A Case Analysis of a Sustainable Food Supply Chain Distribution System – A Multi-Objective Approach

Abstract:
Sustainable supply chain management is a topical area which is continuing to grow and evolve. Within supply chains, downstream distribution from producers to customers plays a significant role in the environmental performance of production supply chains. With consumer consciousness growing in the area of sustainable food supply, food distribution needs to embrace and adapt to improve its environmental performance, while still remaining economically competitive. With a particular focus on the dairy industry, a robust solution approach is presented for the design of a capacitated distribution network for a two-layer supply chain involved in the distribution of milk in Ireland. In particular the green multi-objective optimisation model minimises CO_2 emissions from transportation and total costs in the distribution chain.

These distribution channels are analysed to ensure the non-dominated solutions are distributed along the Pareto fronts. A multi-attribute decision-making approach, TOPSIS, has been used to rank the realistic feasible transportation routes resulting from the trade-offs between total costs and CO_2 emissions. The refined realistic solution space allows the decision-makers to geographically locate the sustainable transportation routes. In addition to geographical mapping the decision maker is also presented with a number of alternative analysed scenarios which forcibly open closed distribution routes to build resiliency into the solution approach. In terms of model performance, three separate GA based optimisers have been evaluated and reported upon. In the case presented NSGA-II was found to outperform its counterparts of MOGA-II and HYBRID.

Keywords: Food supply chain distribution; Dairy market case analysis; Sustainable distribution routes; Multi-objective approach; Scenario analysis.

1. Introduction

The concept of the 'Triple Bottom Line' (Kleindorfer et al. 2005) or the 'Three Pillars' (White and Lee 2009) based on the principles of a balanced approach to the three P's of people, profit (or prosperity) and planet are now well known dimensions in modern business activities. There is now also clearer evidence that consumers are continuing to demand more environmentally friendly products and services, which in itself presents both opportunities and threats to many organisations (Byrne et al. 2013). From a global perspective, the introduction of the Kyoto protocol progressed this agenda while also encouraging firms to reduce carbon emissions throughout their operations (Diabat and Simchi-Levi 2009). It has also been reported that it is in the logistic operations where most organisations can and do implement green supply chain strategies (Kewill 2008).

The food industry is one such example of a dynamic environment where customers have high expectations for food safety and a growing demand for sustainably produced food and a high awareness of how food is produced and offered (Beske et al. 2014). The downstream distribution of food products to retailers or drop-off points plays a significant role in the environmental performance of food supply chains. Efficient logistics and technologies are critical success factors for distribution systems in most supply chain networks, including food (Tarantilis et al. 2005). Traditionally, the critical success factors for an effective distribution system included meeting the requirement of the demand side of the supply chain through delivery of good quality products in appropriate quantities to the right place using the optimal path at the right time with optimal costs (Aghazadeh 2004). However, distribution systems based solely on this singular dimension have over time begun to become obsolete as it does not consider the environmental impact of the system and increasing governmental regulations. The dairy industry is one such sector which is highly regulated and has been subjected to continued introduction of new environmental legislation in the last few years from both European and international directives (Glover et al. 2014). Hence, an effective blueprint for an economically competitive modern food market distribution systems calls for the inclusion of a methodology which can collectively deliver reduced environmental impact, lower operating costs and optimised traversed paths. This distribution strategy promotes an approach that seeks to achieve mutually reinforcing benefits for the economy, environment and society (Ilbery and Maye 2005).

This paper presents a robust solution approach which specifically focuses on a capacitated distribution model for the demand side of a two-layer dairy market supply chain in Ireland. Through a case, the development of the green multi-objective optimisation model which incorporates both cost and environmental performance is reported upon. The main objective of this solution approach is the provision of optimised distribution routes based on carbon output and costs for the demand side of a dairy supply chain producing milk products. The model has also been extended to incorporate a resiliency component, through the presentation of alternative scenarios, which necessitate the opening of heretofore closed routes. Three different Genetic Algorithm (GA) based meta-heuristic optimisers have been applied to the solution approach. GA optimisers are used due to the NP-hard nature of the green distribution problem under investigation, so as to yield feasible optimal and realistic distribution routes. A

comparative assessment of these three GA optimisers aids in precisely selecting the best optimiser for a green distribution system for the case in hand.

The remainder of this paper is organised as follows. The following section highlights the role of distribution systems in the overall sustainable supply chain context and includes identification and analyses of varying optimisation approaches that have been used in varying distribution settings. Section 3 introduces the case of the two-layer Irish dairy market supply chain, discusses the importance of the dairy sector in Ireland and presents the GA based multi-objective solution approach. The solution procedure including case results and model performance is presented in Section 4 using three different Genetic Algorithm (GA)-based optimisers. Section 5 analyses the case results further and provides a scenario analysis based on the realistic solutions. Finally, Section 6 summarizes the findings from the case and presents opportunities for further research in this domain.

2. Distribution Systems and the Food Supply Chain

One of the major sources of environmental concern is in relation to the distribution of products and from the emissions through their transportation. This concern is expected to increase faster than the growth of GNP in the industrialised world (Aronsson and Brodin 2006). Such concerns and proactive planning have been in existence now since the early parts of the 2000's (European Commission, 2001). Since then there have been continued efforts by individual organisations, supply chains and international bodies, including the European Union (EU) to decrease the total emissions from the transportation sector. However, plenty of scope is still available to optimise the carbon emissions from a two-layer distribution system.

The traditional methodologies of handling food market distribution through storage and transportation of perishable food products (Aghazadeh 2004) is not sufficient on its own in today's sustainable environment. In addition to ensuring a regular and complete coverage of all facilities in the supply chain (Aghazadeh 2004) significant management of the carbon issues in the distribution system is also required (Benjaafar et al. 2013). Wu and Dunn (1995) focus on the use of proactive environmental management within the logistics framework. It has been well reported that one of the main challenges for modern logistic systems is to determine how environmental management principles can be incorporated into the system's operational decision-making process (Wu and Dunn 1995; Robinson and Wilcox 2008; Pagell and Wu 2009). An example of a coordinated distribution system, which incorporates an improvement in logistics efficiency while simultaneously reducing environmental impact, is reported by Bosona and Gebresenbet (2011) for a Swedish food market supply chain.

An improved food distribution system can be designed using location routing optimisation techniques (Bosona et al. 2011). Several optimisation techniques have been applied in designing distribution systems. Optimisation techniques are used for reducing operational and overall costs in different distribution systems, for example, food and drink distribution (Watson-Gandy and Dohrn 1973), goods distribution (Perl and Daskin 1984, 1985), agricultural goods transport (Ljungberg et al. 2007), forest harvesting (Rönnqvist et al. 2007), waste collection (Apaydin and Gonullu 2008; Caballero et al. 2007; Kulcar 1996), disposal of

hazardous material (Alumur and Kara 2007), obnoxious facility location-routing (Cappanera et al. 2004), small package shippers (Stenger et al. 2012), shipping industry (Gunnarsson et al. 2006), blood bank location (Or and Pierskalla 1979) and medical evacuation (Chan et al. 2001).

Green supply chain initiatives have been comprehensively categorised by Srivastava (2007). One of these defined initiatives is green operations in the distribution of products. The solution approach presented in this paper focuses on the green operations of a two-layer supply chain from a transportation logistics perspective. Green initiatives associated with distribution in supply chains have in recent years been presented, particularly in green reverse logistics (Fleischmann et al. 2001; Zhu et al. 2008; Neto et al. 2009). Trade-offs between cost factors and environmental impact of a supply chain is reported in Wang et al. (2011). A green-vehicle routing problem is reported by Erdoğan and Miller-Hooks (2012), which uses a mixed integer linear programming approach. A dairy manufacturer's two-layer supply chain distribution system is reported using a multi-objective programming approach (Validi et al. 2012). In addition, several different optimisation techniques have been adopted by researchers in distribution system problems. A short up to date synopsis of optimisation models in distribution systems is presented in Table 1, but for a more detailed historical survey of the varying distribution system techniques and their origins the interested reader is referred to Madsen (1983), Min et al. (1998), Kenyon and Morton (2001), and Nagy and Salhi (2007).

Table 1: A synopsis of the reported optimisation techniques

Optimisation techniques used	Publications
Self-organised optimisation using artificial neural network	Schwardt and Fischer (2009)
Honey bees mating optimisation	Marinakis et al. (2008)
Ant colony optimisation	Bell and McMullen (2004), Bin et al. (2009), Ting and Chen (2013)
Particle swarm optimisation	Yang and Zi-Xia (2009); Liu et al. (2012)
Tabu search	Gendreau et al. (1994), Melechovský et al. (2005), Albareda-Sambola et al. (2005), Caballero et al. (2007)
Simulated annealing	Lin et al. (2002), Yu et al. (2010), Stenger et al. (2012).
Greedy randomised adaptive search optimisation	Prins et al. (2006), Duhamel et al. (2010), Nguyen et al. (2012)
Variable neighbourhood search optimisation	Melechovský et al. (2005), Ghodsi and Amiri (2010), Derbel et al. (2011)
Genetic algorithms	Zhou and Liu (2007), Marinakis and Marinaki (2008), Jin et al. (2010), Karaoglan and Altiparmak (2010)
Branch and cut optimisation	Belenguer et al. (2011), Karaoglan et al. (2011)
Mixed-integer programming; Integer linear programming	Alumur and Kara (2007), Diabat and Simchi-Levi (2009); Laporte et al. (1989); Ambrosino and Scutella (2005)

3. The Dairy Market Supply Chain – Irish Case Review

For a long period of time the Irish dairy sector has been one of the most important sectors within the Irish food processing industry (Collins et al. 1999). As a consumer product, milk is considered as a staple food product in the Irish diet. Ireland is in the third position globally with regard to per capita consumption of liquid milk. In Ireland an average of 5.4 billion litres of cow's milk is produced per annum. The country's pasture-based production system makes Irish dairy farming the world's most efficient one. However, sustainable production of milk which considers all three aspects of environmental, social and economic, is considered as extremely important to the future growth of the sector in an international marketplace (ICOS-a 2012).

The dairy industry in its totality and the milk supply chain has always been of huge importance to Ireland. The dairy sector accounts for 38% of Ireland's total agricultural output. The E.U.'s current Quota level is 231,000 tonnes. However in 2015 the milk quotas are set to disappear thus providing Irish farmers with the opportunity to pursue greater efficiency and profits through increased volumes (ICOS-b). This coupled with worldwide population growth and increased demand for dairy produce from China and Middle Eastern countries makes for a bright future for the Irish dairy sector. Irish farmers currently produce approximately 5 million tonnes per annum, that's enough milk to feed 52 million people (ICOS-b). Liquid milk comprises 47% of the Irish retail dairy market and is valued at close to €450m annually. Ireland provides 4% of the milk for the EU but accounts for only 1% of the population More than €2bn dairy products are exported annually and with international growth and the removal of milk quotas this is expected to grow by up to 50% by 2020. The importance of the dairy industry in Ireland is very significant and is expected to increase in significance over the next number of years (safefood 2008). In addition to this the Irish dairy industry has continued to remain at the forefront of environmental performance over the recent past. As a testament to this in 2011, the JRC of the European Commission found that Ireland's dairy industry had the lowest carbon footprint in Europe. Thus, it is clear to see that both milk production and processing in combination with distribution system advancement from both an environmental and cost perspective are of significant importance to the Irish economy.

The information presented in the case hereafter has been obtained from interactions with a number of dairy processors in Ireland and is typical of the distribution supply chains in existence. As part of the study key informants in the dairy processing organisation were interviewed in a semi-structured format using the outline questionnaire presented in Table 2. The questionnaire was executed in an informal manner and was used as a guide to extract relevant information. Information was gathered from stakeholders at both strategic and tactical management levels from the organisation. For the purpose of anonymity an assumed data set is presented in this paper which is reflective of the real case but not absolute. The case presented in this paper has two dairy processing plants serving twenty two Drop-off Points (DoP), based on a 50 mile radius from both plants, representing each of the main cities/towns in this region of Ireland (Table 3). Demand for milk products is considered to be

proportional to the population base in each of these locations, and in this case is considered to equate to 2/3rd of the population of the city/town (Table 3). Multiple routes are available for connecting these DoPs to the plants.

Table 2: Questionnaire
1. Processing plants: - How many dairy processing plant(s) does your company operate?   - Where are the processing plants located geographically?   - How do you make decision on the geographical location of your dairy processing plants? What criteria are considered? (i.e. costs, distance from market, etc.)
2. Drop-off Points: - How many DoPs does your company own?   - Where are these DoPs located geographically?   - What criteria are considered in making a decision on the geographical location of the DoPs?   - Do you use any decision-making tool in locating the DoPs? If yes please explain.   - What is the capacity of these DoPs?   - How do you make a decision about the capacity of the DoPs?   - Do you rent any DoPs in Ireland? If yes; how do you decide what DoP to rent?
3. Customers (wholesalers/retailers):   - How do you make a decision about which part of the dairy market in Ireland you plan to cover from your processing plants?   - How many counties in Ireland do you consider as your customers?   - How much demand for your products can be attributed to each of these counties?   - What percentage of the total demand in these areas is covered by your own organisation?
4. Transportation decisions   - What criteria are currently considered when selecting the best route to connect each of your processing plants to individual DoPs?   - Do you use any decision-support tool to make distribution decisions?   - Does your company own its own transportation fleet?   If you do own your own transportation fleet   - What types of vehicles are currently used to transport your dairy products from dairy processing plants to DoPs?   - What criteria do you consider when choosing the type of vehicle for transporting your products?   - Do you consider speed limits for vehicles on different types of roads while transporting the dairy products through your dairy supply chain?
5. Environmentally Policies   - Does your company consider 'green' (environmentally friendly) issues in supply chain?   - If 'Yes' – What are these 'green' issues? And how are 'green' policies implemented.   - If your company own its own transportation fleet; have you conducted a study to measure its environmental impact?   - If transportation is outsourced; does your company ask the transportation company to provide information on its environmental impact?   - Do you know your carbon footprint?

The number of layers in the supply chain represents its main tiers. In this paper two-layers of the network are analysed on the demand side of the milk supply chain. More specifically these two layers constitute the dairy processing plants and the downstream DoPs, which in this case represent a plant(s) and customer(s) respectively (Hassanzadeh et al. 2009). Optimisation models for two-layer distribution systems are presented in Berger (1997) and Hassanzadeh et al. (2009). The supply chain distribution system can also be extended to three-layers (Perl 1983; Perl and Daskin 1985) and also four-layers (Hamidi et al. 2012).

The vehicles considered for transportation of the dairy products play a vital role in calculating the CO_2 emission. In the presented case for milk distribution, these vehicles are refrigerated to deliver perishable dairy products and they are either heavy duty vehicles or heavy goods vehicles. The condition and type of roads contribute to the total emission from these vehicles. Speed limits of the vehicles also contribute to emissions. Thus, the speed of the vehicles varies depending on numerous issues on the routes. Therefore, an average speed on each type of road for all possible milk distribution routes is calculated and used. The permissible speed limits stipulated by the 'Road Traffic Act 2004' in Ireland and the average working speeds considered during transportation are depicted in Table 1A.

Table 3: Drop-off points and product demand

Customer ($i \in I$)	Demand (unit)	Customer ($i \in I$)	Demand (unit)
1. Drogheda	25,000	12. Greystones	11,000
2. Dundalk	25,000	13. Clonmel	12,000
3. Navan	19,000	14. Waterford	35,000
4. Tullamore	9,000	15. Tramore	7,000
5. Naas	14,000	16. Kilkenny	16,000
6. Newbridge	14,500	17. Wexford	13,000
7. Leixlip	10,000	18. Enniscorthy	7,000
8. Port Laoise	9,000	19. Dublin City	350,000
9. Bray	21,000	20. Dun Laogharire / Rathdown	138,000
10. Arklow	9,000	21. Fingal	182,000
11. Wicklow	7,000	22. South Dublin	177,000

3.1 Sustainable two-layer dairy market supply chain model

The questionnaire-based survey reveals that the dairy organisations in Ireland are keen to continue to attempt to further minimise the total carbon emission and the total costs associated with the transportation process. The specific two-layer supply chain, being reviewed in this paper, connecting the dairy processing plants and the DoPs is illustrated in Fig. 1.
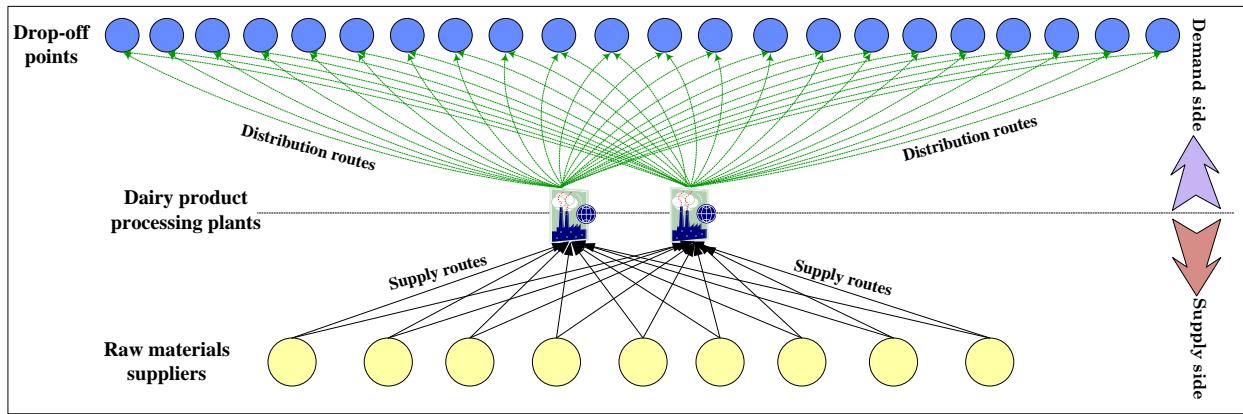
Figure 1: The two-layer diary product distribution system

The overall supply chain has two parts, which consist of supply and distribution routes. The distribution system considers only the demand side of the supply chain which has two interconnected layers – the plant and the DoP layers. There may be distribution centres located in between these two layers. Based on this desire by the Irish dairy processing organisations to continue to advance their environmental agenda and the obvious requirement to do this at minimised cost led to the development of a 'green' distribution multi-objective optimisation model for the two-layer dairy market supply chain with a particular focus on milk distribution in Ireland. The 'green' distribution optimisation model has been developed using integrated multi-objective mathematical programming. The optimisation model is formulated within a mixed integer programming framework. In addition to a cost objective function, the model includes a 'green' objective function that aims to minimise the total CO_2 emission during the transportation of the products from plants to DoPs (Validi 2014).

The two-layer optimisation model as presented was implemented considering some preliminary assumptions. In this sustainable two-layer distribution system multiple DoPs (twenty-two) and a single dairy product (milk) was considered. The two dairy processing plants always remain open. The locations of the two processing plants and twenty-two DoPs (here primary consumers) are known. The questionnaire-based survey also revealed that the total demand from the DoPs is less than or equal to the total capacity of the two plants, thus the processing plants are capable of meeting the demand requirements from all DoPs spread across sixteen counties in Ireland. A portion of the models variable costs is dependent on the demand at the DoPs. Each distribution route and DoP is completely served by one vehicle. Diesel operated refrigerated heavy duty vehicles/heavy goods vehicles with similar vehicle capacities are considered. Transportation of dairy products between the processing plants and DoPs results in CO_2 emissions. Fuel consumption of the vehicles is dependent on the total mass of the vehicles. Three different types of vehicles with two attributes (cost and environmental impact) are considered for the distribution logistics. The nomenclature is presented in Table 4 and the general approach, including the modelling, solution and analysis phase is presented in Fig 1A.

Table 4: Nomenclature (Validi 2014)			
Parameters		S_m	The parameter that takes the values of p_{ji} and c_{jk} depending on the values of B_m
f_j	Sum of fixed cost of plant $\forall j \in J$	**Decision variables**	
c_{jk}	Cost of serving the path $k \in P_j$ $\forall j \in J$	T_n	Vehicles of different specifications
v_j	Sum of variable costs for serving customers at each plant $\forall j \in J$	V_{jk}	Decision variable (=1 if path $k \in P_j$ is operated out of plant $j \in J$, = 0 if not)
r_i	Demand at consumer location $\forall i \in I$	**Sets and indices**	
w_{mn}	Weight matrix for trucks/vehicles	I	Set of consumer locations indexed by i
p_{ji}	CO_2 emission caused from transportation	J	Set of dairy product processing plants indexed by j
a_j	Variable cost of providing the consumer with the dairy products, per unit $\forall j \in J$	P_j	Set of feasible paths for plants $\forall j \in J$
z	Speed in different roads in *km/hr*	K	Set of routes indexed by k
X_j	Dairy product processing plants	M	Number of decision-making attributes indexed by m
B_m	Two limits of the decision-making attributes (Right hand side of the matrix)	N	Number of alternative trucks/vehicles indexed by n

For the dairy supply chain the sets and indices of the integrated methodology are as follows: $i = 1, 2, ..., 22$, $j = I, II$, $k = I1, I2, ..., I22, II1, II2, II22$, $m = 2$ and $n = 3$.

Similarly the decision variables are:

V_{jk} : $V_{I,I1}, V_{I,I2}, ..., V_{I,I22}$; $V_{II,II1}, V_{II,II2}, ..., V_{II,II22}$ and T_N : T_1, T_2, T_3.

In the first instance, the multi-objective model includes a 'green' objective function that aims to minimise the total CO_2 emission during the transportation of the dairy products from plants to the DoPs:

$$\text{Min} \begin{pmatrix} p_{I1} & p_{II1} \\ p_{I2} & p_{II2} \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \\ p_{I22} & p_{II22} \end{pmatrix} \begin{pmatrix} V_{I,I1} & V_{I,I2} & ... & V_{I,I22} \\ V_{II,II1} & V_{II,II2} & ... & V_{II,II22} \end{pmatrix} \qquad \text{... (1)}$$

Secondly, the multi-objective model minimises the total costs associated with the distribution of the products. The total cost involves the summation of the fixed costs for operating the facilities (i.e., plants), the variable costs for serving the customers and the costs for transportation. Hence, the second objective function is:

$$\text{Min} \begin{pmatrix} f_I & f_{II} \end{pmatrix} \begin{pmatrix} X_I \\ X_{II} \end{pmatrix} + \begin{pmatrix} v_I & v_{II} \end{pmatrix} \begin{pmatrix} V_{I,I1} & V_{I,I2} & \cdots & V_{I,I22} \\ V_{II,II1} & V_{II,II2} & \cdots & V_{II,II22} \end{pmatrix} + \begin{pmatrix} c_{I,I1} & c_{II,II1} \\ c_{I,I2} & c_{II,II2} \\ . & . \\ . & . \\ . & . \\ c_{I,I22} & c_{II,II22} \end{pmatrix} \begin{pmatrix} V_{I,I1} & V_{I,I2} & \cdots & V_{I,I22} \\ V_{II,II1} & V_{II,II2} & \cdots & V_{II,II22} \end{pmatrix} \qquad \dots (2)$$

From the survey it is apparent that there are some operational constraints linked to of these two objective functions. The first of these is associated with the demand node on each route of the distribution system, which is illustrated in the first constraint (3) below:

$$\text{subject to:} \begin{pmatrix} V_{I,I1} & V_{II,II1} \\ V_{I,I2} & V_{II,II2} \\ V_{I,I3} & V_{II,II3} \\ \vdots & \vdots \\ \vdots & \vdots \\ V_{I,I20} & V_{II,II20} \\ V_{I,I21} & V_{II,II21} \\ V_{I,I22} & V_{II,II22} \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \\ \vdots \\ \vdots \\ 1 \\ 1 \\ 1 \end{pmatrix} \qquad \dots (3)$$

As the plants are always open and routes have known start and stop points, a route is assigned only to one open processing plant (facility), i.e.,

$$\begin{pmatrix} V_{I,I1} & V_{II,II1} \\ V_{I,I2} & V_{II,II2} \\ V_{I,I3} & V_{II,II3} \\ \vdots & \vdots \\ \vdots & \vdots \\ V_{I,I20} & V_{II,II20} \\ V_{I,I21} & V_{II,II21} \\ V_{I,I22} & V_{II,II22} \end{pmatrix} - \begin{pmatrix} X_I & X_{II} \end{pmatrix} \leq \begin{pmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ \vdots \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \dots (4)$$

An AHP constraint has been integrated with the 0-1 programming model which determines the type of the vehicle used for distribution of the products. This is known as the AHP constraint:

$$\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} \begin{bmatrix} \begin{pmatrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} \end{bmatrix} \leq \begin{pmatrix} B_1 \\ B_2 \end{pmatrix} \qquad \dots (5)$$

One vehicle in each of the iterations is selected. Therefore,

$$\begin{pmatrix} T_1 & T_2 & \cdots & T_n \\ T_1 & T_2 & \cdots & T_n \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \qquad \dots (6)$$

Constraint (5) uses the concept of Analytic Hierarchy Process (AHP) – a multi-criteria decision-making tool. This AHP-integrated constraint within the mixed-integer framework introduces the flexibility in the decision-makers' consensus opinions in selecting the types of the vehicles/trucks used for the distribution of the dairy products in an environmental-friendly manner. The decision-makers in the dairy market supply chain may consider a number of different vehicles depending on their own individual requirements. The level of CO_2 emissions and costs are different for different vehicle types. The two attributes associated with this decision-making process for these vehicles are CO_2 emissions and costs. The element w_{mn} of constraint (5) uses the results obtained through AHP. S_m takes the values of CO_2 emissions (p_{ji}) and costs (c_{jk}) depending on the B_m positional value (e.g. CO2 emissions or costs). A provision has been made for the consideration of a number of vehicles in the integrated model and the AHP process involving the decision makers' consensus opinion.

The decision variables of the 'green' model are:

$$V_{jk} = \begin{cases} 1, & \text{if path } k \in P_j \text{ is operated out of plant } j \in J \\ 0, & \text{if not} \end{cases} \qquad \dots (7)$$

$$T_n = \begin{cases} 1, & \text{if vehicle type } n \in T_n \text{ is selected to transport the products} \\ 0, & \text{otherwise} \end{cases} \qquad \dots (8)$$

The 'green' distribution model considers the variable costs required to serve routes from the plants to drop-off points. This generates the following relationship:

$$v_j = (a_j \cdot r_i) \qquad \dots (9)$$

As there is no direct equivalent in Ireland and there is direct transferability of findings between the UK and Ireland, this research considers the report of the Department of Energy & Climate Change, UK (2010) and Nylund and Erkkilä (2005) in the framing of the relationship between CO_2 emissions and the litres of diesel burnt in trucks. The fuel efficiency was found to be 0.35 l/km and was used to determine the litres of diesel burnt on

each route. Therefore the relationship between the litres of diesel burnt on each route and fuel efficiency is as follows:

Litres of diesel burnt in each path = fuel efficiency × Distance (in *km*)   … (10)

CO_2 emissions from a diesel vehicle has been ascertained from DEFRA's (2008) guidelines on greenhouse gas conversion factors. Thus, the total CO_2 emission from the vehicles is estimated using equation (11).

CO_2 emission from a Diesel vehicle (in *kg*) = Litres of Diesel burnt × 2.64   … (11)

The cost of serving each of the twenty-two distribution routes is the sum of fuel costs and driver's wage:

Cost of serving a route = (Litres of Diesel burnt per *km*× € 1.53)

$+ (€ 11.5× \dfrac{\text{Disance (in } km)}{z})$ … (12)

The fixed and variable costs for operating each of the two dairy processing plants are listed in Tables 2A and 3A respectively. The survey also revealed that a cycle time of 2-3 days is most appropriate for calculating these fixed costs. The demand (in units) at the DoPs is used to determine the variable costs at plants. One 'unit' of demand refers to a two-litre carton of milk. €1.53/litre has been determined as the average price of diesel in Ireland during April/May 2012. The average wage of a driver is €11.50/hour. Variable costs are calculated using equation (9).

A combination of different types of roads constitutes each different distribution route. The shortest routes connecting each plant to each DoPs was determined using Google™ maps. From this the distance of the different types of roads forming the distribution routes connecting the plants to DoPs were found and are shown in Table 4A.

The total CO_2 emission from a Diesel vehicle (in *kg*) is computed using equations (10) and (11). This computation requires the information provided in Table 4A. The corresponding cost of serving each distribution route is also computed using equation (12) and indicated in Table 5.

Table 5: Estimated CO_2 emission and costs of serving each path by heavy duty vehicles from each plant to each consumer (Validi 2014)

Consumer ($i \in I$)	Plant-I (Drogheda)		Plant-II (Ballitore)	
	CO_2 emission from fuel burnt (kg), p_{ji}	Cost of serving path (€) c_{jk}	CO_2 emission from fuel burnt (kg), p_{ji}	Cost of serving path (€) c_{jk}
1. Drogheda	1.85	1.84	108.11	77.70
2. Dundalk	33.63	23.68	134.90	96.59
3. Navan	23.84	19.75	97.02	68.30
4. Tullamore	101.64	74.72	57.75	47.84

5. Naas	69.67	57.72	26.89	22.28
6. Newbridge	95.17	67.00	22.64	18.75
7. Leixlip	43.89	36.36	56.46	39.75
8. Port Laoise	132.13	93.02	34.28	27.38
9. Bray	68.93	48.53	65.97	48.50
10. Arklow	118.27	85.29	53.22	44.09
11. Wicklow	111.80	78.71	44.35	36.74
12. Greystons	77.25	54.38	65.05	53.89
13. Clonmel	208.80	147.01	102.56	73.63
14. Waterford	202.36	142.46	97.02	68.30
15. Tramore	214.37	150.92	108.11	76.11
16. Kilkenny	164.47	115.79	58.58	41.24
17. Wexford	182.03	128.15	87.59	64.39
18. Ennoscorthy	170.02	124.98	66.90	52.64
19. Dublin City	48.42	34.09	55.25	40.62
20. Dun Laogharire / Rathdawn	58.12	40.92	61.63	45.31
21. Fingal	26.98	22.35	79.00	58.08
22. South Dublin	56.83	47.08	41.67	30.63

3.2 Role of the 'green' constraint

One of the functionalities of the green constraint (5) obtained for the dairy market distribution logistics problem is to allow the decision-makers to reach a consensus opinion for the selection of vehicle types. AHP assists in the translation of the decision-makers linguistic representation into non-dimensional quantities by means of trading-off incommensurable units of measurement. The AHP technique results in a weight matrix for the dairy market distribution problem as illustrated in Table 5. The preferences of the decision-makers for different types of vehicles, with respect to the vehicles levels of CO_2 emissions and costs are presented in Table 5A.

The minimum and maximum values for CO_2 emissions and costs associated with milk distribution for this particular case are obtained from Table 5. The values of the right-hand side matrix (B_m) of the green constraint (5) are set as the averages of these limiting values (CO_2 emissions and costs). It is to be noted that the optimisation model can accommodate any limiting values of the CO_2 emission and costs for serving the routes depending on the datasets of Table 5 and the decision maker's preferences. The value set on the right hand side of the matrix will have a bearing on the number of possible solutions created. Situations where the values of the left hand side of the AHP constraint (5) are greater than the right hand side values (for CO2 emissions, costs or both) signify solutions where the vehicle type is inappropriate.

Table 5: w_{mn} matrix for vehicle types

	T₁	T₂	T₃	Sum of weights
CO_2 emission	0.33	0.24	0.43	1.00
Costs	0.32	0.43	0.25	1.00

Fast Pareto convergence was specified as an important dimension in the implementation phase of this 'green' optimisation model. However, at the outset of this study the best

procedure to have a fast Pareto convergence for these discrete variables for the defined constraints of the model was unknown. For this reason, the proposed 'green' distribution model has been solved using three different optimisers and will be discussed in the following section. It should also be noted that the 'green' model is computationally NP-hard in nature, thus the solution to these models grow exponentially with increasing problem size (Erdoğan and Miller-Hooks 2012). Therefore, choice of optimiser is important for the development of a precise feasible solution space

4. Solution Procedure

The solution procedure for the optimisation model considers three Genetic Algorithm (GA)-based optimisers using the modeFRONTIER$^{®}$ (Esteco 2012) platform. They are: Multi-Objective GA of kind II (MOGA-II), Non-Dominated Sorting GA of kind II (NSGA-II) and 'Hybrid' combining GAs and sequential quadratic programming. This is the first case where a dairy market distribution logistics problem is solved using a multi-disciplinary and multi-objective optimisation solution technique fully guided by Design of Experiment (DoE). The distribution problem is handled by way of producing robust designs. DoE is coupled to the optimisers in such a manner that the solution of the AHP-integrated model is possible only if optimal feasible designs are obtained.

The principles of DoE is utilised during the implementation phase of the proposed model. The DoE is invoked at the initial stage of the model implementation stage when an optimiser is called upon to solve the integrated optimisation model. This enables the optimiser to provide the best stable solution space. DoE enables the implementation process to take out solutions having poor design characteristics from the solution space (Esteco 2012). While implementing the integrated optimisation model each optimiser explores the design space, performs a preliminary optimisation process using the GA-based "search" algorithm based on the DoE tables and finally refines the feasible solutions using a converging algorithm.

The 'MOGA-II' optimiser is capable of handling only discrete variables. It is designed to achieve rapid Pareto convergence for the solution. MOGA-II supports directional cross-over and it uses smart multi-search elitism for both robustness and the directional crossover. The optimiser enforces user defined constraints by objective function penalisation. An advantage of this optimiser is that it allows a steady state evolution process while allowing concurrent evaluation of independent individuals (Poles 2003; Poles et al. 2004; modeFRONTIER$^{®}$ 2008).

The NSGA-II optimiser is capable of handling both continuous and discrete variables. The optimiser can operate with a user defined discretisation process. Further, the constraint handling method in the NSGA-II optimiser does not make use of penalty parameters. It adopts different elitism strategies for multi-objective search and it guarantees diversity and a spread of solutions without the use of parameter sharing (Deb et al. 2000; Deb et al. 2002). Similar to MOGA-II, this optimiser concurrently evaluates the independent individuals. NSGA-II optimiser implements a steady-state evolution scheme that cannot guarantee the

repeatability of the design sequences unless the number of concurrent design evaluation is set to 1 (Poles et al. 2009).

The 'Hybrid' optimiser integrates a steady-state GA with Sequential Quadratic Programming (SQP). This implies that the optimiser combines the global exploration capabilities of GAs with the accurate local exploitation guaranteed by SQP implementations (Esteco 2012). This optimiser works using a steady-state scheme. In this optimiser SQP runs are launched as particular operators for the GA. Derivatives are approximated, in the 'Hybrid' optimiser, using either a finite differences method or through response surface method predictions. This optimiser produces repeatable sequences if the number of concurrent design evaluations is 1. The 'Hybrid' optimiser is used for single and multi-objective problems which can be either constrained or unconstrained.

4.1 Case results

The 'green' dairy market distribution logistics optimisation model was implemented using three different GA-based optimisers. A set of non-dominated solutions distributed along the Pareto front (trading-off between CO2 emissions and Costs) was found for each of the three GA-based optimisers. For each of the optimisers N entries (i.e., number of individuals) in the DoE table were used as the problem's initial population. The population of the DoE Table was 61 different designs. These 61 designs comprised of 10 DoE sequence based on a custom user sequence, 10 random designs, 10 Sobol designs, 10 uniform Latin hypercube, 10 incremental space filler designs and 1 design on constraint satisfaction. Based on the DoE table, the 'green' distribution approach was executed using each of the three GA-based optimisers limited to a maximum of 50 generations and 2,550 real feasible solutions. These results were refined and finally 30 results were selected as feasible realistic results for each of the three optimisers. A statistical solution summary on computed maximum and minimum levels of CO_2 emission and costs based on the DoE tables for each optimiser is tabulated in Table 7.

The DoE is responsible for generating the initial design tables before employing the optimisers and based on those initial designs each optimiser generates the results. Thus, the initial results for each optimiser is refined. These 'results' are then further reduced to a set of 'realistic results' which for MOGA-II is 826 results. These 'realistic results' are then further refined ensuring feasibility of both the CO_2 emission and costs, which for MOGA-II reduces this to 187 results. These 'refined realistic results' aid in the further selection of a number of results for each optimiser (in this case 30 from each optimiser). The selected results are based on the two lower-most rows in the 4D bubble plots (described in following sectors). The performance and results of the three optimisers are then compared across these 30 selected results.

Table 7: Statistical solution summary of the results

Optimisers	Results types	Number of real feasible results	CO_2 emission (kg) (Objective function-I)		Costs value (€) (Objective function-II)	
			Min	Max	Min	Max
MOGA-II	Results	2,550	1,182	2,187	186,776	299,444
	Realistic results	826	1,182	2,187	186,776	299,444
	Refined realistic results	187	1,182	2,187	186,776	299,444
	Selected results	30	1,182	1,729	186,776	249,716
NSGA-II	Results	2,550	1,171	2,352	185,948	299,444
	Realistic results	901	1,171	2,187	185,948	299,444
	Refined realistic results	543	1,171	2,187	185,948	299,444
	Selected results	30	1,171	1,729	185,948	248,985
Hybrid	Results	2,550	1,171	2,244	185,902	299,444
	Realistic results	624	1,178	2,244	187,969	299,444
	Refined realistic results	393	1,178	2,244	187,969	299,444
	Selected results	30	1,178	1,951	187,969	242,608

Table 7 shows that the minimum value of CO_2 emission (1,171kg) was achieved by both the NSGA-II and Hybrid optimisers while the minimum value for costs (€ 185,902) was presented by the Hybrid optimiser. The best solution on both of the objective functions independently was achieved by the Hybrid optimiser. This solution is 1,171 kg and € 185,902 for CO_2 and cost respectively. The Hybrid optimiser is a combination of GA and SQP. While SQP reaches a neighbour of Pareto front quickly, the GA is responsible for the final optimisation of the input variables (Turco 2011).

A one-way ANOVA has been performed for both the total CO_2 emission and total costs from the case modelled (Table 8 and 9). The p-values of the ANOVA table for CO_2 emission and costs in the 'Hybrid' optimiser are zero. This suggests that there are significant differences between the groups. At least one sample mean is significantly different from the other sample means.

Table 8: ANOVA for CO_2 emission on the refined realistic results

Optimiser	Source of variation	SS	Df	MS	F-ratio	p-value
MOGA-II	Between groups	6.0825E6	8.1000E1	7.5093E4	3.1338E0	2.5970E-8
	Within groups	2.5160E6	1.0500E2	2.3962E4	—	—
	Total	8.5985E6	1.8600E2			
NSGA-II	Between groups	1.7674E6	4.0000E0	4.4185E5	1.6424E1	1.0559E-12
	Within groups	1.4419E7	5.3600E2	2.6902E4	—	—
	Total	1.6187E7	5.4000E2			
Hybrid	Between groups	6.6896E6	4.7000E1	1.4233E5	2.1207E1	0.0000E0
	Within groups	2.2953E6	3.4200E2	6.7115E3	—	—
	Total	8.9849E6	3.8900E2			

Table 9: ANOVA for costs on the refined realistic results

Optimiser	Source of variation	SS	Df	MS	F-ratio	p-value
MOGA-II	Between groups	6.9805E10	8.1000E1	8.6180E8	2.0491E0	2.8399E-4
	Within groups	4.4160E10	1.0500E2	4.2057E8	—	—
	Total	1.1397E11	1.8600E2			

NSGA-II	Between groups	3.5138E10	4.0000E0	8.7845E9	1.2999E1	4.1364E-10
	Within groups	3.6222E11	5.3600E2	6.7579E8	—	—
	Total	3.9736E11	5.4000E2			
Hybrid	Between groups	2.0953E10	4.7000E1	4.4580E8	5.7653E0	0.0000E0
	Within groups	2.6445E10	3.4200E2	7.7324E7	—	—
	Total	4.7397E10	3.8900E2			

(a) Objective function F1   (b) Objective functions F2
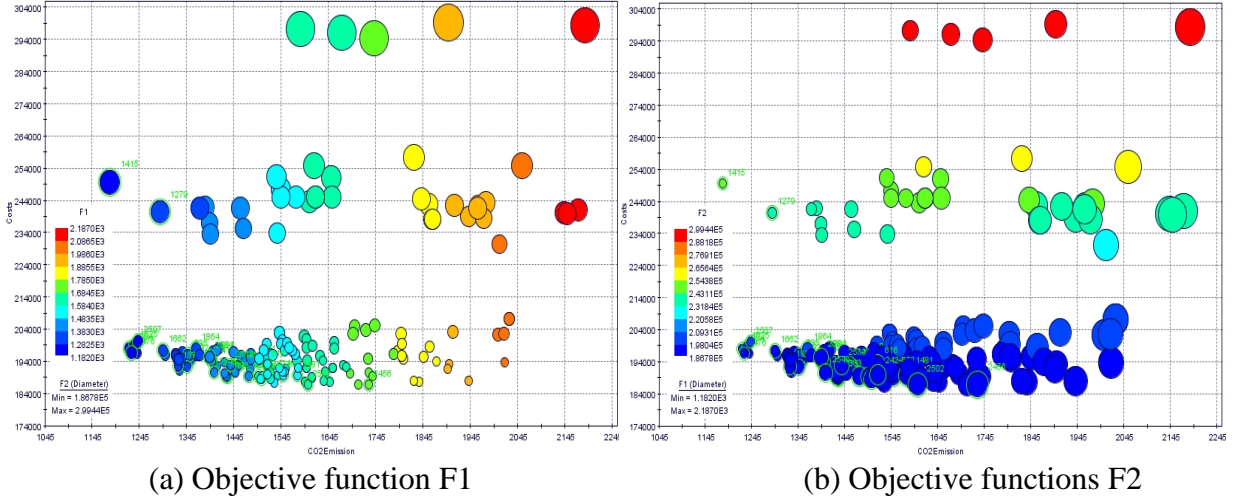
Figure 2: CO_2 vs. costs w.r.t. the objective functions on the refined realistic results for MOGA-II optimiser

Guided by the DoE tables, the MOGA-II, NSGA-II and Hybrid optimisers generate the feasible space of solutions. Figs. 2 and 3 illustrate the characteristic plot of CO_2 vs. costs on the 'realistic' and the 'selected' results respectively for the MOGA-II optimiser. Similarly Figs. 4 and 5 depict the characteristics found using the NSGA-II optimiser and Figs. 6 and 7 for the Hybrid optimiser.

(a) Objective function F1   **(b)** Objective functions F2

Figure 3: CO$_2$ vs. costs with reference to objective functions on selected results for MOGA-II optimiser

The colours and diameters of the bubbles in the plots are related to the objective functions for the case model. In Fig. 5 the diameters of the bubbles refer to F2 values, i.e., costs, whereas the colours of the bubbles refer to F1 values, i.e., CO$_2$ emission. In Fig. 6 the diameters of the bubbles refer to F1 values and the colours of the bubbles refer to F2 values. The colour schemes indicate the feasible solutions, infeasible solutions and solutions with errors.

(a) Objective function F1   (b) Objective functions F2

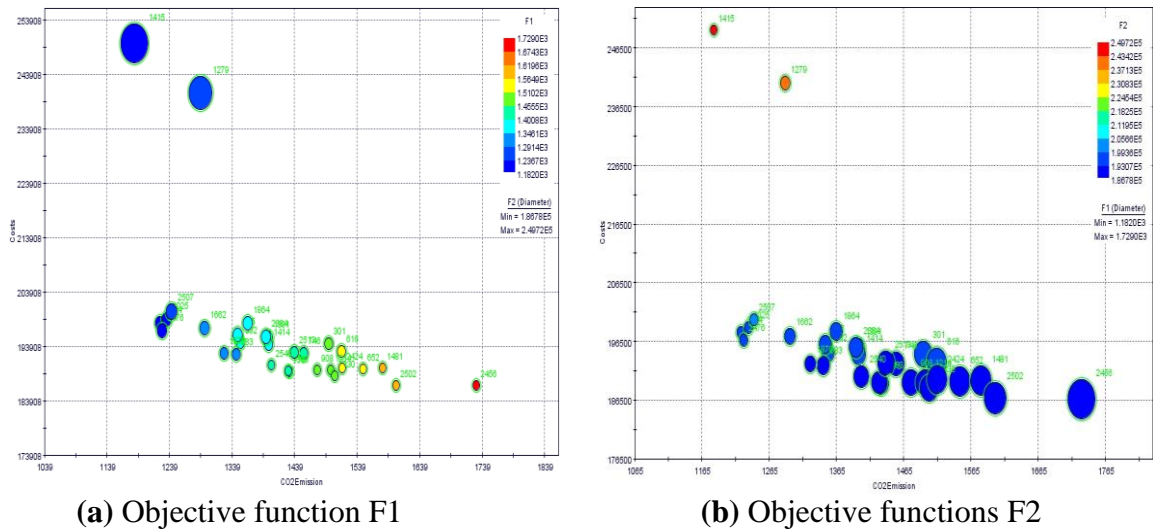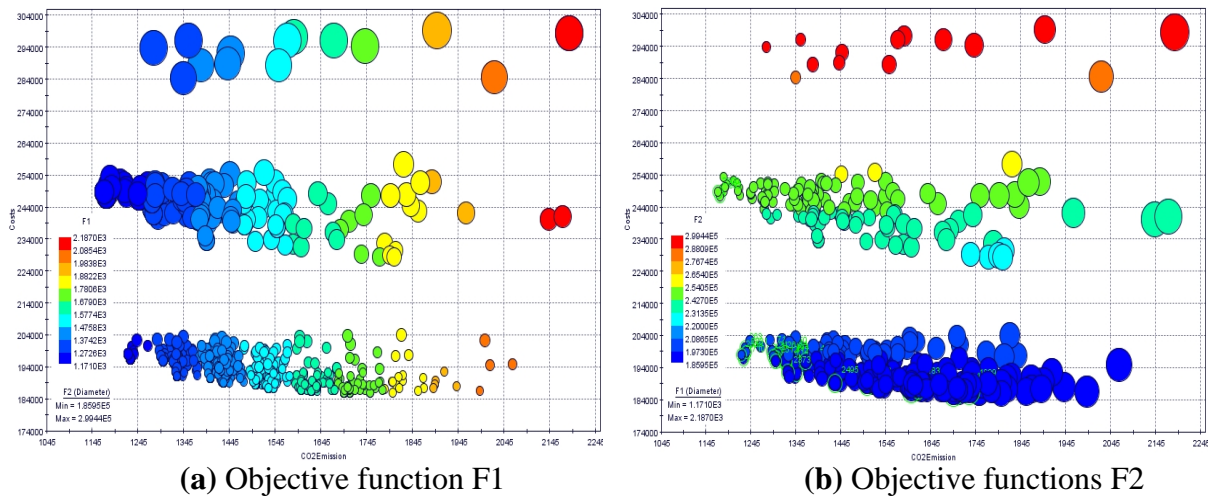**Figure 4**: CO$_2$ vs. costs w.r.t. the objective functions on the refined realistic results for the NSGA-II optimiser

The red coloured solutions in the plots are not realistic in nature. This is because these solutions involve high CO$_2$ emissions and/or high costs. Blue bubbles represent the alternatives with lowest values satisfying both the objective functions of the 'green' distribution approach. Therefore, the selection of the 30 solutions ('selected results') for the MOGA-II optimiser are confined to within the first two layers of optimum realistic solutions shown in Fig. 2. The 30 selected feasible realistic solutions for the MOGA-II optimiser are depicted in Fig. 3. In a similar fashion Figs. 5 and 7 present the selected feasible optimal solutions for the NSGA-II and Hybrid optimisers respectively. Each of these 30 solutions for each of the optimisers are then put forward for evaluation using TOPSIS.
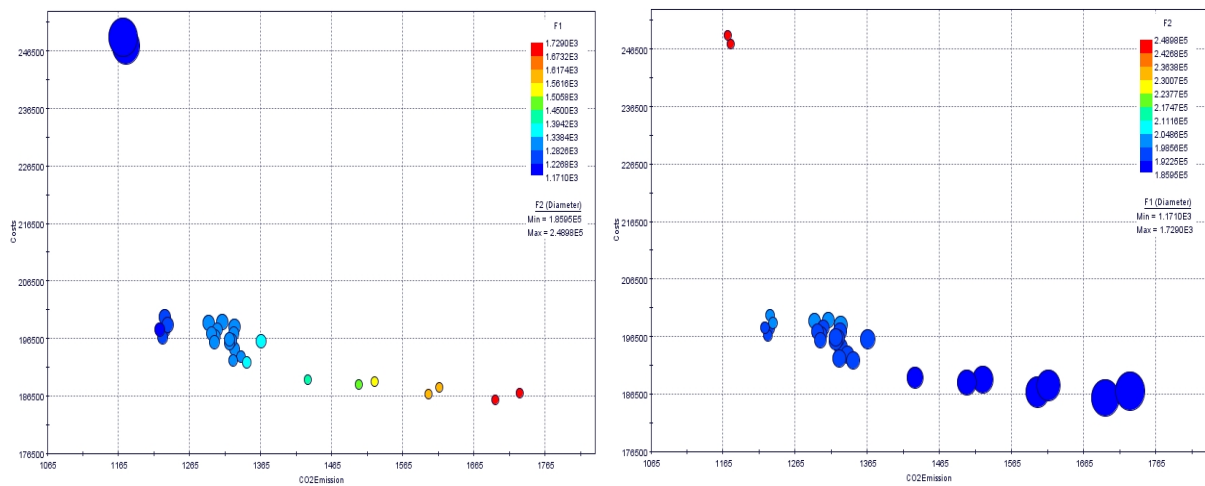
(a) Objective function F1 **(b)** Objective functions F2

Figure 5: CO_2 vs. costs w.r.t. the objective functions on selected results for the NSGA-II optimiser
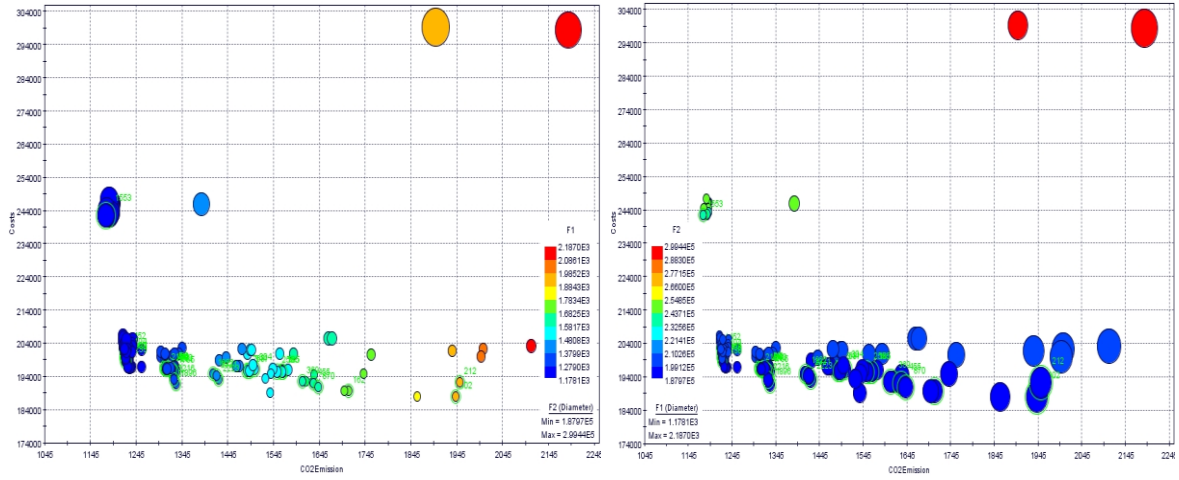
(a) Objective function F1 **(b)** Objective functions F2

Figure 6: CO_2 vs. costs w.r.t. the objective functions on the refined realistic results for the Hybrid optimiser

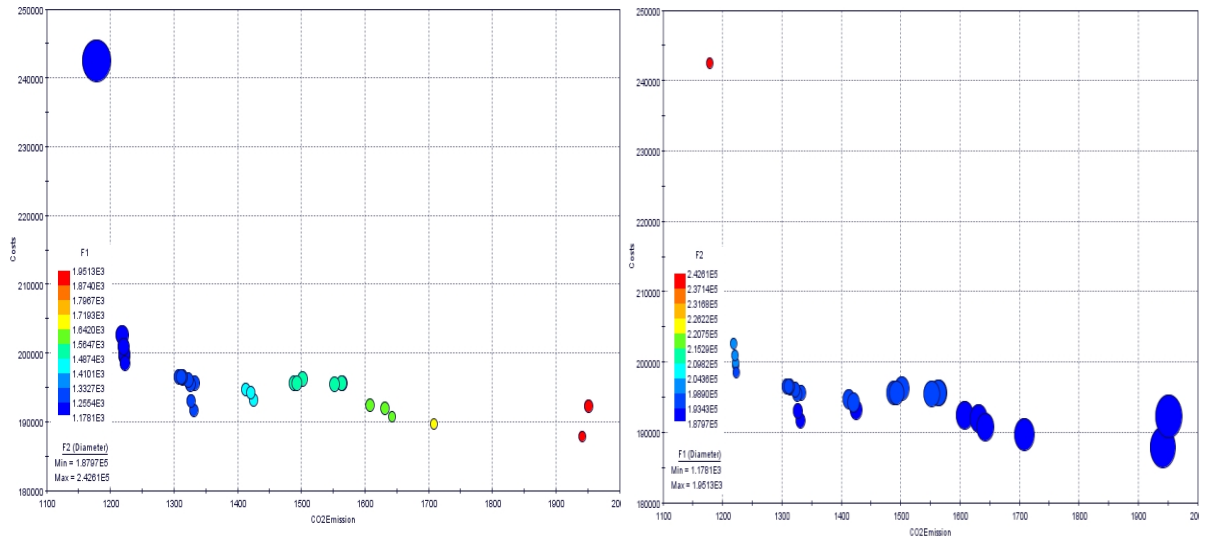**Figure 7**: CO_2 vs. costs w.r.t. the objective functions on selected results for the Hybrid optimiser

4.2 Performance analysis

The performance of the three GA-based optimisers' is evaluated using their individual convergence plots. Fig. 8 delineates two comparative convergence plots for the CO_2 emissions and costs based on the performance of the three optimisers over 50 generations. It is evident from these plots that the solution from the NSGA-II optimiser converges in a comparatively steady mode while it appears the SQP part of the Hybrid optimiser causes convergence of the solution in an erratic manner.
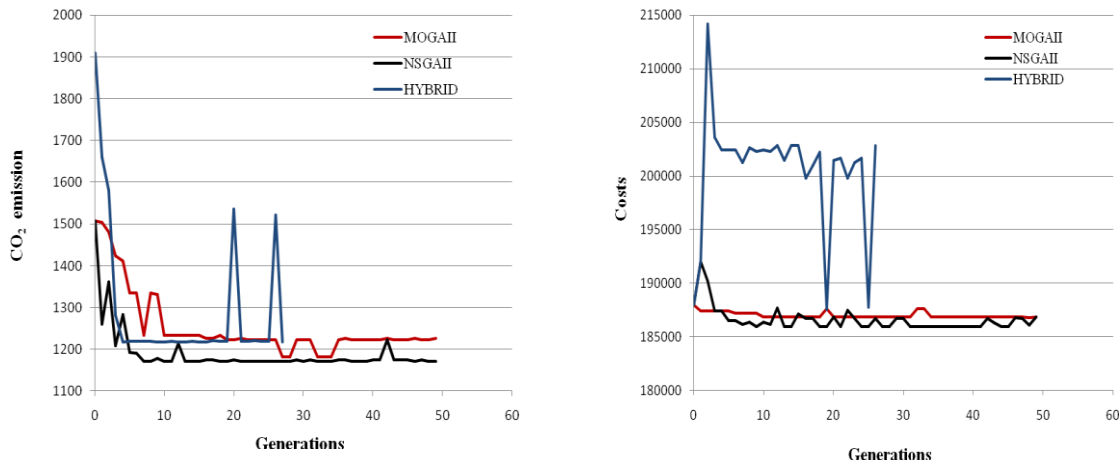
Figure 8: Comparative convergence of the three optimisers for CO_2 emissions and costs

The Pareto efficiency of the solutions is examined in order to further evaluate the performance of the three meta-heuristic optimisers and their 'selected' results. The 30 selected results obtained from the MOGA-II, NSGA-II and Hybrid optimisers (Table 7) were separately analysed with regard to their Pareto efficiency and the Pareto frontier for NSGA-II is illustrated in Fig. 9. The Pareto frontiers from other the MOGA-II and HYBRID optimisers were also compared with that of NSGA-II. From a performance perspective the NSGA-II optimiser has the most efficient Pareto front of the three.
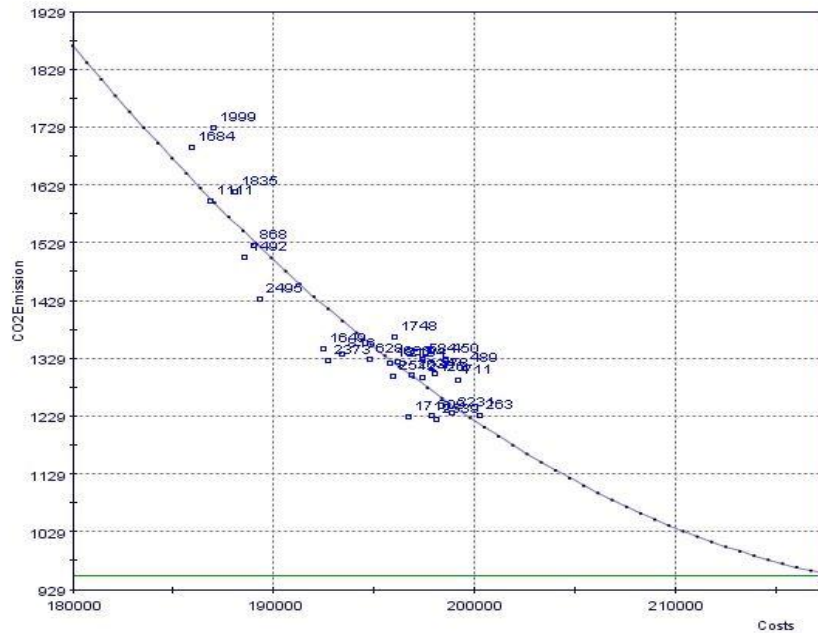
Figure 9: The Pareto frontier for NSGA-II optimiser on the selected realistic results

The selected results from all the three GA-based optimisers follow the Pareto optimality and are efficient. In the selection process of the results (Table 7), extreme decision-making was not considered. Therefore, the extreme results are not considered in the Pareto frontiers. Out of 30 selected results, 2 results in MOGA-II, 2 results in NSGA-II and 1 result in the Hybrid optimiser were not on the Pareto frontier. All of these 5 results, from a collective total of 90 results, represent extreme decision-making conditions and do not affect the Pareto efficiency of the selected results. The results placed outside the Pareto frontiers were however not considered for further analysis of the optimal solutions using TOPSIS.

5. Analysis of the results

The two-layer 'green' distribution system is a combined strategic and tactical decision-making procedure. Therefore, the set of selected feasible realistic optimal solutions on the Pareto frontier are to be ranked according to the Decision-Makers' (DM) preferences. This is done in order to facilitate the decision-making process. TOPSIS (Hwang and Yoon 1981) is executed to evaluate the selected feasible optimal solutions obtained from the optimisers based on the CO_2 emission and costs attributes. Nine weight matrices are used to compare the results. Table 10 shows the comparative results of TOPSIS ranking using a moderate weight matrix on all the GA-based three optimisers. Weight matrices allow the DMs to include the management's judgement on both the CO_2 emission and cost attributes.

TOPSIS aids prioritisation of the optimal results generated by the GA-based optimisers with nine different weight matrices considering all possible preferences of DMs. The weight matrix $W_1 = (0.1 \quad 0.9)$ represents the least weight to CO_2 emission as compared to the cost attribute. The matrix $W_9 = (0.9 \quad 0.1)$ represents the highest weight for CO_2 emissions as compared with the cost attribute. The nine different weight matrices are used to compare the

TOPSIS results: $W_1 = (0.1 \quad 0.9)$, $W_3 = (0.3 \quad 0.7)$, $W_5 = (0.5 \quad 0.5)$, $W_7 = (0.7 \quad 0.3)$, $W_9 = (0.9 \quad 0.1)$, $W_2 = (0.2 \quad 0.8)$, $W_4 = (0.4 \quad 0.6)$, $W_6 = (0.6 \quad 0.4)$, $W_8 = (0.8 \quad 0.2)$. The moderate weight matrix is $W_5 = (0.5 \quad 0.5)$.

Table 10: Comparative outcome of the GA-based optimisers on the basis of TOPSIS weights for $W_5 = (0.5 \quad 0.5)$

	Priority	Design ID	CO_2 emission (Kg)	Costs (€)
MOGA–II	1	2476	1227	196705
	2	1004	1223	198141
	3	1025	1234	198872
NSGA–II	1	628	1328	194778
	2	1710	1227	196705
	3	2539	1223	198141
Hybrid	1	2230	1222	198640
	2	1680	1221	199637
	3	1963	1221	199935

TOPSIS picks the same identical result for the last two weight matrices in MOGA-II. Further, the analytical tool picks the same identical design with four different weight matrices in NSGA-II. TOPSIS picks two set of same identical design with two different weight matrices in the Hybrid optimiser. It has been noticed that five different weight matrices serve the purpose of the decision-makers in a more efficient manner. There are a considerable number of designs offered by each optimiser with each one of the weight matrices. Except for the 5th weight in MOGA-II and NSGA-II, none of the results are identical. A close analysis of the CO_2 emission and costs for disparate optimisers under different TOPSIS weights were obtained and are presented in Table 11.

Table 11: CO_2 emission and costs for optimisers with different TOPSIS weights

TOPSIS weights	MOGA–II		NSGA–II		Hybrid	
	CO_2 emission (Kg)	Costs (€)	CO_2 emission (Kg)	Costs (€)	CO_2 emission (Kg)	Costs (€)
$W_1 = (0.1 \quad 0.9)$	1,431	189,330	1,328	194,778	1,331	191,769
$W_3 = (0.3 \quad 0.7)$	1,326	192,693	1,328	194,778	1,331	191,769
$W_5 = (0.5 \quad 0.5)$	1,227	196,705	1,328	194,778	1,222	198,640
$W_7 = (0.7 \quad 0.3)$	1,223	198,141	1,328	194,778	1,222	198,640
$W_9 = (0.9 \quad 0.1)$	1,223	198,141	1,223	194,778	1,218	202,600

5.1 Scenario analysis of the realistic solutions

Tables 12a and 12b guide the DM in appropriately selecting the best optimal distribution route for the dairy products. The effect on the CO_2 emission and costs, when closed routes are opened, is illustrated in Table 13. A particular case is investigated where costs and CO_2 emission have equal importance. Scenario analysis provides an insight on the closed routes for different design IDs when those are opened. Table 13 presents a scenario analysis for the

dairy product distribution logistics when $W_5 = (0.5 \quad 0.5)$ is considered in the TOPSIS weight matrix for the three different optimisers. Scenario analysis would be different for different TOPSIS weight matrices and design IDs. In the case of the dairy market two-layer supply chain problem the weight matrix is determined by a DM for use in the scenario analysis in order to identify the open and closed routes. The scenario analysis provides information on the CO_2 emissions and costs if closed routes are opened. Hence, it is recommended to conduct a scenario analysis once the appropriate results are identified from the Pareto optimal solution and the solutions are prioritised using TOPSIS.

Table 12a: Open and closed routes available for different TOPSIS weights

Route no. in mF	Routes (V_{jk})	$W_1 = (0.1 \quad 0.9)$			$W_3 = (0.3 \quad 0.7)$			$W_5 = (0.5 \quad 0.5)$			$W_7 = (0.7 \quad 0.3)$			$W_9 = (0.9 \quad 0.1)$		
		MOGA–II	NSGA–II	Hybrid	MOGA–II	NSGA–II	Hybrid	MOGA–II	NSGA–II	Hybrid	MOGA–II	NSGA–II	Hybrid	MOGA–II	NSGA–II	Hybrid
V1	V1I	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V2	V1II	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V3	V2I	0	0	1	1	0	1	1	0	1	1	0	1	1	1	1
V4	V2II	1	1	0	0	1	0	0	1	0	0	1	0	0	0	0
V5	V3I	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V6	V3II	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V7	V4I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V8	V4II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V9	V5I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V10	V5II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V11	V6I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V12	V6II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V13	V7I	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V14	V7II	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V15	V8I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V16	V8II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V17	V9I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V18	V9II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V19	V10I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V20	V10II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V21	V11I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V22	V11II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V23	V12I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V24	V12II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V25	V13I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V26	V13II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V27	V14I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V28	V14II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V29	V15I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V30	V15II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V31	V16I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V32	V16II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V33	V17I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V34	V17II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V35	V18I	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0
V36	V18II	0	1	0	0	1	0	0	1	1	1	1	1	1	1	1
V37	V19I	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V38	V19II	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

V39	V20I	0	0	0	1	0	0	1	0	1	1	0	1	1	1	1
V40	V20II	1	1	1	0	1	1	0	1	0	0	1	0	0	0	0
V41	V21I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V42	V21II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V43	V22I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V44	V22II	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 12b: Available vehicles on different feasible routes for TOPSIS weights

Vehicles	$W_1 = (0.1 \quad 0.9)$			$W_3 = (0.3 \quad 0.7)$			$W_5 = (0.5 \quad 0.5)$			$W_7 = (0.7 \quad 0.3)$			$W_9 = (0.9 \quad 0.1)$		
	MOGA–II	NSGA–II	Hybrid	MOGA–II	NSGA–II	Hybrid	MOGA–II	NSGA–II	Hybrid	MOGA–II	NSGA–II	Hybrid	MOGA–II	NSGA–II	Hybrid
T_1	1	1	0	1	1	0	1	1	0	1	1	0	1	0	0
T_2	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1
T_3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

Table 13: Scenario analysis when a closed route is opened

Route numbers	Routes (V_{jk})	MOGA–II			NSGA–II			Hybrid		
		Open routes	Closed route (effect on CO_2 emission, if open)	Closed route (effect on costs, if open)	Open routes	Closed route (effect on CO_2 emission, if open)	Closed route (effect on costs, if open)	Open routes	Closed route (effect on CO_2 emission, if open)	Closed route (effect on costs, if open)
V1	V1I	1	-	-	1	-	-	1	-	-
V2	V1II	-	108	5,108	-	108	5,108	-	108	5,108
V3	V2I	1	-	-	-	34	3,834	1	-	-
V4	V2II	-	135	1,935	1	-	-	-	135	1,935
V5	V3I	1	-	-	1	-	-	1	-	-
V6	V3II	-	97	2,997	-	97	2,997	-	97	2,997
V7	V4I	-	102	2,102	-	102	2,102	-	102	2,102
V8	V4II	1	-	-	1	-	-	1	-	-
V9	V5I	-	70	4,270	-	70	4,270	-	70	4,270
V10	V5II	1	-	-	1	-	-	1	-	-
V11	V6I	-	96	1,495	-	96	1,459	-	96	1,495
V12	V6II	1	-	-	1	-	-	1	-	-
V13	V7I	1	-	-	1	-	-	1	-	-
V14	V7II	-	34	7,056	-	34	7,056	-	34	7,056
V15	V8I	-	132	1,532	-	132	1,532	-	132	1,532
V16	V8II	1	-	-	1	-	-	1	-	-
V17	V9I	-	69	2,669	-	69	2,669	-	69	2,669
V18	V9II	1	-	-	1	-	-	1	-	-
V19	V10I	-	118	70,118	-	118	70,118	-	118	70,118
V20	V10II	1	-	-	1	-	-	1	-	-
V21	V11I	-	112	36,512	-	112	36,512	-	112	36,512
V22	V11II	1	-	-	1	-	-	1	-	-
V23	V12I	-	77	6,077	-	77	6,077	-	77	6,077

V24	V12II	1	-	-	1	-	-	1	-	-
V25	V13I	-	209	4,769	-	209	4,769	-	209	4,769
V26	V13II	1	-	-	1	-	-	1	-	-
V27	V14I	-	202	3,562	-	202	3,562	-	202	3,562
V28	V14II	1	-	-	1	-	-	1	-	-
V29	V15I	-	214	2,614	-	214	2,614	-	214	2,614
V30	V15II	1	-	-	1	-	-	1	-	-
V31	V16I	-	164	5,204	-	164	5,204	-	164	5,204
V32	V16II	1	-	-	1	-	-	1	-	-
V33	V17I	-	182	1,862	-	182	1,862	-	182	1,862
V34	V17II	1	-	-	1	-	-	1	-	-
V35	V18I	1	-	-	-	170	3,050	-	170	3,050
V36	V18II	-	67	8,467	1	-	-	1	-	-
V37	V19I	1	-	-	1	-	-	1	-	-
V38	V19II	-	55	3,895	-	55	3,895	-	55	3,895
V39	V20I	-	58	3,178	-	58	3,178	1	-	-
V40	V20II	1	-	-	1	-	-	-	62	1,742
V41	V21I	-	27	84,027	-	27	84,027	-	27	84,027
V42	V21II	1	-	-	1	-	-	1	-	-
V43	V22I	-	57	43,737	-	57	43,737	-	57	43,737
V44	V22II	1	-	-	1	-	-	1	-	-

Tables 12a, 12b and 13 guide the DMs to locate the feasible and realistic optimal distribution routes geographically on the map of Ireland (Fig. 10). In the case presented in this paper, the map presents the routes connecting the two plants and twenty-two customers in an optimal manner while minimising the total CO_2 emission from the vehicles during the distribution of dairy products within the dairy market supply chain. Fig. 10 is a sample presentation of the using the findings of NSGA-II for the weight matrix W_5. Similar distribution routes can be mapped for other optimal feasible and realistic solutions and decision-makers' preferences through the weight matrices.

: Plants

: Drop-off points
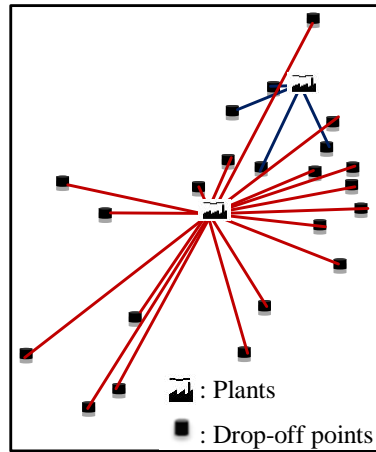
Figure 10: Mapped dairy product distribution routes for NSGA-II optimiser under W_5

6. Discussion and Conclusions

This paper addresses a critical component of modern food supply chains, the distribution system. The paper is based on the dairy industry in Ireland, with a model presented which addresses the multi objectives of carbon reduction and cost minimisation in the design stage of the milk distribution system. The specific case presented in this paper is based on the distribution of milk from two milk processing plants to twenty-two DoPs where the

processing plants are based in the eastern region of Ireland. The model presented is of this two-layer Irish dairy market supply chain, with the case data obtained from semi structured interviews based on survey questionnaires within the key stakeholders in a number of dairy processing plants in Ireland. Three independent DoE-guided GA-based optimisers were used to solve the 'green' capacitated multi-objective optimisation model. The sustainable distribution process presented enables the supply chain decision maker to reduce the total carbon emission from the transportation involved in the entire distribution process while simultaneously optimising total costs. The best vehicle types are offered by considering the two attributes, CO_2 emission and costs. This is done through the use of the AHP constraint which is linked in the optimisation model to the objective functions. The model presented considers utilises boundary values for CO_2 emissions and costs, which are based on inputs from presented by the stakeholders. When the boundary conditions are tightly set the number of feasible solutions is reduced. The default position, which is what is presented in this paper is the average values of both CO_2 emission and costs.

The performances of the three GA-based optimisers involved in the solution phase were compared based on the objective function values and convergence. Each of the optimisers generates 2,550 results. For each of the optimisers 30 results, acquired from the refined realistic results, were evaluated using TOPSIS to highlight the best candidate-result to the decision maker. The Pareto frontier suggests that NSGA-II is the best optimiser as compared with the other two GA-based optimisers for implementing the case of the dairy market logistics problem presented here. From these outputs a number of transportation routes are obtained for the dairy manufacturer. For the purpose of this paper, the best routes are mapped geographically for the NSGA-II optimiser (best performer) and the optimal and sustainable dairy product distribution routes identified. Scenario analyses is then used to analyse the effect of opening the closed dairy product distribution routes. Such situations may arise when disruption events strike the supply chain network thus building resiliency into the modelling framework.

The green, multi-objective, AHP-integrated two-layer optimisation model has been applied to the case of a dairy processing case based on the structures present in Irish dairy market. The case presented considers processing plants which always remain open $X_j = 1$. This is typical of the dairy sector in Ireland where processing plants are not opened and closed regularly. Although this paper only makes claims around the case developed, the model has been designed to facilitate transferability across sectors and to accommodate larger problems in the dairy sector or others, thus the ability to open and close plants has been included in the optimisation model where $X_j \in (0,1)$. Further research is required to evaluate the impact of opening and closing processing plants.

The DoE-guided solution procedure can be extended to conduct preventative post-hoc control to investigate the type-I error rate. This analysis will assist in finding patterns of the GA-based optimisers and relationships among the parameters. Further MANOVA may be used instead of ANOVA in order to test the relationship among several categorical variables (i.e.,

treatments) and two or more dependent variables in the case of the dairy market distribution system.

The solution presented for the case in this paper has a number of simplifying components, which could be extended in future research. In the first instance the case presented was based on two processing plants with twenty-two drop off points. While the model presented for this case still remains NP-hard extended computational experimentation is required across a number of different sectors and in varying problem sizes to evaluate the models generality. In addition the model does not take into account variability in demand. It is proposed that future research which integrates dynamic programming with the existing modelling approach would be a valuable extension of the current proposed solution approach. An additional useful extension from the currently evaluated two layer model is to extend this model to a three layer model, considering distribution centres located between the plants and the DoPs. This could give the model a broader appeal to a number of different types of distribution systems beyond the constraints of the model presented in this paper. Single vehicles serving single DoPs is an assumption of the current model and a logical extension of this model is the extension of this to incorporate the ability for fortification of closely-located multiple consumers served by a single vehicle. Incorporation of these additions, while extending the applicability of the model also is significantly more complex, entailing a large number of objective functions, constraints and parameters

References

Aghazadeh, S.-M., 2004. Improving logistics operations across the food industry supply chain. International Journal of Contemporary Hospitality Management, 16(4), 263-268.

Albareda-Sambola, M., Diaz, J.A. and Fernández, E., 2005. A compact model and tight bounds for a combined location-routing problem. Computers & Operations Research, 32(3), 407–428.

Alumur, S. and Kara, B.Y., 2007. A new model for the hazardous waste location-routing problem. Computers & Operations Research, 34(5), 1406–1423.

Ambrosino, D. and Scutellà, M.G., 2005. Distribution network design: new problems and related models. European Journal of Operational Research, 165(3), 610–624.

Apaydin, O. and Gonullu, M.T., 2008. Emission control with route optimization in solid waste collection process. Sādhanā, 33(2), 71-82.

Aronsson, H. and Brodin, M.H., 2006. The environmental impact of changing logistics structures. The International Journal of Logistics Structures. The International Journal of Logistics Management, 17(3), 394-415.

Belenguer, J.-M., Benavent, E., Prins, C., Prodhon, C. and Calvo, R.W., 2011. A branch-and-cut method for the capacitated location-routing problem. Computers & Operations Research, 38(6), 931–941.

Bell, J.E. and McMullen, P.R., 2004. Ant colony optimization techniques for the vehicle routing problem. Advanced Engineering Informatics, 18(1), 41–48.

Benjaafar, S., Li, Y. and Daskin, M., 2013. Carbon footprint and the management of supply chains: insights from simple models. IEEE Transactions on Automation Science and Engineering, 10(1), 99-116.

Berger, R.T., 1997, Location-routing models for distribution system design. Ph.D. dissertation, Department of Industrial Engineering and Management Sciences, Northwestern University, Evanston, IL.

Beske, P., Land, A. and Seuring, S., 2014. Sustainable supply chain management practices and dynamic capabilities in the food industry: A critical analysis of the literature. International Journal of Production Economics, In Press, 10.1016/j.ijpe.2013.12.026

Bin, Y., Zhong-Zhen, Y. and Baozhen, Y., 2009. An improved ant colony optimization for vehicle routing problem. European Journal of Operational Research, 196(1), 171–176.

Bosona, T.G. and Gebresenbet, G., 2011. Cluster building and logistics network integration of local food supply chain. Biosystems Engineering, 108(4), 293-302.

Bosona, T., Gebresenbet, G., Nordmark, I. and Ljungberg, D., 2011. Integrated logistics network for the supply chain of locally produced food, part I: Location and route optimization analyses. Journal of service science and management, 4(2), 174-183.

Brown, E., Dury, S. and Holdsworth, M., 2009. Motivations of consumers that use local, organic fruit and vegetable box schemes in central England and southern France. Appetite, 53(2), 183-188.

Byrne, P.J., Ryan, P. and Heavey, C., 2013, Sustainable Logistics: A Literature Review and Exploratory Study of Irish Based Manufacturing Organizations. International Journal of Engineering and Technology Innovation, 3(3), 200-213.

Caballero, R., González, M., Guerrero, F.M., Molina, J. and Paralera, C., 2007. Solving a multiobjective location routing problem with a metaheuristic based on tabu search. Application to a real case in Andalusia. European Journal of Operational Research, 177(3), 1751–1763.

Cappanera, P., Gallo, G. and Maffioli, F., 2004. Discrete facility location and routing of obnoxious activities. Discrete Applied Mathematics, 133(1-3), 3–28.

Chan, Y., Carter, W.B. and Burnes, M.D., 2001. A multiple-depot, multiple-vehicle, location-routing problem with stochastically processed demands. Computers and Operations Research, 28(8), 803–826.

Collins, A., Henchion, M. and O'Reilly, P., 1999. The impact of coupled-consolidation: experiences from the Irish food industry. Supply Chain Management: An International Journal, 4(2), 102-111.

Daskin, M.S., Snyder, L.V. and Berger, R.T., 2005. Facility location in supply chain design. *In*: Langevin, A. and Riopel, D. (Eds.), Logistics Systems: Design and Optimization, Springer US, pp 39-65.

Daskin, M.S., Snyder, L.V. and Berger, R.T., 2003. Facility location in supply chain design. Department of Industrial Engineering and Management Sciences, Northwestern University, Evanston, Illinois 60208-3119, U.S.A., Working Paper No. 03-010.

Deb, K., Agrawal, S., Pratap, A. and Meyarivan, T., 2000. A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II. Lecture Notes in Computer Science, Vol. 1917, pp 849-858.

Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T. 2002. A fast and elitist multi-objective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation, 6(2), 182–197.

Department of Energy & Climate Change, UK. 2010. *Monitoring and Understanding CO_2 Emissions from Road Freight Operations*.

Department for Environment, Food and Rural Affairs. *2008 Guidelines to DEFRA's GHG Conversion Factors: Methodology Paper for Transport Emission Factors*. London: UK.

Derbel, H., Jarboui, B., Chabchoub, H., Hanafi, S. and Mladenovic, N., 2011. A variable neighborhood search for the capacitated location-routing problem. *In*: Proceedings of the 4th International Conference on Logistics, 31 May-3 June 2011, Hammamet, Tunisia, pp. 514-519.

Diabat, A. and Simchi-Levi, D., 2009. A carbon-capped supply chain network problem. Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management, 8-11 Dec. 2009, Hong Kong, pp. 523–527.

Duhamel, C., Lacomme, P., Prins, C. and Prodhon, C., 2010. A GRASP×ELS approach for the capacitated location-routing problem. Computers & Operations Research, 37(11), 1912–1923.

Esteco, 2012. modeFRONTIER™ 4 User Manual. URL: http://www.esteco.com/home/mode_frontier/mode_frontier.html, Accessed on 28 November 2012.

Erdoğan, S. and Miller-Hooks, E., 2012. A green vehicle routing problem. Transportation Research Part E: Logistics and Transportation Review, 48(1), 100–114.

European Commission, 2001. European transport policy for 2010: Time to decide, office for official publications of the European communities, Luxembourg.

Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J.M. and Van Wassenhove, L.N., 2001. The impact of product recovery on logistics network design. Production & Operations Management, 10(2), 156–173.

Gendreau, M, Hertz, A and Laporte, G., 1994. A tabu search heuristic for the vehicle routing problem. Management Science, 40(10), 1276-1290.

Ghodsi, R. and Amiri, A.S., 2010. A variable neighborhood search algorithm for continuous location routing problem with pickup and delivery. *In*: Proceedings of the Fourth Asia International Conference on Mathematical/Analytical Modelling and Computer Simulation, 26-28 May, Kota Kinabalu, Malaysia, pp. 199 - 203.

Glover, J.L., Champion, D., Daniels, K.J. and Dainty, A.J.D., 2014. An Institutional Theory perspective on sustainable practices across the dairy supply chain. International Journal of Production Economics, In Press, 10.1016/j.ijpe.2013.12.027

Gunnarsson, H., Rönnqvist, M. and Carlsson, D., 2006. A combined terminal location and ship routing problem. Journal of the Operational Research Society, 57(8), 928-938.

Hamidi, M., Farahmand, K. and Sajjadi, S.R., 2012. Modeling a four-layer location-routing problem. International Journal of Industrial Engineering Computations, 3(1), 43–52.

Hassanzadeh A., Mohseninezhad, L., Tirdad, A., Dadgstari, F., and Zolfagharinia, H., 2009. Location-routing problem. In: R.Z. Farahani and M. Hekmatfar (Eds.), Facility Location: Concepts, models, algorithms and case studies (Contributions to management science), Springer, pp. 395-417.

Hwang, C.L. and Yoon, K., 1981. Multiple attribute decision making. Lecture Notes in Economics and Mathematical Systems, 186, Berlin: Springer-Verlag.

Ilbery, B. and Maye, D., 2005. Food supply chains and sustainability: evidence from specialist food producers in the Scottish/English borders. Land Use Policy, 22(4), 331-344

Jin, L., Zhu, Y., Shen, H. and Ku, T., 2010. A hybrid genetic algorithm for two-layer location-routing problem. 4th International Conference on New Trends in Information Science and Service Science, 11-13 May, Gyeongju, South Korea, pp. 642 - 645.

Karaoglan, I., Altiparmak, F., Kara, I. and Dengiz, B., 2011. A branch and cut algorithm for the location-routing problem with simultaneous pickup and delivery. European Journal of Operational Research, 211(2), 318–332.

Karaoglan, I., Altiparmak, F., Kara, I. and Dengiz, B., 2012. The location-routing problem with simultaneous pickup and delivery: Formulations and a heuristic approach. Omega, 40(4), 465–477.

Kenyon, A.S. and Morton, D.P., 2001. A survey on stochastic location and routing problems. Central European Journal of Operations Research, 9(4), 277–328.

Kewill, 2008. Logistics and Transport Industry Environmental Survey. Transport Intelligence, http://www.supplychainstandard.com/liChannelID/16/Articles/1876/Kewill+ Green+Logistics+Survey.html. Accessed on 05 January 2014

Kleindorfer, P.R., Singhal, K. and Van Wassenhove, L.N., 2005. Sustainable operations management," Production & Operations Management, 14, 482-492.

Kulcar, T., 1996. Optimizing solid waste collection in Brussels. European Journal of Operational Research, 90(1), 71–77.

Laporte, G., Louveaux, F. and Mercure, H., 1989. Models and exact solutions for a class of stochastic location-routing problems. European Journal of Operational Research, 39(1), 71–78.

Lin, C.K.Y., Chow, C.K. and Chen, A., 2002. A location-routing-loading problem for bill delivery services. Computers & Industrial Engineering, 43(1–2), 5–25.

Liu, H., Wang, W. and Zhang, Q., 2012. Multi-objective location-routing problem of reverse logistics based on GRA with entropy weight. Grey Systems: Theory and Application, 2(2), 249–258.

Ljungberg, D., Gebresenbet, G. and Aradom, S., 2007. Logistics chain of animal transport and abattoir operations. Biosystems Engineering, 96(2), 267-277.

Madsen, O.B.G., 1983. Methods for solving combined two level location routing problems of realistic dimension. European Journal of Operational Research, 12(3), 295–301.

Marinakis, Y. and Marinaki, M., 2008. A bilevel genetic algorithm for a real life location routing problem. International Journal of Logistics: Research and Applications, 11(1), 49–65.

Marinakis, Y., Marinaki, M. and Matsatsinis, N., 2008. Honey bees mating optimization for the location routing problem. In: Proceedings of the IEEE International Engineering Management Conference, 28-30 June, Estoril, Portugal, pp. 1–5.

Melechovský, J., Prins, C. and Calvo, R.W., 2005. A metaheuristic to solve a location-routing problem with non-linear costs. Journal of Heuristics, 11(5–6), 375–391.

Min, H., Jayaraman, V. and Srivastava, R., 1998. Combined location-routing problems: a synthesis and future research directions. European Journal of Operational Research, 108(1), 1–15.

modeFRONTIER, 2008. modeFRONTIER V4.0 User manual. Trierste, Italy, ESTECO SpA.

Nagy, G. and Salhi, S., 2007. Location-routing: issues, models and methods. European Journal of Operational Research, 177(2), 649–672.

Neto, J.Q.F., Walther, G., Bloemhof, J., van Nunen, J.A.E.E. and Spengler, T., 2009. A methodology for assessing eco-efficiency in logistics networks. European Journal of Operational Research, 193(3), 670–682.

Nguyen, V.-P., Prins, C. and Prodhon, C., 2012. Solving the two-echelon location routing problem by a GRASP reinforced by a learning process and path relinking. European Journal of Operational Research, 216(1), 113–126.

Nylund, N.-O. and Erkkilä, K., 2005. Heavy-duty truck emissions and fuel consumption simulating real-world driving laboratory conditions. *In*: Presentation on behalf of VTT Technical Research Centre of Finland in the 2005 Diesel Engine Emissions Reduction (DEER) Conference, 21–25 Aug 2005, Chicago, Illinois, USA.

Or, I. and Pierskalla, W.P., 1979. A transportation location-allocation model for regional blood banking. AIIE Transactions, 11(2), 86–94.

Pagell, M. and Wu, Z. 2009. Building a more complete theory of sustainable supply chain management using case studies of 10 exemplars. Journal of Supply Chain Management: A Global Review of Purchasing & Supply. 45. 37-56.

Perl, J., 1983. A unified warehouse location-routing analysis. Unpublished Ph.D. dissertation. Northwestern University, Illinois.

Perl, J. and Daskin, M.S., 1984. A unified warehouse location-routing methodology. Journal of Business Logistics, 5(1), 92–111.

Perl, J. and Daskin, M.S., 1985. A warehouse location-routing problem. Transportation Research Part B: Methodological, 19(5), 381–396.

Poles, S., 2003. MOGA-II An improved Multi-objective Genetic Algorithm: ESTECO Technical Report 2003-006.

Poles, S., Rigoni, E. and Robič, T., 2004. MOGA-II performance on noisy optimization problems. International conference on Bioinspired Optimization Methods and their Applications, 11-12 October, Ljublijana, Slovenia, pp. 51-62.

Poles, S., Fu, Y. and Rigoni, E., 2009. The effect of initial population sampling on the convergence of multi-objective genetic algorithms. Lecture Notes in Economics and Mathematical Systems, Vol. 618, pp 123-133.

Prins, C., Prodhon, C. and Calvo, R.W., 2006. Solving the capacitated location-routing problem by a grasp complemented by a learning process and a path relinking. 4OR: A Quarterly Journal of Operations Research, 4(3), 221–238.

Robinson, D. R. and Wilcox, S. 2008. The greening of supply chains. Supply Chain Management Review. 12. 61-66.

Rönnqvist, M., Flisberg, P. and Forsberg, M., 2007. Optimization based planning tools for routing of forwarders at harvest areas. Canadian Journal of Forest Research, 37(11), 2153-2163.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, 15(3), 234–281.

safefood, March 2008. A review of the milk supply chain. URL: http://www.safefood.eu/SafeFood/media/SafeFoodLibrary/Documents/Publications/Research Reports/safefood_dairy_report_web_version.pdf (visited on 02 January 2014).

Schwardt, M. and Fischer, K., 2009. Combined location-routing problems—a neural network approach. Annals of Operations Research, 167(1), 253-269.

Srivastava, S.K., 2007. Green supply chain management: a state-of-the-art literature review. International Journal of Management Reviews, 9(1), 53–80.

Stenger, A., Schneider, M., Schwind, M. and Vigo, D., 2012. Location routing for small package shippers with subcontracting options. International Journal of Production Economics, 140(2), 702–712.

Tarantilis, C.D., Ioannou, G. and Prastacos, G., 2005. Advanced vehicle routing algorithms for complex operations management problems. Journal of Food Engineering, 70(3), 455–471.

The Irish Co-operative Organisation Society (ICOS)-a. URL: http://www.icos.ie/supply-chain/dairy-supply-chain-intro/. Visited on 28 November 2012.

The Irish Co-operative Organisation Society (ICOS)-b. URL: http://www.icos.ie/members/dairy/ (visited on 02 January 2014).

Ting, C.-J. and Chen, C.-H., 2013. A multiple ant colony optimization algorithm for the capacitated location routing problem. International Journal of Production Economics, 141(1), 34–44.

Turco, A., 2011. Hybrid - description. Esteco Technical Report 2011-003, 1-10.

Validi, S., Bhattacharya, A. and Byrne, P.J., 2012. Greening the Irish food market supply-chain through minimal carbon emission: an integrated multi-objective location-routing approach. In: T. Baines, B. Clegg, and D. Harrison (Eds.), Proceedings of the 10th International Conference on Manufacturing Research, Vol. 2, 11-13th September, Birmingham, UK, pp. 805–810.

Validi, S., 2014. Low-carbon multi-objective location-routing in supply chain network design. Unpublished PhD thesis, Dublin City University Business School.

Wang, F., Lai, X. and Shi, N., 2011. A multi-objective optimization for green supply chain network design. Decision Support Systems, 51(2), 262–269.

Watson-Gandy, C.D.T. and Dohrn, P.J., 1973. Depot location with van salesmen – a practical approach. Omega, 1(3), 321–329.

White, L. and Lee, G.L. 2009. Operational research and sustainable development: Tackling the social dimension. European Journal of Operational Research. 193. 683-692.

Wu, H.-J. and Dunn, S.C., 1995. Environmentally responsible logistics systems. International Journal of Physical Distribution & Logistics Management, 25(2), 20-38.

Yang, P. and Zi-Xia, C., 2009. Two-phase particle swarm optimization for multi-depot location-routing problem. In: Proceedings of International Conference on New Trends in Information and Service Science. Beijing, 30 June–2 July 2009, pp. 240–245.

Yu, V.F., Lin, S.-W., Lee, W. and Ting, C.-J., 2010. A simulated annealing heuristic for the capacitated location routing problem. Computers & Industrial Engineering 58(2), 288–299.

Zhou, J. and Liu, B., 2007. Modeling capacitated location–allocation problem with fuzzy demands. Computers & Industrial Engineering, 53(3), 454–468.

Zhu, Q., Sarkis, J. and Lai, K.-H., 2008. Green supply chain management implications for closing the loop. Transportation Research Part E: Logistics and Transportation Review, 44(1), 1–18.

Table 1A: Speed limits and average working speeds (Validi 2014)

Type of road	Speed limits (Road traffic Act 2004) (km/hr)	Average working speeds (km/hr)
Motorway	120	100
National primary and secondary routes (dual carriageways included)	100	80
Regional and local roads	80	50
Built up areas (Town and city)	50	30

Table 2A: Fixed costs for operating plants (Validi 2014)

Fixed Cost (f_j)	Plant-I	Plant-II
Fixed cost (€)	1,500	2,000

Table 3A: Variable costs at plants (Validi 2014)

Variable Cost (a_j)	Plant-I	Plant-II
Variable cost / unit (€)	0.20	0.24

Table 4A: Distances and the types of the roads in each route serving plants and customers (Validi 2014)

Customer ($i \in I$)	Plant-I (Drogheda)					Plant-II (Ballitore)				
	Total distance (km)	Motorway	National route	Regional and local roads	Built up areas	Total distance (km)	Motorway	National route	Regional and local roads	Built up areas
1. Drogheda	2.0				2.0	117.0	61.7	55.3		
2. Dundalk	36.4	36.4				146.0	89.7	56.3		
3. Navan	25.8			25.8		105.0	105.0			
4. Tullamore	110.0		110.0			62.5			62.5	
5. Naas	75.4			75.4		29.1			29.1	
6. Newbridge	103.0	103.0				24.5			24.5	
7. Leixlip	47.5			47.5		61.1	61.1			
8. Port Laoise	143.0	143.0				37.1		11.8	25.3	
9. Bray	74.6	74.6				71.4		71.4		
10. Arklow	128.0	128.0				57.6			57.6	
11. Wicklow	121.0	121.0				48.0			48.0	
12. Greystones	83.6	83.6				70.4			70.4	
13. Clonmel	239.0	239.0				111.0	61.3	49.7		
14. Waterford	219.0	219.0				105.0	105.0			
15. Tramore	232.0	232.0				117.0	117.0			
16. Kilkenny	178.0	178.0				63.4	63.4			
17. Wexford	197.0	197.0				94.8		94.8		
18. Enniscorthy	184.0		184.0			72.4	24.2		48.2	
19. Dublin City	52.4	52.4				59.8		59.8		
20. Dun Laogharire / Rathdawn	62.9	62.9				66.7		66.7		
21. Fingal	29.2			29.2		85.5		85.5		
22. South Dublin	61.5			61.5		45.1		45.1		

Table 5A: Vehicle types (Validi 2014)

	CO_2 emission	Costs
Vehicle-1 (T_1)	Medium	Medium
Vehicle-2 (T_2)	Low	High
Vehicle-3 (T_3)	High	Low

Modelling phase

Formulation of green model
– Minimisation of CO_2 emission;
– Minimisation of total costs;
AHP-integrated and subject to constraints and decision variables of the distribution system so as to select vehicles/trucks, allocate DoPs to the processing plants & route the vehicles.

Solution phase
– Deployment of design of experiment guided GA-based meta-heuristic optimisers through modeFRONTIER™ commercial solver;
– Selection of realistic feasible optimal solutions;
– Determining the Pareto frontiers;
– Selection of the best optimiser;
These assist to have a convincing outcome of the numerical experiments from the robust solution approach.

Analysis phase
– Determination of non-dominated real feasible scenarios;
– Involvement of decision-makers to have flexible decision-making;
– Prioritisation of the robust solutions using TOPSIS;
– Selection of the distribution routes;
– Geographical mapping of the distribution routes.

Figure 1A: The three inter-linked aspects of the two-layer green distribution system

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