based on rc_p .

6.4 Case study

In this section, a case study was used for examining the applicability of the developed mathematical model with the effectiveness of the proposed solution methods. Data was collected from the Meat Committee (HMC, 2010). A range of application data is presented in Table 16. The transportation distances between meat supply chain facilities were estimated based on Google-map. The computational results were conducted using LINGO¹¹ on a Corei5 2.5-gigahertz personal laptop with an RAM of 4gigabytes.

Table 16. Collected data of the three-echelon meat supply chain

$E = 4$	$TC_{fg} = 15-20$	$D_f = 600-1.5K$	$C_{ef}^t = 0.15$
$F = 4$	$C_e = 1.2K-2.5K$	$D_g = 100-200$	$C_{fg}^t = 0.15$
$G = 11$	$C_f = 1K-1.8K$	$P_e = 0.90-0.98$	$C_{ef}^{m/l} = 800$
$TC_{ef} = 15-20$	$C_l = 20-30$	$P_f = 0.85-1$	$C_{fg}^{m/l} = 800$
$d_{ef} = 23-410$	$d_{fg} = 110-174$	$S^l = 80$	

Figure 19 illustrates the locations of candidate facility in the considered region (Yorkshire/UK) which includes four farms, four abattoirs and eleven retailers.



Figure 19. Locations of candidate facilities in Yorkshire of the UK.

6.4.1 Results and discussions

The computational results were obtained based on the developed three-objective programming model using the three solution methods as described in section 6.3. Eq. 6.29-6.34 were used individually to obtain the lower value and the upper value of each objective function. The results are $(\{L_o, U_o\}) = (\{55,430, 283,260\}, \{26, 52\}, \{56, 260\})$. Table 17 shows an example of the ideal values (bold values) obtained individually of each objective function. It shows the lower value and the upper value obtained based on each objective function in Eq. 6.29-6.34 individually.

Table 17. Optimum values obtained individually by optimizing O_i based on each objective function

Objective functions	$\min O_1$	$\min O_2$	$\min O_3$
OF_1	55430	269360	187673
OF_2	34	26	52
OF_3	165	256	56

The Pareto solutions are determined based on (i) the LP-metrics method; (ii) the ε -constraint method. Ten epsilon values were assigned from 26 to 52 of the objective function two using Eq. 6.41, and from 56 to 260 of the objective function three using Eq. 6.43, respectively; and (iii) the weighted Tchebycheff method (shown in Eq. 6.45). Table 18 shows an assignment of objective-weight values used for obtaining the Pareto-optimal solutions using the LP-metrics method and the weighted Tchebycheff method. The bold values of the three objective functions, which are shown in Table 17, were given as ideal values O_1^*, O_2^*, O_3^* for the solution function O using Eq. 6.39 and 6.46.

Table 18. Assignment of weight values for obtaining Pareto solutions using the LP-metrics method and the weighted Tchebycheff method, respectively

#	Objective weights		
	w_1, l_1	w_2, l_2	w_3, l_3
1	1	0	0
2	0.9	0.05	0.05
3	0.8	0.1	0.1
4	0.7	0.15	0.15
5	0.6	0.2	0.2
6	0.5	0.25	0.25
7	0.4	0.3	0.3
8	0.3	0.35	0.35
9	0.5	0.3	0.2
10	0.3	0.2	0.5

Table 19 shows three sets of ten Pareto solutions obtained using the three methods, respectively as described above by assigning ten values of the satisfaction level α^1 between 0.1 and 1. It also shows the optimum number of farms and abattoirs that should be established for the meat supply chain network. For instance, solution 2 is obtained based on the LP-metrics method by assigning $w_1 = 0.9$, $w_2 = 0.05$ and $w_3 = 0.05$. Accordingly, it gives the minimum total transportation cost of 55,430 GBP, the minimum number of required transportation vehicles of 27 and the minimum travel time of 56.4 h. With this solution, the meat supply chain network consists of farms one and four (1 0 0 1) and abattoirs two and four (0 1 0 1). Table 20 shows the results of satisfaction degree $\mu(x_i)$ based on each objective function, shown in Eq. 6.35-6.37.

Table 19. The computational results obtained by assigning the varying α values

Solution method	#	α - level	Min (O_1) (GBP)	Min (O_2) (unit)	Min (O_3) (h)	Open farms	Open abattoirs	Run time (s)
LP-metrics	1	0.1	55430	27	56.4	1 0 0 1	0 1 0 1	3
	2	0.2	55430	27	56.4	1 0 0 1	0 1 0 1	3
	3	0.3	59343	29	78.5	1 0 1 1	0 1 0 1	2
	4	0.4	64569	32	101	0 0 1 1	0 1 0 1	2
	5	0.5	91234	34	123.5	1 0 1 1	1 0 1 1	4
	6	0.6	224653	45	174.7	1 1 1 1	1 1 0 1	3
	7	0.7	233450	47	196.1	1 1 1 1	1 0 1 1	4
	8	0.8	254000	48	219.6	1 1 1 1	0 1 1 0	4
	9	0.9	269360	50	239.1	1 1 1 1	1 0 1 1	4
	10	1	281060	51	258.5	1 1 1 1	1 0 1 1	5
ϵ -constraint	1	0.1	55430	27	56.4	1 0 0 1	0 1 0 1	2
	2	0.2	55430	27	56.4	1 1 0 0	0 1 1 0	2
	3	0.3	59155	29	78.2	1 1 0 1	0 1 0 1	2
	4	0.4	63943	31	97.5	1 0 1 1	0 1 0 1	1

¹ According to Jiménez's approach (see page 91), it is supposed that the fuzzy constraints in the model should be satisfied with a confidence value which is denoted as α and it is normally determined by decision makers.

	5	0.5	91858	34	123.5	1 0 0 1	1 0 1 1	3
	6	0.6	221340	44	168.1	1 1 1 1	1 1 0 1	4
	7	0.7	233130	47	196.1	1 1 1 1	1 1 0 1	4
	8	0.8	253800	48	219.6	1 1 1 1	0 1 1 0	4
	9	0.9	269312	50	239.1	1 1 1 1	1 0 1 1	4
	10	1	280950	50	255.6	1 1 1 1	1 0 1 1	3
Weighted Tchebycheff	1	0.1	55430	27	56.4	1 0 0 1	0 1 0 1	3
	2	0.2	55454	27	56.6	1 0 0 1	0 1 0 1	3
	3	0.3	59388	29	79.1	1 0 1 1	1 0 0 1	3
	4	0.4	64834	33	102.6	1 0 1 1	1 0 1 1	2
	5	0.5	91263	34	123.5	1 1 0 1	0 1 1 1	4
	6	0.6	224653	45	175.1	1 1 1 1	1 1 0 1	4
	7	0.7	233891	47	196.6	1 1 1 1	1 1 1 1	5
	8	0.8	254020	48	219.6	1 1 0 1	0 1 0 1	5
	9	0.9	269360	50	239.2	1 1 1 1	1 0 1 1	4
	10	1	283260	52	259.6	1 1 1 1	1 0 1 1	4

Table 20. Result of satisfaction degree of each objective function

$\mu(x_1)$	0.988	0.805	0.681	0.786	0.536	0.476	0.315	0.281	0.211	0.116
$\mu(x_2)$	0.988	0.805	0.690	0.797	0.541	0.479	0.321	0.298	0.224	0.147
$\mu(x_3)$	0.988	0.792	0.621	0.761	0.519	0.422	0.295	0.244	0.270	0.180

Shown in Table 19, by increasing the satisfaction level α , it leads to an increase of the undesired value of the three objectives. Decision makers can alter the importance of the weight value (w_i or l_i) of the three objective functions and the satisfaction level α based on their preferences to obtain a compromising solution as it is impossible to obtain an optimal value of all the conflicting objectives at a time. In other words, it is hard to obtain the Pareto-optimal solutions by optimizing one objective without worsening its performance in other

objectives. Decision makers can also use the TOPSIS method to gain a best solution among the Pareto-optimal solutions. Table 21 shows a list of the ranking Pareto-optimal solutions based on their scores using the TOPSIS method. As shown in Table 21, with the ε -constraint method, solution 4 is the best solution based on its score 0.279 which is the highest. This solution was determined by assigning $\varepsilon_1 = 32$ and $\varepsilon_2 = 116.5$ that yields a minimum total transportation cost of 63,943 GBP and a minimum travel time of 97.5 h with 31 transportation vehicles. The solution was also obtained based on an establishment of three farms which supplies livestock to two abattoirs. Table 22 shows the computational result of the Pareto solutions in terms of an optimum quantity of product flow between farms (1, 3, and 4) and abattoirs (2 and 4); and between abattoirs (2 and 4) and eleven retailers, respectively. It shows, for instance, farm three ought to supply 800 livestock to abattoir one and 1200 livestock to abattoir four. Abattoir two ought to supply 850 packages of processed meats to retailer one and 210 packages of processed meats to retailer three.

Table 21. Pareto-optimal solutions ranked based on scores using the TOPSIS method

Solution	Score		
	LP-metrics	ε -constraint	Weighted Tchebycheff
1	0.245	0.245	0.245
2	0.234	0.234	0.234
3	0.266	0.266	0.264
4	0.278	0.279	0.273
5	0.253	0.256	0.256
6	0.245	0.245	0.245
7	0.236	0.234	0.235
8	0.233	0.235	0.233
9	0.231	0.232	0.233
10	0.230	0.229	0.231

Table 22. The result of Pareto solutions in terms of optimum quantity of product flow throughout the three-echelon meat supply chain

Facilities	Quantity	Facilities	Quantity	Facilities	Quantity
u _{1,4}	1200	v _{2,1}	850	v _{2,11}	700
u _{3,1}	800	v _{2,3}	210	v _{4,6}	850
u _{3,4}	1200	v _{2,6}	690	v _{4,7}	450
u _{4,1}	1000	v _{2,5}	290	v _{4,9}	110
u _{4,2}	290	v _{2,10}	100	v _{4,2}	350
u _{4,4}	100	v _{2,8}	160	v _{4,4}	220

6.5 Conclusions

This chapter presents a study in developing a multi-objective possibilistic programming model based on a three-echelon meat supply chain. The developed model comprises three objective functions aimed at (1) minimizing the total transportation cost, (2) minimizing the required number of transportation vehicles, and (3) minimizing the delivery time. Three methods are proposed in order to obtain the Pareto solutions and based on these to determine the optimal solution. Further, the developed model can be useful for decision makers to determine the numbers of farms and abattoirs that need to be established, and the quantity of livestock from farms to abattoirs and the quantity of meat products from abattoirs to retailers. In order to examine the applicability and effectiveness of the developed mathematical model that can be a useful tool for food supply chain designers, a case study was investigated based the collected data and the computational results were obtained using LINGO.

The fuzzy multi-objective distribution planner for a green meat supply chain

7.1 Introduction

It is often a complex task for developing a product distribution plan of a supply chain network and a supportive decision tool can be useful for easing the role of decision-making. On the other hand, it has been increasingly becoming a demand in design of a supply chain network considering the environmental impact as a new dimension as required by authorities in many countries. It is expected that the global demand for food may be doubled by 2050, this makes food supply chains as one of the key sectors in economy. Thus, a robust design of food supply chain network is essential for a success to survive in an increasingly competitive market. This involves a strategic decision in a determination of location and allocation of relevant facilities and a tactical decision in quantity flow of products travelling throughout the supply chain network. Today, environmental issues are equally important and should be taken into account when designing a supply chain network. As mentioned previously, issues of uncertainty (such as varying costs and demands) need also to be taken into account when design a supply chain network (Fattahi et al., 2015; Davis, 1993). A number of researchers applied fuzzy multi-objective methods to tackle the fuzziness in the input data of supply chain networks (Wang & Hsu, 2010; Qin & Ji, 2010; Gholamiana et al., 2015).

This chapter presents a development of a fuzzy multi-objective optimization model used for tackling a distribution planning problem for a meat supply chain network under multiple uncertainties (i.e., costs, demand and capacity levels of related facilities) aiming to minimize the total transportation and implementation cost, the amount of CO₂ emissions in transportation, the distribution time of products from farms to retailers, and maximize the average delivery rate in satisfying product quantity as requested by abattoirs and retailers. Different solution methods that transform the fuzzy multi-objective model into a fuzzy mono-objective model were also investigated. A case study was employed to demonstrate the applicability of the developed model and the proposed solution methods.

7.2 Developing the fuzzy multi-objective distribution planner

In this work, a fuzzy multi-objective distribution planner was developed for a three-echelon meat supply chain network consisting of farms, abattoirs and retailers. Figure 20 depicts the structure of the three-echelon mean supply chain network. A FMOPM was developed and used for optimizing (i) the number and locations of farms and abattoirs that should be opened, and (ii) the optimum quantity of product flows between farms and abattoirs and between abattoirs and retailers.

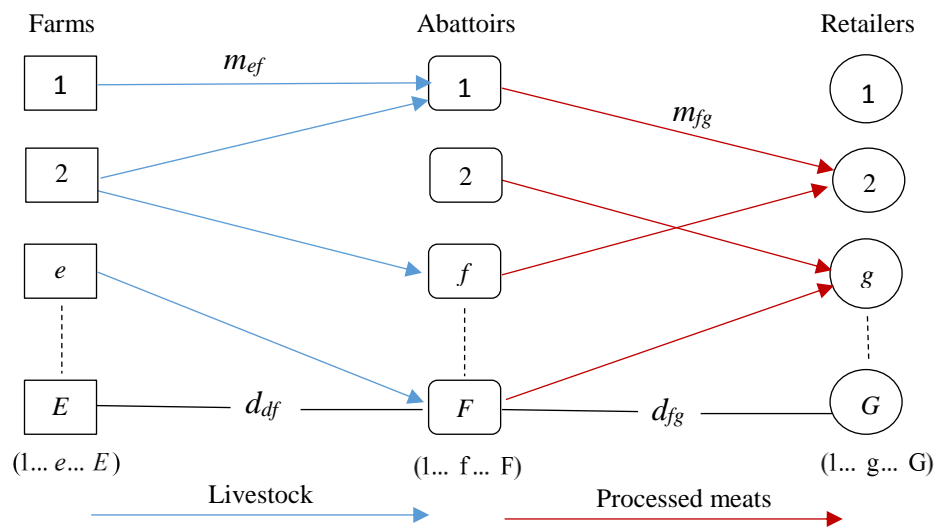


Figure 20. The three-echelon meat supply chain network.

The following sets, parameters and decision variables were used:

Sets

E set of farms (1... e ... E)

F set abattoirs (1... f ... F)

G set retailers (1... g ... G)

Parameters

C_{ef}^t RFID tag cost (GBP) per item transported from farm e to abattoir f

C_{fg}^t RFID tag cost (GBP) per item transported from abattoir f to retailer g

- $C_{ef}^{m/l}$ RFID system cost (GBP) required per lorry l travelling from farm i to abattoir j
- $C_{fg}^{m/l}$ RFID system cost (GBP) required per lorry l travelling from abattoir f to retailer g
- R_e working rate (items) per labourer at farm e
- R_f working rate (items) per labourer at abattoir f
- N_e minimum required number of working hours for labourer at farm e
- N_f minimum required number of working hours for labourer at abattoir f
- TC_{ef} unit transportation cost (GBP) per mile from farm e to abattoir f
- TC_{fg} unit transportation cost (GBP) per mile from abattoir f to retailer g
- C_e^h handling cost per livestock at farms e
- C_f^h handling cost per meat piece at abattoir f
- d_{ef} transportation distance (mile) of livestock from farm e to abattoir f
- d_{fg} transportation distance (mile) of processed meats from abattoir f to retailer g
- W_l transportation capacity (units) per lorry l
- V_l velocity (m/h) of lorry l
- C_e maximum supply capacity (units) of farm e
- C_f maximum supply capacity (units) of abattoir f
- D_f minimum demand (in units) of abattoir f
- D_g minimum demand (in units) of retailer g
- CO_{2e} CO₂ emission in gram for opening farm e
- CO_{2f} CO₂ emission in gram for opening abattoir f
- CO_{2ef} CO₂ emissions in gram per mile for each vehicle travelling from farm e to abattoir f

CO_{2fg} CO₂ emissions in gram per mile for vehicle travelling from abattoir f to retailer g

Decision variables

m_{ef} quantity of livestock transported from farm e to abattoir f

m_{fg} quantity of processed meats transported from abattoir f to retailer g

Binary decision variables:

$$u_e = \begin{cases} 1: & \text{if farm } e \text{ is open} \\ 0: & \text{otherwise} \end{cases}$$

$$v_f = \begin{cases} 1: & \text{if abattoir } f \text{ is open} \\ 0: & \text{otherwise} \end{cases}$$

Four conflicting objectives, which include minimizing the total transportation and implementation cost Z_1 , minimizing the environmental impact Z_2 , maximizing the average delivery rate Z_3 and minimizing the distribution time Z_4 , can be defined as objective functions below:

$$\begin{aligned} \text{Min } Z_1 = & \sum_{e \in E} \sum_{f \in F} TC_{ef} \left[\frac{m_{ef}}{W_l} \right] d_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} \left[\frac{m_{fg}}{W_l} \right] d_{fg} \\ & + \sum_{e \in E} \sum_{f \in F} C_e^d m_{ef} + \sum_{f \in F} \sum_{g \in G} C_f^d m_{fg} + \sum_{e \in E} \sum_{f \in F} C_{ef}^t m_{ef} + \sum_{f \in F} \sum_{g \in G} C_{fg}^t m_{fg} \\ & + \sum_{e \in E} \sum_{f \in F} C_{ef}^{m/l} \left[\frac{m_{ef}}{W_l} \right] + \sum_{f \in F} \sum_{g \in G} C_{fg}^{m/l} \left[\frac{m_{fg}}{W_l} \right] \end{aligned} \quad (7.2)$$

$$\text{Min } Z_2 = \sum_{e \in E} CO_{2e} u_e + \sum_{f \in F} CO_{2f} v_f + \sum_{e \in E} \sum_{f \in F} CO_{2ef} \left[\frac{m_{ef}}{W_l} \right] d_{ef} + \sum_{f \in F} \sum_{g \in G} CO_{2fg} \left[\frac{m_{fg}}{W_l} \right] d_{fg} \quad (7.3)$$

$$Max Z_3 = \frac{\sum_{f \in F} \left(\frac{\sum_{e \in E} m_{ef}}{D_f} \right) + \sum_{g \in G} \left(\frac{\sum_{f \in F} m_{fg}}{D_g} \right)}{2} \quad (7.3)$$

$$Min Z_4 = \sum_{e \in E} \sum_{f \in F} \frac{d_{ef}}{V_l} m_{ef} + \sum_{f \in F} \sum_{g \in G} \frac{d_{fg}}{V_l} m_{fg} \quad (7.4)$$

Subject to:

$$\sum_{e \in E} m_{ef} \leq C_e u_e \quad \forall f \in F \quad (7.5)$$

$$\sum_{f \in F} m_{fg} \leq C_f v_f \quad \forall g \in G \quad (7.6)$$

$$\sum_{e \in E} m_{ef} \geq D_f \quad \forall f \in F \quad (7.7)$$

$$\sum_{f \in F} m_{fg} \geq D_g \quad \forall g \in G \quad (7.8)$$

$$D_f \geq \sum_{g \in G} m_{fg} \quad \forall f \in F \quad (7.9)$$

$$\sum_{f \in F} m_{ef} \leq x_e R_e \quad \forall e \in E \quad (7.10)$$

$$\sum_{g \in G} m_{fg} \leq x_f R_f \quad \forall f \in F \quad (7.11)$$

$$m_{ef}, m_{fg} \geq 0 \quad \forall e, f, g \quad (7.12)$$

$$u_e, v_f \in \{1, 0\}, \quad \forall e, f \quad (7.13)$$

Where, for Eq. 7.1 it minimizes the total transportation and implementation cost which includes transportation cost in the meat supply network, handling cost at farms and abattoirs, RFID-tag cost for each item, RFID reader cost required for each transportation vehicle and labor costs saved after the RFID implementation due to the elimination of several manual operations (e.g. inventory cost). For Eq. 7.2 it minimizes the amount of CO₂ emissions (i) as a result of opening network related facilities (e.g. farms and abattoirs), and (ii) throughout the two-level transportation routes from farms to abattoirs and from abattoirs to retailers. For Eq. 7.3 it maximizes the average delivery rate in terms of quantity of products requested by

abattoirs and retailers. For Eq. 74 it minimizes the distribution time of all products transported from farms to abattoirs and from abattoirs to retailers. For Eq. 7.5 it limits the amount of livestock shipped from farms to abattoirs so that it cannot exceed the full capacity farms. For Eq. 7.6 it ensures the flow of meat products from abattoirs to retailer does not exceed the full capacity of abattoirs. For Eq. 7.7-7.10, these maintain the flow of product quantity between farms and abattoirs, and between abattoirs and retailers. For Eq. 7.10 and 7.11, these determine the required number of labourer at farms and abattoirs. For Eq. 7.12 and 7.13, these limit the non-binary and non-negativity restrictions on decision variables.

7.2.1 Modelling the uncertainty

In this work, a fuzzy multi-objective programming model was developed incorporating the uncertain parameters of transportation and implementation costs and demand. To this aim, the multi-objective programming model was transformed to a crisp model using an approach proposed by Jiménez et al. (2007). Based on Jiménez's approach, the equivalent crisp model is expressed as follows:

$$\begin{aligned}
Min Z_1 = & \sum_{e \in E} \sum_{f \in F} \left(\frac{TC_{ef}^{pes} + 2TC_{ef}^{mos} + TC_{ef}^{opt}}{4} \right) \left\lceil \frac{m_{ef}}{W_l} \right\rceil d_{ef} + \sum_{f \in F} \sum_{g \in G} \left(\frac{TC_{fg}^{pes} + 2TC_{fg}^{mos} + TC_{fg}^{opt}}{4} \right) \left\lceil \frac{m_{fg}}{W_l} \right\rceil d_{fg} \\
& + \sum_{e \in E} \sum_{f \in F} \left(\frac{C_e^{dpes} + 2C_e^{dmos} + C_e^{dopt}}{4} \right) m_{ef} + \sum_{f \in F} \sum_{g \in G} \left(\frac{C_f^{dpes} + 2C_f^{dmos} + C_f^{dopt}}{4} \right) m_{fg} \\
& + \sum_{e \in E} \sum_{f \in F} \left(\frac{C_{ef}^{tpes} + 2C_{ef}^{tmos} + C_{ef}^{topt}}{4} \right) m_{ef} + \sum_{f \in F} \sum_{g \in G} \left(\frac{C_{fg}^{tpes} + 2C_{fg}^{tmos} + C_{fg}^{topt}}{4} \right) m_{fg} \\
& + \sum_{e \in E} \sum_{f \in F} \left(\frac{C_{ef}^{l pes} + 2C_{ef}^{l mos} + C_{ef}^{l opt}}{4} \right) \left\lceil \frac{m_{ef}}{W_l} \right\rceil + \sum_{f \in F} \sum_{g \in G} \left(\frac{C_{fg}^{l pes} + 2C_{fg}^{l mos} + C_{fg}^{l opt}}{4} \right) \left\lceil \frac{m_{fg}}{W_l} \right\rceil
\end{aligned} \tag{7.14}$$

$$\begin{aligned}
Min Z_2 = & \sum_{e \in E} CO_{2e} u_e + \sum_{f \in F} CO_{2f} v_f + \sum_{e \in E} \sum_{f \in F} CO_{2ef} \left\lceil \frac{m_{ef}}{W_l} \right\rceil d_{ef} + \sum_{f \in F} \sum_{g \in G} CO_{2fg} \left\lceil \frac{m_{fg}}{W_l} \right\rceil d_{fg}
\end{aligned} \tag{7.15}$$

$$Max Z_3 = \frac{\sum_{f \in F} \left(4 \frac{\sum_{e \in E} m_{ef}}{D_f^{pes} + 2D_f^{mos} + D_f^{opt}} \right) + \sum_{g \in G} \left(4 \frac{\sum_{f \in F} m_{fg}}{D_g^{pes} + 2D_g^{mos} + D_g^{opt}} \right)}{2} \quad (7.16)$$

$$Min Z_4 = \sum_{e \in E} \sum_{f \in F} \frac{d_{ef}}{V_l} m_{ef} + \sum_{f \in F} \sum_{g \in G} \frac{d_{fg}}{V_l} m_{fg} \quad (7.17)$$

Subject to:

$$\sum_{e \in E} m_{ef} \leq C_e u_e, \quad \forall f \in F \quad (7.18)$$

$$\sum_{f \in F} m_{ef} \leq C_f v_f, \quad \forall g \in G \quad (7.19)$$

$$\sum_{e \in E} m_{ef} \geq \left[\frac{\alpha}{2} \cdot \frac{D_{f1} + D_{f2}}{2} + \left(1 - \frac{\alpha}{2} \right) \frac{D_{f3} + D_{f4}}{2} \right], \quad \forall f \in F \quad (7.20)$$

$$\sum_{f \in F} m_{fg} \geq \left[\frac{\alpha}{2} \cdot \frac{D_{g1} + D_{g2}}{2} + \left(1 - \frac{\alpha}{2} \right) \frac{D_{g3} + D_{g4}}{2} \right], \quad \forall g \in G \quad (7.21)$$

$$\left[\frac{\alpha}{2} \cdot \frac{D_{f1} + D_{f2}}{2} + \left(1 - \frac{\alpha}{2} \right) \frac{D_{f3} + D_{f4}}{2} \right] \geq \sum_{g \in G} m_{fg}, \quad \forall f \in F \quad (7.22)$$

$$m_{ef}, m_{fg} \geq 0 \quad \forall e, f \quad (7.23)$$

$$u_e, v_f, \alpha \in \{1, 0\}, \quad \forall e, f \quad (7.24)$$

According to Jiménez's approach, it is supposed that the fuzzy constraints in the model should be satisfied with a confidence value which is denoted as α and it is normally determined by decision makers. The four objectives functions were proposed to be optimized using the flowing steps:

Step 1 : Determine a maximum bound and a minimum bound (*Max*, *Min*) for each objective function as follows:

For the Max bound solution:

$$Max Z_1(Max_1) = \sum_{e \in E} \sum_{f \in F} TC_{ef} \left[\frac{m_{ef}}{W_l} \right] d_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} \left[\frac{m_{fg}}{W_l} \right] d_{fg} \quad (7.25)$$

$$+ \sum_{e \in E} \sum_{f \in F} C_e^d m_{ef} + \sum_{f \in F} \sum_{g \in G} C_f^d m_{fg} + \sum_{e \in E} \sum_{f \in F} C_{ef}^t m_{ef} + \sum_{f \in F} \sum_{g \in G} C_{fg}^t m_{fg}$$

$$+ \sum_{e \in E} \sum_{f \in F} C_{ef}^{m/l} \left[\frac{m_{ef}}{W_l} \right] + \sum_{f \in F} \sum_{g \in G} C_{fg}^{m/l} \left[\frac{m_{fg}}{W_l} \right]$$

$$Max Z_2(Max_2) = \sum_{e \in E} CO_{2e} u_e + \sum_{f \in F} CO_{2f} v_f \quad (7.26)$$

$$+ \sum_{e \in E} \sum_{f \in F} CO_{2ef} \left[\frac{m_{ef}}{W_l} \right] d_{ef} + \sum_{f \in F} \sum_{g \in G} CO_{2fg} \left[\frac{m_{fg}}{W_l} \right] d_{fg}$$

$$Max Z_3(Max_3) = \frac{\sum_{f \in F} \left(\frac{\sum_{e \in E} m_{ef}}{D_f} \right) + \sum_{g \in G} \left(\frac{\sum_{f \in F} m_{fg}}{D_g} \right)}{2} \quad (7.27)$$

$$Max Z_4(Max_4) = \sum_{e \in E} \sum_{f \in F} \frac{d_{ef}}{V_l} m_{ef} + \sum_{f \in F} \sum_{g \in G} \frac{d_{fg}}{V_l} m_{fg} \quad (7.28)$$

For the Min bound solution:

$$Min Z_1(Min_1) = \sum_{e \in E} \sum_{f \in F} TC_{ef} \left[\frac{m_{ef}}{W_l} \right] d_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} \left[\frac{m_{fg}}{W_l} \right] d_{fg} \quad (7.29)$$

$$+ \sum_{e \in E} \sum_{f \in F} C_e^d m_{ef} + \sum_{f \in F} \sum_{g \in G} C_f^d m_{fg} + \sum_{e \in E} \sum_{f \in F} C_{ef}^t m_{ef} + \sum_{f \in F} \sum_{g \in G} C_{fg}^t m_{fg}$$

$$+ \sum_{e \in E} \sum_{f \in F} C_{ef}^{m/l} \left[\frac{m_{ef}}{W_l} \right] + \sum_{f \in F} \sum_{g \in G} C_{fg}^{m/l} \left[\frac{m_{fg}}{W_l} \right]$$

$$Min Z_2(Min_2) = \sum_{e \in E} CO_{2e} u_e + \sum_{f \in F} CO_{2f} v_f \quad (7.30)$$

$$+ \sum_{e \in E} \sum_{f \in F} CO_{2ef} \left[\frac{m_{ef}}{W_l} \right] d_{ef} + \sum_{f \in F} \sum_{g \in G} CO_{2fg} \left[\frac{m_{fg}}{W_l} \right] d_{fg}$$

$$\text{Min } Z_3(\text{Min}_3) = \frac{\sum_{f \in F} \left(\frac{\sum_{e \in E} m_{ef}}{D_f} \right) + \sum_{g \in G} \left(\frac{\sum_{f \in F} m_{fg}}{D_g} \right)}{2} \quad (7.31)$$

$$\text{Min } Z_4(\text{Min}_4) = \sum_{e \in E} \sum_{f \in F} \frac{d_{ef}}{V_1} m_{ef} + \sum_{f \in F} \sum_{g \in G} \frac{d_{fg}}{V_1} m_{fg} \quad (7.32)$$

Step 2 : Each objective function corresponds to an equivalent linear membership function, which can be obtained by implementing Eq. 7.33-7.36. Further illustration about these membership functions is depicted in Figure 21.

$$\mu_1(Z_1(x)) = \begin{cases} 1 & \text{if } Z_1(x) \leq \text{Max}_1 \\ \frac{\text{Min}_1 - Z_1(x)}{\text{Min}_1 - \text{Max}_1} & \text{if } \text{Min}_1 \leq Z_1(x) \leq \text{Max}_1 \\ 0 & \text{if } Z_1(x) \geq \text{Min}_1 \end{cases} \quad (7.33)$$

$$\mu_2(Z_2(x)) = \begin{cases} 1 & \text{if } Z_2(x) \leq \text{Max}_2 \\ \frac{\text{Min}_2 - Z_2(x)}{\text{Min}_2 - \text{Max}_2} & \text{if } \text{Min}_2 \leq Z_2(x) \leq \text{Max}_2 \\ 0 & \text{if } Z_2(x) \geq \text{Min}_2 \end{cases} \quad (7.34)$$

$$\mu_3(Z_3(x)) = \begin{cases} 1 & \text{if } Z_2(x) \leq \text{Max}_2 \\ \frac{\text{Min}_2 - Z_2(x)}{\text{Min}_2 - \text{Max}_2} & \text{if } \text{Min}_2 \leq Z_2(x) \leq \text{Max}_2 \\ 0 & \text{if } Z_2(x) \geq \text{Min}_2 \end{cases} \quad (7.35)$$

$$\mu_4(Z_4(x)) = \begin{cases} 1 & \text{if } Z_4(x) \leq \text{Max}_4 \\ \frac{\text{Min}_4 - Z_4(x)}{\text{Min}_4 - \text{Max}_4} & \text{if } \text{Min}_4 \leq Z_4(x) \leq \text{Max}_4 \\ 0 & \text{if } Z_4(x) \geq \text{Min}_4 \end{cases} \quad (7.36)$$

where Eq. 7.33-7.36 indicates the satisfaction degree of the three objective functions respectively.

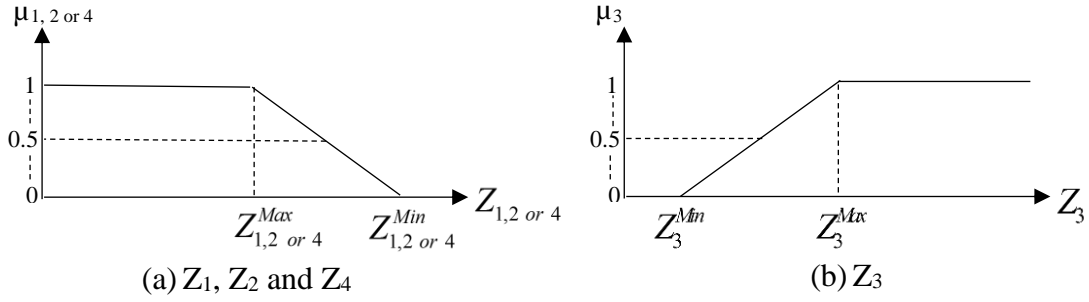


Figure 21. Membership functions related to the four objectives (a) Z_1, Z_2 and Z_4 , (b) Z_3 .

- Step 3 : Solve the crisp FMOPM obtained from section 7.2.1 by transforming it to a mono-objective model using the proposed solution methods described in section 7.2.2.
- Step 4 : Use the Max-Min method (described in section 7.2.3) to select the best Pareto solution.

7.3 Solution methods

7.3.1 LP-metrics

With this approach (see 3.1.1.7), the FMOPM is transformed to a single objective model using the following formula:

$$\text{Min } Z = \left[w_1 \frac{Z_1 - Z_1^*}{Z_1^*} + w_2 \frac{Z_2 - Z_2^*}{Z_2^*} + w_3 \frac{Z_3 - Z_3^*}{Z_3^*} + w_4 \frac{Z_4 - Z_4^*}{Z_4^*} \right] \quad (7.37)$$

Subject to Eq. 18-24.

7.3.2 ϵ -constraint

With this approach, the equivalent solution formula Z is given by:

$$\text{Min } Z = \text{Min } Z_1 \quad (7.38)$$

Subject to:

$$Z_2 \leq \epsilon_1 \quad (7.39)$$

$$[Z_2]^{\min} \leq \epsilon_1 \leq [Z_2]^{\max} \quad (7.40)$$

$$Z_3 \geq \epsilon_2 \quad (7.41)$$

$$[Z_3]^{\min} \leq \varepsilon_2 \leq [Z_3]^{\max} \quad (7.42)$$

$$Z_4 \leq \varepsilon_3 \quad (7.43)$$

$$[Z_4]^{\min} \leq \varepsilon_3 \leq [Z_4]^{\max} \quad (7.44)$$

And Eq. 18-24.

In this work, minimization of the total transportation and implementation cost is the objective function as Eq.7.38 and minimization of CO₂ emissions, maximization of average delivery rate and minimization of distribution time are shifted to constraints Eq. 39, 41 and 43 respectively.

7.3.3 Goal programming

The purpose of Goal programming is to find a solution that minimizes undesirable deviations between the objective functions and their corresponding goals (Pasandideh et al., 2015). Eq. 36-39 show the used solution functions for this problem.

$$\text{Min } Z \quad (7.45)$$

$$\frac{\xi^1}{G^1} \leq Z \quad (7.46)$$

$$\frac{v^2}{G^2} \leq Z \quad (7.47)$$

$$\frac{v^3}{G^3} \leq Z \quad (7.48)$$

$$\frac{v^4}{G^4} \leq Z \quad (7.49)$$

The equivalent objective functions are expressed as follows.

$$\text{Min } Z_1 = \sum_{e \in E} \sum_{f \in F} TC_{ef} \left[\frac{m_{ef}}{W_l} \right] d_{ef} + \sum_{f \in F} \sum_{g \in G} TC_{fg} \left[\frac{m_{fg}}{W_l} \right] d_{fg} \quad (7.50)$$

$$+ \sum_{e \in E} \sum_{f \in F} C_e^d m_{ef} + \sum_{f \in F} \sum_{g \in G} C_f^d m_{fg} + \sum_{e \in E} \sum_{f \in F} C_{ef}^t m_{ef} + \sum_{f \in F} \sum_{g \in G} C_{fg}^t m_{fg}$$

$$+ \sum_{e \in E} \sum_{f \in F} C_{ef}^{m/l} \left[\frac{m_{ef}}{W_l} \right] + \sum_{f \in F} \sum_{g \in G} C_{fg}^{m/l} \left[\frac{m_{fg}}{W_l} \right] = G^1$$

$$\text{Min } Z_2 = \sum_{e \in E} CO_{2e} u_e + \sum_{f \in F} CO_{2f} v_f \quad (7.51)$$

$$+ \sum_{e \in E} \sum_{f \in F} CO_{2ef} \left[\frac{m_{ef}}{W_l} \right] d_{ef} + \sum_{f \in F} \sum_{g \in G} CO_{2fg} \left[\frac{m_{fg}}{W_l} \right] d_{fg} + \zeta^2 - \nu^2 = G^2$$

$$\text{Max } Z_3 = \frac{\sum_{f \in F} \left(\frac{\sum_{e \in E} m_{ef}}{D_f} \right) + \sum_{g \in G} \left(\frac{\sum_{f \in F} m_{fg}}{D_g} \right)}{2} + \zeta^3 - \nu^3 = G^3 \quad (7.52)$$

$$\text{Min } Z_4 = \sum_{e \in E} \sum_{f \in F} \frac{d_{ef}}{V_l} m_{ef} + \sum_{f \in F} \sum_{g \in G} \frac{d_{fg}}{V_l} m_{fg} + \zeta^4 - \nu^4 = G^4 \quad (7.53)$$

Where

- G^1 goal of the objective 1
- G^2 goal of the objective 2
- G^3 goal of the objective 3
- G^4 goal of the objective 4
- ζ^1 negative deviation variable of the objective 1
- ζ^2 negative deviation variable of the objective 2
- ζ^3 negative deviation variable of the objective 3
- ζ^4 negative deviation variable of the objective 4
- ν^1 positive deviation variable of the objective 1
- ν^2 positive deviation variable of the objective 2
- ν^3 positive deviation variable of the objective 3
- ν^4 positive deviation variable of the objective 4

Subject to the additional non-negativity restriction where:

$$\zeta, \nu \geq 0, \quad (7.54)$$

And Eq. 18-24.

7.3.4 The decision-making method

In this work, a decision-making method was used to select the best trade-off solution. Accordingly, the selection formula is expressed as follows:

$$BT = \sum_{i=1}^4 \frac{Z_i}{Z_i^*} \quad (7.55)$$

The development and optimization of the MOPM can be concluded as follows:

1. Identify elements required for formulating the model which include objectives, parameters, output variables and constraint.
2. Formulate the MOPM using the identified elements.
3. Handle the uncertainty in the input data by transforming the fuzzy model to a crisp model.
4. Solve the three objective functions individually to obtain the best and worst solutions for each objective.
5. Determine the membership function and solve the multi-objective optimization problem using the three solution approaches (i.e., LP-metrics, ϵ -constraint and goal programming).
6. Apply the Max-Min approach to select the final Pareto solution from three sets of Pareto solutions obtained by using the three solution approaches. Figure 22 shows the procedure in developing and optimizing the FMOPM.

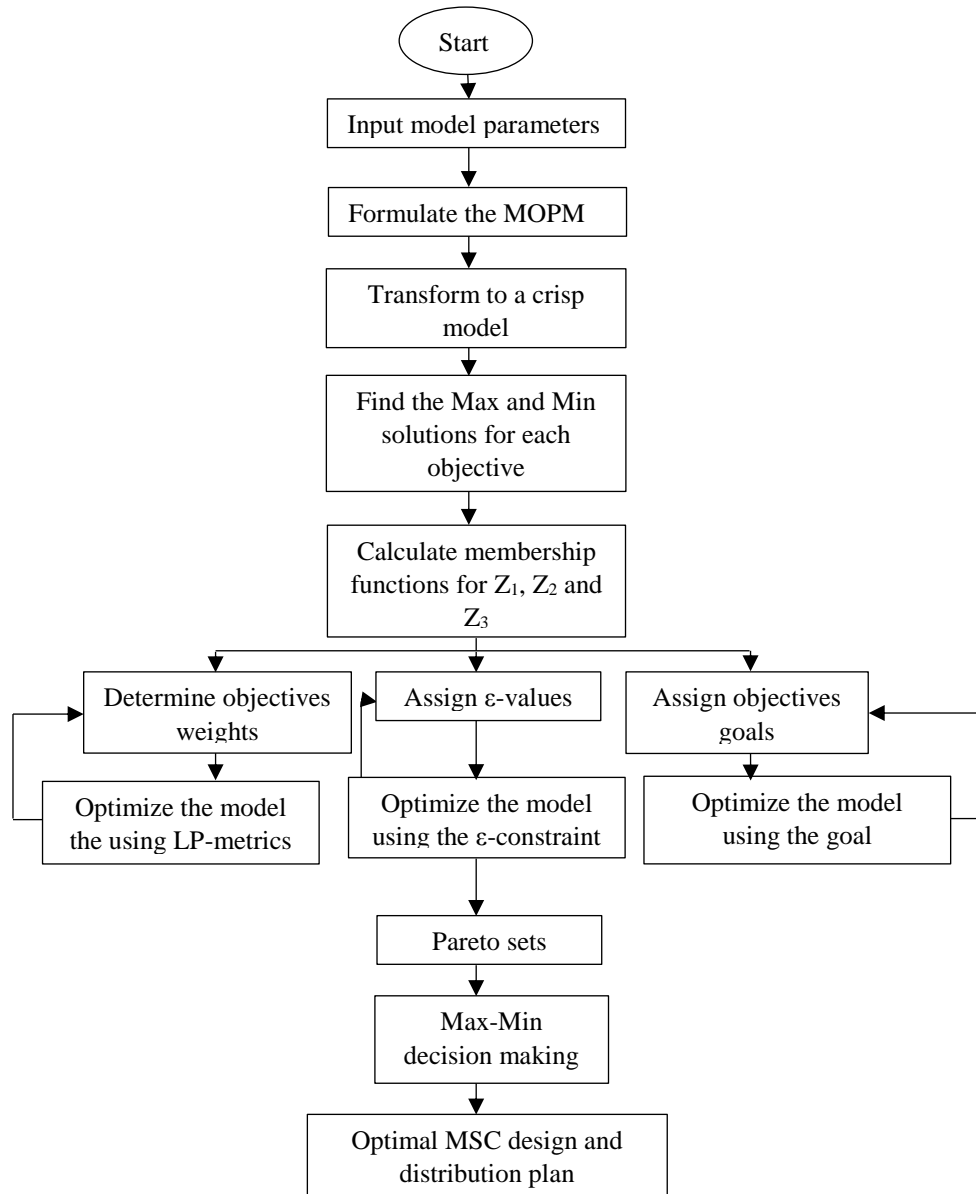


Figure 22. Procedures in developing and optimizing the FMOPM.

7.4 Application and evaluation of the FMOPM

In this section, a case study was used for evaluating the applicability of the developed FMOPM and the performance of the proposed solution methods. Table 23 shows the relevant parameters and their values used for the case study. Data, which are related to locations of farms, abattoirs and retailers, were collected from the Meat Committee in the UK (HMC, 2015) and Google Map was used to estimate travelling distances in locations between farms, abattoirs and retailers in the South-West of London. The developed model was coded using the LINGO¹¹ optimization software to obtain the solution based on the developed FMOPM.

Table 23. The values of parameters

Parameters	Values	Parameters	Values
TC_{ef}	(15, 18)	D_g	(1400, 1500)
TC_{fg}	(15, 18)	C_e	(1500, 1800)
C_{ef}^t	(0.15, 0.18)	C_f	(1700, 2000)
L_e	(6.5, 8.5)	L_f	(8.5, 10.5)
C_{fg}^t	(0.15, 0.18)	W_t	(20, 31)
C_{ef}^{mil}	(800, 950)	d_{ef}	(43, 210)
C_f^{mil}	(800, 950)	d_{fg}	(110, 174)
C_e^d	(3.5, 4)	CO_{2ef}	(271, 294)
C_f^d	(3.5, 4)	CO_{2fg}	(271, 294)
D_f	(2200, 3000)	V_L	(90-110)
R_e	(50, 65)	R_f	(50, 65)
CO_{2f}	(220000, 250000)	CO_{2e}	(82000, 85000)
N_e	(9, 12)	N_f	(9, 12)

7.4.1 Computational results

First, the Max and Min bounds for the four objectives needed to be determined, to this end Eq. 7.25-7.32 were applied. Table 24 shows the obtained results related to Z_1 , Z_2 , Z_3 and Z_4 . For instance, Z_1 {Max, Min} = {195,400, 43,540}. These values were used to obtain the membership functions for each objective.

Table 24. Max and Min values in responding to objective Z_1 , Z_2 , Z_3 and Z_4 , respectively

Objective functions	Max	Min
Z_1	195400	43540
Z_2	2572500.11	739782.55
Z_3	0.98	0.76
Z_4	245	54.5

To minimize the total transportation and implementation cost, CO₂ emissions and distribution time, and maximize the average delivery rate, the three methods previously described were implemented as follows:

1. LP-metrics: Table 25 shows the results in which each objective function was optimized independently under the predefined constraints. As shown in Table 25, by optimizing the first objective Z_1 individually, it gives the value of each objective function is: $Z_1 = 43540$, $Z_2 = 769600.22$, $Z_3 = 0.77$, and $Z_4 = 56$, respectively. The possible ideal values for the objective functions are boldfaced in the table: $Z_1 = 43540$, $Z_2 = 739782.55$, $Z_3 = 0.98$ and $Z_4 = 54.5$. Then, the Pareto solutions of the FMOPM were obtained based on the weights of the objective functions (See Table 26). Table 27 shows the varying computation result in response to one of ten different weights for each of the four objectives.
2. ϵ -constraints: as the maximum value and the minimum value for each objective can be obtained by Eq.7.25-7.32, the range between the two values was segmented into ten segments, the grid points (ϵ -points) in between were assigned as ϵ values (See Table 28) in Eq. 39, 41 and 43. Then, Pareto solutions were obtained by Eq. 7.38. The total transportation and implementation cost is the objective function which can be minimized while the CO₂ emissions, the average delivery rate and the distribution time are considered as constraints. Table 29 shows the computation results of the FMOPM for ten ϵ -iterations.
3. Goal Programming: each objective can be given a goal value to be approached by minimizing the undesired deviation towards to the goal value to be achieved. To this aim, each objective was solved individually and its value is given as a target for the approaching function. The values of objective functions are presented in Table 30.

It can be seen that the three methods were applied, respectively with ten α levels (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1). By setting these ten levels to the α , with steps 0.1 and implementing it to the model, ten Pareto solutions were obtained. Therefore, the model should be frequently solved for each α level.

Table 25. Values of Z_1 , Z_2 , Z_3 and Z_4 obtained by optimizing them individually

Objective functions	Min Z_1	Min Z_2	Max Z_3	Min Z_4
Z_1	43540	44670	195380	464000
Z_2	769600.22	739782.55	2373200.11	769600.22
Z_3	0.77	0.76	0.98	0.76
Z_4	56	56	213	54.5

Table 26. Weights allocation related to the LP-metrics approach

Assigned Weights	
#	W_1, W_2, W_3, W_4
1	0.9,0.025,0.025,0.05
2	0.8,0.1,0.05,0.05
3	0.7,0.1,0.1,0.1
4	0.64,0.12,0.12,0.12
5	0.6,0.13,0.13,0.14
6	0.5,0.25,0.125,0.125
7	0.4,0.2,0.2,0.2
8	0.34,0.22,0.22,0.22
9	0.3,0.23,0.23,0.24
10	0.22,0.26,0.26,0.26

Table 27. Computational results of Z_1 , Z_2 , Z_3 and Z_4 obtained by the LP-metrics

#	Satisfaction level				Objective function solutions				Facilities open		Run time (s)
	$\mu_1(Z_1)$	$\mu_2(Z_2)$	$\mu_3(Z_3)$	$\mu_4(Z_4)$	Min Z_1 (GBP)	Min Z_2 (Kg)	Max Z_3 (%)	Min Z_4 (h)	Farms	Abattoirs	
1	0.98	0.95	0.01	0.95	43540	741612	0.766	54.5	(3) Warwick (5) Leicester	(3) Birmingham (4) Balham	2
2	0.85	0.83	0.11	0.82	43540	741612	0.766	54.5	(3) Warwick (5) Leicester	(3) Birmingham (4) Balham	2
3	0.68	0.78	0.22	0.70	73271	1121612	0.811	72.4	(2) Warwick (3) Warwick (5) Leicester	(2) West Midland (3) Birmingham (4) Balham	3
4	0.78	0.65	0.32	0.66	85521	1296120	0.855	99.5	(2) Warwick (3) Warwick (5) Leicester	(2) West Midland (3) Birmingham (5) Norfolk	3
5	0.61	0.5	0.43	0.52	99507	1499015	0.888	121.5	(2) Warwick (3) Warwick (5) Leicester	(1) Warrick (3) Birmingham (4) Balham	3
6	0.48	0.47	0.55	0.49	114472	1688015	0.9	167.3	(2) Warwick (3) Warwick (5) Leicester	(2) West Midland (3) Birmingham (4) Balham (5) Norfolk	3
7	0.31	0.35	0.66	0.33	127498	1876227	0.922	192.5	(2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (3) Birmingham (4) Balham (5) Norfolk	4
8	0.28	0.25	0.74	0.28	144388	2066347	0.944	215.7	(1) Yorkshire (2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (2) West Midland (3) Birmingham (4) Balham (5) Norfolk	4
9	0.2	0.17	0.88	0.14	172680	2256347	0.977	235.8	(1) Yorkshire (2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (2) West Midland (3) Birmingham (4) Balham (5) Norfolk	4
10	0.09	0.1	0.98	0.11	194231	2406074	0.977	243.1	(1) Yorkshire (2) Warwick (3) Warwick (4) Yorkshire	(1) Warrick (2) West Midland (3) Birmingham (4) Balham	4

Table 28. Assignment of ε -value related to the ε -constraint approach

#	Assigned ε -value		
	ε_1	ε_2	ε_3
1	743000	0.76	54.5
2	933000	0.79	60.5
3	1123000	0.82	80.5
4	1313000	0.85	110.5
5	1503000	0.8	130.5
6	1693000	0.9	180.5
7	1883000	0.91	210.5
8	2073000	0.93	220.5
9	2263000	0.95	240.5
10	2453000	0.97	245

Table 29. Computational results of Z_1 , Z_2 , Z_3 and Z_4 obtained by the ϵ -constraint

#	Satisfaction level				Objective function solutions				Facilities open		Run time (s)
	$\mu_1(Z_1)$	$\mu_2(Z_2)$	$\mu_3(Z_3)$	$\mu_4(Z_4)$	Min Z_1 (GBP)	Min Z_2 (Kg)	Max Z_3 (%)	Min Z_4 (h)	Farms	Abattoirs	
1	0.98	0.95	0.01	0.95	43540	740010	0.766	54.5	(3) Warwick (5) Leicester	(3) Birmingham (4) Balham	2
2	0.85	0.83	0.11	0.84	43540	740010	0.766	56.6	(3) Warwick (5) Leicester	(3) Birmingham (4) Balham	2
3	0.64	0.72	0.25	0.72	74510	930010	0.82	75.5	(2) Warwick (3) Warwick (5) Leicester	(2) West Midland (3) Birmingham (4) Balham	2
4	0.73	0.64	0.36	0.66	88321	1120010	0.855	102.4	(2) Warwick (3) Warwick (5) Leicester	(1) Warrick (3) Birmingham (5) Norfolk	3
5	0.64	0.47	0.45	0.48	98398	1310010	0.888	125.6	(2) Warwick (3) Warwick (5) Leicester	(1) Warrick (3) Birmingham (4) Balham	3
6	0.45	0.44	0.56	0.45	118499	1500010	0.9	171	(2) Warwick (3) Warwick (4) Yorkshire	(2) West Midland (3) Birmingham (4) Balham (5) Norfolk	3
7	0.33	0.36	0.65	0.34	125293	1690010	0.911	201.8	(2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (3) Birmingham (4) Balham (5) Norfolk	3
8	0.26	0.21	0.77	0.20	145591	1880010	0.955	218.8	(1) Yorkshire (2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (2) West Midland (3) Birmingham (4) Balham (5) Norfolk	3

9	0.22	0.2	0.88	0.18	168591	2070010	0.966	237.7	(1) Yorkshire (2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (2) West Midland (3) Birmingham (4) Balham (5) Norfolk	4
10	0.09	0.1	0.98	0.09	194992	2283010	0.97	244.5	(1) Yorkshire (2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (2) West Midland (3) Birmingham (4) Balham (5) Norfolk	4

Table 30. Computation results of Z_1 , Z_2 , Z_3 and Z_4 obtained by the goal programming

#	Satisfaction level				Objective function solutions				Facilities open		Run time (s)
	$\mu_1(Z_1)$	$\mu_2(Z_2)$	$\mu_3(Z_3)$	$\mu_4(Z_4)$	Min Z_1 (GBP)	Min Z_2 (Kg)	Max Z_3 (%)	Min Z_4 (h)	Farms	Abattoirs	
1	0.98	0.95	0.01	0.95	43540	741612	0.766	54.5	(3) Warwick (5) Leicester	(3) Birmingham (4) Balham	2
2	0.85	0.83	0.11	0.82	43540	931621	0.766	54.5	(3) Warwick (5) Leicester	(3) Birmingham (4) Balham	2
3	0.66	0.75	0.24	0.70	69340	1200987	0.844	78.5	(2) Warwick (4) Yorkshire (5) Leicester	(2) West Midland (3) Birmingham (4) Balham	3
4	0.76	0.67	0.35	0.64	86550	1388987	0.888	105.1	(2) Warwick (3) Warwick (5) Leicester	(1) Warrick (3) Birmingham (4) Balham	3
5	0.65	0.48	0.46	0.44	97119	1578987	0.9	130.5	(2) Warwick (3) Warwick (5) Leicester	(1) Warrick (3) Birmingham (4) Balham	4
6	0.48	0.48	0.55	0.39	124650	1738985	0.955	179.5	(2) Warwick (3) Warwick (5) Leicester	(2) West Midland (3) Birmingham (4) Balham (5) Norfolk	3
7	0.35	0.36	0.62	0.33	120989	194254	0.911	210.5	(2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (3) Birmingham (4) Balham (5) Norfolk	4
8	0.28	0.23	0.79	0.18	139490	2130911	0.96	220.5	(1) Yorkshire (2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (2) West Midland (3) Birmingham (4) Balham (5) Norfolk	4
9	0.23	0.21	0.83	0.15	166210	2336122	0.977	237	(1) Yorkshire (2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (2) West Midland (3) Birmingham (4) Balham (5) Norfolk	4
10	0.13	0.14	0.98	0.08	188764	2421118	0.977	245	(1) Yorkshire (2) Warwick (3) Warwick (4) Yorkshire (5) Leicester	(1) Warrick (2) West Midland (3) Birmingham (4) Balham (5) Norfolk	4

As shown in Tables 27, 29 and 30, the results are also associated with numbers and geographical locations of farms and abattoirs that should be opened. As an example, solution 1 in Table 27 has two opened farms, which are located in Warwick and Leicester, to supply livestock to two abattoirs located in Birmingham and Balham. This solution leads to a transportation and implementation cost of 435,40 GBP, CO₂ emissions of 740,010 kg, an average delivery rate of 76.6% and a distribution time of 54.5 h. It can be seen in these Tables that increasing the desired value of Z_3 leads to increasing the undesired values of Z_1 , Z_2 and Z_4 .

The Pareto solutions can be categorized into three sections. Section 1 (solutions 1-3) shows a cost-oriented MSC network when the undesired values of Z_1 , Z_2 and Z_4 are increased modestly i.e., the MSC network is designed with the lowest total transportation and implementation cost, CO₂ emissions and the distribution time. In contrast, within section 2 (solutions 4-6) it shows the design the MSC with compromised solutions based on the three objectives. In section 3 (solutions 7-10), it shows a design the MSC with a highest average delivery rate. On the other hand, this section requires the decision makers to invest more money to achieve higher delivery rate.

Figure 23 illustrates the objective values (using LP-metrics) corresponding to different α -level. As shown in Figure 23, by increasing the satisfaction level (α -level) it leads to an increase in the undesired value of Z_1 , Z_2 and Z_4 but an increase in the desired value of Z_3 . In other words, values of Z_1 , Z_2 and Z_4 for the α close to 0.1 are better than levels of α . However, decision makers can vary the satisfaction level (α -level) based on their preferences to obtain a trade-off solution.

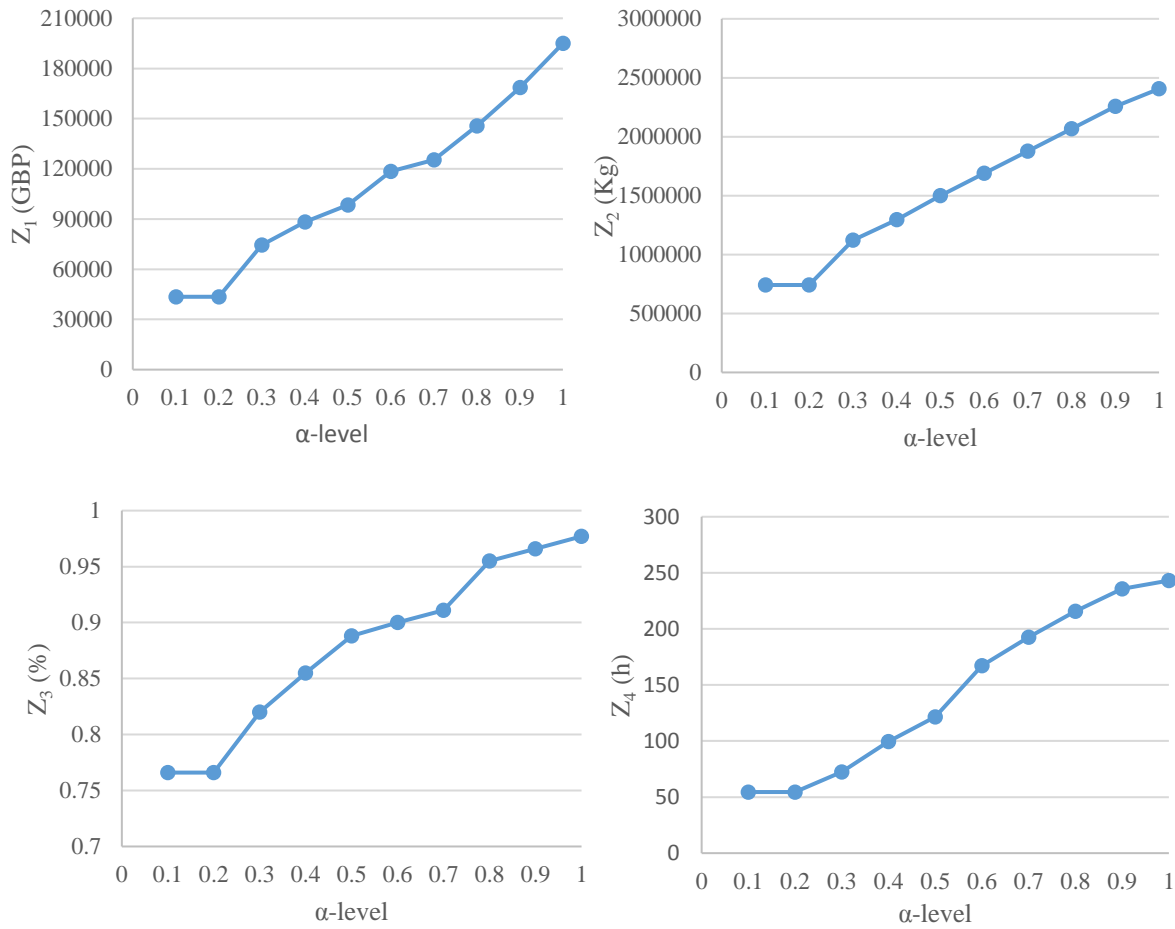


Figure 23. Z_1 , Z_2 , Z_3 and Z_4 values for various α -level.

Figure 24 depicts a comparison of Z_1 , Z_2 , Z_3 and Z_4 values obtained by three solution methods. It is shown that no solution is ideal as none of the solution methods can optimize the four objective functions, simultaneously. The direct selection of the best Pareto solution is impossible due to the value of each of the four objectives obtained by the three methods has minor difference.

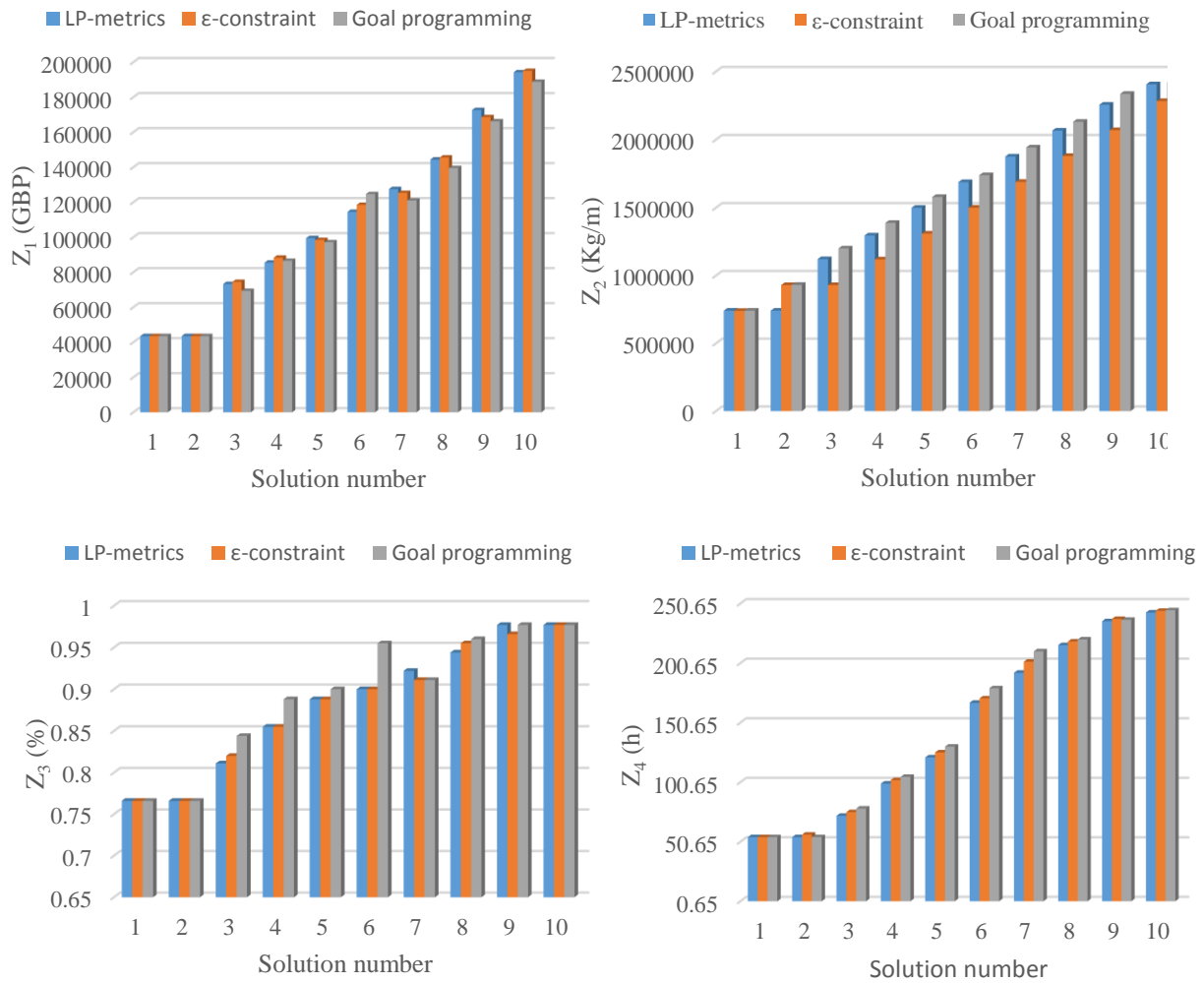


Figure 24. Comparative results obtained based on the three objective functions using the three proposed methods, respectively.

Hence, the solutions can be evaluated further via the Max-Min method aiming to select the best Pareto solution that has the minimum distance to the one of objectives' ideal values. As shown in Table 27, solution 4 was chosen as the best solution as it has the closest value of 3.097 to ideal objective value. Therefore, rather than the goal programming and LP-metrics, the ϵ -constraint method is more effective for this model. Besides, the run time of using the ϵ -constraint method for the ten iterations was slightly faster than using the goal programming method and the LP-metrics method. Based on solution 4 shown in Table 27, three farms located in Warwick and Leicester were selected to supply livestock to three abattoirs located in Warwick, Birmingham and Norfolk. This solution requires a minimum total transportation and implementation cost of 88,321 GBP. It yields CO₂ emissions equivalent to 1,120,010 Kg, a delivery rate up to 85.8% and a distribution time of 102.4 h. Figure 25 shows the optimal

design of the distribution plan which illustrates the number of the selected farms and abattoirs and the optimal flow of product quantity from farms to abattoirs and from abattoirs to retailers. It shows that farm two supplies 800 livestock to abattoir five and abattoir three supplies 95 packages of meats to retailer two as in this way it gives an optimal distribution plan. Figure 26 shows the geographical locations of these facilities.

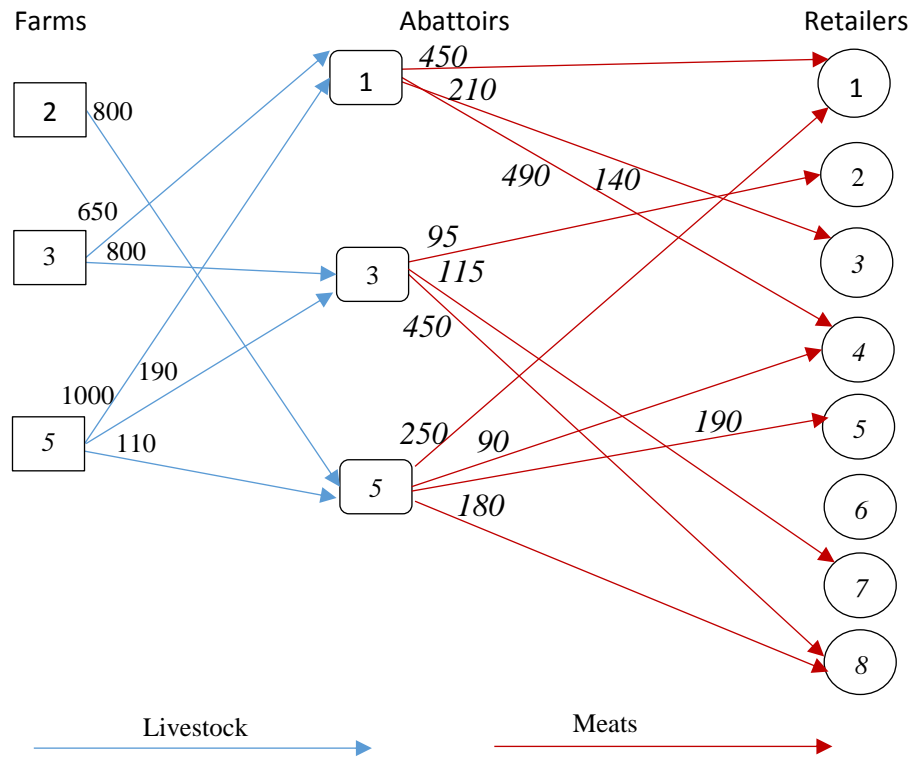
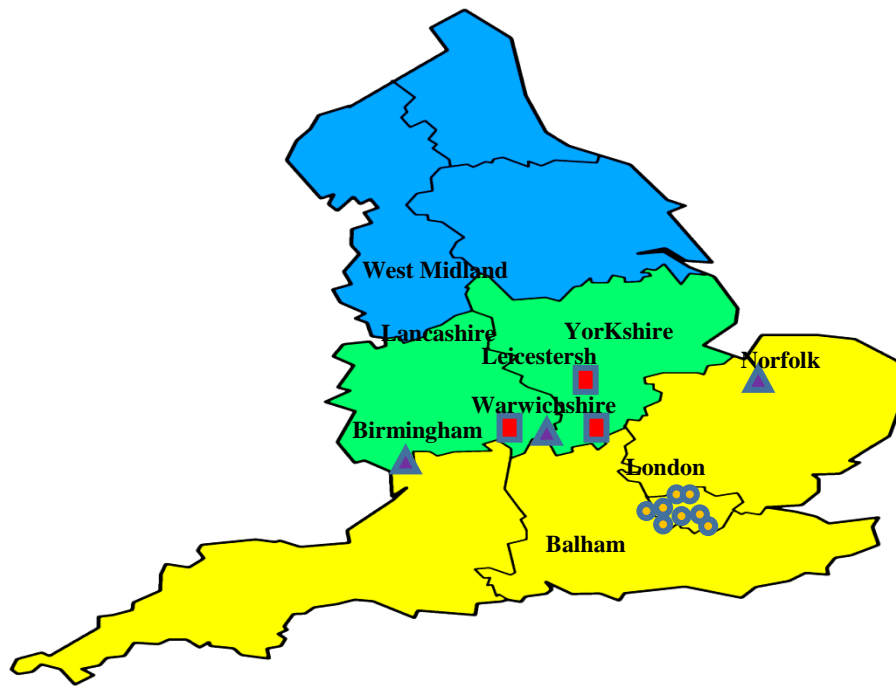


Figure 25. The optimal design of the distribution plan for the MSC.



Facilities legend:

Farms

Abattoirs

Retailers



Figure 26. Geographical locations of the selected facilities for solution 4.

7.5 Conclusions

This chapter presents a case study of a three-echelon meat supply chain by developing a fuzzy multi-objective programming model aimed at minimizing the total transportation and implementation cost, the amount of CO₂ emissions and the distribution time of products from farms to abattoirs and from abattoirs to retailers, and maximizing the average delivery rate. Three different methods were employed to obtain the Pareto solutions. The developed fuzzy multi-objective model was applied to a case study to examine if it is robust enough to achieve an optimal MSC network design. The study shows that the developed fuzzy multi-objective model is helpful to (i) determine the numbers of facilities with locations that should be opened in response to the quantity flow of products, and (ii) obtain a trade-off decision in terms of an optimal solution in designing the MSC based on the conflicting objectives. The result demonstrates that the ε -constraint method outperforms the goal programming method and the LP-metrics method.

Design and Optimization of an RFID-enabled automated warehousing system under uncertainties: A multi-criterion fuzzy programming approach

8.1 Introduction

Warehouses are one of main components of a supply chain network. A warehouse receives and stores merchandising products that are transported from suppliers to retailers. Reduction and accuracy of transportation time is one of the important performance measures to maintain a supply chain network in the competitive market, traditionally it relies on a well-organized warehouse management system (Choi et al., 2013; Yeung et al., 2011). For the last decade, it has been seen a growing trend in application and implementation of automated warehouses aiming to improve the warehouse efficiency and capacity utilization, and reduce the material-handling time of warehouses. On the other hand, automation of warehouses is subject to additional costs that need to be considered; this led to research interests in optimization of automated warehouse designs by enhancing efficiency and reducing unnecessary costs.

A review of the literature reveals that there were no previous studies in applying the fuzzy multi-criterion optimization approach in the context of the RFID-enabled automated warehouse design (Lerher et al., 2013). This study addresses a contribution in developing a fuzzy tri-criterion optimization model based on a proposed RFID-enabled automated warehousing system incorporating the uncertainty in varying demand, costs and items locations. The developed model was aimed at simultaneously optimizing a number of conflicting criteria: minimization of the total cost, maximization of the warehouse capacity utilization and minimization of travel time of products in a proposed RFID-enabled warehousing system.

8.2 Problem description and model formulation

Figure 27 illustrates the structure of the proposed RFID-enabled automated storage and retrieval racks (AS/RR) used for this study (Wang et al., 2010). The module comprises of two

types of powered conveyors aligned next to one another; these are input conveyors (storage racks) and output conveyors. The entire operation of each conveyor system is controlled by a programmable logic controller that communicates with mounted sensors via a local area network. Within the RFID-inventory management system, a chosen SKU can be released by the mechanical control system based on a number of assignment policies or rules. These rules include for example the rule of being nearest to a collection point and/or a modular arm which is free or adjacent to the chosen SKU.

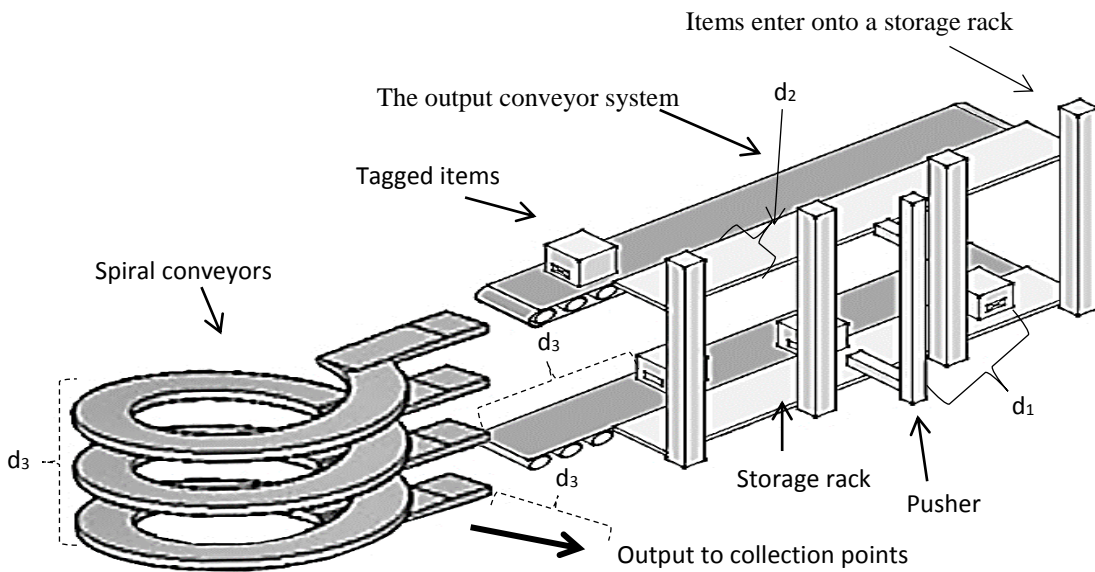


Figure 27. Structure of the proposed RFID-enabled AS/RR (Wang et al., 2010).

One of the main issues to be addressed in designing the proposed RFID-enabled automated warehouse include allocating the optimum number of racks and collection points with respect to three criterion functions: (1) minimization of total cost, (2) maximization of capacity utilization of the warehouse, and (3) minimization of travel time of products from storage racks to collection points.

8.2.1 Notations

The following sets, parameters and decision variables were used in the formulation of the model:

Sets:

I set of nominated storage racks $i \in I$

J set of nominated collection points $j \in J$

K set of fixed departure gates $k \in K$

Given parameters:

C_i^r fixed cost required for establishing an RFID-enabled rack i

C_j^c fixed cost required for establishing a collection point j

C_i^t unit RFID tag cost per item at rack i

C_{jk}^T unit transportation cost per meter from collection point j to departure point k

C_j^l unit labor cost per hour at collection point j

R_j^l working rate (items) per labourer at collection point j

N_j^h minimum required number of working hours for labourer l at collection point j

W transportation capacity (units) per forklift

S_i maximum supply capacity (units) of rack i

S_j maximum supply capacity (units) of collection point j

D_j demand (in units) of collection point j

d_1 travel distance needed (m) for a pusher from its location to a selected item

d_2 travel distance (m) of a selected item from its position at a storage rack to an output conveyor

d_3 travel distance (m) of a selected item from its position at an output conveyor to a collection point

d_{jk} travel distance (m) of a selected item from collection point j to departure gate k

S_p speed (m/s) of the moving-pusher along d_1

S_{pp} speed (m/s) of the moving-pusher to push a selected item onto an output conveyer.

S_c speed (m/s) of the output conveyer and the spiral conveyer.

Decision variables

q_{ij} quantity in units ordered from rack i to collection point j

q_{jk} quantity in units dispatched from collection point j to departure gate k

x_j required number of labourer at collection point j

y_i $\left\{ \begin{array}{l} 1: \text{if rack } i \text{ is opened} \\ 0: \text{otherwise} \end{array} \right.$

y_j $\left\{ \begin{array}{l} 1: \text{if collection point } j \text{ is opened} \\ 0: \text{otherwise} \end{array} \right.$

8.2.2 Formulating the multi-criterion optimization problem

The three criteria, which include minimization of total cost, maximization of capacity utilization and minimization of travel time, are formulated as follows:

Criterion function 1 (F_1)

In this case, the total cost of establishing the RFID-enabled automated warehouse includes the costs of establishing RFID-enabled racks, collection points, RFID tags, transportation of products and labourers in the warehouse. Thus, minimization of the total cost F_1 can be expressed below:

$$\begin{aligned} \text{Min } F_1 = & \sum_{i \in I} C_i^r y_i + \sum_{j \in J} C_j^c y_j + \sum_{i \in I} \sum_{j \in J} C_i^t q_{ij} + \sum_{j \in J} \sum_{k \in K} C_{ij}^T \left[q_{jk} / W_f \right] d_{jk} \\ & + \sum_{j \in J} C_j^l x_j N_j^h \end{aligned} \quad (8.1)$$

Criterion function 2 (F_2)

The capacity utilization is defined as the used capacity divided by the actual capacity. Thus, maximization of capacity utilization F_2 is expressed as follows:

$$Max F_2 = \left(\sum_{i \in I} \frac{[(C_a) - (C_u)]^2}{\sum i} \right)^{\frac{1}{2}} \quad (8.2)$$

Where $C_a = \sum_{j \in J} \frac{q_{ij}}{S_i}$ and $C_u = \frac{\sum_{i \in I} \sum_{j \in J} q_{ij}}{\sum_{i \in I} S_i}$, which refer to the actual (a) and used (u) capacity (C).

Criterion function 3 (F₃)

Travel time (tt) of an in-store item includes, tt of a pusher from its location to an item, tt of an item from its location at the storage rack to an output conveyer and tt of an item onto a conveyer system to the collection point. Thus, minimization of travel time F₃ is expressed as follows:

$$Min F_3 = \sum_{i \in I} \sum_{j \in J} \left(\frac{d_1}{S_p} + \frac{d_2}{S_{pp}} + \frac{d_3}{S_c} \right) q_{ij} \quad (8.3)$$

8.2.3 Constraints

The above model was developed under the following constraints:

$$\sum_{i \in I} q_{ij} \leq S_i y_i \quad \forall j \in J \quad (8.4)$$

$$\sum_{j \in J} q_{jk} \leq S_j y_j \quad \forall k \in K \quad (8.5)$$

$$\sum_{i \in I} q_{ij} \geq D_j \quad \forall j \in J \quad (8.6)$$

$$D_j \geq \sum_{k \in K} q_{jk} \quad \forall j \in J \quad (8.7)$$

$$\sum_{j \in J} q_{ij} \leq x_j R_j^1 \quad \forall i \in I \quad (8.8)$$

$$q_{ij}, q_{jk} \geq 0, \quad \forall i, j, k; \quad (8.9)$$

$$y_i, y_j \in \{0,1\}, \quad \forall i, j; \quad (8.10)$$

Eq. 8.4 and 8.5 refer to the flow balance of a product travelling from a storage rack to a collection point and from a collection point to a departure gate. Eq. 8.6 and 8.7 refer to demands in quantity to be satisfied. Eq. 8.8 determines the required number of labourer at collection points. Eq. 8.9 and 8.10 limit the decision variables to binary and non-negative.

8.3 The proposed optimization methodology

8.3.1 Solution procedures

To reveal the alternative Pareto-optimal solutions using the developed model, the following procedures were used:

- (1) Convert the developed model into an equivalent crisp model (section 8.3.2).
- (2) Find the upper and lower bound (U, L) solution for each criterion function. This can be obtained by:

Upper bound solutions:

$$\begin{aligned} \text{Max } F_1(U_1) = & \sum_{i \in I} C_i^r y_i + \sum_{j \in J} C_j^c y_j + \sum_{i \in I} \sum_{j \in j} C_i^t q_{ij} + \sum_{j \in J} \sum_{k \in K} C_{ij}^T \left[q_{jk} / W_f \right] d_{jk} \\ & + \sum_{j \in J} C_j^l x_j N_j^h \end{aligned} \quad (8.11)$$

$$\text{Max } F_2(U_2) = \left(\frac{\sum_{i \in I} [(C_a) - (C_u)]^2}{\sum i} \right)^{\frac{1}{2}} \quad (8.12)$$

$$\text{Max } F_3(U_3) = \sum_{i \in I} \sum_{j \in J} \left(\frac{d_1}{S_p} + \frac{d_2}{S_{pp}} + \frac{d_3}{S_c} \right) q_{ij} \quad (8.13)$$

Lower bound solutions:

$$\begin{aligned} \text{Min } F_1(L_1) = & \sum_{i \in I} C_i^r y_i + \sum_{j \in J} C_j^c y_j + \sum_{i \in I} \sum_{j \in j} C_i^t q_{ij} + \sum_{j \in J} \sum_{k \in K} C_{ij}^T \left[q_{jk} / W_f \right] d_{jk} \\ & + \sum_{j \in J} C_j^l x_j N_j^h \end{aligned} \quad (8.14)$$

$$\text{Min } F_2(L_2) = \left(\sum_{i \in I} \frac{[(C_a) - (C_u)]^2}{\sum i} \right)^{\frac{1}{2}} \quad (8.15)$$

$$\text{Min } F_3(L_3) = \sum_{i \in I} \sum_{j \in J} \left(\frac{d_1}{S_p} + \frac{d_2}{S_{pp}} + \frac{d_3}{S_c} \right) q_{ij} \quad (8.16)$$

(3) Find the respective satisfaction degree $\mu(x_i)$ for each criterion as follows:

$$\mu_1(F_1(x)) = \begin{cases} 1 & \text{if } F_1(x) \geq U_1 \\ \frac{F_1(x) - L_1}{U_1 - L_1} & \text{if } L_1 \leq F_1(x) \leq U_1 \\ 0 & \text{if } F_1(x) \leq L_1 \end{cases} \quad (8.17)$$

$$\mu_2(F_2(x)) = \begin{cases} 1 & \text{if } F_2(x) \geq U_2 \\ \frac{F_2(x) - L_2}{U_2 - L_2} & \text{if } L_2 \leq F_2(x) \leq U_2 \\ 0 & \text{if } F_2(x) \leq L_2 \end{cases} \quad (8.18)$$

$$\mu_3(F_3(x)) = \begin{cases} 1 & \text{if } F_3(x) \geq U_3 \\ \frac{F_3(x) - L_3}{U_3 - L_3} & \text{if } L_3 \leq F_3(x) \leq U_3 \\ 0 & \text{if } F_3(x) \leq L_3 \end{cases} \quad (8.19)$$

(4) Transform the crisp model obtained from section 8.3.2 to a single criterion function using the proposed solution approaches (section 8.3.3).

(5) Vary the weight combination set consistently for the three criteria to reveal Pareto-optimal solutions. Usually, the weight combination set is allocated by decision makers based on the importance of each objective.

(6) Select the best Pareto-optimal solution using the proposed decision making algorithm.

8.3.2 Formulating the uncertainty

To incorporate the uncertainty in varying demand, costs and items locations, the developed tri-criterion model is converted into an equivalent crisp model using the Jiménez method (Jiménez et al., 2007). Accordingly, the equivalent crisp model can be formulated as follows:

$$\text{Min } F_1 = \sum_{i \in I} \left(\frac{C_i^{rpes} + 2C_i^{rmos} + C_i^{ropt}}{4} \right) y_i + \sum_{j \in J} \left(\frac{C_j^{cpes} + 2C_j^{cmos} + C_j^{copt}}{4} \right) y_j \quad (8.20)$$

$$+ \sum_{i \in I} \sum_{j \in J} \left(\frac{C_i^{tpes} + 2C_i^{tmos} + C_i^{topt}}{4} \right) q_{ij} + \sum_{j \in J} \sum_{k \in K} \left(\frac{C_{ij}^{Tpes} + 2C_{ij}^{Tmos} + C_{ij}^{Topt}}{4} \right) \lceil q_{jk} / W_f \rceil d_{jk}$$

$$+ \sum_{j \in J} \left(\frac{C_j^{lpes} + 2C_j^{lmos} + C_j^{lopt}}{4} \right) x_j N_j^h$$

$$\text{Max } F_2 = \left(\frac{\sum_{i \in I} \left[(C_a) - (C_u) \right]^2}{\sum i} \right)^{\frac{1}{2}} \quad (8.21)$$

$$\text{Min } F_3 = \sum_{i \in I} \sum_{j \in J} \left(\frac{d_1^{pes} + 2d_1^{mos} + d_1^{opt}}{4S_p} + \frac{d_2^{pes} + 2d_2^{mos} + d_2^{opt}}{4S_{pp}} + \frac{d_3^{pes} + 2d_3^{mos} + d_3^{opt}}{4S_c} \right) q_{ij} \quad (8.22)$$

Subject to:

$$\sum_{i \in I} q_{ij} \leq S_i y_i \quad \forall j \in J \quad (8.23)$$

$$\sum_{j \in J} q_{jk} \leq S_j y_j \quad \forall k \in K \quad (8.24)$$

$$\sum_{i \in I} q_{ij} \geq \frac{\lambda}{2} \frac{D_{j1} + D_{j2}}{2} + \left(1 - \frac{\lambda}{2} \right) \frac{D_{j3} + D_{j4}}{2} \quad \forall j \in J \quad (8.25)$$

$$\frac{\lambda}{2} \cdot \frac{D_{j1} + D_{j2}}{2} + \left(1 - \frac{\lambda}{2} \right) \frac{D_{j3} + D_{j4}}{2} \geq \sum_{k \in K} q_{jk} \quad \forall j \in J \quad (8.26)$$

$$\sum_{j \in J} q_{ij} \leq x_j \frac{\lambda}{2} \cdot \frac{x_{j1} + x_{j2}}{2} + \left(1 - \frac{\lambda}{2} \right) \frac{x_{j3} + x_{j4}}{2} R_j^1 \quad \forall i \in I \quad (8.27)$$

$$q_{ij}, q_{jk} \geq 0, \quad \forall i, j, k; \quad (8.28)$$

$$y_i, y_j \in \{0, 1\}, \quad \forall i, j; \quad (8.29)$$

According to Jiménez's approach, it is supposed that the constraints in the model should be satisfied with a confidence value which is denoted as λ and it is normally determined by decision makers. Also, mos, pes and opt are the three prominent points (the most likely, the most pessimistic and the most optimistic values), respectively (Jiménez et al., 2007).

8.3.3 Optimization approach

8.3.3.1 The developed approach

The developed approach previously described in chapter 4 was used. The solution function (F) is formulated as follows:

$$\text{Min } F = \left(\sum_{n=1}^3 \sum_{f=1}^3 g_n \mu_f(x) \right) - F_d, \quad \sum_{n=1}^3 g_n = 1 \quad (8.30)$$

Set $g_n^* = \frac{g_n F_n^*}{F_n^* - F_n}$, then

$$F_d = g_1^* F_1 + g_2^* F_2 + g_3^* F_3 = \frac{g_1 F_1^*}{F_1^* - F_1} F_1 + \frac{g_2 F_2^*}{F_2^* - F_2} F_2 + \frac{g_3 F_3^*}{F_3^* - F_3} F_3 \quad (8.31)$$

Based on the aforementioned procedures, the developed approach's criterion function can be written as follows.

$$\text{Min } F = (g_1 \mu_1 - g_2 \mu_2 - g_3 \mu_3) - \left(\frac{g_1 F_1^*}{F_1^* - F_1} F_1 + \frac{g_2 F_2^*}{F_2^* - F_2} F_2 + \frac{g_3 F_3^*}{F_3^* - F_3} F_3 \right) \quad (8.32)$$

Subject to equations (4) - (10).

8.3.3.2 SO approach

In this approach, the auxiliary crisp model in section 8.3.2 is converted to mono-criterion function using the following solution formula (Selim and Ozkarahan, 2008a):

$$\text{Max } \lambda(x) = \gamma \lambda_o + (1 - \gamma) \sum_{f \in F} \theta_f \lambda_f \quad (8.33)$$

Subject to:

$$\lambda_o + \lambda_f \leq \mu(x), \quad f=1,2,3 \quad (8.34)$$

$$x \in F(x), \quad \lambda_o \text{ and } \lambda \in [0, 1] \quad (8.35)$$

In which, the value of variable $\lambda_o = \min \mu \{ \mu(x) \}$, which indicates the minimum satisfaction degree for each criterion function. Also, λ_f refers the difference between the satisfaction degree of each criterion and minimum satisfaction degree of criteria ($\lambda_f = \mu(x) - \lambda_o$).

8.3.4 The decision-making algorithm

The next step after revealing the Pareto solutions is to determine the best trade-off solution. The best Pareto optimal solution can be determined based on decision maker's preferences or by using a decision-making algorithm, although there are a number of approaches which can be utilized to determine the best solution in multi-criterion problems. In this study, TOPSIS (previously described in section 6.3.1.4) was employed for revealing the best trade-off solution. Figure 2 shows a flowchart of the proposed optimization methodology.

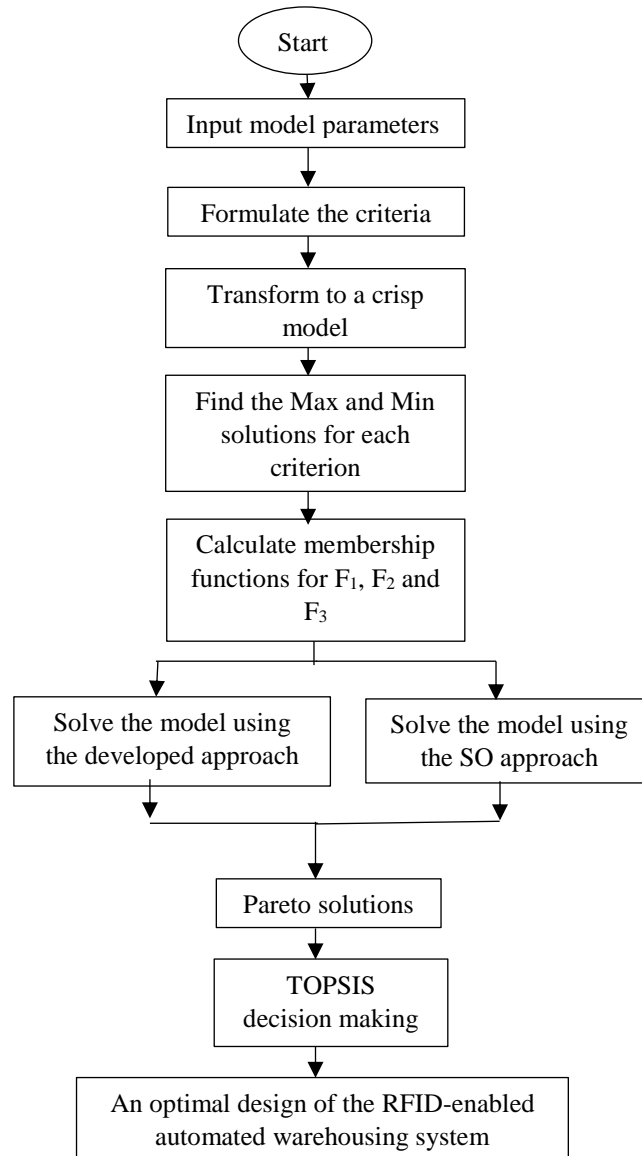


Figure 28. Flowchart of the optimization methodology.

8.4 Application and evaluation

In this section, a case study was used for examining the applicability of the developed tri-criterion model and evaluating the performance of the proposed optimization methodology. A range of application data is presented in Table 31. It is assumed that (1) width, length and height of each rack are $W = 0.3$ m, $L = 18$ m and $H = 5$ m, (2) the distance between the start of a spiral conveyer to the end of a collection points is 2 m, and (3) the pusher is located at the center of each rack. All these parameters are taken from a real-world automated warehouse design; the prices of RFID equipment and its implementation were estimated based on the marketing prices. The optimizer of the developed tri-criterion model is LINGO¹¹. All computational experiments were conducted on a laptop with a 2.60 GHz CPU and a 4 G memory.

Table 31. Application data used for the case study

$I = 12$	$C_i^t = 0.25$ £	$d_{jk} = 20-45$ m	$d_1 = 0.1 - 4$ m
$J = 15$	$C_{jk}^r = 0.4 - 0.7$ £	$S_c = 35$ m/s	$d_2 = 0.3$ m
$K = 2$	$R_j^l = 100$	$W = 48$	$d_3 = 7 - 23$ m
$C_j^l = 6.5 - 9$ £	$S_i = 25-35$ K£	$D_j = 6K - 9K$	$S_p = 1$ m/s
$C_i^r = 60-90$ K£	$S_j = 20-29$ K£	$C_j^c = 15-18$ K£	$S_{pp} = 0.8$ m/s

8.4.1 Results and discussions

This section presents the results which were obtained based on the developed fuzzy tri-criterion model using the proposed fuzzy solution approaches for the problem previously defined. The solution steps of the developed model are described as follows:

- 1) Obtain the upper and lower values for each criterion function by solving them individually. The results are $(\{U_{F_i}, L_{F_i}\}) = (\{504, 1,230\}, \{0.66, 0.94\}, \{4.27, 12.25\})$.
- 2) Convert the multi-objective crisp model to a single criterion model using (i) the developed approach by assigning weight values shown in Table 32, and (ii) the SO

approach by assigning the value of γ which is set as 0.33 by the decision makers who consider a balance in importance of each of the three criteria. The two approaches are compared by assigning different λ levels. Table 33 shows the computational results obtained using the two approaches. Accordingly, Table 34 shows the corresponding optimum numbers of storage racks and collection points that should be established. Figure 29 illustrates Pareto fronts among the three criterion functions obtained by using the two approaches.

- 3) Find the respective satisfaction degree $\mu(x_i)$ for each criterion function. The satisfaction degrees are reported in Table 35.
- 4) Select the best solution using the TOPSIS method, the scored values of Pareto-optimal solutions are reported in Table 36.

Table 32. Assignment of weight values for obtaining Pareto solutions using two approaches

#	Criteria weights		
	\mathcal{G}_1, θ_1	\mathcal{G}_2, θ_2	\mathcal{G}_3, θ_3
1	1	0	0
2	0.9	0.05	0.05
3	0.8	0.1	0.1
4	0.7	0.15	0.15
5	0.6	0.2	0.2
6	0.5	0.25	0.25
7	0.4	0.3	0.3
8	0.3	0.35	0.35

Table 33. The results obtained by assigning the varying values to each of the three criterion functions

378 non-zero elements, 64 constraints, 129 total variables, 68 integer variables									
#	λ -level	Developed approach				SO approach			
		Min F ₁ (K£)	Max F ₂ (%)	Min F ₃ (h)	Run time (s)	Min F ₁ (K£)	Max F ₂ (%)	Min F ₃ (h)	Run time (s)
1	0.3	504	0.66	4.29	2	504	0.66	4.29	2
2	0.4	595	0.71	5.31	2	595	0.71	5.31	3
3	0.5	678	0.78	6.51	2	681	0.78	6.58	2
4	0.6	795	0.84	7.75	1	790	0.84	7.69	3
5	0.7	894	0.89	8.92	3	913	0.89	9.12	4
6	0.8	978	0.92	10.18	4	1053	0.93	11.91	3
7	0.9	1064	0.93	11.97	4	969	0.92	10.33	4
8	1	-	-	-	-	1096	0.94	12.19	4

Table 34. The optimal number of storage racks and collection points that should be established

#	Developed approach		SO approach	
	Opened storage racks	Opened collection points	Opened storage racks	Opened collection points
1	6	9	6	9
2	6	9	6	9
3	7	8	7	8
4	9	11	9	11
5	10	12	10	13
6	11	13	12	14
7	11	13	11	13
8	-	-	12	15

Table 35. Result of satisfaction degree of each criterion function

$\mu(x_1)$	0.95	0.93	0.85	0.81	0.7	0.623	0.6	0.55
$\mu(x_2)$	0.7	0.78	0.83	0.88	0.92	0.97	0.98	0.99
$\mu(x_3)$	0.97	0.96	0.93	0.90	0.85	0.84	0.81	0.76

Table 36. Pareto-optimal solutions ranked based on scores using the TOPSIS method

Developed approach								
Solution	1	2	3	4	5	6	7	8
Score	0.245	0.234	0.266	0.245	0.2544	0.279	0.273	-
SO approach								
Solution	1	2	3	4	5	6	7	8
Score	0.245	0.234	0.266	0.245	0.2544	0.267	0.273	0.243

As mentioned above, Table 33 shows the obtained two sets of Pareto-optimal solutions, which were obtained based on the three criterion functions to determine the numbers of storage racks and collection points that should be established. For instance, solution 1 shown in Table 33 is obtained using the developed approach under an assignment of $\mathcal{G}_1 = 1, \mathcal{G}_2 = 0$ and $\mathcal{G}_3 = 0$, it gives the minimum total cost of 504 K£, the maximum capacity utilization of 66% and the minimum travel time for all the requested products of 4.29 h. The result shown in Table 34, the solution consists of six storage racks and nine collection points and these trade-off results are obtained based on the three criteria towards the minimization of total cost, the maximization of capacity utilization and the minimization of travel time. Nevertheless, as shown in Figure 29, with the Pareto optimal method, it cannot generate a better overall result by gaining one best result based on one criterion function without worsening the results in the other criterion functions, although all Pareto-optimal solutions are feasible. It proves the confliction among the three criteria. For instance, an increase in the

desired value of criterion two (e.g. maximization of capacity utilization) leads to an increase in the undesired value of criterion one (e.g. minimization of total cost).

It can be noted in Table 33 that by increasing the satisfaction level λ , it leads to an increase in the undesired value of the first and third criterion functions (e.g. minimization of total cost and minimization of travel time, respectively). Although it yields an increase in the desired value of the second criterion function (e.g. maximization of capacity utilization). In this case, decision makers have to spend more money to cope with the uncertainties. However, decision makers can vary weight the importance (ϱ_n , or Θ_f) of each of the three criterion functions and the satisfaction level λ based on their preferences in order to obtain another compromised solution.

Through a comparison of the two sets of Pareto-optimal solutions shown in Table 33, the values obtained based on the three criterion functions using the developed approach are more balanced than those (of solutions 6-8) using the SO approach. The optimization run time of using the developed approach for the eight iterations was slightly faster than the SO method. It also indicates that there is no feasible solution obtained using the developed approach when the weight for the first criterion (minimization of total cost) is set less than 0.4. This implies that decision makers cannot ignore the importance of cost as it yields an inapplicable warehouse design. In other words, with the developed approach it gives a more realistic and balanced solution.

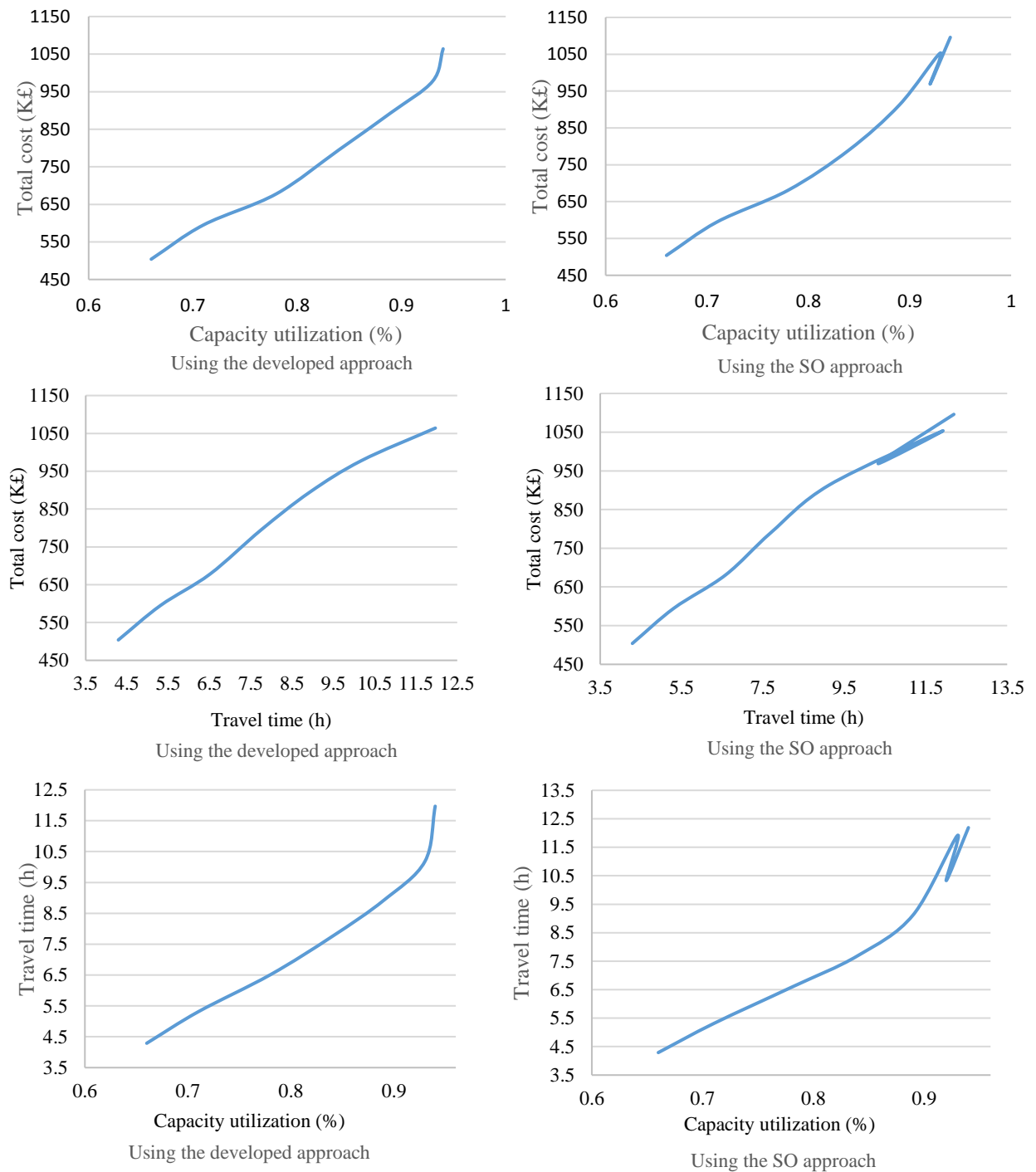


Figure 29. Pareto optimal fronts among the three criterion functions obtained by the two approaches.

After obtaining a set of Pareto-optimal solutions, decision makers may determine a solution depending on their preferences or using a decision-making algorithm. In this work, the TOPSIS method was employed to select the best solution. As shown in Table 36, solution 6 is chosen as the best solution as its score is the highest ($rcp = 0.279$) with the total cost of £

978K, 92% capacity utilization and the travel time of 10.18 h. Also, it requires an establishment of eleven storage racks to supply products to thirteen collection points.

8.5 Conclusions

In this chapter, a design of the proposed RFID-enabled automated warehousing system was studied using the multi-objective optimization approach. The work involved the optimization of the design in terms of (1) allocating the optimal number of storage racks and collection points that should be established, and (2) obtaining a trade-off decision between the negative impact of costs and the positive impact of maximization of the warehouse capacity utilization and minimization of travel time of products travelling from storage racks to collection points. To this aim, a tri-criterion programming model was developed and the model was also converted to be a fuzzy programming model for incorporating parameters that varied which include demands, costs and random locations of items in a warehouse. A two-stage solution methodology was proposed to solve the fuzzy multi-criterion optimization problem. At the first stage, the developed approach and the SO approach were used for obtaining two Pareto-optimal sets. The results, which were obtained using the two different approaches, are compared and it shows that both approaches are appropriate and efficient for the fuzzy multi-criterion model; for revealing a trade-off decision among the considered criteria. Nevertheless, the developed approach has more advantages, which includes (1) the solutions gained using this approach are more balanced than using the SO approach, (2) the run time (s) for using the developed approach is slightly faster than using the SO approach, and (3) it gives more realistic solutions for an applicable warehouse design. In the second stage, the TOPSIS method was employed to reveal the best Pareto solution. Finally, a case study was used to demonstrate the applicability of the developed model and the effectiveness of the proposed optimization methodology which can be useful as an aid for optimizing the design of the RFID-enabled automated warehousing system.

Design and optimization of an RFID-enabled Passport Tracking System

9.1 Introduction

The implementation of RFID technology has been subject to ever-increasing popularity in relation to the traceability of products as one of the most cutting edge technologies. Implementing such a technology leads to an increase in the visibility management of products. Notwithstanding this, RFID communication performance is potentially greatly affected by interference between the RFID devices. It is also subject to additional costs in investment that should be taken into account which are considered as a barrier for decision makers particularly for small-size manufactures. Karippacheril et al. (2011) have argued that reducing the cost of new tracking technologies, such as having cheaper RFID tags promotes better supply chains. Further, reducing costs and delivering efficient performance is expected to encourage (i) decision makers to contribute to the development and implementation of tracking systems and (ii) countries like China to implement tracking systems aimed at increasing their competitiveness in global industry (Xiao-hui et al., 2011). Thus, seeking a cost-effective design with a desired communication performance for the RFID-enabled systems becomes a key factor for competing among today's competitive markets. The design and optimisation of such systems needs to take into account both economical and performance criteria, to obtain a cost-effective design with reasonable performance. The optimisation of an RFID-enabled system is a typical multi-objective problem associated with several variables and imprecise parameters.

In this chapter, a multi-objective optimisation model (MOOM) for tackling a design problem for a proposed RFID-enabled passport tracking network is developed. The model is aimed at minimising the implementation and operational costs, minimising the RFID reader interference and maximising the social impact measured via the number of jobs created. Furthermore, to cope with the uncertainty in critical input parameters (i.e., costs and demands), the model is developed in terms of a fuzzy multi-objective model (FMOM). A decision-making algorithm previously described (see section 4.4.2) was used to select the

final trade-off. To the best of our knowledge, this is the first research work to apply the fuzzy multi-objective optimization model in such an RFID-enabled system considering all the three objectives (e.g. economical, performance and social) together that are considered in this research.

9.2 Model development

In In this work, a fuzzy multi-objective model is presented for a passport tracking system consisting of a set of three stages, called office 1, office 2 and office 3. Fig. 1 depicts the structure of the concerned three-stage passport tracking network. Office 1 receives the request for new/or to renew passports from clients. It is also responsible for checking whether the required documents are correct before sending them to office 2. Office 2 is responsible for issuing the new passports and checking whether the relevant information is correct (in case of renewing a passport). After that, it sends them to office 3 to be filled in and delivered to the clients. The RFID is proposed for implementation to improve system performance in terms of information accuracy, passport tracking for security purposes and to ease their issuing and renewing processes for the clients. Accordingly, such a system is subject to extra costs in investment that need to be considered. The developed FMOM is used for obtaining a cost-effective design in relation to the numbers of each office that should be established. Also, the aim is to obtain optimal trade-offs among the objectives previously described.

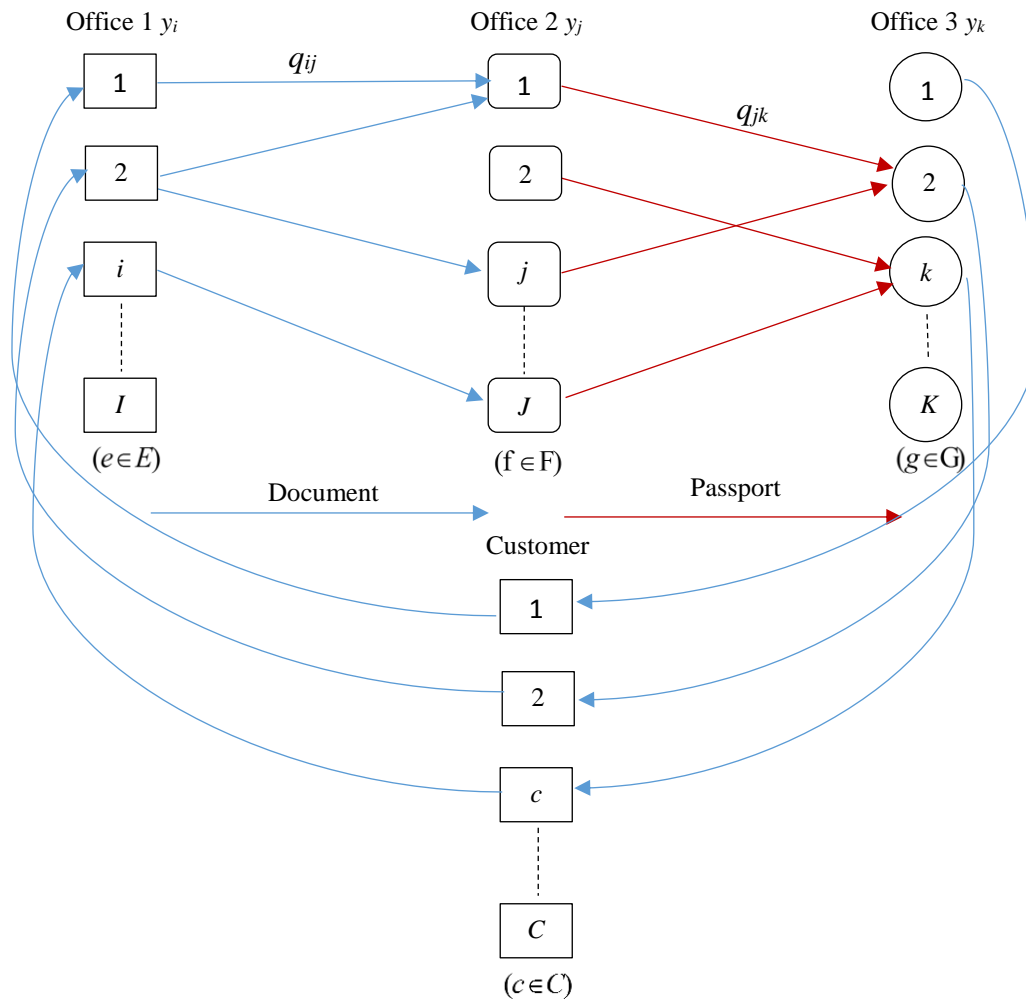


Figure 30. Structure of the system under study.

The aims of the fuzzy multi-objective model are:

- Minimise the costs required for implementing and operating the proposed RFID-enabled passport location tracking system;
- Minimise the interference that may occur among the RFID readers;
- Maximise the social impact in terms of the value generated due to establishing such a system and the creation of career opportunities.

The model is also aimed at determining a strategic design decision of the numbers of office 1s, 2s and 3s that should be established.

The following sets, parameters and decision variables were used for formulating the FMOM model:

Sets

I	set of nominated office 1 $i \in I$
J	set of nominated office 2 $j \in J$
K	set of nominated office 3 $k \in K$
C	set of customers $c \in C$

Parameters

C_{ij}^g	RFID tag cost (GBP) per item sent from office 1 i to office 2 j
C_i^r	RFID reader cost (GBP) required per office 1 i
C_j^r	RFID reader cost (GBP) required per office 2 j
C_k^r	RFID reader cost (GBP) required per office 3 k
C_i^s	fixed cost (GBP) required for the RFID management system
C_i^t	training cost (GBP) required per labourer at office 1 i
C_j^t	training cost (GBP) required per labourer at office 2 j
C_k^t	training cost (GBP) required for labourer at office 3 k
C_i^l	labourer cost per hour (GBP) at office 1 i
C_j^l	labourer cost per hour (GBP) at office 2 j
C_k^l	labourer cost per hour (GBP) at office 3 k
C_{ij}^l	cost (GBP) required for labourer transporting documents from office 1 i to office 2 j
C_{jk}^l	cost (GBP) required for labourer transporting passports from office 2 j to office 3 k
R_i	working rate (items) per labourer at office 1 i
R_j	working rate (items) per labourer at office 2 j
R_k	working rate (items) per labourer at office 3 k
R_{ij}	working rate (items) per labourer that transport document from office 1 i to office 2 j
R_{jk}	working rate (items) per labourer that transport passport from office 2 j to office 3 k
H_i	minimum required number of working hours (h) of labourers at office 1 i

- H_j minimum required number of working hours (h) of labourers at office 2 j
- H_k minimum required number of working hours (h) of labourers at office 3 k
- H_{ij} minimum required number of working hours (h) of labourers transporting documents from office 1 i to office 2 j
- H_{jk} minimum required number of working hours (h) of labourer transporting passports from office 2 j to office 3 k
- C_i maximum handling capacity (items) of office 1 i
- C_j maximum handling capacity (items) of office 2 j
- C_k maximum handling capacity (items) of office 3 k
- D_j demand (in units) of office 2 j
- D_k demand (in units) of office 3 k
- D_c demand (in units) of customer c
- ac_i number of career created if office 1 i is opened
- ac_j number of career created if office 2 j is opened
- ac_k number of career created if office 3 k is opened

Decision variables

- q_{ij} quantity of documents sent from office 1 i to office 2 j
- q_{jk} quantity of passports sent from office 2 j to office 3 k
- q_{kc} quantity of passports handed to customer c from office 3 k
- x_i required number of labourers at office 1 i
- x_j required number of labourers at office 2 j
- x_k required number of labourers at office 3 k
- x_{ij} required number of labourers required to transfer documents from office 1 i to office 2 j
- x_{jk} required number of labourer required to transfer passports from office 2 j to office 3 k

$$y_i = \begin{cases} 1: & \text{if office 1 } i \text{ is opened} \\ 0: & \text{otherwise} \end{cases}$$

$$y_j = \begin{cases} 1: & \text{if office 2 } j \text{ is opened} \\ 0: & \text{otherwise} \end{cases}$$

$$y_k = \begin{cases} 1: & \text{if office 3 } k \text{ is opened} \\ 0: & \text{otherwise} \end{cases}$$

9.2.1 Formulating the multi-objective optimization model

The model was developed based on the following assumption:

- There are no restrictions for sharing network resources as any office 1 may serve any office 2 and any office 2 may serve any office 3.
- Parameters related to costs and demands were considered as uncertain parameters.
- Each office is equipped with a RFID reader.
- Documents and/or passports are attached individually with a RFID tag.
- All demands from customers should be fulfilled.
- There is a certain capacity level of offices 1, 2 and 3.
- The quantity flow of documents from customer c to office 1 i is neglected as it considered as demands at office 1.
- Office 2 j and office 3 k are aware of the number of documents submitted to office 1 i and their demands are determined accordingly.

The three objectives (i.e., minimization of implementation and operational costs and RFID reader interference and maximization of social impact) are formulated as follows:

Objective function 1 (F_1)

Minimization of the implementation and operational costs of the RFID-enabled passport location tracking system = RFID tag cost of each item + RFID reader cost required for office 1 i , office 2 j and office 3 k + labourers costs at office 1 i , office 2 j and office 3 k + labourers costs required to transport documents from office 1 i to office 2 j and from office 2 j to office

3 k + training costs for labourer (s) at office 1 i , office 2 j and office 3 k . Thus, minimum F_1 is formulated as follows:

$$\begin{aligned} \text{Min } F_1 = & \sum_{i \in I} \sum_{j \in J} C_{ij}^g q_{ij} + \sum_{i \in I} C_i^r y_i + \sum_{j \in J} C_j^r y_j + \sum_{k \in K} C_k^r y_k + C_i^s + \sum_{i \in I} C_i^l x_i H_i \\ & + \sum_{j \in J} C_j^l x_j H_j + \sum_{k \in K} C_k^l x_k H_k + \sum_{i \in I} \sum_{j \in J} C_{ij}^l x_{ij} H_{ij} + \sum_{j \in J} \sum_{k \in K} C_{jk}^l x_{jk} H_{jk} + \sum_{i \in I} C_i^t x_i \\ & + \sum_{j \in J} C_j^t x_j + \sum_{k \in K} C_k^t x_k \end{aligned} \quad (9.1)$$

Objective function 2 (F_2)

Minimization of RFID reader interference is formulated as follows (Ma et al., 2014):

$$\begin{aligned} \text{Min } F_2 = & \sum_{m_i \in RS_i} \sum_{n_i \in TS_{m_i}} \left(\delta - \left(P_{n_i}^{m_i} - \sum_{l_i \in RS}^{l_i \neq m_i} P_{m_i}^{l_i} y_i \right) \right) + \sum_{m_j \in RS_j} \sum_{n_j \in TS_{m_j}} \left(\delta - \left(P_{n_j}^{m_j} - \sum_{l_j \in RS}^{l_j \neq m_j} P_{m_j}^{l_j} y_j \right) \right) \\ & + \sum_{m_k \in RS_k} \sum_{n_k \in TS_{m_k}} \left(\delta - \left(P_{n_k}^{m_k} - \sum_{l_k \in RS}^{l_k \neq m_k} P_{m_k}^{l_k} y_k \right) \right) \end{aligned} \quad (9.2)$$

where, $TS_{m_i, j \text{ or } k}$ is three sets of tags in the interrogation area of reader m at Offices 1, 2 and 3, respectively. $RS_{i, j \text{ or } k}$ is three sets of readers, which have tag n in their interrogation area at offices 1, 2 and 3, respectively. δ is the preferred power level; $P_{n_i, j, and k}^{m_i, j, and k}$ is the actual power level received by tag n in the interrogation area of reader m in office 1 i , office 2 j and office 3 k ; $P_{n_i, j, and k}^{l_i, j, and k}$ is the received power by tag n in the interrogation area of reader l in office 1 i , office 2 j and office 3 k (Ma et al., 2014). It should be noted that the number of readers is equal to the number of offices that need to be established. Also, the number of tags is equal to the quantity of items transported from office 1 to office 2, where each document is attached with a tag. This objective is aimed at taking into account all the readers, excluding the best, as sources of interference.

Objective function 3 (F_3)

Maximisation of social impact = Career opportunities created at office 1 i + career opportunities created at office 2 j + career opportunities created at office 3 k . Thus, maximum F_3 is formulated as follows:

$$Max F_3 = \sum_{i \in I} ac_i y_i + \sum_{j \in J} ac_j y_j + \sum_{k \in K} ac_k y_k \quad (9.3)$$

9.2.2 Constraints

There are a number of constraints that need to be looked at and included in the optimization.

The constraints are:

$$\sum_{i \in I} q_{ij} \leq C_i y_i \quad \forall j \in J \quad (9.4)$$

$$\sum_{j \in J} q_{jk} \leq C_j y_j \quad \forall k \in K \quad (9.5)$$

$$\sum_{k \in K} q_{kc} \leq C_c y_c \quad \forall c \in C \quad (9.6)$$

$$\sum_{i \in I} q_{ij} \geq D_j \quad \forall j \in J \quad (9.7)$$

$$D_j \geq \sum_{k \in K} q_{jk} \quad \forall j \in J \quad (9.8)$$

$$\sum_{k \in K} q_{kc} \geq D_c \quad \forall c \in C \quad (9.9)$$

$$\sum_{c \in C} q_{kc} \leq D_k \quad \forall k \in K \quad (9.10)$$

$$\sum_{j \in J} q_{jk} \geq D_k \quad \forall k \in K \quad (9.11)$$

$$\sum_{i \in I} q_{ij} \leq x_i R_i \quad \forall j \in J \quad (9.12)$$

$$\sum_{j \in J} q_{jk} \leq x_j R_j \quad \forall k \in K \quad (9.13)$$

$$\sum_{k \in K} q_{kc} \leq x_c R_c \quad \forall c \in C \quad (9.14)$$

$$\sum_{i \in I} q_{ij} \leq x_{ij} R_i \quad \forall j \in J \quad (9.15)$$

$$\sum_{j \in J} q_{jk} \leq x_{jk} R_j \quad \forall k \in K \quad (9.16)$$

$$q_{ij}, q_{jk}, q_{kc}, x_i, x_j, x_k, x_{ij}, x_{jk} \geq 0, \quad \forall i, j, k; \quad (9.17)$$

$$y_i, y_j, y_k \in \{0,1\}, \quad \forall i, j, k; \quad (9.18)$$

Equations 9.4-9.5 ensure the flow balance of documents from office 1 to office 2 and from office 2 to office 3 with respect to their capacity. Equations 9.7-9.11 ensure that all demands are satisfied. Equations 9.12-9.16 determine the number of labourer (s) required at office 1,

office 2, office 3, between office 1 and office 2 and between office 2 and office 3. Equations 9.17 and 9.18 limit the decision variables to binary and non-negative.

9.2.3 Modelling the uncertainty

To come closer to reality, the multi-objective model needs to handle the uncertainty of some input parameters i.e. costs and demands. Therefore, the model is converted into an equivalent crisp model using the Jiménez method as used previously (see sections 7.2.1 and 8.3.2). Accordingly, the equivalent crisp model can be formulated as follows:

$$\text{Min } F_1 = \sum_{i \in I} \sum_{j \in J} \left(\frac{C_{ij}^{gpes} + 2C_{ij}^{gmos} + C_{ij}^{gopt}}{4} \right) q_{ij} + \sum_{i \in I} \left(\frac{C_i^{rpes} + 2C_i^{rmos} + C_i^{ropt}}{4} \right) y_i \quad (9.19)$$

$$\begin{aligned} & + \sum_{j \in J} \left(\frac{C_j^{lpes} + 2C_j^{lmos} + C_j^{lopt}}{4} \right) y_j + \sum_{k \in K} \left(\frac{C_k^{rpes} + 2C_k^{rmos} + C_k^{ropt}}{4} \right) y_k + C_i^s + \sum_{i \in I} \left(\frac{C_i^{lpes} + 2C_i^{lmos} + C_i^{lopt}}{4} \right) x_i H_i \\ & + \sum_{j \in J} \left(\frac{C_j^{lpes} + 2C_j^{lmos} + C_j^{lopt}}{4} \right) x_j H_j + \sum_{k \in K} \left(\frac{C_k^{lpes} + 2C_k^{lmos} + C_k^{lopt}}{4} \right) x_k H_k + \sum_{i \in I} \sum_{j \in J} \left(\frac{C_{ij}^{lpes} + 2C_{ij}^{lmos} + C_{ij}^{lopt}}{4} \right) x_{ij} H_{ij} \\ & + \sum_{j \in J} \sum_{k \in K} \left(\frac{C_{jk}^{lpes} + 2C_{jk}^{lmos} + C_{jk}^{lopt}}{4} \right) x_{jk} H_{jk} + \sum_{i \in I} \left(\frac{C_i^{tpes} + 2C_i^{tmos} + C_i^{topt}}{4} \right) x_i + \sum_{j \in J} \left(\frac{C_j^{tpes} + 2C_j^{tmos} + C_j^{topt}}{4} \right) x_j \\ & + \sum_{k \in K} \left(\frac{C_k^{tpes} + 2C_k^{tmos} + C_k^{topt}}{4} \right) x_k \end{aligned}$$

$$\text{Min } F_2 = \sum_{m_i \in RS_i} \sum_{n_i \in TS_{m_i}} \left(\delta - \left(P_{n_i}^{m_i} - \sum_{l_i \in RS}^{l_i \neq m_i} P_{m_i}^{l_i} y_i \right) \right) + \sum_{m_j \in RS_j} \sum_{n_j \in TS_{m_j}} \left(\delta - \left(P_{n_j}^{m_j} - \sum_{l_j \in RS}^{l_j \neq m_j} P_{m_j}^{l_j} y_j \right) \right) \quad (9.20)$$

$$+ \sum_{m_k \in RS_k} \sum_{n_k \in TS_{m_k}} \left(\delta - \left(P_{n_k}^{m_k} - \sum_{l_k \in RS}^{l_k \neq m_k} P_{m_k}^{l_k} y_k \right) \right)$$

$$\text{Max } F_3 = \sum_{i \in I} ac_i y_i + \sum_{j \in J} ac_j y_j + \sum_{k \in K} ac_k y_k \quad (9.21)$$

Subject to:

$$\sum_{i \in I} q_{ij} \leq C_i y_i \quad \forall j \in J \quad (9.22)$$

$$\sum_{j \in J} q_{jk} \leq C_j y_j \quad \forall k \in K \quad (9.23)$$

$$\sum_{k \in K} q_{kc} \leq C_k y_k \quad \forall c \in C \quad (9.24)$$

$$\sum_{i \in I} q_{ij} \geq \frac{\lambda}{2} \frac{D_{j1} + D_{j2}}{2} + \left(1 - \frac{\lambda}{2} \right) \frac{D_{j3} + D_{j4}}{2} \quad \forall j \in J \quad (9.25)$$

$$\frac{\lambda}{2} \frac{D_{j1} + D_{j2}}{2} + \left(1 - \frac{\lambda}{2}\right) \frac{D_{j3} + D_{j4}}{2} \geq \sum_{k \in K} q_{jk} \quad \forall j \in J \quad (9.26)$$

$$\sum_{k \in K} q_{kc} \geq \frac{\lambda}{2} \frac{D_{c1} + D_{c2}}{2} + \left(1 - \frac{\lambda}{2}\right) \frac{D_{c3} + D_{c4}}{2} \quad \forall c \in C \quad (9.27)$$

$$\sum_{c \in C} q_{kc} \leq \frac{\lambda}{2} \frac{D_{k1} + D_{k2}}{2} + \left(1 - \frac{\lambda}{2}\right) \frac{D_{k3} + D_{k4}}{2} \quad \forall k \in K \quad (9.28)$$

$$\sum_{j \in J} q_{jk} \geq \frac{\lambda}{2} \frac{D_{k1} + D_{k2}}{2} + \left(1 - \frac{\lambda}{2}\right) \frac{D_{k3} + D_{k4}}{2} \quad \forall k \in K \quad (9.29)$$

$$\sum_{i \in I} q_{ij} \leq x_i R_i \quad \forall j \in J \quad (9.30)$$

$$\sum_{j \in J} q_{jk} \leq x_j R_j \quad \forall k \in K \quad (9.31)$$

$$\sum_{k \in K} q_{kc} \leq x_k R_k \quad \forall c \in C \quad (9.32)$$

$$\sum_{i \in I} q_{ij} \leq x_{ij} R_i \quad \forall j \in J \quad (9.33)$$

$$\sum_{j \in J} q_{jk} \leq x_{jk} R_j \quad \forall k \in K \quad (9.34)$$

$$q_{ij}, q_{jk}, q_{kc}, x_i, x_j, x_k, x_{ij}, x_{ij} \geq 0, \quad \forall i, j, k; \quad (9.35)$$

$$y_i, y_j, y_k \in \{0,1\}, \quad \forall i, j, k; \quad (9.36)$$

As mentioned previously (see sections 7.2.1 and 8.3.2), according to Jiménez's approach, it is assumed that the constraints in the model should be fulfilled with a confidence value which is denoted as λ and it is normally determined by decision makers. Also, *mos*, *pes* and *opt* are the three prominent points (the most likely, the most pessimistic and the most optimistic values), respectively (Jiménez et al., 2007).

9.3 Optimization methodology

The following solution procedures were followed to solve the fuzzy multi-objective optimization problem.

- (1) Find the upper and lower bound (U, L) solutions for each objective function. This can be obtained by:

Upper bound solutions:

$$Max F_1(U_1) = \sum_{i \in I} \sum_{j \in J} C_{ij}^g q_{ij} + \sum_{i \in I} C_i^r y_i + \sum_{j \in J} C_j^r y_j + \sum_{k \in K} C_k^r y_k + C_i^s + \sum_{i \in I} C_i^l x_i H_i \quad (9.37)$$

$$+ \sum_{j \in J} C_j^l x_j H_j + \sum_{k \in K} C_k^l x_k H_k + \sum_{i \in I} \sum_{j \in J} C_{ij}^l x_{ij} H_{ij} + \sum_{j \in J} \sum_{k \in K} C_{jk}^l x_{jk} H_{jk} + \sum_{i \in I} C_i^l x_i$$

$$+ \sum_{j \in J} C_j^l x_j + \sum_{k \in K} C_k^l x_k \quad (9.38)$$

$$Max F_2(U_2) = \sum_{m_i \in RS_i} \sum_{n_i \in TS_{m_i}} \left(\delta - \left(P_{n_i}^{m_i} - \sum_{l_i \in RS}^{l_i \neq m_i} P_{m_i}^{l_i} y_i \right) \right) + \sum_{m_j \in RS_j} \sum_{n_j \in TS_{m_j}} \left(\delta - \left(P_{n_j}^{m_j} - \sum_{l_j \in RS}^{l_j \neq m_j} P_{m_j}^{l_j} y_j \right) \right)$$

$$+ \sum_{m_k \in RS_k} \sum_{n_k \in TS_{m_k}} \left(\delta - \left(P_{n_k}^{m_k} - \sum_{l_k \in RS}^{l_k \neq m_k} P_{m_k}^{l_k} y_k \right) \right)$$

$$Max F_3(U_3) = \sum_{i \in I} ac_i y_i + \sum_{j \in J} ac_j y_j + \sum_{k \in K} ac_k y_k \quad (9.39)$$

Lower bound solutions:

$$Min F_1(L_1) = \sum_{i \in I} \sum_{j \in J} C_{ij}^g q_{ij} + \sum_{i \in I} C_i^r y_i + \sum_{j \in J} C_j^r y_j + \sum_{k \in K} C_k^r y_k + C_i^s + \sum_{i \in I} C_i^l x_i H_i \quad (9.40)$$

$$+ \sum_{j \in J} C_j^l x_j H_j + \sum_{k \in K} C_k^l x_k H_k + \sum_{i \in I} \sum_{j \in J} C_{ij}^l x_{ij} H_{ij} + \sum_{j \in J} \sum_{k \in K} C_{jk}^l x_{jk} H_{jk} + \sum_{i \in I} C_i^l x_i$$

$$+ \sum_{j \in J} C_j^l x_j + \sum_{k \in K} C_k^l x_k$$

$$Min F_2(L_2) = \sum_{m_i \in RS_i} \sum_{n_i \in TS_{m_i}} \left(\delta - \left(P_{n_i}^{m_i} - \sum_{l_i \in RS}^{l_i \neq m_i} P_{m_i}^{l_i} y_i \right) \right) + \sum_{m_j \in RS_j} \sum_{n_j \in TS_{m_j}} \left(\delta - \left(P_{n_j}^{m_j} - \sum_{l_j \in RS}^{l_j \neq m_j} P_{m_j}^{l_j} y_j \right) \right) \quad (9.41)$$

$$+ \sum_{m_k \in RS_k} \sum_{n_k \in TS_{m_k}} \left(\delta - \left(P_{n_k}^{m_k} - \sum_{l_k \in RS}^{l_k \neq m_k} P_{m_k}^{l_k} y_k \right) \right)$$

$$Min F_3(L_3) = \sum_{i \in I} ac_i y_i + \sum_{j \in J} ac_j y_j + \sum_{k \in K} ac_k y_k \quad (9.42)$$

(2) Find the respective satisfaction degree $\mu(x_i)$ for each objective as follows:

$$\mu_1(F_1(x)) = \begin{cases} 1 & \text{if } F_1(x) \geq U_1 \\ \frac{F_1(x) - L_1}{U_1 - L_1} & \text{if } L_1 \leq F_1(x) \leq U_1 \\ 0 & \text{if } F_1(x) \leq L_1 \end{cases} \quad (9.43)$$

$$\mu_2(F_2(x)) = \begin{cases} 1 & \text{if } F_2(x) \geq U_2 \\ \frac{F_2(x) - L_2}{U_2 - L_2} & \text{if } L_2 \leq F_2(x) \leq U_2 \\ 0 & \text{if } F_2(x) \leq L_2 \end{cases} \quad (9.44)$$

$$\mu_3(F_3(x)) = \begin{cases} 1 & \text{if } F_3(x) \geq U_3 \\ \frac{F_3(x) - L_3}{U_3 - L_3} & \text{if } L_3 \leq F_3(x) \leq U_3 \\ 0 & \text{if } F_3(x) \leq L_3 \end{cases} \quad (9.45)$$

Where, equations 9.43-9.45 indicate the satisfaction degree of the three objective functions, respectively. Further illustration about these membership functions is depicted in Figure 9.2.

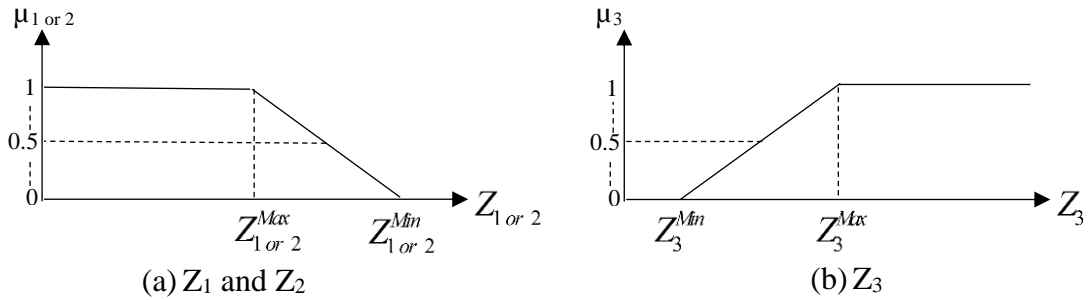


Figure 31. Membership functions of the objective functions (a) Z_1 and Z_2 , (b) Z_3 .

- (3) Optimize the crisp model obtained from section 9.2.3 using the proposed solution methods (section 9.3.1).
- (4) Select the best Pareto-optimal solution using the developed decision-making algorithm (section 9.3.2).

9.3.1 Solution approaches

9.3.1.1 The ϵ -constraint approach

With this approach, the equivalent solution formula F is given by:

$$\text{Min } F = \text{Min } F_1 \quad (9.46)$$

Subject to:

$$F_2 \leq \varepsilon_1 \quad (9.47)$$

$$[F_2]^{\min} \leq \varepsilon_1 \leq [F_2]^{\max} \quad (9.48)$$

$$F_3 \geq \varepsilon_2 \quad (9.49)$$

$$[F_3]^{\min} \leq \varepsilon_2 \leq [F_3]^{\max} \quad (9.50)$$

And Eq. 9.22-9.36.

In this work, minimization of the implementation and operational costs is kept as an objective function (Eq. 9.46) and minimization of reader interference and maximization of social impact are shifted to constraints (Eq. 9.47 and 9.49 respectively). Pareto solutions can be obtained by varying the ε value (Eq. 9.48 and 9.50). It should be noted that the selection of any objective to be an objective function or a constraint is not limited.

9.3.1.2 The developed approach

With the developed approach previously described (see section 4.4.1), the solution function F can be formulated as follows:

$$\begin{aligned} \text{Min } F = & (w_1\mu_1 - w_2\mu_2 - w_3\mu_3) \quad (9.51) \\ & - \left(\frac{w_1 F_1^*}{F_1^* - F_1} F_1 + \frac{w_2 F_2^*}{F_2^* - F_2} F_2 + \frac{w_3 F_3^*}{F_3^* - F_3} F_3 \right) \end{aligned}$$

Subject to Eq. 9.22-9.36.

9.3.2 The decision-making algorithm

With this method previously described (see section 4.4.2), the selection formula can be expressed as follow:

$$S = \sum_{i=1}^3 |F_i^+ - F_i| - \sum_{i=1}^3 |F_i - F_i^-| \quad (9.52)$$

Figure 32 shows a flowchart in developing and optimizing the FMOM.

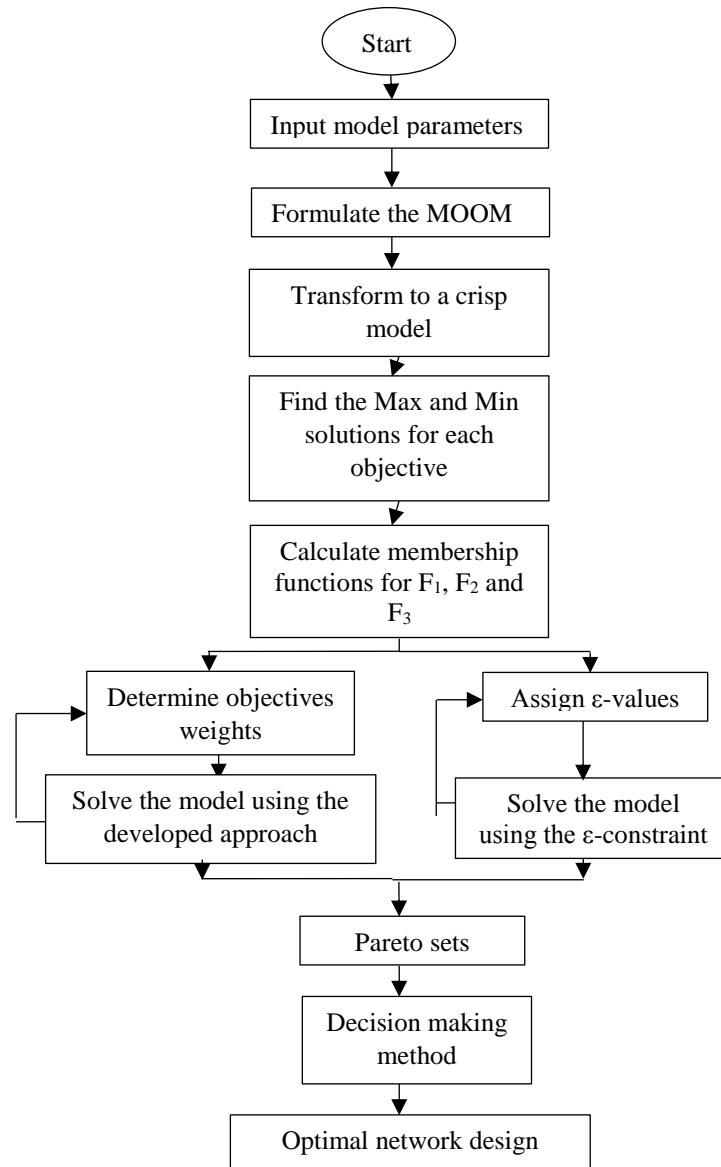


Figure 32. Flowchart of the FMOM.

9.4 Application and evaluation

Conducive to a quantifying of the applicability of the developed mathematical model and the proposed optimization methodology, a case study was applied. Table 37 shows data related to the investigated case study. Data was collected from the ministry of interior in Saudi Arabia. The demand reported in Table 37 is the total demand over a year horizon received from costumers to renew/or issue passports. Using the case study data, the proposed optimization methodology described in section 9.3 was applied to obtain Pareto solutions derived from the developed FMOM described in section 9.2.3.

Table 37. The values of parameters

Parameter	Value	Parameter	Value
C_{ij}^l	(15, 18)	D_j	(1400, 1500)
C_{jk}^l	(15, 18)	D_k	(1500, 1800)
C_{ij}^g	(0.15, 0.18)	D_k	(1700, 2000)
C_{jg}^t	(0.15, 0.18)	R_i	(43, 210)
C_i^r	(800, 950)	R_j	(110, 174)
C_j^r	(800, 950)	R_k	(110, 174)
C_k^r	(800, 950)	R_{ij}	(110, 174)
C_i^t	(800, 950)	R_{jk}	(110, 174)
C_j^t	(800, 950)	H_i	(271, 294)
C_i^l	(3.5, 4)	H_j	(271, 294)
C_i^l	(3.5, 4)	H_k	(271, 294)
C_i^l	(3.5, 4)	H_{ij}	(271, 294)
C_j^l	(3.5, 4)	H_{jk}	(271, 294)
C_k^l	(3.5, 4)	C_i	(1500, 1800)
D_f	(2200, 3000)	C_j	(1700, 2000)
ac_i	(8, 10)	C_k	(1700, 2000)
ac_j	(6, 8)	ac_k	(8, 10)

9.4.1 Results

This section presents the computational results derived from the FMOM using the proposed optimization methodology for the problem previously defined. The solution procedures are as follows:

- 1) Apply equations 9.37-9.42 to determine the upper and lower values for each objective function via optimizing them independently. The values are $(\{U_{F_i}, L_{F_i}\}) = (\{1419900, 498101\}, \{0.501, 0.128\}, \{58, 194\})$.
- 2) Optimize the FMOM model employing the two methods as follows (i) for the ϵ -constraint method: as illustrated in procedure 1, maximum and minimum values for each objective were obtained. The range between the maximum and minimum values was segmented into eight parts, the points in between were assigned as ϵ values (See Table 38) in equations 9.47 and 9.49. Then, Pareto solutions were obtained by implementing equation 9.46. The objective function related to the implementation and

operational costs was minimized while the reader interference and social impact were considered as constraints. Table 39 illustrates the results for eight ε -iterations; and (ii) for the developed method: each objective function was optimized independently under the defined constraints; the results are shown in Table 40. For example, optimizing the second objective (F_2) independently, the solutions of the three objective functions are determined as $F_1 = 498101$, $F_2 = 0.137$, and $F_3 = 63$. As illustrated in Table 40, the ideal solutions of the three objectives are boldfaced which are: $F_1 = 498101$, $F_2 = 0.128$, and $F_3 = 194$. Then, different combinations of weights were assigned (See Table 41) for the three objectives to obtain Pareto solutions. Table 42 shows Pareto solutions obtained by determining eight different weights for the three objectives. These solutions are associated with the number of offices 1, 2 and 3 that should be established.

- 3) Apply equations 9.43-9.45 to determine the satisfaction degree $\mu(x_i)$ for each objective function.
- 4) Choose the final Pareto solution using the developed decision-making algorithm, the calculated score values of the obtained solutions are shown in Table 42.

It should be noted that the ε -constraint approach and the developed approach were implemented with eight λ levels (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8). By setting these eight levels to λ , with steps 0.1 and implementing it to the model, eight Pareto solutions were obtained. Therefore, the model should be frequently solved for each λ level.

Table 38. Assignment of ε -value related to the ε -constraint approach

#	Assigned ε -value	
	ε_1	ε_2
1	0.141	58
2	0.174	76
3	0.222	94
4	0.258	112
5	0.291	130
6	0.355	160
7	0.400	178
8	0.500	194

Table 39. Results related to F_1 , F_2 and F_3 using the ε -constraint based on different λ values

#	λ -level	$\mu_1(F_1)$	$\mu_2(F_2)$	$\mu_3(F_3)$	Min F_1	Min F_2	Max F_3	Open office 1	Open office 2	Open office 3
1	0.1	0.955	0.922	0.244	505960	0.134	58	2	3	3
2	0.2	0.702	0.711	0.295	609141	0.174	76	3	3	3
3	0.3	0.583	0.495	0.422	715141	0.201	96	4	4	3
4	0.4	0.464	0.410	0.519	825141	0.251	115	4	4	4
5	0.5	0.354	0.307	0.761	960016	0.301	130	6	7	4
6	0.6	0.235	0.163	0.621	1035669	0.343	166	6	7	5
7	0.7	0.120	0.101	0.792	1145891	0.399	181	6	7	7
8	0.8	0.082	0.014	0.922	1379050	0.472	194	6	8	7

Table 40. Values of F_1 , F_2 and F_3 obtained by optimizing them individually

Objective functions	Min F_1	Min F_2	Max F_3
F_1	498101	0.137	59
F_2	520090	0.128	63
F_3	1399053	0.499	194

Table 41. Weights allocation related to the developed approach

#	w_1	w_2	w_3
1	1	0	0
2	0.9	0.05	0.05
3	0.8	0.1	0.1
4	0.7	0.15	0.15
5	0.6	0.2	0.2
6	0.5	0.25	0.25
7	0.4	0.3	0.3
8	0.3	0.35	0.35

Table 42 Results related to F_1 , F_2 and F_3 using the developed approach based on different λ values

#	λ -level	$\mu_1(F_1)$	$\mu_2(F_2)$	$\mu_3(F_3)$	Min F_1	Min F_2	Max F_3	Open office 1	Open office 2	Open office 3
1	0.1	0.967	0.922	0.244	515000	0.134	59	2	3	3
2	0.2	0.731	0.726	0.295	517118	0.138	76	3	3	3
3	0.3	0.598	0.526	0.422	741000	0.231	97	4	5	3
4	0.4	0.515	0.432	0.519	842222	0.277	116	4	5	5
5	0.5	0.369	0.329	0.761	926106	0.288	130	5	6	5
6	0.6	0.261	0.195	0.621	1050119	0.343	166	6	7	5
7	0.7	0.222	0.123	0.792	1172229	0.378	180	6	8	8
8	0.8	0.085	0.016	0.988	1390000	0.491	194	6	8	8

Table 43. Pareto-optimal solutions ranked based on scores using the developed decision-making algorithm

ϵ-constraint approach								
Solution	1	2	3	4	5	6	7	8
Score	0.27	0.26	0.23	0.21	0.21	0.29	0.28	0.31
Developed approach								
Solution	1	2	3	4	5	6	7	8
Score	0.27	0.25	0.22	0.20	0.19	0.27	0.27	29

As previously mentioned, Tables 39 and 42, show values of the three objective functions and number of offices 1, 2 and 3 that should be established. For example, solution#2 in Table 42 yields minimum implementation and operational costs that equals to 517,118 GBP, minimum reader interference that equals to 0.138 and maximum social impact that equals to 76. This solution was obtained by an assignment of $w_1 = 0.9$, $w_2 = 0.05$ and $w_3 = 0.05$. As shown in Table 42, this solution includes an establishment three offices 1, three offices 2 and three offices 3. It is noteworthy in these results that trade-offs among the three objectives (i.e., minimization of implementation and operational costs, minimization of reader interference and minimization of social impact) can be achieved. It can be noted in Table 39 and 42 that increasing the satisfaction level (λ -level) yields an increase in the undesired value of the first and second objective functions. On the contrary, it gives an increase in the desired value of the third objective function. This means that decision makers have to spend more money to cope with the uncertainties. However, decision makers can vary the importance weight of the

three objective functions (w), ε values and the satisfaction level (λ -level) based on their preferences to obtain another Pareto solution.

To compare the two Pareto sets obtained by using two different approaches, Figure 33 illustrates Pareto fronts corresponding to the optimization of the three objectives concurrently, using two solution approaches. The two approaches performed well in presenting alternative Pareto solutions. As shown in Figure 33, the objectives (i.e. implementation and operational costs, reader interference and social impact) are conflicting as it is impossible to obtain ideal values of the three objectives, simultaneously. In other words, Pareto solutions cannot get improved in one objective without deteriorating its performance in the other objectives.

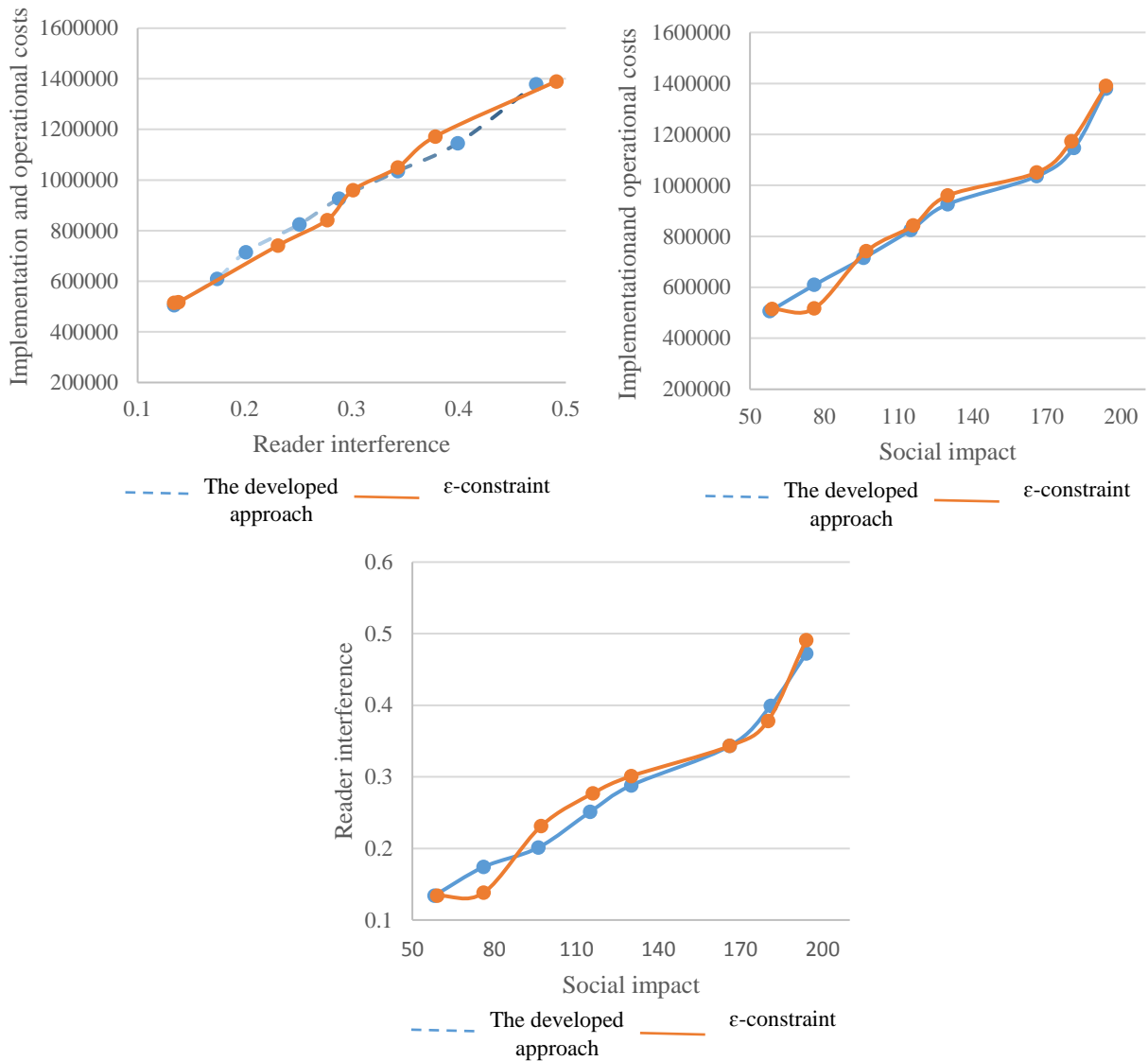


Figure 33. Pareto fronts for the three objective functions obtained using the two approaches. After obtaining Pareto solutions, stakeholders should choose one solution to design their system. As shown in Figure 33, the values of minimum implementation and operational costs and reader interference and maximum social impact are not considerably different for the two approaches. This makes direct selection of the final solution a challenge. Consequently, the developed decision-making algorithm was employed to reveal the final solution. As revealed in Table 42, solution#5 obtained using the developed approach is the best solution, since its score is the lowest ($FT = 0.19$). This solution requires 926,106 GBP as a minimum implementation and operational costs, a minimum reader interference equals 0.288 and a maximum social impact equals 130. It also needs an establishment of five office 1, six office 2 and five office 3.

9.5 Conclusions

In this study, a problem of a proposed RFID-enabled document location tracking system was investigated using a multi-objective optimisation approach. The system consisted three stages namely office 1, office 2 and office 3. The problem involved the design and optimisation of the proposed system by (i) allocating the optimal number of offices that should be opened and (2) obtaining compromised solutions among three objectives (e.g. minimisation of the implementation and operational costs, minimization of RFID reader interference and maximisation of social impact) of the proposed RFID-enabled document location tracking system. The problem was formulated as a multi-objective model that considers the objectives previously described. Moreover, to come closer to reality, critical parameters were considered as imprecise, these being demands, costs, and value generated due to implementing the proposed system. Accordingly, the model was developed in terms of a fuzzy multi-objective model, with a two-stage solution methodology being proposed to solve the problem. At the first stage, two solution approaches including ϵ -constraint approach and the developed approach were used for obtaining two sets of Pareto solutions. Moreover, evaluation of these two approaches in solution values is presented and the results are discussed. In general, ϵ -constraint and the developed approaches are appropriate and efficient for solving the fuzzy multi-objective problem; hence they can reveal trade-offs among the considered conflicting objective. Notwithstanding, the developed method has an advantage in revealing Pareto solutions that are closer to the ideal values of the three objectives. As a second stage, a developed decision-making algorithm was employed to help the decision makers in selecting the final Pareto solution. The selected solution was obtained via the developed approach which proved its efficiency over the ϵ -constraint approach. Finally, implementation within a case study verified the applicability of the developed mathematical model as well as the effectiveness of the proposed optimisation methodology in terms of: (i) presenting an optimal design for the RFID-enabled document location tracking system; (ii) obtaining trade-offs among the three objectives; and (iii) coping with the uncertainty in the input data. Consequently, the model can be configured and utilised as a reference for the designers of similar RFID-enabled passport tracking systems.

Conclusions and recommendations for future work

10.1 Concluding remarks

The aim of the study was to (1) present a framework for the development of an RFID-enabled monitoring system for a HMSC supply chain network for enhancing traceability of integrity and safety of Halal meat products, (2) develop a cost-effective decision making algorithm aimed at investigating the economic feasibility of the proposed RFID-enabled monitoring system, (3) examine the impact of the RFID system in terms of implementation and operational costs on HMSCs, and (4) develop effective multi-objective mathematical models and optimization approaches to support the meat supply chain configurations and analyses. A literature review shows that this area is overlooked by researchers.

10.2 Research contributions

The research outcomes based on the above studies demonstrate that it provides a framework for processing Halal meat products from farmers to retailers. Based on the developed Halal meat processes, the RFID-based monitoring system for the HMSC was developed for enhancing the traceability of integrity and quality of Halal meat products.

A multi-objective model based on the RFID-based HMSC was developed as an aid for examining the economic feasibility of the proposed RFID-based HMSC. The developed model was also aimed at maximizing the average integrity number of Halal meat products, the ROI and the capacity utilization of facilities and minimizing the total investment cost of the proposed RFID-monitoring system. To this aim, first, a deterministic multi-objective mixed integer linear programming model was developed and used for optimizing the proposed RFID-based HMSC network towards a comprised solution based on four conflicting objectives as described above. Second, a stochastic programming model was developed and used for examining the impact on the number of Halal meat products by altering the value of integrity percentage. The ϵ -constraint method and a developed method

were proposed for acquisition of non-inferior solutions obtained from the developed models. The research outcome shows the applicability of the developed method using a real case study. It also shows that a relatively higher ROI can be achievable by implementing RFID into the HMSC network. The study shows the developed methodology can be a useful tool for designers to determine a cost-effective design of food supply chain networks.

In Chapter 6, a study in developing a cost-effective three-echelon meat supply chain network design with a focus on the transportation activity was presented with an aim of minimizing the total cost of transportation, the number of transportation vehicles and the delivery time of meat products. The developed model was also used for determining the optimum numbers and allocations of farms and abattoirs that need to be established as well as the optimal quantity flow of livestock from farms to abattoirs and meat products from abattoirs to retailers. The three-echelon meat supply chain network was formulated as a multi-objective possibilistic mixed integer linear programming model with a focus on minimizing the total cost of transportation, the number of transportation vehicles and the delivery time of meat products. Three sets of Pareto-optimal solutions were obtained using the three different solution methods. These methods are the LP-metrics method, the ϵ -constraint method and the weighted Tchebycheff method, respectively. The TOPSIS method was used for seeking a best Pareto solution as a trade-off decision when optimizing the three conflicting objectives (i.e., the total cost of transportation, the number of transportation vehicles and the delivery time of meat products in this case study). A case study was also applied for examining the effectiveness and applicability of the developed multi-objective model and the proposed solution methods. The research concludes that the ϵ -constraint method has the superiority over the other two proposed methods as it offers a better solution outcome. The developed multi-objective possibilistic programming model can be used for determining a best solution for meat supply chains network design. The developed model can be a quick decision maker to tackle the relevant optimization issues in practice for supply chains network design as demonstrated through a case study.

The developed multi-objective optimization approaches were also applied to other 3 case studies. In Chapter 7, a product distribution planner for a three-echelon MSC design and distribution problem was developed. This includes numbers and locations of facilities that should be opened in association with the product quantity flows. The problem is formulated as a multi-objective programming model with an aim to minimize total transportation cost and environmental impact, particularly the CO₂ emission, as well as maximize average

delivery rate in satisfying product quantity as requested by abattoirs and retailers. Furthermore, the model is formulated in terms of a fuzzy multi-objective programming model to handle the uncertainties of the input data in the considered MSC. To optimize the three objectives simultaneously three solution methods are investigated namely LP-metrics, ϵ -constraint and goal programming. The obtained three Pareto sets of solutions are compared and the Max-Min method is implemented to find the best Pareto solution. The application of the developed model within a case study has proved its efficiency in presenting an optimal product distribution plan and trade-offs among the three objectives.

In Chapter 8, the developed solution approach was applied in a case study in investigating the design and optimization of a proposed RFID-enabled automated warehousing system in terms of the optimal number of storage racks and collection points that should be established in an efficient and cost-effective approach. To this aim, a fuzzy tri-criterion programming model was developed and used for obtaining trade-off decisions by measuring three conflicting objectives. These objectives are minimization of the warehouse total cost, maximization of the warehouse capacity utilization and minimization of the travel time of products from storage racks to collection points. To reveal the alternative Pareto-optimal solutions using the developed model, the developed solution approach was used and compared with a recently developed fuzzy approach so-called SO (Selim and Ozkarahan). A decision-making algorithm was used to select the best Pareto-optimal solution and the applicability of the developed model was examined using a case-study. Research findings demonstrate that the developed model is capable of generating an optimal solution as an aid for the design of the proposed RFID-enabled automated warehousing system.

In Chapter 9, it presents a cost and performance-effective design for a proposed RFID-enabled passport tracking system through the development of a multi-objective model that takes in account economic, performance and social criteria. The developed model is aimed at solving the design problem by (i) allocating the optimal numbers of related facilities that should be established and (ii) obtaining trade-offs among three objectives: minimising implementation and operational costs; minimising RFID reader interference; and maximising the social impact measured in the number of created jobs. To come closer to real design in terms of considering the uncertain parameters, the developed multi-objective model was developed in terms of a fuzzy multi-objective model. To solve the fuzzy multi-objective optimization problem, two solution methods were used. Subsequently, a developed decision-making method was used to select the final trade-off solution. A case study was applied to

examine the applicability of the developed model and the proposed solution methods. Research findings indicate that the developed model is capable of presenting a design for the RFID-enabled passport tracking system and trade-offs among the three objectives.

10.3 Recommendations for future work

The future work is recommended below:

- ❖ Implement the proposed RFID-enabled HMSC on a real case study.
- ❖ Compare the developed solution approach with the other approaches such as augmented e-constraint.
- ❖ Develop a multi-objective model to design a sustainable meat supply chain network considering economic, environmental and social responsibilities.
- ❖ Consider the facility disruption in the designed MSC network. This work aims to develop a resilient MSC network.
- ❖ Develop an integrated multi-criteria decision making-fuzzy multi-objective approach to obtain a sustainable supplier selection.
- ❖ Develop a methodology to formulate meat quality deterioration as an objective function within the multi-objective model used for decision-making on production and distribution of meat products in a MSC.
- ❖ Develop the fuzzy optimization models in terms of robust optimization models and compare the results.
- ❖ Optimize the developed mathematical models using a meta-heuristic algorithm as it was reported useful for handling large-sized problems in a reasonable time.
- ❖ Extend the multi-objective models to be multi-objective, multi-product and multi-period models.
- ❖ Present a comparison between the RFID-enabled automated warehousing system and the non-RFID-enabled automated warehousing system based on three criteria (e.g. minimization of total cost, maximization of capacity utilization and minimization of travel time). This includes a development of two multi-criteria models for the RFID-enabled automated warehouse and the non-RFID-enabled automated warehouse, respectively.

Acronyms

FSCM	Food Supply Chain Management
FSC	Food Supply Chain
FSCND	Food Supply Chain Network Design
HMSC	Halal Meat Supply Chain
MSC	Meat Supply Chain
HMC	Halal Meat Committee
RFID	Radio Frequency Identification
MOOM	Multi-Objective Optimization Model
FMOPM	Fuzzy Multi-Objective Programming Model
TOPSIS	The Technique for Order of Preference by Similarity to Ideal Solution
LP	Linear Programming
ROI	Return of Investment
GPS	Global Positioning System
GPRS	General Packet Radio Service

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