# A MULTI-OBJECTIVE OPTIMIZATION AND THE ANALYTIC HIERARCHY PROCESS INTEGRATED APPROACH FOR SUSTAINABLE SUPPLY CHAIN DESIGN

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# A MULTI-OBJECTIVE OPTIMIZATION AND THE ANALYTIC HIERARCHY PROCESS INTEGRATED APPROACH FOR SUSTAINABLE SUPPLY CHAIN DESIGN

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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# ABSTRACT

# A MULTI-OBJECTIVE OPTIMIZATION AND THE ANALYTIC HIERARCHY PROCESS INTEGRATED APPROACH FOR SUSTAINABLE SUPPLY CHAIN DESIGN


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Sustainability of supply chains has started to become more important topic for consumers, companies and governments since last decade and some urgent solutions are expected to improve the quality of systems. This thesis presents two-stage hybrid solution method for designing sustainable supply chain in manufacturing of flexible packaging. The proposed solution algorithm includes two main stages; firstly, the Analytic Hierarchy Process (AHP) method is applied to select the most efficient suppliers by considering different performance indicators of the company. The outcomes obtained at this stage are used in the mixed-integer linear multi-objective mathematical model to optimize the design of the sustainable supply chain proposed in the second stage in terms of total cost, time and social factors. To help decision makers, mathematical modelling approach and data analysis are presented and Pareto solution sets of the multi-objective mathematical programming problem for minimization of cost and time; and maximization of sustainability by using augmented $\varepsilon$-constraint method are outlined. The mathematical model of proposed approach is implemented in GAMS (General Algebraic Modelling System). Some sensitivity analyses are made to highlight the details of illustrative cases designed based on data from a company.



***Keywords***: *Sustainable Supply Chain, Multi-Objective Optimization, Mixed-Integer Linear Programming, Analytic Hierarchy Process*

# ÖZET


## SÜRDÜRÜLEBİLİR TEDARİK ZİNCİRİ TASARIMI İÇİN ÇOK AMAÇLI OPTİMİZASYON VE ANALİTİK HİYERARŞİ SÜRECİ ENTEGRE YAKLAŞIMI



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Tedarik zincirlerinin sürdürülebilirliği, son on yıldan beri tüketiciler, şirketler ve hükümetler için daha önemli bir konu olmaya başlamış ve bazı acil çözümlerin sistemlerin kalitesini iyileştirmesi beklenmektedir. Bu çalışma, esnek ambalaj üretiminde sürdürülebilir tedarik zinciri tasarımı için iki aşamalı hibrit çözüm yöntemi sunmaktadır. Önerilen çözüm algoritması iki ana aşamadan oluşmaktadır. İlk olarak, şirketin farklı performans göstergelerini dikkate alarak en verimli tedarikçileri seçmek için Analitik Hiyerarşi Süreci (AHP) yöntemi uygulanmaktadır. Bu aşamada elde edilen sonuçlar, toplam maliyet, zaman ve sosyal faktörler açısından ikinci aşamada önerilen sürdürülebilir tedarik zincirinin tasarımını optimize etmek için karmaşık tamsayı doğrusal çok amaçlı matematiksel modelde kullanılır. Karar vericilere yardımcı olmak için matematiksel modelleme yaklaşımı ve veri analizi sunulmakta, maliyet ve zamanının minimizasyonu ve sürdürülebilirliğin maksimizasyonu için çok amaçlı matematiksel programlama probleminin Pareto çözüm setleri artırılmış epsilon kısıt yöntemi kullanılarak özetlenmiştir. Önerilen yaklaşımın matematiksel modeli, GAMS (Genel Cebirsel Modelleme Sistemi) programında uygulanmaktadır. Ambalaj üretiminde faaliyet gösteren bir şirketten elde edilen verilere dayanarak tasarlanmış örnek vakaların ayrıntılarını vurgulamak için bazı duyarlılık analizleri yapılmaktadır.



***Anahtar Kelimeler****: Sürdürülebilir Tedarik Zinciri, Çok Amaçlı Optimizasyon, Karmaşık Tamsayı Doğrusal Programlama, Analitik Hiyerarşi Prosesi*

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# I. INTRODUCTION

Considering global competition conditions, socio-economic developments and increased awareness to the environmental factors in trade activities, companies begin to develop innovative and adaptive management and production mechanisms in their systems. The needs and systemic complexities resulting from globalizing activities and increased customer satisfaction expectations should be considered in a sustainable perspective. This conversion stage requires elimination of unnecessary activities from current systems to decrease unit production cost and cycle times as well as increase environmental awareness and customer satisfaction in the lifecycle of products and services. The sustainability concept introduced by Massaroni et al. (2014) and defined as "*Sustainability is a multi-dimensional construct that enlarges the economic bottom line concept, which focuses on the efficient use of resources and on achieving a return on investments, by adding social considerations and promoting greater ecological responsibility*". Therefore, responsibilities of the companies to achieve this challenge include not only their own production activities, but also the activities of other stakeholders operating in their supply chains due to the high pressure of both customer expectations and legal obligations in this direction. Companies adopting the sustainable supply chain strategy should locate themselves as part of the ecological system and use natural resources in the most efficient way, and they should also provide recycling of their products. The protection and development of human rights is also an important issue that companies should be sensitive to. The companies should ensure that employees work on healthier and safer conditions, access education and health services, and not be exposed to human rights violations. The companies must also care about water usage, air and noise pollution and environmental damage due to production systems.

This conversion stage is also started in plastic packaging industry and most of the middle or high level companies prepared their sustainability strategies. Plastic packaging industry plays very essential role in Turkish economy and has very complex supply chain mechanisms including suppliers, logistics, production, inventory management, etc. Many companies in the plastic packaging industry produce a wide variety of products and the production capacities of the products of the companies cannot be described on a certain unit basis. The total production capacity of companies registered according to The Union of Chambers and Commodity Exchanges of Turkey (TOBB) is 1.188.2008 tons + 2.626.400.207 m2 + 421.630.400 meters + 4.497.991 units (PAGEV, 2016).

Flexible packaging, which has an important place in the plastic packaging sector and continues to grow rapidly, combines the best qualities with the minimum material usage of plastic, film, paper and aluminum foils to ensure that the products reach the end user safely. Flexible packages are films made of certain micron values such as OPP (Oriented Polypropylene), CPP (Cast Polypropylene), PET (Polyester terephthalate), polyethylene, pearlized, aluminum and metallized. The structure of the packaging depends on the physical and chemical properties of the product. Many materials can be also used by laminating. Co-extrusion, coating techniques are utilized in production processes of flexible packages. Therefore, flexible packaging can be defined as any package or any part of a package of which shape can be easily changed.

Flexible packaging has many advantages in operational level. First benefit is that consumer waste sent to landfills is reduced dramatically, this leads to less waste in landfill facilities. Secondly, manufacturers of flexible packaging need fewer natural resources in the production of their packaging. It makes shelf life of products longer, enables freshness and sustainability of packaging is positive. Moreover, water and energy consumption, greenhouse gas emissions and volatile organic compounds decrease due to developments in production technologies. Furthermore, less energy consumed during transportation, environmental pollution and also fossil fuel consumption are enabled with light-weight flexible packaging. Flexible packaging is more appealing to customers and enables visibility of contents (Flexible Packaging Association, 2016). When compared with metal can, production of a flexible food service bag needs 75% less energy and creates just 1/10 of $CO_2$ emissions during manufacturing processes. 1,5 pounds of flexible packaging contain same amount of beverage as 50 pounds of glass can. Flexible packaging contributes to decreasing waste. According to study which is realized by Natural Resources Defense Council, 40% of food in the U.S. is wasted. Food waste is reduced from 11.0% to 0.8% when bread is packaged in BOPP (Bi-axially Oriented Polypropylene) film. Flexible packaging extends shelf life of products. There are some examples proving protection of flexible packaging. When packed in polyethylene shrink wrap, the shelf life of cucumbers increases from 3 days to 14 days. Unless bananas are packaged, their shelf life is 5 days. On the other hand, if they are packaged in perforated polyethylene bags, the shelf life becomes 36 days. The shelf life of meat is extended from 4 days to up to 30 days if vacuum package is used. Recently, it is found out that materials and production processes have helped decreasing weight of flexible packages up to 50%. Depending on this fact, it has reduced shipping costs while it has ensured product protection. Flexible packages simplify the storage. 70% of parents with children under 18 in their households are willing to spend more for products that are easy to store. The top three packaging attributes as rated by consumers are easy to store (66%), ability to reseal (65%) and easy to open (60%). Flexible packaging creates less footprint. Because energy consumption and environmental impact during transportation is greatly reduced. 26 trucks are needed for unfilled glass jars while a truck is enough for unfilled flexible pouches (Flexible Packaging Association, 2017).

Management of the social, environmental, economic impacts of the supply chain to create high-level corporate perception is very tough task and companies should consider all of these objectives at the same time. According to the literature survey, only cost and time conditions are considered in most of the proposed models; however, when environmental and social aspects are included to cost based models, the flexible packaging supply chain network design becomes more complex. The main reason of this complexity is that sustainability cannot be fully integrated and measured in single step optimization problems. To overcome this challenge, a multi-objective modelling approach including economic growth, environmental protection and social conditions must be created. Although there are many studies on sustainability in the supply chains, there is only a few studies containing these different aspects in flexible packaging industry.

With this study, it is aimed to design a sustainable flexible packaging supply chain with a new hybrid approach. Although many studies are published on supply chain design, this study provides a significant contribution to literature and propose a solution methodology of mixed-integer linear mathematical model supported with the AHP method. Therefore, Pareto solution sets for sustainable supply chains are obtained in the light of sustainability indicators of companies. In addition, multi criteria decision support system is combined with multi-objective optimization models that includes minimization of cost and time and maximization of sustainability indexes of the system.

In this study, a new hybrid optimization approach is proposed to design sustainable supply chain for flexible packaging industry using a multi-objective optimization approach. The steps of study are as follows. In Section I, sustainability concept, sustainable supply chain concept, general information about flexible packaging and details of multi-objective optimization problems are explained. Literature survey related with sustainable supply chain, decision making methods and optimization of mathematical models are reviewed in Section II. Solution methodology of proposed approach, problem definition, algorithm of the AHP method and mathematical model formulation are explained in detail in Section III. In Section IV, proposed approach is explained with an illustrative example. The data of a company operating in the flexible packaging sector is used in this example. The results of both AHP method and mixed-integer linear mathematical model are discussed in Section V. With using AHP method, optimum supplier selection is proposed. Mathematical model performed in GAMS gives the feasible solution set for different objective functions. In Section VI, the concluding remarks and future research are presented.

# II. LITERATURE SURVEY

## A. Sustainability in Flexible Packaging Supply Chain

In the last decade, interest in sustainable supply chain has increased considerably both academically and practically. Many companies began to implement sustainable supply chain activities due to the pressure of stakeholders, government, non-governmental organizations, community activists and the global competition (Hassine et al., 2012). According to Carter and Rogers (2008), sustainable supply chain management is defined as "*the strategic, transparent integration and achievement of an organization's social, environmental and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term economic performance of the individual and its supply chain*". Seuring and Müller (2008) described sustainable supply chain management as the management of material, cash flows and information and collaboration with other firms along the supply chain. Sustainable supply chain management has economic, social and environmental dimensions that are obtained from needs of stakeholder and consumer. Pagell and Wu (2009) pointed out that a sustainable supply chain should indicate good results when measuring social and environmental dimensions as well as profit and loss. In recent times, sustainability has led to increased concern for many companies due to increased consumer demands and legal obligations. The design and management of the food packaging supply chain has also become very important topic in terms of the competitive advantage of the companies in the sector. Firms in the packaging industry must regard environmental issues such as lifestyle changes, technological changes, consumer demands and supply chain relationships, when designing their supply chain (James, 2003).

Flexible packaging is usually used for food packaging because it improves the quality and safety of food. It protects food from contamination and deterioration, and at the same time eases the transport and storage of food. It also helps advertising, distribution and mass merchandising of products and makes products more user friendly and proper (Robertson, 2009). Although flexible packaging industry is important for healthy foods, there are only a few studies about flexible packaging supply chains in the literature. The complexity of the structure of the supply chain is one of the main reasons for this situation and many companies work together to response the market demand for products. Lisińska-Kuśnierz and Kawecka (2013) stated that physical flow of food packaging materials and packaging is carried out in supply chain. Main stakeholders of this supply chain are suppliers and converters delivering packaging materials or packaging, fillers or users, sellers, consumers and end of life managers. In order to protect human health and life, specific legal arrangements and other conditions have been taken to ensure the safety of food packaging, so all stakeholders must comply with legal regulations.

## B. Analytical Models for Sustainable Supply Chain

Sustainable supply chain practices in companies are realized together with strategic, tactical and operational decisions such as, sustainable supplier selection (Amindoust et al., 2014), sustainable supply chain network design (Eskandarpour et al., 2015), sustainable procurement (Meehan and Bryde, 2011), sustainable transportation (Litman, 2009), sustainable manufacturing (Li et al., 2007) and sustainable information technology (Clemons, 1986).

In this study, it is aimed to integrate two important issues which are sustainable supplier selection and optimization of sustainability performance indicators in flexible packaging supply chain network design. There is a little attention on this topic in the flexible packaging sector, so this study is the one of the first studies about this subject. Massaroni et al. (2014) has the most relevant work focusing on sustainable supply chain management. They gave a perfect literature review to demonstrate the main properties of sustainability in supply chain management studies. As a result of their research in the literature, they identified the performances of all stakeholders in the supply chain for the sustainability of the supply chain with researching examples from many articles. There is another study about supplier selection in the flexible packaging industry. Cristea and Cristea (2017) presented a multiple criteria decision making analysis assisting to the selection of the most appropriate supplier in the flexible packaging industry. They introduced a new solution method that also evaluates the other important criteria instead of selection methods that only care about costs in supplier selection. Since there is a little attention in literature about sustainable flexible packaging supply chain design and also multi-objective methods, this study designs quantitative models dealing with assisted decision making methods and tools for supply chain design.

### 1. Single Criterion Decision Making Methods

In the single criterion decision making methods, while choosing the alternative, the aim is dependent on the single criteria. Most of the studies dealing with this method in the literature, focused only on economic measurements in sustainable supply chains. In some of these studies, sustainability problems which have triple bottom-line approach that balances economic, environmental and social dimensions are transformed into a single criterion.

There is many approaches such as Branch-and-Bound and Bender Decomposition to solve supply chain design problems with only economic measurements. Although these methods are ideal for solving small-scale problems, they cannot provide feasible solutions when the size of the problem expands. In large-sized problems, there are many constraints and variables. Therefore, it is hard to solve the problems with these methods since the computation time is not practical. Since a sustainable supply chain has economic, environmental and social factors, single criterion decision making methods are not useful for this study.

### 2. Multiple Criteria Decision Making Methods

Multiple Criteria Decision Making (MCDM) is expressed as the process of assigning values to each alternative by evaluating a lot of criteria together. MCDM method has two different techniques. First one is Multiple Attribute Decision Making (MADM) technique which ranks the attributes to select the best alternatives. According to their purpose, MADM problems are classified as choice, ranking and sorting problems. Figure 1 shows the models of MADM which are Value Measurement, Outranking and Goal or Aspiration Level. Second technique is Multiple Objective Decision Making (MODM) technique which solves design and search problems to obtain optimal results. MODM techniques are applied to solve problems in cases where the parameters of the objective functions and constraints cannot be definitively identified by decision makers in multiple criteria problems. Economic, social and environmental criteria are very important in a sustainable supply chain. In order to solve multi-objective optimization problems such as sustainable supply chain, MODM methods are generally used. There are a lot of studies related with MADM problems in the literature.

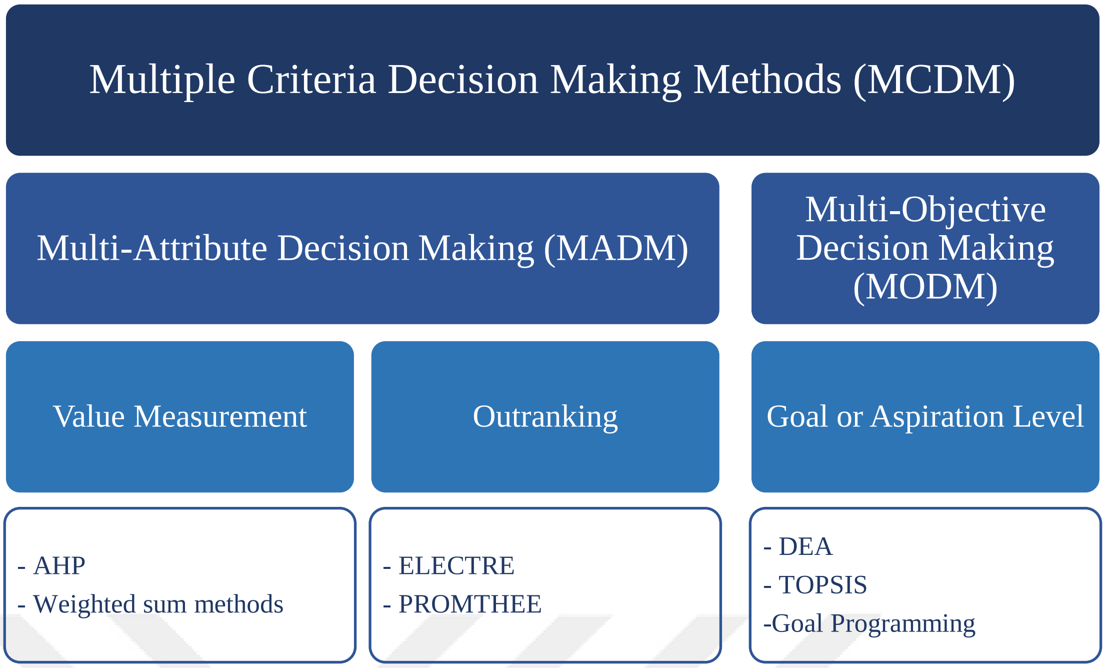


Figure 1: Overview of Multiple Criteria Decision Making Methods

Shaw et al. (2012) explained the effect of carbon emission in supplier evaluation in their work. Fuzzy AHP and fuzzy multi-criteria linear programming were used to select the best suppliers. AHP method was applied to calculate the weights. Calculated weights were used as data for fuzzy multi-criteria linear programming. Noorizadeh (2014) proposed Data Envelopment Analysis (DEA) to select green suppliers which have less carbon emission. Carbon emission quantities were reported as undesirable results by DEA at the end of the study.

In literature, there are many methods to solve multi-objective problems by finding Pareto optimal sets. Mele et al. (2009), proposed a decision making method using a mixed integer linear model. Pareto solution sets of cost negative environmental effect minimization were demonstrated after applying the model. Hong et al. (2005) also developed a mixed-integer linear programming model to the select best supplier. The optimal number of suppliers and the optimal order quantity were calculated as a result.

According to Kannan et al. (2013), Goal Programming (GP) is a useful method to solve multi criteria decision making problems since it is simple to apply. In Goal programming method, large numbers of objectives, variables and constraints can be used to solve complex problems. Jolai et al. (2011) obtained the efficiency ranks of suppliers and chose the high ranked ones with using a fuzzy multiple criteria method.

Then, they calculated the order quantities of supplier using a multi-objective mathematical model. Ku et al. (2010) presented an approach combined fuzzy analytic hierarchy process (FAHP) with fuzzy goal programming (FGP) methods for solving supplier selection problem.

Simple Multi-Attribute Rating Technique (SMART) and The Analytical Hierarchy Process (AHP) which are weighting methods are evaluated all alternatives and calculated the weights of each criteria. AHP is a method that compares all the criteria which affect the decisions and it determines the importance level of each. To generate the performance measurement system, Durdudiler (2006) used AHP method that is designed to solve decision making problems involving multiple criteria. In the model, a product group was selected in a retail firm. Performance criteria for this group were determined. Expert Choice software was used to determine the weights of the criteria and to calculate the final scores of the suppliers. In addition, taking into account the uncertain data in the model, fuzzy AHP was applied and the results were examined.

Boran et al. (2009) used a hybrid approach combined intuitionistic fuzzy sets with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to apply a decision making problem which is about supplier selection.

Deng (1982) developed "*Grey Theory*" which can be defined as "*According to the concept of the black box, a system containing knowns and unknowns is called a grey system*". This method is used for incompletely described information with few data available. Li et al. (2007) proposed a new approach based on Grey Theroy to select the best suppliers. The final scores of the suppliers were determined with using a Grey possibility degree.

A new method which is a combination of entropy weight and an improved Elimination and Choice Translating Reality (ELECTRE) III method were proposed by Liu and Zhang (2011) to select best suppliers. Weights of each indicator were determined based on entropy. Then, the harmoniousness and the inharmoniousness index were determined. As a result, all alternative suppliers were ranked according to their advantage values.

Köksalan and Özpeynirci (2009) proposed an interactive approach that combines UTADIS with Köksalan and Ulu's (2003) approaches to sort non-reference and reference alternatives. UTADIS was used for estimating the additive utility function which uses alternatives assigned to categories. Köksalan and Ulu's (2003) approach proposed an interactive procedure for the sorting problems.

To prioritize supply chain risks, Prasanna et al. (2012) proposed an approach combined AHP with Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE). A case example of a typical plastic industry was presented to outline the performance of the proposed approach. Bas (2013) used SWOT-fuzzy TOPSIS methodology combined with Analytic Hierarchy Process (AHP) to analyze an electricity supply chain. Since SWOT analysis is only used for qualitative factors of supply chain, AHP was integrated with identified SWOT factors to create strategy plan.

OWA operator introduced by Yager (1988), was aimed to collect information and recommended a method to compute the weights of the OWA operator with using linguistic quantifiers.

VIKOR method was used by Fu et al. (2011) for benchmarking analysis of 26 international hotels. The fuzzy analytic hierarchy process (AHP) was applied to determine the weights of the performance criteria.

### C. Multi-Objective Mathematical Models for Supply Chain Design

Systematic and concurrent optimization of multi-objectives in a performance criterion is called multi-objective optimization. In multi-objective optimization problems, it may be difficult to construct the objective function while modeling the decision problem. In a majority of decision problems, there are multiple criteria to assess the quality of the solution. Collecting these criteria in a single objective function may not always be possible. Different problems arise when the criteria conflict with each other. There are multiple solutions for multi-objective optimization problems. In solution of this kind of problems, using the algorithm of single-objective optimization problems can sometimes lead to problems such as not being able to scan whole solution space and not getting good results. Researchers have developed methods to cover the entire solution space to achieve effective results in the solution of multi-objective problems and have adapted them to solution algorithms (Kaya and Fığlalı, 2017).

Especially in the last two decades, use of multi-objective optimization for real world problem increased dramatically. Although there are many techniques for single objective optimization, there are not many varieties of techniques for multi objective optimization. Generally, to define search space in single objective optimization problems is simple. When there are many possible contrary objectives to be optimized at the same time, there is not any more single optimal solution but rather a set of possible solutions of same quality. (Abraham and Jain, 2005).

There are some classical methods to solve multi-objective optimization problems for supply chain design. "Weighted Sum Method" and "Epsilon-Constraint Method" are the most commonly used methods.

### 1. Weighted Sum Method

This method is the simplest, traditional and probably the most preferred method that changes the weights between objective functions of mathematical model to get the Pareto front. First research about Weighted Sum Method has done by Zadeh (1963). Koski (1988) presented a study about the weighted sum method as part of multi-criteria truss optimization. Schy and Giesy (1988) studied about multi-objective optimization applications for designing aircraft control system.. Kim and de Weck (2005) proposed a weighted sum method to expand existing presented bi-objective adaptive weighted sum method to problems that have more than two objectives.

### 2. Epsilon-Constraint Method

The Epsilon-Constraint Method has been developed for general multi-objective problems. Yang et al. (2014) defined The Epsilon-Constraint Method as *"The Epsilon-Constraint Method is an algorithm transformation method, which can convert constrained optimization problems to unconstrained ones using the epsilon level comparison, which compares search points based on the pair of objective value and constraint violation of them"*.

The Epsilon-Constraint Method was initially proposed by Haimes (1971) for generating Pareto optimal solutions. In this method, a criteria is selected as a single-objective to be optimized while each of the other criteria is defined as a constraint. To bound on the objectives, the extreme points are calculated. A single objective function and constraints are used to find Pareto optimal sets (Becerra and Coello, 2006). Pérez-

Fortes et al. (2012) developed a mathematical model which has economic, environmental and social criteria. But, only environmental criterion was demonstrated in the $\epsilon$-constraint because the social criteria is discrete. Pozo et al. (2012) used an epsilon-constraint approach to solve the problem. Then, to decrease the dimensionality of the model, they used Principal Component Analysis. The ϵ-constraint approach was adapted again on the dimensionally reduced model at last. Non-convex mathematical model was developed by Guillén-Gosálbez and Grossmann (2010). The epsilon-constraint used the net values. Finally, the mathematical model was solved with a spatial branch-and-bound.

Mavrotas (2007) presented a new version of the ϵ-constraint method named Augmented Epsilon-Constraint Method (AUGMECON Method). The ϵ-constraint method was improved along with the weighting method for producing the Pareto solution sets. Esmaili et al. (2011) proposed a new multi-objective solution method which is combined augmented $\epsilon$-constraint technique with the weighting method in their study.

Mavrotas (2009) specified the advantages of the epsilon-constraint method in his study. According to him, the $\epsilon$-constraint method created alternatives to the original feasible region can generate non-extreme efficient solutions. The $\epsilon$-constraint method can generate effective solutions in multi-objective problems. In the $\epsilon$-constraint method, the number of produced solutions can be controlled. Mavrotas and Florios (2013) presented a new version of AUGMECON named AUGMECON2. AUGMECON2 is an improvement of the original AUGMECON method (Mavrotas, 2009) which was a new approach to apply the well-known $\epsilon$-constraint method for generating the Pareto optimal solutions in Multi-Objective Programming models.

As can be understood from the literature survey mentioned above, authors were generally able to focus on limited criteria in their approach. They were able to focus on only a few indicators even in MCDM approaches. Since developing a model with a wide range of criteria is very complicated, there was not any study about flexible packaging supply chain design with sustainability dimensions. The optimization models that will be created for a new sustainable supply chain design are very complicated since they must include the economic, social and environmental factors required for sustainability. A lot of indicators should be included in the supply chain design to evaluate all the dimensions required for sustainability in the flexible packaging supply chain. In One Stage Optimization Problems there are a number of indicators which could not be modelled. If all these issues are taken into consideration, there is a little effort in the literature. With using all various indicators of sustainability, an effective two stage hybrid multi objective decision making model is proposed for flexible packaging supply chain network design in this study.

# III. RESEARCH METHODOLOGY

## A. Research Design

As mentioned in the first part of the study, to determine the indicators required for a sustainable flexible packaging supply chain design is quite complicated since they involve both numerical and linguistic data. Considering this, it is impossible to add all indicators to the objective functions of the mathematical model. Therefore, a two-step hybrid approach is proposed as a solution methodology in this study to be able to add the largest number of indicators that can be used in the mathematical model of sustainable flexible packaging supply chain design. Figure 2 shows the steps of this approach. This proposed approach requires performing an initial evaluation of suppliers of supply chain under several criteria and sub-criteria in the first stage. There may be complicated criteria to integrate into the objective function in the second stage. Such criteria can be considered in the first stage of approach. There are different sets of key performance indices to determine and evaluate efficiency score of performance of supplier in the supply chain. Analytic Hierarchy Process (AHP) method is used for calculation of the efficiency scores of suppliers and obtained scores will be considered and taken as one of the objectives to be optimized in the second stage. In the second stage, approach includes application of a mathematical model with multi-objective functions. In addition to the efficiency scores calculated in the first stage, all three dimensions of sustainability (economic, environmental and social) are considered.

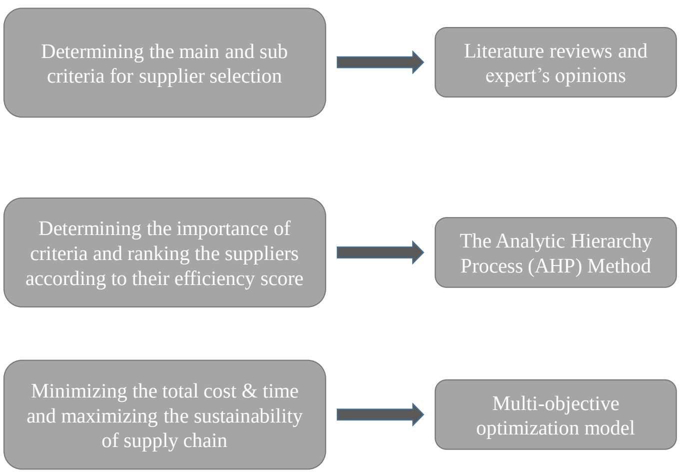


Figure 2: Research framework for sustainable supply chain design

### B. The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process which is a Multiple Attribute Decision Making method is used for ranking the suppliers according to their efficiency score. Figure 3 demonstrates phases of AHP.

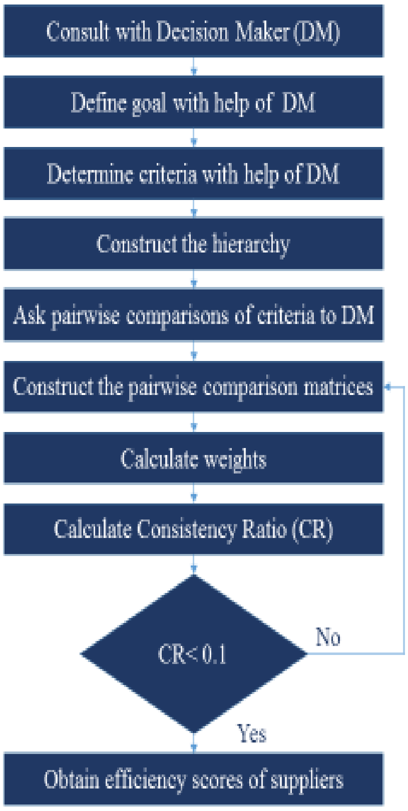


Figure 3: Working Principle of Analytic Hierarchy Process (AHP)

In the first step of AHP, a complex decision problem is structured at hierarchical levels. To decrease complexity in multi-criteria problems, decision alternatives are generated by AHP. The objectives, criteria and alternatives are organized in a hierarchical structure. (Ozkan et al., 2011). The decision hierarchy begins from the most general objectives to the most specific one. The alternatives are indicated in the last level of the hierarchy. Figure 4 indicates the hierarchical structure considered in this study. And Table 1 shows the indicators most appropriate for this study.

- Product Cost is the total unit cost of purchasing of raw materials used in production.

- Product Quality is the percentage of products delivered in the expected quality.

- Technology Capability indicates how much suppliers applies technological and product developments

- Organization and Management refers to the supplier's managerial success.

- Production Facilities and Capacity expresses the production capacity of suppliers.

- Organization and Management refers to the supplier's managerial success.

- Delivery Availability indicates the share of the deliveries completed in the due date.

- Usage of Renewable Resources refers to suppliers' renewable resource consumption rates.

- Flexibility indicates the responsiveness of the suppliers to the unexpected or additional order.

- Environmental Costs refers to the destructive processes that suppliers have.

- Recyclability is the recycle rate of the suppliers.

- Environmental Management System expresses how good the suppliers are about environmental protection systems.

- Pollution Control refers to the environmental pollution rates of suppliers.

- Chemicals specifies the percentage of ozone depleting chemicals that suppliers used in their production.

- Worker's right specifies the workers' contract conditions.

- Health and safety at work indicates how much the supplier attaches importance to safety training for newly hired workers.

• Safety Training describes rate of training that suppliers provide to their workers about safety.

• Supportive Activities for Worker specifies the rate of supportive activities of suppliers to motivate their employees.

Table 1: Indicators of Stage 1

| Economic | Environmental | Social |
|---|---|---|
| Product Cost | Environmental Costs | Worker's Right |
| Product Quality | Recyclability | Safety Training |
| Technology Capability | Environmental Management System | Health and Safety at Work |
| Organization and Management | Pollution Control | Supportive Activities for Worker |
| Production Facilities and Capacity | Chemical Usage | |
| Delivery Availability | | |
| Usage of Renewable Resources | | |
| Flexibility | | |

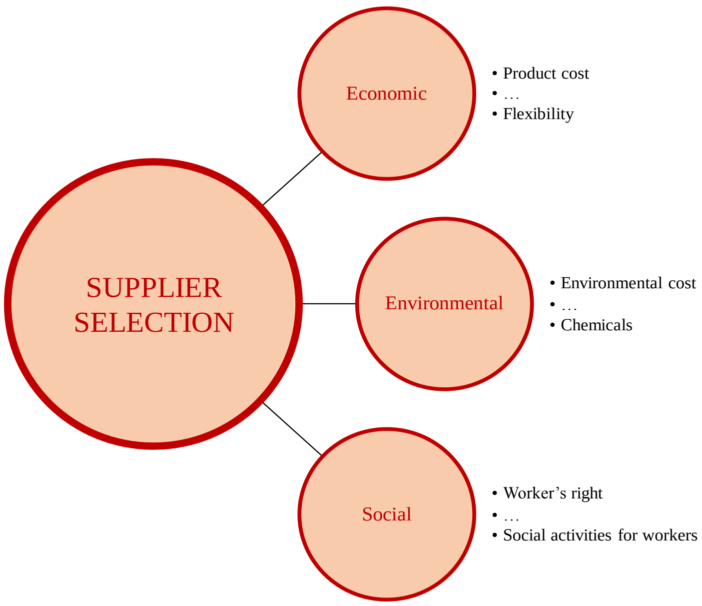


Figure 4: Hierarchical Structure of the decision problem

The second step is the comparison of the alternatives and the criteria. After the problem is structured at hierarchical levels, relative weights of the criteria are calculated for prioritization. The pairwise judgment is applied at all level of alternatives. Multiple pairwise comparisons have a comparison scale of nine levels proposed by Saaty (1980). The levels 1, 3, 5, 7 and 9 are defined as follows: equal, moderate, strong, very strong and extreme level respectively. The intermediate values are represented by 2, 4, 6, and 8.

In the first step, let $A_1$, $A_2$, $A_3$…, $A_n$, are defined as the set of indicators. The pairwise judgments of criteria $A_i$ and $A_j$ are symbolized by an $(n \times n)$ matrix $A = (a_{ij})$; $i, j = 1, 2 \ldots n$. In A, a single number is appointed to each $a_{ij}$ which is the element of row $i$ and column $j$ matrix.

The entries $a_{ij}$ are described as follows:

- **Rule 1:** If $a_{ij} = x$, then, $a_{ji} = {}^{1}/_{x}$ = 1, 2,…9)
- **Rule 2:** If $A_i$ is judged, to be of equal, relative intensity to $A_j$, then, $a_{ij} = a_{ji} = 1$
- **Rule 3:** $a_{ii} = 1$ for all $i$

So, the matrix turns into this form (Saaty, 2007):

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \ldots & 1 \end{bmatrix}$$

Finally, priority vector, which is the normalized Eigen vector of the matrix is calculated. The method approximates Eigen vector (and Eigen value) of a reciprocal matrix. To understand these calculations, there is an example:

Suppose that 3 by 3 reciprocal matrix is generated from paired comparison of X, Y and Z.

$$X \qquad Y \qquad Z$$

$$A = \begin{matrix} X \\ Y \\ Z \end{matrix} \begin{bmatrix} 1 & 1/3 & 5 \\ 3 & 1 & 7 \\ 1/5 & 1/7 & 1 \end{bmatrix}$$

Sum of each column gives the reciprocal matrix (4$^{th}$ row).

$$A = \begin{matrix} \\ X \\ Y \\ Z \\ \textbf{Sum} \end{matrix} \begin{matrix} X & Y & Z \\ \left[\begin{matrix} 1 & 1/3 & 5 \\ 3 & 1 & 7 \\ 1/5 & 1/7 & 1 \\ \mathbf{21/5} & \mathbf{31/21} & \mathbf{13} \end{matrix}\right] \end{matrix}$$

Then dividing each element of the matrix with the sum of its column gives the normalized relative weight. The sum of each column is again 1.

$$A = \begin{matrix} \\ X \\ Y \\ Z \\ \textbf{Sum} \end{matrix} \begin{matrix} X & Y & Z \\ \left[\begin{matrix} 5/21 & 7/31 & 5/13 \\ 15/21 & 21/31 & 7/13 \\ 1/21 & 3/31 & 1/13 \\ \mathbf{1} & \mathbf{1} & \mathbf{1} \end{matrix}\right] \end{matrix}$$

The normalized principal Eigen vector is obtained by averaging across the rows.

$$W = \frac{1}{3} \begin{bmatrix} 5/21 & 7/31 & 5/13 \\ 15/21 & 21/31 & 7/13 \\ 1/21 & 3/31 & 1/13 \end{bmatrix} = \begin{bmatrix} 0,2828 \\ 0,6434 \\ 0,0738 \end{bmatrix}$$

Since Eigen vector is normalized, the sum of all elements in this vector is 1. It also demonstrates relative weights of compared criteria. According to example, X is 28.28%, Y is 64.34% and Z is 7.38%. The best choice is Y followed by X and Z.

The consistency of results can be analyzed with "Principal Eigen" value. Principal Eigen value is calculated from the summation of products between each element of Eigen vector and the sum of columns of the reciprocal matrix.

$$\lambda_{max} = \frac{21}{5}(0.2828) + \frac{31}{21}(0.6434) + 130.0738 = 3.0967$$

To measure consistency of opinion Principal Eigen value is utilized. In this example, Y>X and X>Z. Since Y>Z and X>Z, logically it is expected that Y>Z which means Y have to be preferable than Z. This logic of choice is called "transitive property". To understand consistency of judgment, results in the last comparison should be checked. If the results are transitive, the judgment is consistent.

Saaty (1980) defined a measure of consistency called "Consistency Index" as deviation or degree of consistency using the following formula.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

In the example, $\lambda_{max} = 3.0967$ and $n$=3, so the CI is as follows:

$$CI = \frac{3.0967 - 3}{3 - 1} = 0.0484$$

Consistency Index can only utilized by comparing it with the appropriate one. The appropriate Consistency index that is proposed by Saaty (1980) is called" Random Consistency Index" (RI). Table 2 derived by Saaty (2000) shows values of the RI for matrices of 1 to 10 obtained by approximating random indices using a sample size of 500.

Table 2: Random Consistency Index (RI)

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **RI** | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

Consistency Ratio is obtained by comparing Consistency Index with Random Consistency Index. CR is shown as follows:

$$CR = \frac{CI}{RI} \quad \text{.....................................................(2)}$$

If the Consistency Ratio is smaller or equal to 10%, the inconsistency is acceptable. If the Consistency Ratio is greater than 10%, the judgment should be revised.

In the example $CI = 0.0484$ and $RI = 0.58$ (since *n*=3 from Table 2), then

$$CR = \frac{0.0484}{0.58} = 8.3\% < 10\%$$

Thus, it can be said that the evaluation is consistent because consistency ratio is less than the critical value of 10%.

The AHP method is applied to determine weights for each of the criteria illustrating their importance level. A hierarchical model for decision making problems is generated by AHP with considering each alternative separately. In AHP model, each of the alternatives has an associated importance. To determine final score, weights are used in the aggregation process in the AHP. The efficiency score calculated here is used in one of the objective functions of mathematical modeling in the second stage.

# IV. MATHEMATICAL MODEL

In the second stage, a multi-objective optimization model will be developed. The developed multi-objective linear supply chain model aims to select effective suppliers among potential suppliers. The new model is proposed trying to improve the optimization of sustainable supply chain network design and answering the research questions. A mathematical model that have the basic structure of the supply chain design and the preliminary assumptions will be developed. A multi-objective model with three objective functions and relevant constraints is presented. The model has a set of indices, parameters and decision variables. The notation used for this model is as follows:

## SETS

| | |
|---|---|
| *i & i'*: Product Type | (*i & i'* = 1, … , *I*) |
| *j*: Customers of the company | (*j* = 1, … , *J*) |
| *g*: Factories of the company | (*g* = 1, … , *G*) |
| *m*: Transportation Modes | (*m* = 1, … , *M*) |
| *s*: Suppliers of the company | (*s* = 1, … , *S*) |
| *t*: Time Periods (monthly) | (*t* = 1, … , *T*) |

## PARAMETERS

$c_p^R = Unit\ production\ cost\ in\ regular\ working\ hours$ [$/pc]

$c_p^O = Unit\ production\ cost\ in\ overtime\ working\ hours$ [$/pc]

$c_p^I = Unit\ production\ cost\ in\ idle\ working\ hours$ [$/pc]

$c_i^+ = Inventory\ cost\ of\ keeping\ Product\ i\ in\ warehouse$ [$/pc]

$c_i^- = Backorder\ cost\ of\ unsatisfied\ Product\ i$ [$/pc]

$c_{Setup} = Setup\ cost\ \ for\ giving\ an\ order\ [\$/pc]$

$\theta = Average\ container\ capacity\ [20\ tons]$

$M = The\ Big - M\ Parameter\ Value\ [10^8]$

$Speed_m = Average\ speed\ of\ transportation\ mode\ m$

$c_m^{Tran} = \ Unit\ transportation\ cost\ for\ Mode\ m\ [\$/pc]$

$Cap_g^W\ = \ Warehouse\ capacity\ of\ Factory\ g$

$Cap_g^P\ = \ Production\ capacity\ of\ Factory\ g$

$\beta_i\ = \ Raw\ material\ conversion\ factor\ to\ produce\ Product\ Type\ i$

$t_{i,g}^P = \ Production\ time\ of\ Product\ i\ in\ Factory\ g$

$Demand_{i,j,t} = \ Demand\ of\ Product\ Type\ i\ from\ Customer\ j\ in\ time\ Period\ t$

$Distance'_{s,g} = \ Distance\ from\ Supplier\ s\ to\ Factory\ g$

$Distance''_{g,j} = \ Distance\ from\ Factory\ g\ to\ Customer\ j$

$$Network'_{s,g,m} = \begin{cases} 1 & If\ there\ is\ a\ connection\ between\ Supplier\ s\ and\ Factory\ g\ via\ Mode\ m \\ 0 & else \end{cases}$$

$$Network''_{g,j,m} = \begin{cases} 1 & If\ there\ is\ a\ connection\ between\ Factory\ g\ and\ Customer\ j\ via\ Mode\ m \\ 0 & else \end{cases}$$

$\pi_s = Final\ score\ of\ Supplier\ s$

$Cap_{i,s}^P = Raw\ material\ capacity\ of\ Product\ Type\ i\ in\ Supplier\ s$

$Setcost_{i,i'} = Setup\ cost\ required\ to\ change\ Product\ type\ i\ to\ Type\ i'$

$t_{i,i'}^{setup} = Setup\ time\ required\ to\ change\ Product\ type\ i\ to\ Type\ i'$

## DECISION VARIABLES

$Q^{+}_{i,j,g,m,t} = Quantity\ of\ Product\ i\ from\ Factory\ g\ to\ Customer\ j\ with\ Mode\ m\ in\ Period\ t$

$Q^{-}_{i,s,g,m,t}$ = Quantity of Raw Material for Product $i$ from Supplier $s$ to Factory $g$ with Mode $m$ in Period $t$

$PrR_{i,g,t} = Regular\ Production\ quantity\ of\ Product\ i\ in\ Factory\ g\ in\ Period\ t$

$PrO_{i,g,t} = Overtime\ Production\ quantity\ of\ Product\ i\ in\ Factory\ g\ in\ Period\ t$

$PrI_{i,g,t} = Idle\ Time\ of\ Product\ i\ in\ Factory\ g\ in\ Period\ t$

$PrR^{P}_{i,g,t} = Relaxed\ Regular\ Production\ quantity\ of\ Product\ i\ in\ Factory\ g\ in\ Period\ t$

$PrO^{P}_{i,g,t} = Relaxed\ Overtime\ Production\ quantity\ of\ Product\ i\ in\ Factory\ g\ in\ Period\ t$

$Inv^{+}_{i,g,t} = Inventory\ level\ of\ Product\ i\ kept\ in\ Factory\ g\ in\ Period\ t$

$Inv^{-}_{i,g,t} = Backorder\ level\ of\ Product\ i\ in\ Factory\ g\ in\ Period\ t$

$$\delta_{i,s,t} = \begin{cases} 1 & If\ Raw\ material\ of\ Product\ i\ is\ ordered\ from\ Supplier\ s\ in\ Period\ t \\ 0 & else \end{cases}$$

$$\alpha'_{i,g,t} = \begin{cases} 1 & If\ there\ is\ regular\ production\ of\ Product\ i\ in\ Factory\ g\ in\ Period\ t \\ 0 & else \end{cases}$$

$$\alpha''_{i,g,t} = \begin{cases} 1 & If\ there\ is\ overtime\ production\ of\ Product\ i\ in\ Factory\ g\ in\ Period\ t \\ 0 & else \end{cases}$$

$$\gamma_{i,i',g,t} = \begin{cases} 1 & If\ there\ is\ change\ from\ Product\ i\ to\ Product\ i'\ in\ Factory\ g\ in\ Period\ t \\ 0 & else \end{cases}$$

$$Min\ f_1 = \sum_{i\in I}\sum_{i'\in I}\sum_{g\in G}\sum_{t\in T}\gamma_{i,i',g,t} \times Setcost_{i,i'} + \sum_{i\in I}\sum_{s\in S}\sum_{g\in G}\sum_{m\in M}\sum_{t\in T}\frac{Q^{-}_{i,s,g,m,t}}{\theta} Distance'_{s,g} \times c^{Tran}_{m} + \sum_{i\in I}\sum_{g\in G}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}\frac{Q^{+}_{i,j,g,m,t}}{\theta}\ Distance''_{g,j} \times c^{Tran}_{m} + \sum_{i\in I}\sum_{g\in G}\sum_{t\in T} PrR^{P}_{i,g,t} \times c^{R}_{p} + \sum_{i\in I}\sum_{g\in G}\sum_{t\in T} PrO^{P}_{i,g,t} \times c^{O}_{p} + \sum_{i\in I}\sum_{g\in G}\sum_{t\in T} PrI_{i,g,t} \times c^{I}_{p} + \sum_{i\in I}\sum_{g\in G}\sum_{t\in T} Inv^{+}_{i,g,t} \times c^{+}_{I} + \sum_{i\in I}\sum_{g\in G}\sum_{t\in T} Inv^{-}_{i,g,t} \times c^{-}_{I} + \sum_{i\in I}\sum_{s\in S}\sum_{t\in T}\delta_{i,s,t} \times C_{Setup} \ldots\ldots (3)$$

$$Min\ f_2 = \sum_{i\in I}\sum_{i'\in I}\sum_{g\in G}\sum_{t\in T}\gamma_{i,i',g,t} \times t^{setup}_{i,i'} + \sum_{i\in I}\sum_{s\in S}\sum_{g\in G}\sum_{m\in M}\sum_{t\in T}\frac{Q^{-}_{i,s,g,m,t}}{\theta \times Speed_m} Distance'_{s,g} + \sum_{i\in I}\sum_{g\in G}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}\frac{Q^{+}_{i,j,g,m,t}}{\theta \times Speed_m}\ Distance''_{g,j} + \sum_{g\in G}\sum_{t\in T}\left(\sum_{i\in I} 8\alpha'_{i,g,t}\right) + \sum_{g\in G}\sum_{t\in T}\left(\sum_{i\in I} 4\alpha''_{i,g,t}\right) + \sum_{i\in I}\sum_{g\in G}\sum_{t\in T}\frac{PrR^{p}_{i,g,t} + PrO^{p}_{i,g,t} - PrI_{i,g,t}}{t^{P}_{i,g}} \ldots\ldots (4)$$

$$Max\ f_3 = (\sum_{s\in S}(\sum_{i\in I}\sum_{g\in G}\sum_{m\in M}\sum_{t\in T} Q^-_{i,s,g,m,t}) \times \pi_S) \quad (5)$$

***<u>Subject to:</u>***

$$\sum_{g\in G}\sum_{m\in M} Q^+_{i,j,g,m,t} = Demand_{i,j,t}\,, \quad \forall i \in I, j \in J, t \in T \quad if\ \ Network''_{g,j,m} = 1 \quad (6)$$

$$\sum_{g\in G}\sum_{m\in M} Q^-_{i,s,g,m,t} \leq Cap^P_{i,s}\delta_{i,s,t}, \quad \forall i \in I, s \in S, t \in T \quad if\ \ Network'_{s,g,m} = 1 \quad (7)$$

$$PrR^P_{i,g,t} + PrO^P_{i,g,t} - PrI_{i,g,t} - \sum_{j\in J}\sum_{m\in M} Q^+_{i,g,j,m,t} + Inv^+_{i,g,t-1} - Inv^-_{i,g,t-1} = Inv^+_{i,g,t} - Inv^-_{i,g,t}\,, \quad \forall i \in I, g \in G, t \in T \quad if\ \ t > 1 \quad (8)$$

$$\sum_{s\in S}\sum_{m\in M} Q^-_{i,s,g,m,t} = \beta_i * (PrR^P_{i,g,t} + PrO^P_{i,g,t} - PrI_{i,g,t}), \quad \forall i \in I, g \in G, t \in T \quad (9)$$

$$\sum_{i\in I} Inv^+_{i,g,t} \leq Cap^W_g, \quad \forall g \in G, t \in T \quad (10)$$

$$\sum_{i\in I}(PrR^P_{i,g,t} + PrO^P_{i,g,t} - PrI_{i,g,t}) \leq Cap^P_g, \quad \forall g \in G, t \in T \quad (11)$$

$$PrR^P_{i,g,t} \leq PrR_{i,g,t}, \quad \forall i \in I, g \in G, t \in T \quad (12)$$

$$PrR^P_{i,g,t} \geq PrR_{i,g,t} - M(1 - \alpha'_{i,g,t}), \quad \forall i \in I, g \in G, t \in T \quad (13)$$

$$PrR^P_{i,g,t} \leq M\alpha'_{i,g,t}, \quad \forall i \in I, g \in G, t \in T \quad (14)$$

$$PrO^P_{i,g,t} \leq PrO_{i,g,t}, \quad \forall i \in I, g \in G, t \in T \quad (15)$$

$$PrO^P_{i,g,t} \geq PrO_{i,g,t} - M(1 - \alpha''_{i,g,t}), \quad \forall i \in I, g \in G, t \in T \quad (16)$$

$$PrO^P_{i,g,t} \leq M\alpha''_{i,g,t}, \quad \forall i \in I, g \in G, t \in T \quad (17)$$

$$\alpha'_{i,g,t} \geq \alpha''_{i,g,t}, \quad \forall i \in I, g \in G, t \in T \quad (18)$$

$$\gamma_{i,i',g,t} = \alpha'_{i,g,t} + \alpha'_{i',g,t} - 1, \quad \forall i \in I, g \in G, t \in T \quad if\ i < I \quad (19)$$

$$Q^+_{i,j,g,m,t} \geq 0, \quad \forall i \in I, j \in J, g \in G, m \in M, t \in T \quad (20)$$

$$Q^-_{i,s,g,m,t} \geq 0, \quad \forall i \in I, s \in S, g \in G, m \in M, t \in T \quad (21)$$

$$PrR_{i,g,t}, PrO_{i,g,t}, PrI_{i,g,t}, PrR^P_{i,g,t}, PrO^P_{i,g,t}, Inv^+_{i,g,t}, Inv^-_{i,g,t} \geq 0, \forall i \in I, g \in G, t \in T \quad (22) - (28)$$

$$\alpha'_{i,g,t}, \alpha''_{i,g,t} \in \{0,1\}, \quad \forall i \in I, g \in G, t \in T \quad (29) - (30)$$

$$\delta_{i,s,t} \in \{0,1\}, \quad \forall i \in I, s \in S, t \in T \text{ ......} (31)$$

$$\gamma_{i,i',g,t} \in \{0,1\}, \quad \forall i \in I, i' \in I, g \in G, t \in T \text{ ......} (32)$$

Equation (3) indicates the minimization of total cost function. The first term shows total setup cost if there is a change from Product *i* to Product *i'* in factories for all periods. Second term refers to total transportation cost for movement of raw materials between suppliers to factories. Third term shows the total transportation cost for supplying the final products to the customers from factories. Fourth, fifth and sixth terms aims to calculate total production cost in regular, overtime and idle time working hours respectively. Seventh term shows the inventory cost of products kept in warehouses. Eighth term refers to backorder cost of products and last term shows setup cost for orders given to suppliers. Equation (4) aims minimizing the time passed during all the processes of supply chain. First term shows total setup time if there is change from Product *i* to Product *i'* in factories for all periods. In the second and third terms the total transportation time when receiving raw material from suppliers to factories and when sending final products from factories to customers are calculated, respectively. Fourth term indicates regular production time of products. Fifth term shows the total overtime production durations. Last term refers to the total production time of all products produced in factories. Equation (5) aims to maximize sustainability of the company considering the quantity of raw material purchased from different suppliers. In this equation, model tries to increase quantity of raw material taken from suppliers with higher final score. Equation (6) provides that quantity of products sent from factories by using suitable transportation modes should satisfy demand of each Customer *j* for each Product Type *i* at each Period *t*. Equation (7) ensures that quantity of raw material purchased from Supplier *s* to factories via available transportation modes should be in a range of production capacity of suppliers for each Product Type *i* at each Period *t*. Equation (8) provides mass balance of each Factory *g* for each Product Type *i* at each Period *t*. Total production, previous inventory level and backordered quantities should be equal to summation of the outgoing material to customers and current inventory level. Equation (9) indicates the balance between total incoming Product Type *i* from all suppliers via transportation modes and total production capacities for each Factory *g* at each Period *t*. Equation (10) indicates that the amount of total inventory for each Factory *g* at each Period *t* can not be greater than the warehouse capacity. Equation (11) ensures that the total production quantity of products does not exceed the production capacity of the Factory *g* at each Period t. Equation (12) - (17) are used for relaxation of regular and overtime production quantities. These equations are valid for the linearization of the multiplication of continuous and binary variables by using big-M parameter. Equation (18) ensures that there should be no overtime production if there is no regular production of Product *i* in Factory *g* at Period *t*. Equation (19) ensures that if there is any change from Product *i* to Product *i'* in Factory *g* at Period *t*, this change should be indicated cost and time functions. Equation (20) - (28) indicates non-negativity constraints for continuous variables. Equation (29) - (32) shows the binary variables and they take only value of 0 or 1.

In this mathematical model, three objective functions aim cost minimization ($f_1$), time minimization ($f_2$) and sustainability maximization by selecting suppliers ($f_3$). As given in the literature review section, there are some ways to handle multi-objective cases. The augmented $\epsilon$-constraint method is used to generate the Pareto optimal solutions for the decision makers in this study.

Since cost minimization always has more importance than the other objectives for real-life cases due to harsh competitive conditions. Therefore, $f_1$ is selected as a prior function and $f_2$ and $f_3$ are taken as secondary and third objectives and inserted as constraints in the augmented $\epsilon$-constraint method. The multiplication of positive continous slack variables ($X^1_{slack}$ and $X^2_{slack}$) with some small constant value ($\epsilon = 0.00001$) is the objective function, however the same slack variables are included/substracted into/from $f_2$ and $f_3$ at the same time and summation/subtraction of these slack variables from $f_2$ and $f_3$ should be equal to the upper/lower bound of the $f_2$ and $f_3$.

$$Min\ f_1 - \epsilon * (X^1_{slack} - X^2_{slack}) \qquad (33)$$

***Subject to:***

$$f_2 + X^1_{slack} = f_2^{up} \qquad (34)$$

$$f_3 - X^2_{slack} = f_3^{low} \qquad (35)$$

$$X^1_{slack}, X^2_{slack} \geq 0 \qquad (36)$$

*Equation (6) – Equation (32)*

# V. COMPUTATIONAL EXPERIMENTS

A case study is carried out by using real-life obtained from a flexible packaging manufacturing company. Aim of this case study is to represent the two-stage hybrid optimization approach, and demonstrate the detailed calculation for sustainable supply chain. The proposed approach is applied to design new supply chain for the company. While designing the supply chain, not only cost minimization but also environmental and economic effects are considered.

## A. Data

In this section, we shared all necessary data for comprehensive analysis of design and development of proposed sustainable supple chain system for company in detail.

### 1. Product Types

The company has eleven different product types (films) which are Coextruded (BOPP), Plain (BOPP), Polyester (BOPET), Metallized (BOPP, BOPET, CPP), Cast (CPP), Pearlized (BOPP), Label (BOPP), Tape (BOPP), Barrier (CPP), Cast anti-fog (CPP), and Coated (BOPP, BOPET). BOPP, BOPET and CPP films are generally used for food packaging.

### 2. Production and Transportation Systems

The company has two factories in Turkey and adopts the make-to-order production system. Factory 1 operates in Izmir and Factory 2 operates in Kayseri. The company also has a sales office in Istanbul. The company has 157 different customers and sells 60 percent of its products to the domestic market and 40 percent to the foreign market. 80 percent of exports of the company goes to European countries, 10 percent to countries located in US, and the remaining to the other Middle East countries. The company uses road, sea and rail transportation modes by using 20’ DC (Dry Container) containers when receiving their raw materials from suppliers or sending their final products to customers. Cost of using road, sea and rail transportation modes are 0.003 Euro per ton product, 0.0005 Euro and 0.001 Euro respectively. The speed of road, sea and rail transportation modes are 90 km/h, 20 km/h and 45 km/h respectively. The company purchases raw materials from 10 different suppliers located in India, the Netherlands, South Korea, France, Saudi Arabia, Italy, Singapore and Germany.

Factory 1 has an annual production capacity of 5.000 tons/month while Factory 2 has a capacity of just 300 tons/month. The firm keeps very little inventory in the warehouse because the inventory cost is very high. Warehouse of Factory 1 has 2.5 tons/month capacity and warehouse of Factory 2 has 1.5 tons/month capacity. Unit cost of 1 kg product is 1.45 Euro that is same for both factories. Table 3 demonstrates the raw material productivity and production capacities of factories. Raw material productivity, how many of the input raw material is transformed into the product and production capacity states how many tons are produced in one day from one product type.

Table 3: Raw material productivity and production capacity of factories

| **Product Type** | **Raw Material Productivity for each factory (%)** | **Factory 1 Production Capacity (Tons/Day)** | **Factory 2 Production Capacity (Tons/Day)** |
|---|---|---|---|
| COEXTRUDED | 88% | 68 | 55 |
| PLAIN | 84% | 72 | 60 |
| POLYESTER | 82% | 65 | 52 |
| METALLIZED | 81,5% | 50 | 40 |
| CAST | 86% | 16 | 14 |
| PEARLIZED | 79% | 23 | 16 |
| LABEL | 83% | 25 | 15 |
| TAPE | 84% | 26 | 17 |
| BARRIER | 76% | 9 | 7 |
| CAST ANTI-FOG | 79% | 0,5 | 0,5 |
| COATED | 81% | 1 | 0,8 |

Table 4 shows distances between suppliers and Factory 1 and Factory 2. There are 10 suppliers located in different countries. However, in the second stage of the study, 7 of these 10 suppliers are used in the mathematical model, according to the supplier rankings determined in the first stage. The distances of each supplier to Factory 1 and Factory 2 are expressed in kilometers.

Table 4: Distance from supplier to factories

| Suppliers - Locations | Distance to Factory 1 (Izmir) (km) | Distance to Factory 2 (Kayseri) (km) |
|---|---|---|
| **Supplier A - India** | 6,930 | 7,730 |
| **Supplier B - Netherlands** | 6,323 | 7,123 |
| **Supplier C - South Korea** | 15,377 | 16,177 |
| **Supplier D - France** | 2,108 | 2,908 |
| **Supplier E - Saudi Arabia** | 2,795 | 3,595 |
| **Supplier F - Italy (Trieste)** | 2,108 | 2,908 |
| **Supplier G - Singapore** | 10,621 | 11,421 |
| **Supplier H - India** | 6,930 | 7,730 |
| **Supplier I - Germany** | 6,637 | 7,437 |
| **Supplier J - Italy (Napoli)** | 2,243 | 3,043 |

Figure 5 indicates network schema of the current supply chain of the company under multi-echelon structure. The company uses rail, sea and road transportation modes indicated with different colors in Figure 5. The thicker the arrows, the greater the amount of raw materials or products carried.

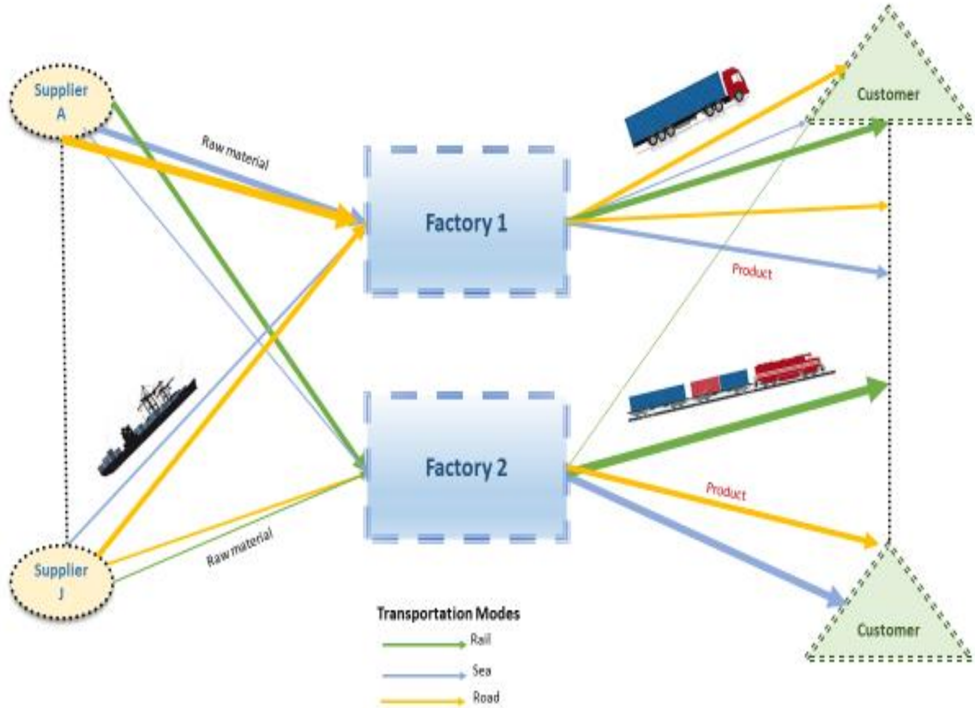


Figure 5: Network Scheme of the Company

### 3. Supplier Criteria

In this section, supplier selection process is shared in detail. Considering the company's mission and vision, competition in flexible packaging sector and consumer's demand, criteria which will be used in the case study are determined by Supply Chain Director of the company as follows; Product price, Delivery, Product quality, Flexibility, Chemicals, Worker's right, Health and safety at work and Social activities. These criteria are determined by using the primary performance indicators of the company expected from suppliers. In the next section of the study, Supply Chain Director scores each supplier on determined criteria with a scale of 1-10.

- Product price sub-criteria includes two attributes. First one is the total unit cost of purchasing of raw materials used in production. It should be minimized. The maximum unit cost of the raw material is determined as $ 1.2 by the company. The supplier with the lowest unit cost is scored higher by Supply Chain Director. Second attribute is payment conditions which specifies the payment date. This sub-criterion is maximized. The supplier which sells the product with a longer pay period, gets a higher score.

- Delivery specifies the share of the deliveries completed in the due date. It is the maximized criterion. Suppliers who deliver raw materials on time get the highest score. Suppliers that send raw materials early or late get fewer score.

- Product quality specifies the percentage of products delivered in the expected quality. It is the maximized criterion. The maximum defect rate is determined 5% by the company. Suppliers with a lower defect rate get a higher score.

- Flexibility enables the responsiveness to the unexpected or additional order and can be described as the number of days that the supplier needs to complete an unexpected order made by the company. The sub-criterion is minimized. Suppliers responding faster to unexpected orders get higher scores.

- Chemicals specifies the percentage of ozone depleting chemicals that suppliers used in their production. It is the minimized criterion. Suppliers that have less ozone depleting chemicals usage rate get higher score.

- Worker's right specifies the workers' contract conditions. The criterion is maximized. Suppliers that offer better contract conditions for their employees are given higher score by Supply Chain Director.

- Health and safety at work indicates how much the supplier attaches importance to safety training for newly hired workers. The criterion is maximized. Suppliers who pay more attention to the health and safety of their employees get a higher score.

- Social activities specifies the rate of supportive activities of suppliers to motivate their employees. The criterion is maximized. Suppliers who perform more social activities for their employees get a higher score.

# VI. RESULTS

The first stage includes performing an initial evaluation of potential suppliers of a flexible packaging supply chain with many criteria and sub-criteria to calculate their efficiencies and effectiveness according to their performance in the flexible packaging supply chain. If the criteria are too complicated to integrate into an objective function in the second stage, it could be evaluated in the first stage. Each alternative is evaluated separately in order to rank them and select more competitive suppliers. The evaluation is applied by using the Analytic Hierarchy Process (AHP) method. The suppliers reached the best performance will be chosen for the next stage.

## A. Result of AHP

Result of AHP is given step by step as follows.

AHP process starts with ranking of each supplier. The criteria of the suppliers specified by the Supply Chain Director of the company who is very experienced in flexible packaging supply chain processes, are scored by him according to 1-10 scale. Table 5 demonstrates the rank of each attribute for each supplier. Then, the next step is identification of the pairwise comparison matrix for all criteria and it is shared in Table 6. For example, Delivery vs. Product Price has a value of 1/9 means that Product price is extremely more important than delivery. On the other hand, Delivery vs Product Quality has a value of 9 means that product quality criteria is extremely preferable comparing with delivery. Then, as a second stage the columns of this pairwise comparison matrix is summed up (shown in Table 7) and normalized as given in Table 8. As a result of Table 7, Product Price and Product Quality criteria are significantly important than the other criteria. As seen in Table 8, Social criteria has little importance in supplier selection.

Table 5: Data of Potential Suppliers

| | | Suppliers | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sub-Criteria** | **Attributes** | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** |
| **Product price** | Unit cost of the product delivered | 8 | 9 | 7 | 8 | 9 | 6 | 8 | 8 | 6 | 7 |
| | Payment conditions | 6 | 7 | 6 | 9 | 9 | 10 | 9 | 8 | 8 | 8 |
| **Delivery** | On time delivery | 8 | 9 | 10 | 8 | 8 | 8 | 7 | 9 | 9 | 6 |
| **Product quality** | Quality level | 8 | 8 | 8 | 6 | 8 | 7 | 6 | 7 | 9 | 10 |
| **Flexibility** | Flexibility in ordering | 8 | 8 | 9 | 6 | 7 | 8 | 7 | 6 | 7 | 7 |
| **Chemicals** | Usage of ozone depleting chemicals | 7 | 7 | 8 | 7 | 6 | 5 | 8 | 7 | 9 | 9 |
| **Worker's right** | Workers contracts conditions | 10 | 9 | 8 | 8 | 7 | 10 | 9 | 8 | 9 | 10 |
| **Health and safety at work** | Safety training for new workers | 8 | 8 | 8 | 9 | 9 | 7 | 6 | 6 | 8 | 8 |
| **Social activities** | Social activities for workers | 6 | 6 | 7 | 8 | 6 | 7 | 6 | 5 | 7 | 8 |

Table 6: Criteria pairwise comparison

| | Product price | Delivery | Product quality | Flexibility | Chemicals | Worker's right | Health and safety at work | Social activities |
|---|---|---|---|---|---|---|---|---|
| **Product price** | 1 | 9 | 1 | 9 | 3 | 4 | 7 | 7 |
| **Delivery** | 1/9 | 1 | 1/9 | 1 | 1/3 | 1/3 | 1 | 1 |
| **Product Quality** | 1 | 9 | 1 | 9 | 3 | 4 | 7 | 7 |
| **Flexibility** | 1/9 | 1 | 1/9 | 1 | 1/3 | 1/3 | 1 | 1 |
| **Chemicals** | 1/3 | 3 | 1/3 | 3 | 1 | 1 | 2 | 2 |
| **Worker's right** | 1/4 | 3 | 1/4 | 3 | 1 | 1 | 2 | 2 |
| **Health and safety at work** | 1/7 | 1 | 1/7 | 1 | 1/2 | 1/2 | 1 | 1 |
| **Social activities** | 1/7 | 1 | 1/7 | 1 | 1/2 | 1/2 | 1 | 1 |

Table 7: Criteria pairwise comparison mathematical expression

| | **Product price** | **Delivery** | **Product Quality** | **Flexibility** | **Chemicals** | **Worker's right** | **Health and safety at work** | **Social activities** |
|---|---|---|---|---|---|---|---|---|
| **Product price** | 1,00 | 9,00 | 1,00 | 9,00 | 3,00 | 4,00 | 7,00 | 7,00 |
| **Delivery** | 0,11 | 1,00 | 0,11 | 1,00 | 0,33 | 0,33 | 1,00 | 1,00 |
| **Product qulity** | 1,00 | 9,00 | 1,00 | 9,00 | 3,00 | 4,00 | 7,00 | 7,00 |
| **Flexibility** | 0,11 | 1,00 | 0,11 | 1,00 | 0,33 | 0,33 | 1,00 | 1,00 |
| **Chemicals** | 0,33 | 3,00 | 0,33 | 3,00 | 1,00 | 1,00 | 2,00 | 2,00 |
| **Worker's right** | 0,25 | 3,00 | 0,25 | 3,00 | 1,00 | 1,00 | 2,00 | 2,00 |
| **Health and safety at work** | 0,14 | 1,00 | 0,14 | 1,00 | 0,50 | 0,50 | 1,00 | 1,00 |
| **Social activities** | 0,14 | 1,00 | 0,14 | 1,00 | 0,50 | 0,50 | 1,00 | 1,00 |
| **Sum** | **3,09** | **28,00** | **3,09** | **28,00** | **9,67** | **11,67** | **22,00** | **22,00** |

Table 8: Normalized relative weight

| | Product price | Delivery | Product Quality | Flexibility | Chemicals | Worker's right | Health and Safety at work | Social Activities |
|---|---|---|---|---|---|---|---|---|
| **Product price** | 0,32 | 0,32 | 0,32 | 0,32 | 0,31 | 0,34 | 0,32 | 0,32 |
| **Delivery** | 0,04 | 0,04 | 0,04 | 0,04 | 0,03 | 0,03 | 0,05 | 0,05 |
| **Product Quality** | 0,32 | 0,32 | 0,32 | 0,32 | 0,31 | 0,34 | 0,32 | 0,32 |
| **Flexibility** | 0,04 | 0,04 | 0,04 | 0,04 | 0,03 | 0,03 | 0,05 | 0,05 |
| **Chemicals** | 0,11 | 0,11 | 0,11 | 0,11 | 0,10 | 0,09 | 0,09 | 0,09 |
| **Worker's Right** | 0,08 | 0,11 | 0,08 | 0,11 | 0,10 | 0,09 | 0,09 | 0,09 |
| **Health and Safety at work** | 0,05 | 0,04 | 0,05 | 0,04 | 0,05 | 0,04 | 0,05 | 0,05 |
| **Social Activities** | 0,05 | 0,04 | 0,05 | 0,04 | 0,05 | 0,04 | 0,05 | 0,05 |
| **Sum** | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |

Then, the normalized principal Eigen vector is obtained by averaging across the rows (as given in Table 9). According to the results, the most important criteria are found as product price and delivery. Delivery and flexibility are the least important criteria.

Table 9: The normalized principal Eigen vector

| Attribute | Weights |
|---|---|
| Product price | 0,322 |
| Delivery | 0,037 |
| Product quality | 0,322 |
| Flexibility | 0,037 |
| Chemicals | 0,100 |
| Worker's right | 0,093 |
| Health and safety at work | 0,044 |
| Social activities | 0,044 |
| **Sum** | 1,000 |

Now, the consistency of weights should be checked. As mentioned in Section III, Principal Eigen value should be calculated to determine the consistency with following formula.

$$\lambda_{max} = 3{,}09(0{,}3224) + 28(0{,}0372) + 3{,}09(0{,}3224) + 28(0{,}0372) + 9{,}67(0{,}1001) + 11{,}67(0{,}0934) + 22(0{,}0437) + 22(0{,}0437) = 8{,}0566$$

After calculating Principle Eigen value, Consistency Index (CI) should be calculated with following Equation (1).

$$CI = \frac{8{,}0566 - 8}{8 - 1} = 0{,}0081$$

Random Consistency Index (RI) is 1,41 for *n*=8 (Table 2). Then, Consistency Ratio (CR) should be calculated by using Equation (2).

$$CR = \frac{0{,}0081}{1{,}41} = 0{,}006$$

$$CR = 0{,}006 < 0{,}1$$

If the value of Consistency Ratio is smaller or equal to 10%, the inconsistency is acceptable.

The next step is to calculate the final scores of the suppliers according to the calculated weights of the criteria. To calculate the final scores of potential suppliers, the specified ranks from 1 to 10 for each supplier are multiplied by the calculated weights of the criteria (Table 10).

Table 10: Calculating Final Score of Potential Suppliers

| Sub-Criteria | Attributes | Suppliers A | B | C | D | E | F | G | H | I | J | Weights |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Product price** | Unit cost of the product delivered | 8 | 9 | 7 | 8 | 9 | 6 | 8 | 8 | 6 | 7 | **0,3224** |
| | Payment conditions | 6 | 7 | 6 | 9 | 9 | 10 | 9 | 8 | 8 | 8 | |
| **Delivery** | On time delivery | 8 | 9 | 10 | 8 | 8 | 8 | 7 | 9 | 9 | 6 | **0,0372** |
| **Product quality** | Quality level | 8 | 8 | 8 | 6 | 8 | 7 | 6 | 7 | 9 | 10 | **0,3224** |
| **Flexibility** | Flexibility in ordering | 8 | 8 | 9 | 6 | 7 | 8 | 7 | 6 | 7 | 7 | **0,0372** |
| **Chemicals** | Usage of ozone depleting chemicals | 7 | 7 | 8 | 7 | 6 | 5 | 8 | 7 | 9 | 9 | **0,1001** |
| **Worker's right** | Workers contracts conditions | 10 | 9 | 8 | 8 | 7 | 10 | 9 | 8 | 9 | 10 | **0,0934** |
| **Health and safety at work** | Safety training for new workers | 8 | 8 | 8 | 9 | 9 | 7 | 6 | 6 | 8 | 8 | **0,0437** |
| **Social activities** | Social activities for workers | 6 | 6 | 7 | 8 | 6 | 7 | 6 | 5 | 7 | 8 | **0,0437** |

Table 11 shows the total score of potential suppliers. According to these results, supplier J has the highest score. Supplier C has the lowest score. Final rank is as follows **J > E > B > I > D > G > F > A > H > C**.

Table 11: Final Score of Potential Suppliers

| | Suppliers | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sub-Criteria** | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** |
| **Unit cost of the product delivered** | 2,579 | 2,902 | 2,257 | 2,579 | 2,902 | 1,934 | 2,579 | 2,579 | 1,934 | 2,257 |
| **Payment conditions** | 1,934 | 2,257 | 1,934 | 2,902 | 2,902 | 3,22 | 2,902 | 2,579 | 2,579 | 2,579 |
| **Delivery** | 0,298 | 0,334 | 0,372 | 0,298 | 0,298 | 0,298 | 0,260 | 0,335 | 0,3345 | 0,223 |
| **Product quality** | 2,579 | 2,579 | 2,579 | 1,934 | 2,579 | 2,257 | 1,934 | 2,257 | 2,902 | 3,224 |
| **Flexibility** | 0,299 | 0,298 | 0,335 | 0,223 | 0,260 | 0,298 | 0,260 | 0,223 | 0,260 | 0,260 |
| **Chemicals** | 0,701 | 0,701 | 0,801 | 0,701 | 0,601 | 0,501 | 0,801 | 0,701 | 0,901 | 0,901 |
| **Worker’s right** | 0,934 | 0,841 | 0,747 | 0,747 | 0,654 | 0,934 | 0,841 | 0,747 | 0,841 | 0,934 |
| **Health and safety at work** | 0,350 | 0,345 | 0,350 | 0,393 | 0,393 | 0,306 | 0,262 | 0,262 | 0,350 | 0,350 |
| **Social activities** | 0,262 | 0,262 | 0,306 | 0,350 | 0,262 | 0,306 | 0,262 | 0,219 | 0,306 | 0,350 |
| **TOTAL SCORE** | **9,935** | **10,523** | **9,681** | **10,127** | **10,850** | **10,057** | **10,102** | **9,902** | **10,407** | **11,078** |

In this case study, firstly 70% potential suppliers with better performances in comparison to others is allowed to enter to the second stage. Table 12 shows the percentage of final scores for each suppliers. According to calculations, **Suppliers J, E, B, I, D, G, F w**hich have total percentage 71,25% is allowed to enter to the second stage.

Table 12: Percentage of Final Scores

| | **Suppliers** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **TOTAL** |
| **TOTAL SCORE** | 9,93 | 10,52 | 9,68 | 10,12 | 10,85 | 10,05 | 10,10 | 9,90 | 10,40 | 11,07 | 102,66 |
| **PERCENTAGE [%]** | **9,68** | **10,25** | **9,43** | **9,86** | **10,57** | **9,80** | **9,84** | **9,65** | **10,14** | **10,79** | **100,00** |

## B. Result of Mathematical model

The second stage of the case study includes application of the proposed mathematical model given the details in Section III. Application of the model is performed in GAMS (General Algebraic Modelling System) which is a high-level modeling system for mathematical optimization. Multi-objective function that has three objective functions is used in this application. Optimal results of these three objective functions are obtained by using GAMS. Main objective function of the model aims to minimize total cost of the supply chain design. Second objective function minimizes the total transportation time and third one maximizes sustainability of the company. The augmented $\epsilon$-constraint method is applied as stated in literature review to use the multi-objective function in GAMS application. The $\epsilon$ value which is a small constant value and two positive continous slack variables is added to apply this method.

The proposed linear model for this problem is written in GAMS modelling environment and solved with IBM ILOG CPLEX 12.1 (CPLEX, 2009). Both models are executed on a computer with Intel Core I5 2520 M CPU with 2.50 GHz dual core processor, and with 4.00 GB of RAM. An optimality gap of 1% is set for the solutions. Pareto Optimal Sets of the mathematical model are as follows:

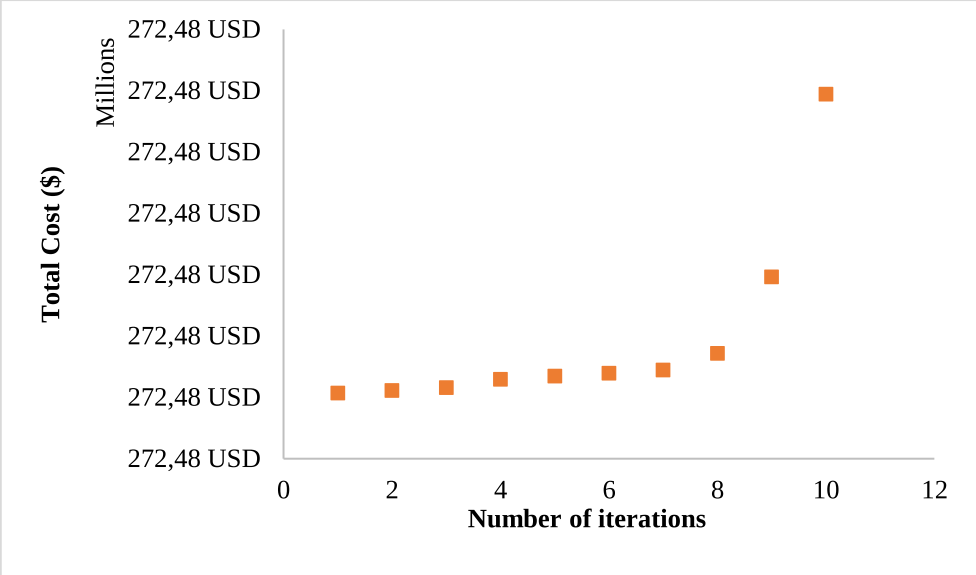


Figure 6: Results of objective function 1 ($f_1$)

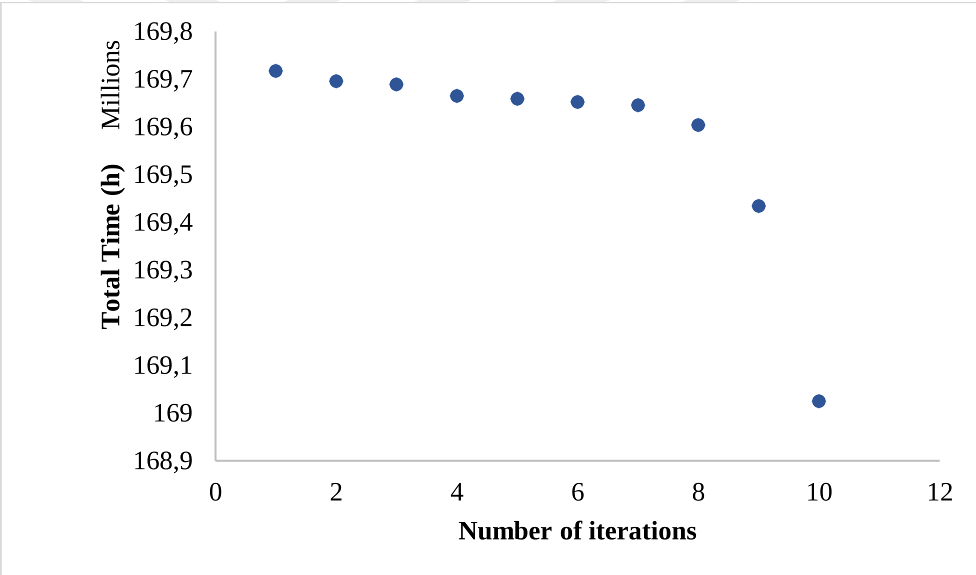


Figure 7: Results of objective function 2 ($f_2$)

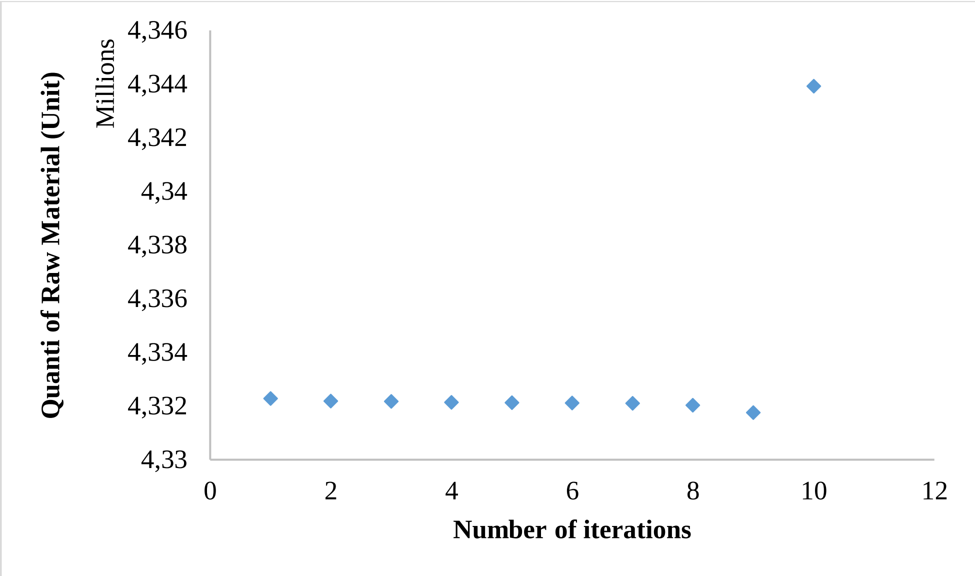


Figure 8: Results of objective function 3 *($f_3$)*

Figures 6, 7 and 8 shows results of objective functions $f_1$, $f_2$ and $f_3$ respectively.

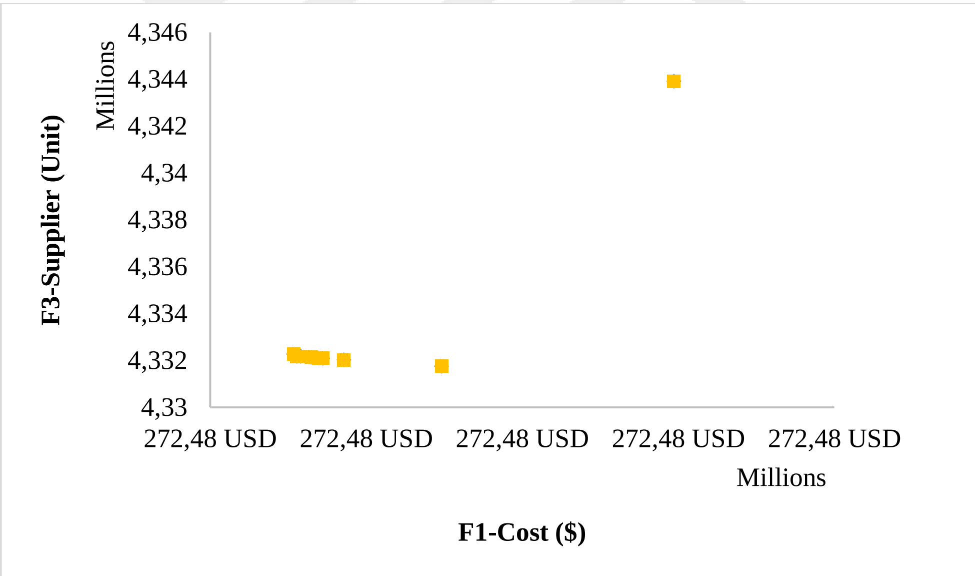


Figure 9: Pareto solution set for 10 iterations $f_1$ and $f_3$

Figure 9 shows the change in cost and sustainability. The graph shows the nadir points of cost (min, max) and sustainability (min, max) which symbolize the boundaries of the graph by performing 10 iterations in the GAMS. According to the graph, there is no direct relation between cost and sustainability. Each point on the graph represents a feasible solution. Decision makers can choose any of these points.

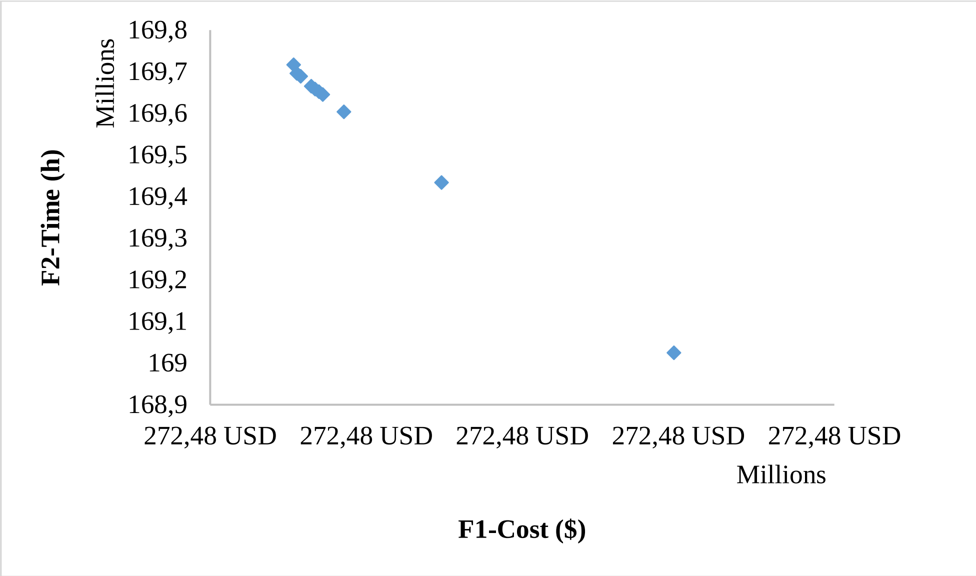


Figure 10: Pareto solution set for 10 iterations $f_1$ and $f_2$

Figure 10 demonstrates the values of cost objective function and time objective function. In this problem, time and cost are directly proportional. The cost increases as the transportation time decreases. Since each point on the graph represents a feasible solution, decision makers can choose the most appropriate point for them.

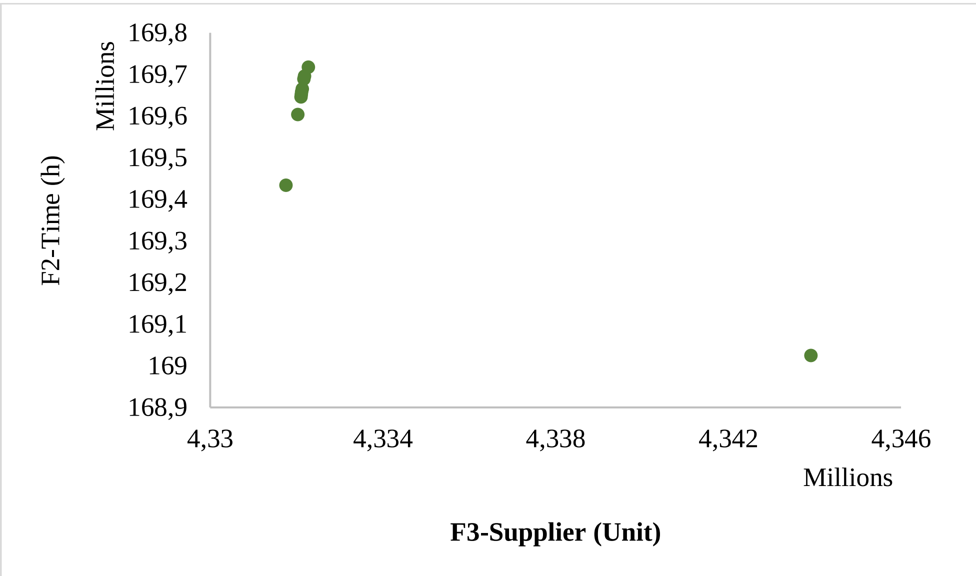


Figure 11: Pareto solution set for 10 iterations $f_2$ and $f_3$

Figure 11 represents the change in transportation time and sustainability. If the transportation time increases, the amount of $CO_2$ emission decreases accordingly.

Increasing in $CO_2$ emission causes negative impact on sustainability. The graph shows this case clearly. The decision makers can choose any of the points in the graph as an optimal solution according to the criterion that is important to them.

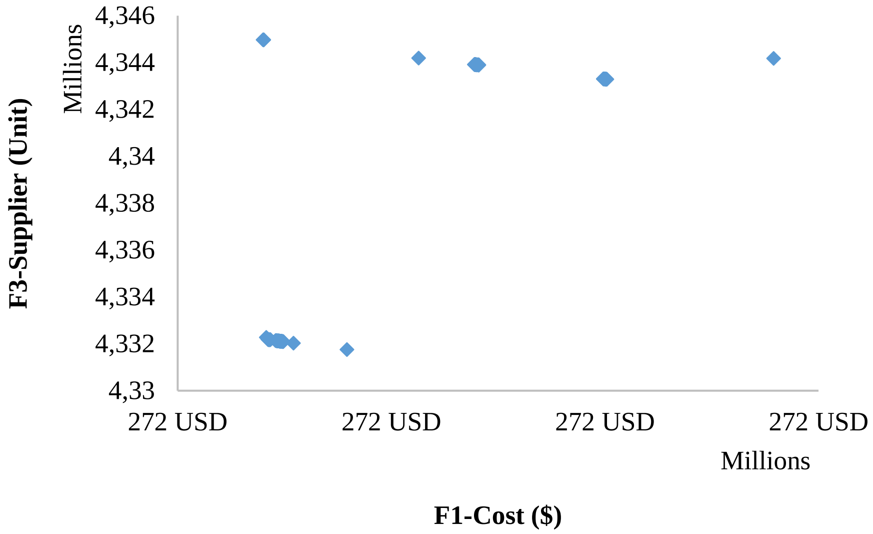


Figure 12: Pareto solution set for 100 iterations $f_1$ and $f_3$

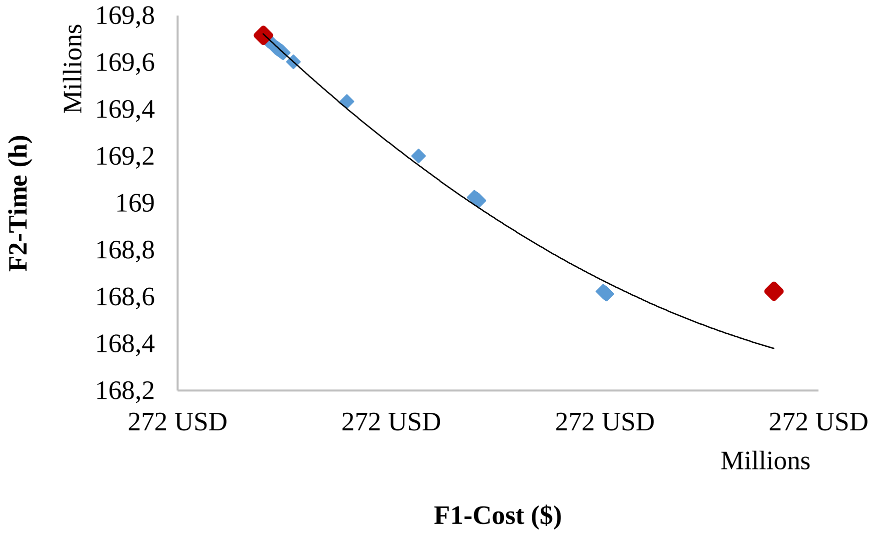


Figure 13: Pareto solution set for 100 iterations $f_1$ and $f_2$

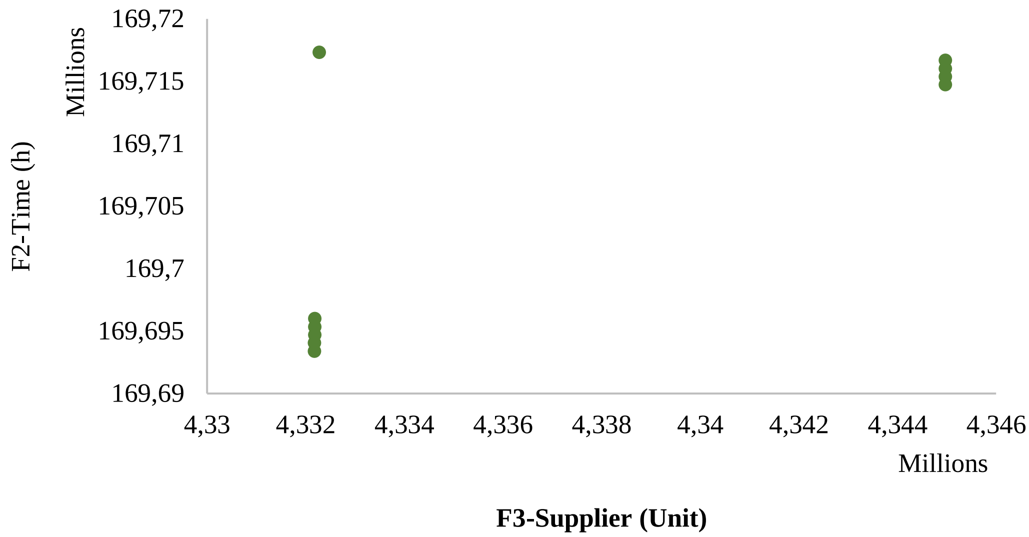


Figure 14: Pareto solution set for 100 iterations $f_2$ and $f_3$

Figures 12, 13 and 14 demonstrate Pareto solution sets of the objective functions $f_1$, $f_2$ and $f_3$. In Figure 13, there are two randomly selected points marked in red. The values of the top are as follows: $274,477,002 USD for cost and 169,716,673 h for time. The values of the bottom point are $272,488,953 for and 168,624,298 h for time. From top to the bottom, the cost value is decreased by 0.72% and the time value is also decreased by 0.64%. This data clearly shows that faster transportation increases the cost.

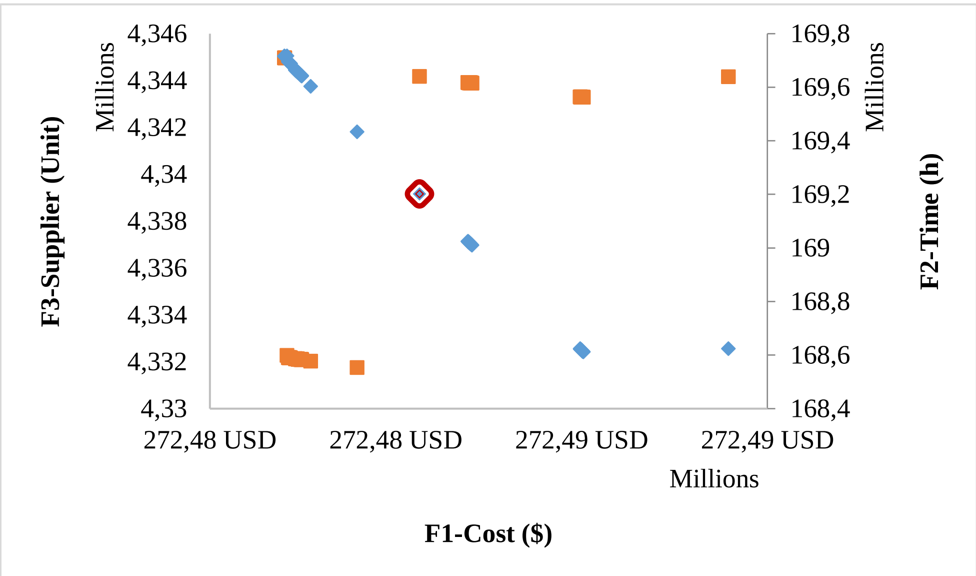


Figure 15: Pareto solution set for 100 iterations $f_1$, $f_2$ and $f_3$

Figure 15 shows Pareto solution sets of the objective functions for 100 iterations $f_1$, $f_2$ and $f_3$. According to the point marked in red in this figure, feasible solutions of $f_1$, $f_2$ and $f_3$ are $272480640 USD, 169201755 h and 4344182 units respectively. This selected point can be used as optimum solution by the company. Based on this point, the optimal quantity of raw materials and products for some product types and time periods are shown by the figures as follows. Results of these figures can also be used as optimum solution by the company.

Figures 16, 17, 18 and 19 show the total quantity of raw materials purchased from suppliers to be used in Factory 1 and Factory 2, and the total quantity of products sent to different customers from Factory 1 and Factory 2, for the Coextruded products during Periods 1-12. The colors of the arrows in the figure symbolize the transportation modes. The thickness of the arrows indicates the amount of the raw material or product. As the arrows become thicker, the quantities increase.

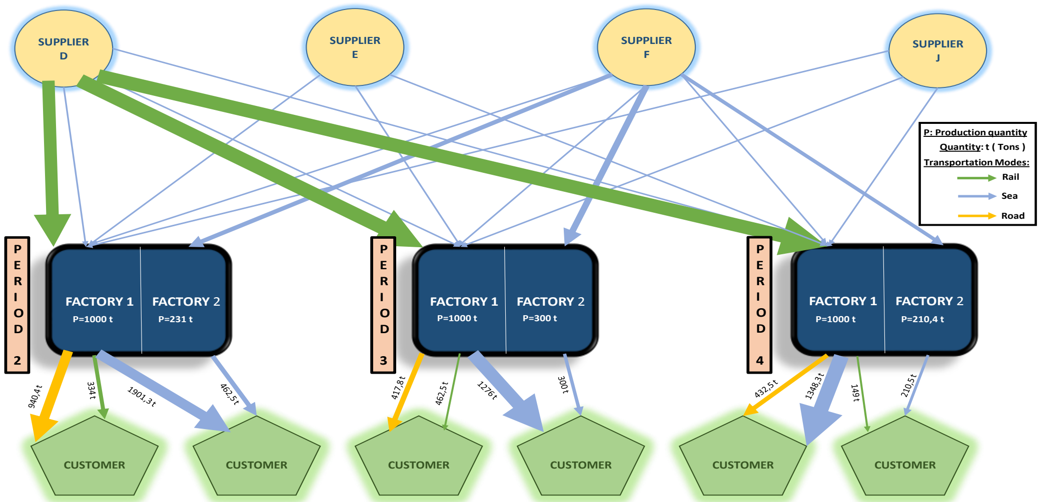


Figure 16: Raw material quantity (Supplier to Factory) and product quantity (Factory to customer) for Coextruded products in Period 2, Period 3 and Period 4

According to Figure 16, most of the raw materials are purchased from Supplier D for each periods.  Raw materials are supplied to Factory 2 only from Supplier F. The largest amount of raw material supply occurs in Period 3. Products are usually sent to customers by sea transportation. Factory 2 always uses seaway while sending products to customers. The most product sales are realized in Period 4.

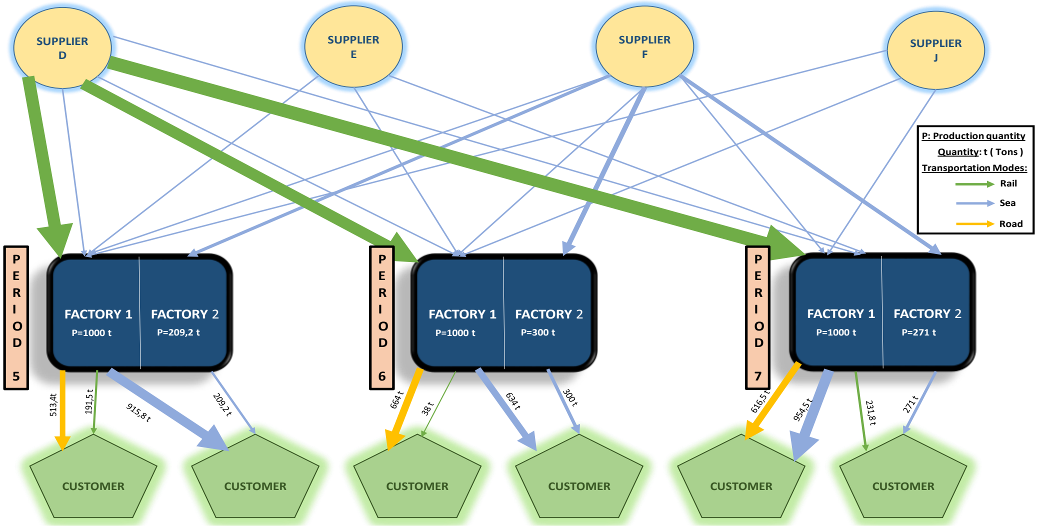


Figure 17: Raw material quantity (Supplier to Factory) and product quantity (Factory to customer) for Coextruded products in Period 5, Period 6 and Period 7

As seen in Figure 17, there is a decrease in the amount of raw material procurement compared to the previous quarter of the year. Starting from Period 5 to Period 7, sales volumes are increasing steadily. Especially at Period 5, railway is frequently used in delivering the products to the customer.

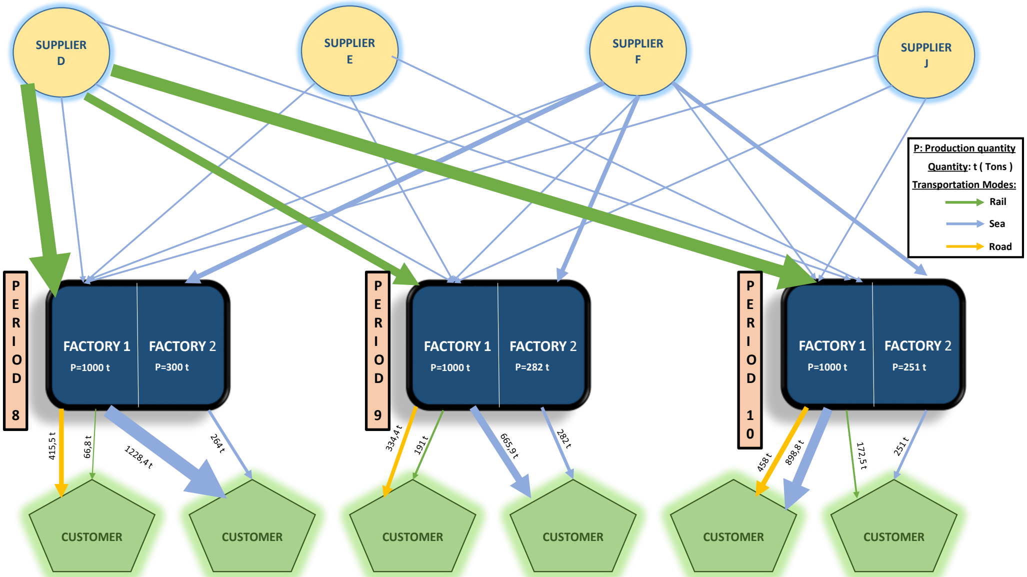


Figure 18: Raw material quantity (Supplier to Factory) and product quantity (Factory to customer) for Coextruded products in Period 8, Period 9 and Period 10

Figure 18 demonstrates that the decrease in raw material purchases continues at Periods 7, 8 and 9. Especially in Period 9, the amount of raw materials purchased is rather small. In these periods, the railway is used very little while the seaway is still preferred at high altitude to send products to the customers. The amount of sales that is high in Period 7 and falls in Period 8. Sales increase again at the end of Period 9.

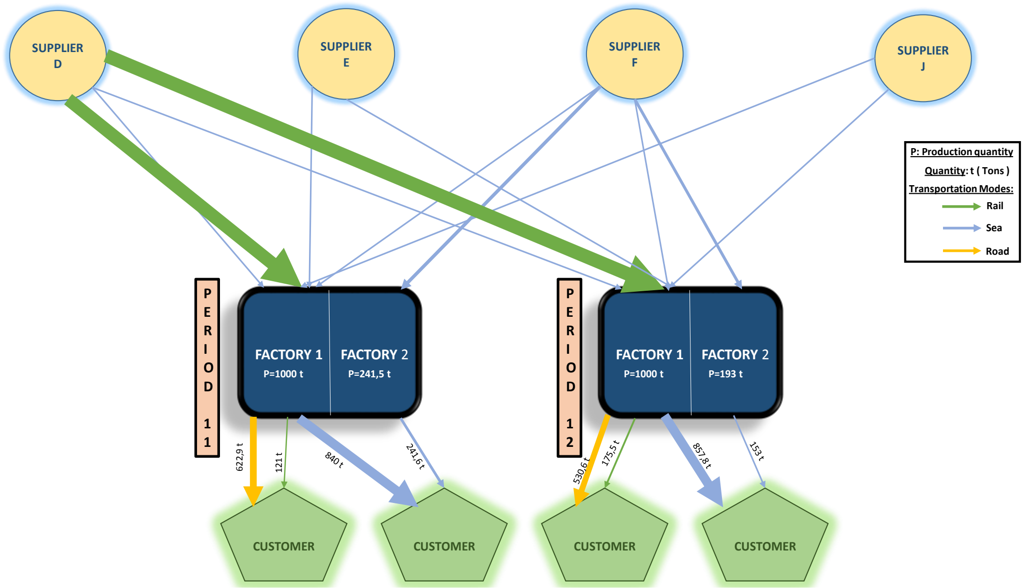


Figure 19: Raw material quantity (Supplier to Factory) and product quantity (Factory to customer) for Coextruded products in Period 11 and Period 12

Last two months of the year is shown in Figure 19. In Period 11 and 12, the amount of raw material purchase is very close to the annual average amount. As in each period of the year, raw materials are only purchased from Supplier F for Factory 2. The sales volume that is high in Period 11, falls towards the end of the year.

Figure 20, 21, 22 and 23 demonstrate the total quantity of raw materials purchased from suppliers to be used in Factory 1 and Factory 2, and the total quantity of products sent to different customers from Factory 1 and Factory 2, for the Label products during Periods 1-12. The colors of the arrows in the figure symbolize the transportation modes. The thickness of the arrows indicates the amount of the raw material or product. As the arrows become thicker, the quantities increase.

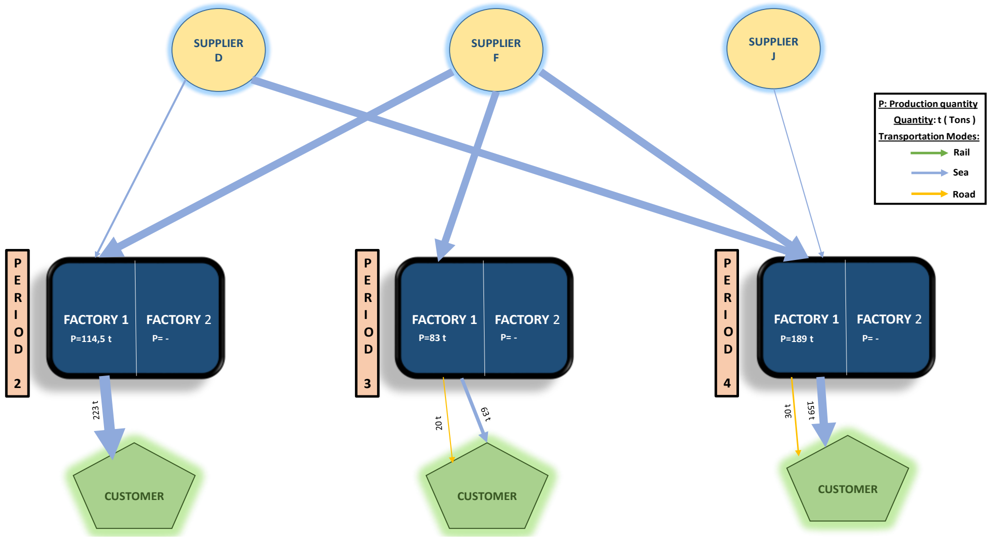


Figure 20: Raw material quantity (Supplier to Factory) and product quantity (Factory to customer) for Label products in Period 2, Period 3 and Period 4

According to Figure 20, the company prefers to purchase raw materials from Supplier D for Period 2 and 4. Supplier F sends raw material in both three periods. Supplier J supplies raw materials only in Period 4. All raw materials is moved to the factory by seaway. For Factory 2, no raw materials are supplied in these three periods. Period 2 is the highest sales period. From Factory 2, the products are delivered to the customer only in Period 4.

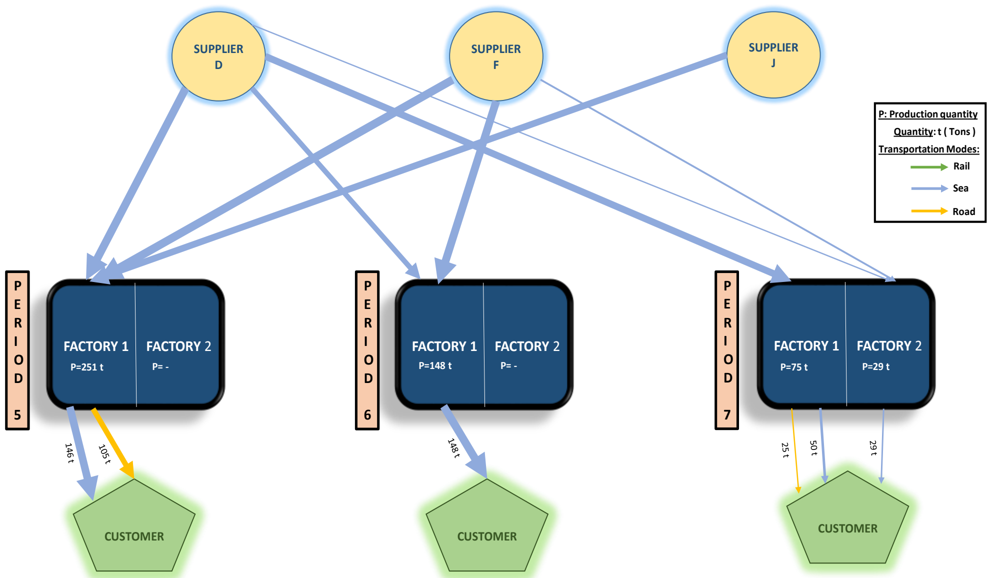


Figure 21: Raw material quantity (Supplier to Factory) and product quantity (Factory to customer) for Label products in Period 5, Period 6 and Period 7

According to Figure 21, during the first 7 periods of the year, although there is no raw material purchased for Factory 2, Supplier D and Supplier F start to supply raw materials in Period 7. The company prefers Supplier J for Factory 1 only in Period 5. While roadway is not much preferred for sending the products to the customers, seaway is more preferable for the company as always. Factory 2 is only operated for Label products in Period 7.

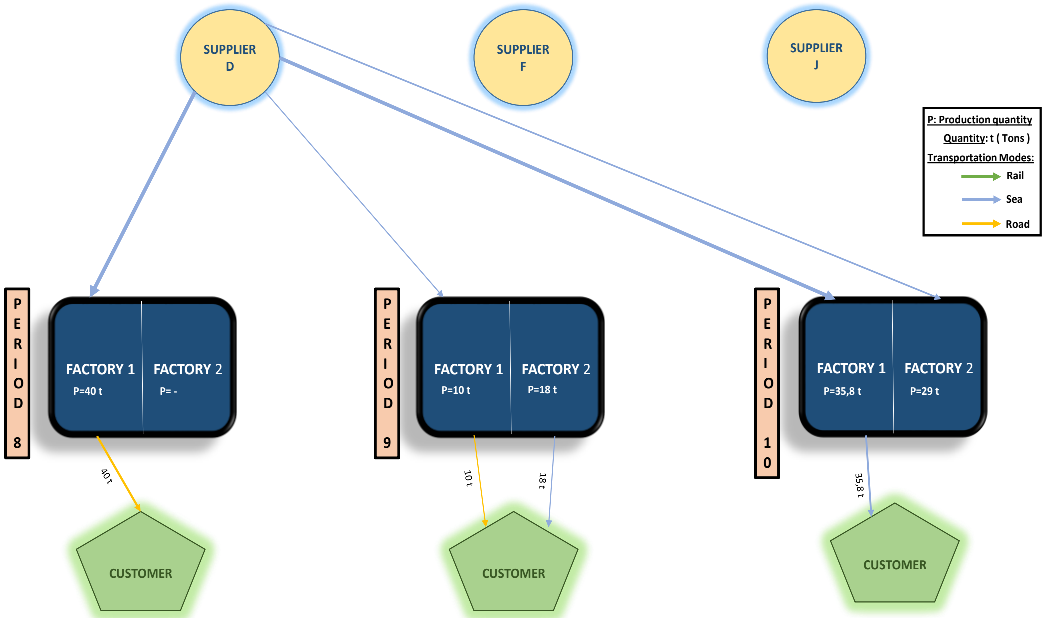


Figure 22: Raw material quantity (Supplier to Factory) and product quantity (Factory to customer) for Label products in Period 8, Period 9 and Period 10

Figure 22 shows that raw materials are purchased and products are produced only in Period 10 in Factory 2. In Period 9, there is not many raw materials purchased from Supplier D for Factory 1. The company prefers only seaway while purchasing raw material in Period 8, 9 and 10. Sales are three times lower than the previous quarter of the year in these periods.

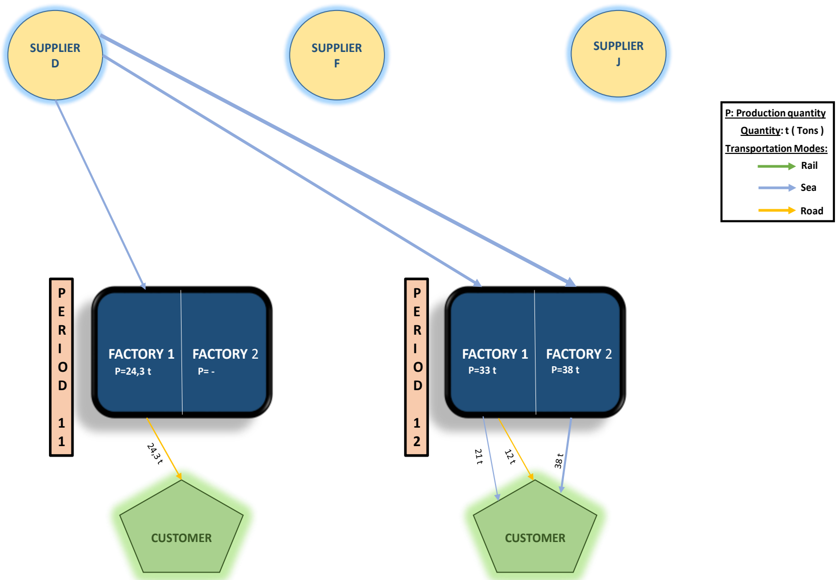


Figure 23: Raw material quantity (Supplier to Factory) and product quantity (Factory to customer) for Label products in Period 11 and Period 12

Figure 23 gives information about last two periods of the year. In Period 11, raw materials are supplied from Supplier D for only Factory 1. In Period 12. They are purchased for both Factory 1 and Factory 2. The company prefers Supplier D for the last two periods of the year. Sales volumes are quite low in these periods. In Period 11 the products are sent only by roadway however, both the roadway and seaway are preferred in Period 12.

Table 13 demonstrates the raw material quantity required for different product types during between Period 2 – Period 12. In addition, it is also shown on the table, which supplier and transportation mode is preferred. The factories where raw materials are used are indicated on the table. Obviously, the amount of raw material required for Coextruded product is significantly higher than the amount required for the other products. It is possible to say that even by looking at these data, the company's best-selling product is Coextruded. Plain product is the second product that needs the highest volume of raw material. However, the quantity of raw materials procured for Coextruded product is two times greater than that procured for Plain product. The amount of raw materials required for Coextruded and Plain products is followed by Polyester, Metallized, Cast, Pearlized, Label, Tape, Barrier, Coated and Cast anti-fog products respectively. Almost half of the supplied raw materials is delivered to the factory by using railway. Most of the raw materials supplied by Supplier D reach the Factory 1 by train. The other half of the amount of raw material supplied is delivered to the factory by seaway. Seaway transportation is preferred so much, since it is the cheapest among other modes of transportation. Since the production capacity of Factory 2 is lower compared to Factory 1, the amount of raw materials supplied is also lower than Factory 1. The raw materials are sent to the Factory 2 only by seaway. Since Coextruded, Metallized, Label and Cast anti-fog products are produced in Factory 2, only the raw materials of these products are supplied.

Table 13: Quantity of Raw materials from Supplier to Factory with Transportation Mode for Products [kg]

| | | | | Periods (Months) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PRODUCT** | **SUPPLIER** | **FACTORY** | **MODE** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| **COEXTRUDED** | **SUPPLIER D** | **FACTORY 1** | **RAIL** | 1163573 | 1413253 | 1398251 | 1126197 | 1104543 | 1339284 | 1293515 | 748313 | 1151406 | 1178335 | 1217050 |
| **COEXTRUDED** | **SUPPLIER D** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **COEXTRUDED** | **SUPPLIER E** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **COEXTRUDED** | **SUPPLIER F** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **COEXTRUDED** | **SUPPLIER F** | **FACTORY 2** | **SEA** | 203280 | 264000 | 185200 | 184052 | 264000 | 238480 | 264000 | 248160 | 220880 | 212564 | 169840 |
| **COEXTRUDED** | **SUPPLIER J** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **PLAIN** | **SUPPLIER D** | **FACTORY 1** | **RAIL** | 417318 | 503376 | 486408 | 474060 | 436596 | 233568 | 335880 | 513960 | 639834 | 415764 | 493590 |
| **PLAIN** | **SUPPLIER D** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **PLAIN** | **SUPPLIER E** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **PLAIN** | **SUPPLIER F** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **PLAIN** | **SUPPLIER J** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **POLYESTER** | **SUPPLIER D** | **FACTORY 1** | **RAIL** | 217577 | 386496 | 100791 | 24659,3 | 87198,3 | 295227 | 481440 | 426908 | 375380 | 182035 | 338672 |
| **POLYESTER** | **SUPPLIER D** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **POLYESTER** | **SUPPLIER E** | **FACTORY 1** | **SEA** | 75000 | 61253,6 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **POLYESTER** | **SUPPLIER F** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **POLYESTER** | **SUPPLIER J** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **METALLIZED** | **SUPPLIER D** | **FACTORY 1** | **RAIL** | 7682,88 | 60839,6 | 50955,3 | 10026 | 36574,3 | 111467 | | | 16070 | | 45543,7 |
| **METALLIZED** | **SUPPLIER D** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **METALLIZED** | **SUPPLIER E** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | | | 56687,6 | | 75000 | 74960,8 | 75000 |
| **METALLIZED** | **SUPPLIER F** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **METALLIZED** | **SUPPLIER F** | **FACTORY 2** | **SEA** | 56235 | | 72535 | 72535 | | | | | 39935 | 47270 | 56235 |
| **METALLIZED** | **SUPPLIER J** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 48493,3 | 75000 | 75000 | 75000 |
| **CAST** | **SUPPLIER D** | **FACTORY 1** | **RAIL** | 24830 | 50192 | | 13220 | 7157 | 25174 | | 6598 | | 38082,6 | |
| **CAST** | **SUPPLIER D** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **CAST** | **SUPPLIER E** | **FACTORY 1** | **SEA** | | 75000 | 65250 | | | | 67056 | | 66755 | | |
| **CAST** | **SUPPLIER F** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 |
| **CAST** | **SUPPLIER J** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 75000 | 61615,9 |
| **PEARLIZED** | **SUPPLIER D** | **FACTORY 1** | **SEA** | 20511 | 75000 | 44290 | 75000 | 54915,5 | | 57088 | 16205,5 | 59853 | 24342,5 | 75000 |
| **PEARLIZED** | **SUPPLIER F** | **FACTORY 1** | **SEA** | 75000 | 75000 | 75000 | 75000 | 75000 | 64464 | 75000 | 75000 | 75000 | 75000 | 75000 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PEARLIZED** | **SUPPLIER J** | **FACTORY 1** | **SEA** | | 12858,5 | | 14043,5 | | | | | | | 13372 |
| **LABEL** | **SUPPLIER D** | **FACTORY 1** | **SEA** | 20035 | | 75000 | 75000 | 47840 | 62250 | 33200 | 8300 | 29714 | 20127,5 | 27390 |
| **LABEL** | **SUPPLIER D** | **FACTORY 2** | **SEA** | | | | | | 12750 | | 14940 | | | 31540 |
| **LABEL** | **SUPPLIER F** | **FACTORY 1** | **SEA** | 75000 | 68890 | 75000 | 75000 | 75000 | | | | | | |
| **LABEL** | **SUPPLIER F** | **FACTORY 2** | **SEA** | | | | | | 11320 | | | | | |
| **LABEL** | **SUPPLIER J** | **FACTORY 1** | **SEA** | | | 6870 | 58330 | | | | | | | |
| **TAPE** | **SUPPLIER D** | **FACTORY 1** | **SEA** | | | | 29605,2 | | | 37459,2 | | | | 12108 |
| **TAPE** | **SUPPLIER F** | **FACTORY 1** | **SEA** | 49022,4 | 60757,2 | 43440,6 | 75000 | 60664,8 | 68838 | 75000 | 74970 | 69686,4 | 70694,4 | 75000 |
| **BARRIER** | **SUPPLIER D** | **FACTORY 1** | **SEA** | 21280 | 33538,8 | 33972 | 4070,4 | 22800 | | 32300 | 36100 | 31452,6 | 18620 | 22800 |
| **BARRIER** | **SUPPLIER F** | **FACTORY 1** | **SEA** | | | | 75000 | | 41800 | | | | | |
| **CAST ANTI-FOG** | **SUPPLIER F** | **FACTORY 2** | **SEA** | | | 430,55 | 1461,5 | | | | | | 355,5 | |
| **COATED** | **SUPPLIER D** | **FACTORY 1** | **SEA** | 12934,1 | 2430 | 10125 | 8100 | 12462,7 | | 11542,5 | 7695 | | 8667 | |
| **COATED** | **SUPPLIER F** | **FACTORY 1** | **RAIL** | | | | | | 405 | | | 810 | | |

Table 14: Production quantities of Factories for Products [kg]

| | | Periods (Months) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PRODUCT** | **FACTORY** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| **COEXTRUDED** | **FACTORY 1** | 1000000 | 1000000 | 1000000 | 1000000 | 1000000 | 1000000 | 1000000 | 1000000 | 1000000 | 1000000 | 1000000 |
| **COEXTRUDED** | **FACTORY 2** | 231000 | 300000 | 210455 | 209150 | 300000 | 271000 | 300000 | 282000 | 251000 | 241550 | 193000 |
| **PLAIN** | **FACTORY 1** | 853950 | 956400 | 936200 | 921500 | 876900 | 635200 | 757000 | 969000 | 1000000 | 852100 | 944750 |
| **POLYESTER** | **FACTORY 1** | 631191 | 820426 | 488769 | 395926 | 472193 | 725887 | 952976 | 886473 | 823634 | 587847 | 778868 |
| **METALLIZED** | **FACTORY 1** | 377525 | 442748 | 430620 | 380400 | 320950 | 412843 | 345629 | 243550 | 387816 | 368050 | 423980 |
| **METALLIZED** | **FACTORY 2** | 69000 | | 89000 | 89000 | | | | | 49000 | 58000 | 69000 |
| **CAST** | **FACTORY 1** | 290500 | 407200 | 337500 | 277000 | 269950 | 290900 | 339600 | 269300 | 339250 | 305910 | 246065 |
| **PEARLIZED** | **FACTORY 1** | 120900 | 206150 | 151000 | 207650 | 164450 | 81600 | 167200 | 115450 | 170700 | 125750 | 206800 |
| **LABEL** | **FACTORY 1** | 114500 | 83000 | 189000 | 251000 | 148000 | 75000 | 40000 | 10000 | 35800 | 24250 | 33000 |
| **LABEL** | **FACTORY 2** | | | | | | 29000 | | 18000 | | | 38000 |
| **TAPE** | **FACTORY 1** | 58360 | 72330 | 51715 | 124530 | 72220 | 81950 | 133880 | 89250 | 82960 | 84160 | 103700 |
| **BARRIER** | **FACTORY 1** | 28000 | 44130 | 44700 | 104040 | 30000 | 55000 | 42500 | 47500 | 41385 | 24500 | 30000 |
| **CAST-ANTIFOG** | **FACTORY 2** | | | 545 | 1850 | | | | | | 450 | |
| **COATED** | **FACTORY 1** | 15968 | 3000 | 12500 | 10000 | 15386 | 500 | 14250 | 9500 | 1000 | 10700 | |

Table 14 shows the production quantities for different products in factories during time between Period 2 – Period 12. The most produced product is Coextruded product. Approximately 28 and 85 percent of the total production quantities in Factory 1 and 2 respectively, is for this product. Plain that is only produced in Factory 1 is the second most important product when total production is taken into consideration. Polyester, Cast, Pearlized, Tape, Barrier and coated products are also produced in Factory 1. Cast anti-fog product is the least produced by the company and is only produced in Factory 2. While periods are considered, the highest production quantity is realized at Period 2. Production quantities in Period 6, 7 and 11 are lower than the other periods. Almost all products are produced in all periods however; cast anti-fog is only produced in 3 periods.

Table 15: Inventory level of products in Warehouses

| | | Periods (Months) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **PRODUCT** | **WAREHOUSE** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **COEXTRUDED** | **FACTORY 1** | 924 | | | | | | | |
| **COEXTRUDED** | **FACTORY 2** | 1500 | | | | | | | |
| **CAST-ANTIFOG** | **FACTORY 1** | 1576 | 1400 | 1400 | 1400 | 1400 | | | |
| **CAST-ANTIFOG** | **FACTORY 2** | | | | | 1500 | 900 | 550 | 200 |

Inventory levels of products is shown in Table 15. Since the company adopts make to order production system and inventory cost is too high, the company does not prefer to stock up products. Coextruded product is only stocked in the first period. Cast anti-fog product is kept in stock for 8 periods.

Optimal results of objective functions are achieved by means of GAMS as follows.

Table 16: Model Statistics - Computational Performance Unit (CPU)

| Model Statistics | | | |
|---|---|---|---|
| **Block of Equations** | 20 | **Single Equations** | 25,484 |
| **Block of Variables** | 19 | **Single Variables** | 143,622 |
| **Non Zero Elements** | 663,324 | **Discrete Variables** | 4,752 |

Computational Performance Unit (CPU) times taken by GAMS to get a single feasible solution under the optimality gap conditions is 1,295 sec on average for mathematical model.

# VII. CONCLUSIONS

With the development of social and environmental awareness, it is becoming compulsory for companies to consider environmental awareness. Firms need to redesign their supply chain structures to design less polluting production systems, reduce waste and reduce environmental risks. Supply chain management is one of the key forces to move forward between competitors. In this context, the location, capacity and other characteristics of stakeholders in a supply chain and types of transportation within the network are determined. Due to the increased responsibility of companies in the sustainability of supply chains, there is a need to develop decision support tools for the evaluation and optimization of multi-criteria and multi-objective problems, especially in the flexible packaging supply chain. Although there are many studies on optimal network design of supply chains, the number of studies that have the economic, environmental and social factors required for a sustainable supply chain is limited.

In this study, a two-stage approach to design a sustainable flexible packaging supply chain network is proposed. In the first stage, the criteria for the sustainable supply chain are determined. Then, decision makers rank each of these criteria. Weights are calculated using the AHP method for each of these criteria. The optimum supplier selection is made by using these calculated weights. In the second stage, a multi-objective mathematical model is developed. The mathematical model has three objective functions aimed cost and time minimization and sustainability maximization. To obtain solution sets in this mixed-integer linear multi-objective problem, the augmented $\epsilon$-constraint method is used.

A case study is included in this study to better understand the proposed approach. A company that manufactures flexible packaging with two factories in Izmir and Kayseri is considered in this case study. In the first phase of the study, the supplier criteria are evaluated and the inconsistency of this evaluation is calculated. And it is shown that evaluation criteria can be acceptable because the calculated consistency ratio (CR) is smaller than 0,1 ($CR = 0{,}006 < 0{,}1$). After finding that the calculated weights are consistent, final score of each supplier is obtained according to the ranks given by the decision makers and the calculated weights by using AHP for each criterion. The supplier final rankings according to the calculated final scores is determined as J> E> B> I> D> G> F> A> H> C. First 70% potential suppliers with better final scores are allowed to enter to the second stage. Suppliers J, E, B, I, D, G, F are selected for second stage to use in mathematical model as data since they have total percentage of final scores 71,25%. In the second stage of the case study, the proposed mixed-integer multi-objective mathematical model is applied. The GAMS codes of the mathematical model are written and arranged with all the data obtained from the company. By running GAMS program, the optimal results are achieved. After obtaining Pareto optimal sets, a point is selected as the optimum solution on Figure 13 which shows cost and time minimization and sustainability maximization objective functions together. According to this point, the optimum results are proposed to the company. These results recommend not only the supplier, factory and transportation mode selection but also raw material quantity that company needs and production quantity according to customer demands for different product types. The company can use these results to design their supply chain more sustainable. Since the company has 11 different product types, this case study includes sample representation with figures only for products Coextruded and Label. In this study, there are 100 different feasible solutions obtained by GAMS program. Decision makers can use any of these feasible solutions as an optimal result to design a sustainable supply chain according to their priorities. Each of these feasible solutions contains different objective function values. While cost minimization is more important at some points, time minimization may be more important in others. For example, if cost minimization is a priority for decision makers, the point with the least value for cost minimization should be used as the optimum result by them.

In the future research, fuzzy set theory can be used with AHP method. With an integrated approach, where fuzzy numbers are also used, judgments about criteria and alternatives can be evaluated better. In the study, the company's annual data was used. With using longer time data, the results can be made more consistent. Recycling of the raw materials and by-products is another important aspect of sustainability in circular economies. By adding recycling criteria to the next studies on sustainable supply chain design, significant contributions can be made to the conservation of natural balance.

# VIII. APPENDIX

**Appendix A:** Parameters used in mathematical model

Table 17: Distance from factories to customers

| Customers | Distance from Factory 1 (Izmir) to Customer (km) | Distance from Factory 2 (Kayseri) to Customer (km) |
|---|---|---|
| **Customer 1**<br>Turkey | 534 | 1334 |
| **Customer 10**<br>Turkey | 433 | 1233 |
| **Customer 102**<br>Turkey | 30 | 830 |
| **Customer 106**<br>Turkey | 453 | 1253 |
| **Customer 112**<br>Turkey | 453 | 1253 |
| **Customer 117**<br>Turkey | 30 | 830 |
| **Customer 119**<br>Turkey | 30 | 830 |
| **Customer 122**<br>Turkey | 1 | 801 |
| **Customer 126**<br>France | 2108 | 2908 |
| **Customer 128**<br>France | 2108 | 2908 |
| **Customer 13**<br>Turkey | 455 | 1255 |
| **Customer 131**<br>France | 2108 | 2908 |
| **Customer 132**<br>Italy | 2108 | 2908 |
| **Customer 133**<br>Germany | 6637 | 7437 |
| **Customer 134**<br>Italy | 2108 | 2908 |
| **Customer 135**<br>Slovenia | 2108 | 2908 |
| **Customer 136**<br>Greece | 617 | 1417 |
| **Customer 137** | 2720 | 3520 |

| | | |
|---|---|---|
| Spain | | |
| **Customer 139** Italy | 2108 | 2908 |
| **Customer 14** Turkey | 455 | 1255 |
| **Customer 140** France | 2108 | 2908 |
| **Customer 142** Italy | 2108 | 2908 |
| **Customer 143** Italy | 2108 | 2908 |
| **Customer 144** France | 2108 | 2908 |
| **Customer 147** America | 1017 | 1817 |
| **Customer 148** Brazil | 11093 | 11893 |
| **Customer 149** Israel | 1550 | 2350 |
| **Customer 15** Turkey | 30 | 830 |
| **Customer 150** America | 1017 | 1817 |
| **Customer 153** Hungary | 8265 | 9065 |
| **Customer 155** Germany | 6637 | 7437 |
| **Customer 156** Italy | 2243 | 3043 |
| **Customer 157** Netherlands | 6323 | 7123 |
| **Customer 16** Turkey | 433 | 1233 |
| **Customer 160** France | 2108 | 2908 |
| **Customer 163** Italy | 2108 | 2908 |
| **Customer 164** France | 2108 | 2908 |
| **Customer 165** Germany | 6637 | 7437 |
| **Customer 170** Italy | 2243 | 3043 |
| **Customer 171** France | 2108 | 2908 |

| | | |
|---|---|---|
| **Customer 172** Bulgaria | 335 | 1135 |
| **Customer 173** Italy | 2243 | 3043 |
| **Customer 174** England | 5448 | 6248 |
| **Customer 175** Israel | 1550 | 2350 |
| **Customer 176** Italy | 2243 | 3043 |
| **Customer 177** Israel | 1550 | 2350 |
| **Customer 18** Turkey | 455 | 1255 |
| **Customer 183** Italy | 2108 | 2908 |
| **Customer 184** Belgium | 5863 | 6663 |
| **Customer 185** France | 2243 | 3043 |
| **Customer 186** Italy | 2243 | 3043 |
| **Customer 187** Italy | 2243 | 3043 |
| **Customer 189** Switzerland | 2108 | 2908 |
| **Customer 19** Turkey | 395 | 1195 |
| **Customer 190** France | 2243 | 3043 |
| **Customer 191** Israel | 1550 | 2350 |
| **Customer 193** Italy | 2243 | 3043 |
| **Customer 196** Italy | 2243 | 3043 |
| **Customer 197** Italy | 2243 | 3043 |
| **Customer 198** France | 2243 | 3043 |
| **Customer 2** Turkey | 433 | 1233 |
| **Customer 20** Turkey | 455 | 1255 |
| **Customer 200** | 2720 | 3520 |

| | | |
|---|---|---|
| Spain | | |
| **Customer 201** England | 5448 | 6248 |
| **Customer 202** France | 2243 | 3043 |
| **Customer 205** Italy | 2243 | 3043 |
| **Customer 206** Germany | 6637 | 7437 |
| **Customer 208** Netherlands | 6323 | 7123 |
| **Customer 209** Italy | 2243 | 3043 |
| **Customer 21** Turkey | 435 | 1235 |
| **Customer 210** Italy | 2243 | 3043 |
| **Customer 212** Italy | 2243 | 3043 |
| **Customer 214** Czech Republic | 2108 | 2908 |
| **Customer 216** Spain | 2720 | 3520 |
| **Customer 218** Denmark | 6877 | 7677 |
| **Customer 219** England | 5448 | 6248 |
| **Customer 22** Turkey | 465 | 1265 |
| **Customer 220** Italy | 2243 | 3043 |
| **Customer 221** Hungary | 8265 | 9065 |
| **Customer 222** Portugal | 3887 | 4687 |
| **Customer 224** Greece | 617 | 1417 |
| **Customer 225** France | 2243 | 3043 |
| **Customer 226** Macedonia | 852 | 1652 |
| **Customer 227** Macedonia | 852 | 1652 |
| **Customer 228** France | 2243 | 3043 |

| | | |
|---|---|---|
| **Customer 23**<br>Turkey | 646 | 1446 |
| **Customer 231**<br>Spain | 2720 | 3520 |
| **Customer 232**<br>Italy | 2243 | 3043 |
| **Customer 234**<br>Italy | 2243 | 3043 |
| **Customer 235**<br>England | 5448 | 6248 |
| **Customer 237**<br>Russia | 904 | 1704 |
| **Customer 24**<br>Turkey | 32 | 832 |
| **Customer 245**<br>Netherlands | 6323 | 7123 |
| **Customer 25**<br>Turkey | 433 | 1233 |
| **Customer 251**<br>Serbia | 1254 | 2054 |
| **Customer 252**<br>Romania | 1101 | 1901 |
| **Customer 255**<br>England | 5448 | 6248 |
| **Customer 256**<br>Germany | 6637 | 7437 |
| **Customer 258**<br>Spain | 2720 | 3520 |
| **Customer 260**<br>Spain | 2720 | 3520 |
| **Customer 261**<br>Italy | 2243 | 3043 |
| **Customer 270**<br>America | 1017 | 1817 |
| **Customer 272**<br>Italy | 2243 | 3043 |
| **Customer 274**<br>Spain | 2720 | 3520 |
| **Customer 276**<br>Italy | 2243 | 3043 |
| **Customer 277**<br>Turkey | 32 | 832 |
| **Customer 280**<br>Turkey | 28 | 828 |
| **Customer 281** | 30 | 830 |

| | | |
|---|---|---|
| Turkey | | |
| **Customer 288**<br>Turkey | 33 | 833 |
| **Customer 290**<br>Turkey | 433 | 1233 |
| **Customer 3**<br>Turkey | 534 | 1334 |
| **Customer 30**<br>Turkey | 32 | 832 |
| **Customer 300**<br>Germany | 6637 | 7437 |
| **Customer 306**<br>France | 2108 | 2908 |
| **Customer 309**<br>England | 5448 | 6248 |
| **Customer 32**<br>Turkey | 452 | 1252 |
| **Customer 322**<br>Lebanon | 1500 | 2300 |
| **Customer 326**<br>Spain | 2720 | 3520 |
| **Customer 327**<br>Italy | 2243 | 3043 |
| **Customer 33**<br>Turkey | 433 | 1233 |
| **Customer 334**<br>Brazil | 11093 | 11893 |
| **Customer 335**<br>Italy | 2243 | 3043 |
| **Customer 336**<br>Hungary | 8265 | 9065 |
| **Customer 35**<br>Turkey | 1088 | 1888 |
| **Customer 360**<br>İran | 3088 | 3888 |
| **Customer 364**<br>Italy | 2243 | 3043 |
| **Customer 38**<br>Turkey | 30 | 830 |
| **Customer 39**<br>Turkey | 422 | 1222 |
| **Customer 4**<br>Turkey | 33 | 833 |
| **Customer 40**<br>Turkey | 33 | 833 |

| | | |
|---|---|---|
| **Customer 43**<br>Turkey | 455 | 1255 |
| **Customer 44**<br>Turkey | 432 | 1232 |
| **Customer 45**<br>Turkey | 644 | 1444 |
| **Customer 46**<br>Turkey | 1100 | 1900 |
| **Customer 47**<br>Turkey | 564 | 1364 |
| **Customer 48**<br>Turkey | 488 | 1288 |
| **Customer 49**<br>Turkey | 30 | 830 |
| **Customer 5**<br>Turkey | 30 | 830 |
| **Customer 50**<br>Turkey | 32 | 832 |
| **Customer 53**<br>Turkey | 455 | 1255 |
| **Customer 56**<br>Turkey | 455 | 1255 |
| **Customer 57**<br>Turkey | 433 | 1233 |
| **Customer 58**<br>Turkey | 395 | 1195 |
| **Customer 60**<br>Turkey | 388 | 1188 |
| **Customer 63**<br>Turkey | 488 | 1288 |
| **Customer 64**<br>Turkey | 455 | 1255 |
| **Customer 65**<br>Turkey | 32 | 832 |
| **Customer 68**<br>Turkey | 32 | 832 |
| **Customer 71**<br>Turkey | 644 | 1444 |
| **Customer 75**<br>Turkey | 455 | 1255 |
| **Customer 76**<br>Turkey | 455 | 1255 |
| **Customer 77**<br>Turkey | 433 | 1233 |
| **Customer 8** | 32 | 832 |

| | | |
|---|---|---|
| Turkey | | |
| **Customer 80**<br>Turkey | 32 | 832 |
| **Customer 9**<br>Turkey | 30 | 830 |
| **Customer 90**<br>Turkey | 455 | 1255 |
| **Customer 91**<br>Turkey | 453 | 1253 |

## **Appendix B:** Result obtained from GAMS

Table 18: Quantity of Products in a Factory with a Transportation Mode [kg]

| PRODUCT | FACTORY | CUSTOMER | MODE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COEXTRUDED | FACTORY 1 | Customer1 | RAIL | 42000 | | | | 72500 | | | | | 99000 | 33000 | 45000 |
| COEXTRUDED | FACTORY 1 | Customer102 | ROAD | | | | 75000 | | | | | | | | |
| COEXTRUDED | FACTORY 1 | Customer128 | ROAD | 80000 | 40000 | | | | 58000 | | | | | | 40000 |
| COEXTRUDED | FACTORY 1 | Customer13 | ROAD | 104500 | | | 45000 | 99000 | | | 40000 | | | | |
| COEXTRUDED | FACTORY 1 | Customer131 | ROAD | 60000 | 35000 | | | | | | | | | | |
| COEXTRUDED | FACTORY 1 | Customer136 | SEA | | | | | | 43500 | | | | | | |
| COEXTRUDED | FACTORY 1 | Customer139 | SEA | | 60000 | | 100000 | 80000 | | 80000 | | | 80000 | | 120000 |
| COEXTRUDED | FACTORY 1 | Customer14 | SEA | 86000 | 153000 | 325000 | | | | 140000 | 70000 | 33965 | 221000 | 99000 | |
| COEXTRUDED | FACTORY 1 | Customer140 | SEA | | | 78000 | | | | | | | | | |
| COEXTRUDED | FACTORY 1 | Customer142 | SEA | | | | | | 74000 | | 39000 | | | | |
| COEXTRUDED | FACTORY 1 | Customer147 | ROAD | | | 24144 | | 85673 | 235872 | 172376 | | | 16428 | | 179100 |
| COEXTRUDED | FACTORY 1 | Customer150 | ROAD | | | 54284 | | | 53039 | | | 6200 | | 48454 | |
| COEXTRUDED | FACTORY 1 | Customer157 | SEA | 30500 | | | | | | | | | | | |
| COEXTRUDED | FACTORY 1 | Customer16 | SEA | | | | | | 30500 | | 91500 | | | | |
| COEXTRUDED | FACTORY 1 | Customer160 | SEA | 60000 | 60000 | | 60000 | | 60000 | 60000 | | 100000 | 80000 | 80000 | 80000 |
| COEXTRUDED | FACTORY 1 | Customer164 | ROAD | 60000 | 80000 | | | | | 40000 | | | | 34000 | 120000 |
| COEXTRUDED | FACTORY 1 | Customer171 | SEA | 40000 | | | | | 49000 | | | | | | |
| COEXTRUDED | FACTORY 1 | Customer173 | SEA | | | | | | 40000 | | | | | | |
| COEXTRUDED | FACTORY 1 | Customer186 | RAIL | 38000 | 38000 | | | | 38000 | | | | | | |

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| **COEXTRUDED** | **FACTORY 1** | **Customer189** | **SEA** | | | | | 42000 | 40000 | 78000 | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer19** | **SEA** | | 158900 | 127800 | 268650 | 205250 | 29300 | | 61700 | 116750 | 112250 | 217850 | 59150 |
| **COEXTRUDED** | **FACTORY 1** | **Customer191** | **SEA** | 34970 | | | 122300 | | | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer196** | **SEA** | 80000 | | | | 120000 | 80000 | | 40000 | 60000 | 100000 | | 80000 |
| **COEXTRUDED** | **FACTORY 1** | **Customer198** | **SEA** | 144000 | | | | 72000 | | | | | | 36000 | |
| **COEXTRUDED** | **FACTORY 1** | **Customer20** | **RAIL** | 40000 | 81000 | 54000 | 7081 | 50000 | | 125500 | 26788 | 137500 | | 88000 | 52000 |
| **COEXTRUDED** | **FACTORY 1** | **Customer205** | **SEA** | | 40000 | 60000 | | | | | 59500 | | 40000 | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer206** | **ROAD** | | | | | | | 60000 | | | 40000 | 60000 | |
| **COEXTRUDED** | **FACTORY 1** | **Customer208** | **ROAD** | 60000 | 100000 | | 80000 | | | 80000 | 140000 | | 40000 | 60000 | 60000 |
| **COEXTRUDED** | **FACTORY 1** | **Customer209** | **ROAD** | | | | | | | | | | | 47000 | |
| **COEXTRUDED** | **FACTORY 1** | **Customer21** | **ROAD** | | 46400 | | | | | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer212** | **SEA** | | | | | | | | | 36000 | | 36000 | |
| **COEXTRUDED** | **FACTORY 1** | **Customer218** | **SEA** | | | 46000 | 40000 | | 40000 | 60000 | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer219** | **SEA** | | 100000 | | | | | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer22** | **SEA** | 63000 | 65000 | 75000 | 133000 | | 60000 | 235000 | 152000 | 75000 | 146000 | 75000 | 230000 |
| **COEXTRUDED** | **FACTORY 1** | **Customer220** | **SEA** | 36000 | | 118000 | 136000 | 85000 | 80000 | | 180000 | | | 40000 | 80000 |
| **COEXTRUDED** | **FACTORY 1** | **Customer221** | **ROAD** | | | 60000 | | | 50000 | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer226** | **ROAD** | | | | | | | | | | 46950 | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer227** | **ROAD** | | | | | | 36000 | | 36000 | | 54000 | 82000 | |
| **COEXTRUDED** | **FACTORY 1** | **Customer23** | **ROAD** | 68000 | 89500 | 123000 | 93000 | 121250 | 32000 | | | 71850 | 83250 | 108500 | |
| **COEXTRUDED** | **FACTORY 1** | **Customer234** | **SEA** | | 40000 | 100000 | 46000 | | | 50000 | | 122000 | | | 122600 |
| **COEXTRUDED** | **FACTORY 1** | **Customer235** | **SEA** | | | 45000 | | | | 41000 | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer24** | **SEA** | | | | | | | 42000 | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer245** | **ROAD** | | | | | | | | 40000 | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer25** | **ROAD** | | | | | | | | 38450 | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer251** | **ROAD** | | | | | | | 79500 | 60000 | | 60500 | 34500 | |

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| **COEXTRUDED** | **FACTORY 1** | **Customer252** | **SEA** | | | 60000 | | | | | 45000 | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer255** | **SEA** | | | | 84000 | | | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer274** | **SEA** | | | | | 54155 | 59111 | 59497 | 38825 | | 39497 | 78117 | |
| **COEXTRUDED** | **FACTORY 1** | **Customer280** | **ROAD** | | | | | | | | | | 41000 | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer3** | **ROAD** | | | | | | | | | | | 55900 | |
| **COEXTRUDED** | **FACTORY 1** | **Customer300** | **SEA** | | | | | 60500 | | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer309** | **SEA** | | | | | | 40000 | 95000 | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer335** | **SEA** | | | | | | | | | | | | 102500 |
| **COEXTRUDED** | **FACTORY 1** | **Customer35** | **SEA** | 91200 | 189200 | 171200 | 171000 | | 72500 | | 64000 | 48000 | 51550 | 128300 | |
| **COEXTRUDED** | **FACTORY 1** | **Customer4** | **SEA** | | | 45200 | | | | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer40** | **SEA** | 344000 | | | | | | | 240000 | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer49** | **ROAD** | | | | | | 29050 | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer50** | **ROAD** | | 36000 | 67000 | | 82000 | | | 60000 | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer53** | **SEA** | | | 84850 | 142300 | 111500 | 96150 | 74000 | 88300 | 74150 | 55550 | 45100 | 98350 |
| **COEXTRUDED** | **FACTORY 1** | **Customer56** | **SEA** | | 34500 | | | | | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer57** | **SEA** | | | | | | | | | | | 40705 | 45220 |
| **COEXTRUDED** | **FACTORY 1** | **Customer60** | **ROAD** | | | 79150 | | | 47950 | 52950 | | 76100 | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer64** | **ROAD** | | | | | | 30100 | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer65** | **ROAD** | | | | | | | 44400 | 48600 | 43250 | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer68** | **ROAD** | 74500 | 126500 | 64250 | 139500 | 125500 | 92000 | 87300 | 52500 | 137000 | 115850 | 152500 | 131500 |
| **COEXTRUDED** | **FACTORY 1** | **Customer71** | **RAIL** | 50000 | | | 76000 | 69000 | | 106300 | 40000 | 53500 | 73500 | | 78500 |
| **COEXTRUDED** | **FACTORY 1** | **Customer76** | **SEA** | | 44150 | | | | | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer77** | **SEA** | | 46925 | | | 85350 | | | 58650 | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer9** | **RAIL** | 45000 | | 85000 | 66000 | | | | | | | | |
| **COEXTRUDED** | **FACTORY 1** | **Customer91** | **SEA** | | | | 45000 | | | | | | 53000 | | |
| **COEXTRUDED** | **FACTORY 2** | **Customer1** | **SEA** | | 61000 | | | | | | 40000 | | | | |

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| **COEXTRUDED** | **FACTORY 2** | **Customer126** | **SEA** | | | | | 60000 | 30000 | | | | | | 40000 |
| **COEXTRUDED** | **FACTORY 2** | **Customer144** | **SEA** | | | | | | | | | | 40024 | 39754 | |
| **COEXTRUDED** | **FACTORY 2** | **Customer147** | **SEA** | | 72000 | 300000 | 49896 | 59479 | | 145000 | | 144000 | 110702 | 90000 | 32400 |
| **COEXTRUDED** | **FACTORY 2** | **Customer149** | **SEA** | | | | | | | 72000 | | | 39274 | | |
| **COEXTRUDED** | **FACTORY 2** | **Customer150** | **SEA** | 72280 | | | 108140 | 89671 | 157400 | | 36288 | 29800 | | 5546 | |
| **COEXTRUDED** | **FACTORY 2** | **Customer153** | **SEA** | 40500 | | | | | | | | | | | |
| **COEXTRUDED** | **FACTORY 2** | **Customer174** | **SEA** | | 36000 | | | | 72000 | 54000 | 36000 | | | | |
| **COEXTRUDED** | **FACTORY 2** | **Customer175** | **SEA** | 38500 | | | | | 40600 | | | 68200 | | | 80600 |
| **COEXTRUDED** | **FACTORY 2** | **Customer177** | **SEA** | | | | | | | | 36000 | | | 46250 | |
| **COEXTRUDED** | **FACTORY 2** | **Customer184** | **SEA** | 42000 | 60000 | | | | | | | 40000 | | 60000 | 40000 |
| **COEXTRUDED** | **FACTORY 2** | **Customer20** | **SEA** | | 3500 | | 52419 | | | | 121712 | | | | |
| **COEXTRUDED** | **FACTORY 2** | **Customer290** | **SEA** | | | | | | | | 30000 | | | | |
| **COEXTRUDED** | **FACTORY 2** | **Customer364** | **SEA** | | | | | | | | | | 61000 | | |
| **COEXTRUDED** | **FACTORY 2** | **Customer60** | **SEA** | 36750 | | | | | | | | | | | |
| **PLAIN** | **FACTORY 1** | **Customer1** | **RAIL** | 112000 | | | 98500 | | | | | | 145000 | | |
| **PLAIN** | **FACTORY 1** | **Customer112** | **ROAD** | | | | 50000 | 87000 | 145000 | 50000 | 140000 | 80000 | 100000 | | 316000 |
| **PLAIN** | **FACTORY 1** | **Customer14** | **SEA** | 90000 | | | | 115000 | 135000 | 51200 | | 90000 | | 70000 | 80000 |
| **PLAIN** | **FACTORY 1** | **Customer143** | **SEA** | | | 120000 | 80000 | | 120000 | | 80000 | | | | |
| **PLAIN** | **FACTORY 1** | **Customer147** | **ROAD** | | 108000 | | | | | | | | 72000 | | |
| **PLAIN** | **FACTORY 1** | **Customer176** | **ROAD** | | | 80000 | | | | | | | | | |
| **PLAIN** | **FACTORY 1** | **Customer18** | **ROAD** | | 232000 | 300000 | 250000 | 300000 | 300000 | 300000 | 150000 | 300000 | 327000 | 210000 | 170000 |
| **PLAIN** | **FACTORY 1** | **Customer185** | **ROAD** | 60000 | | | | | | | | | | | |
| **PLAIN** | **FACTORY 1** | **Customer187** | **RAIL** | 44000 | | | | | | | | | | | |
| **PLAIN** | **FACTORY 1** | **Customer19** | **SEA** | | 105950 | 81150 | 79200 | 86750 | | | | | 101850 | 135600 | 71250 |
| **PLAIN** | **FACTORY 1** | **Customer272** | **SEA** | | | | | | | | 80000 | | | | |
| **PLAIN** | **FACTORY 1** | **Customer276** | **SEA** | | | | | | | | 80000 | 80000 | 100000 | | |

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| **PLAIN** | **FACTORY 1** | **Customer3** | **ROAD** | | | | | | | | | | | 89000 | |
| **PLAIN** | **FACTORY 1** | **Customer33** | **SEA** | 100000 | | | | | | | | | | | |
| **PLAIN** | **FACTORY 1** | **Customer47** | **ROAD** | | | | 59000 | | | | | | | | |
| **PLAIN** | **FACTORY 1** | **Customer68** | **ROAD** | 61000 | 153000 | 160250 | 104500 | 162750 | 90000 | 144000 | 102000 | 228000 | 172000 | 121500 | 204500 |
| **PLAIN** | **FACTORY 1** | **Customer8** | **ROAD** | 115000 | 255000 | 215000 | 215000 | 170000 | 86900 | 90000 | 125000 | 191000 | 101000 | 226000 | 103000 |
| **PLAIN** | **FACTORY 2** | **Customer18** | **SEA** | 220000 | | | | | | | | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer10** | **ROAD** | | | 27100 | 57950 | 21300 | | | | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer106** | **ROAD** | | | | | | | | | | 26500 | | |
| **POLYESTER** | **FACTORY 1** | **Customer119** | **RAIL** | | | | | | | | 27000 | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer132** | **ROAD** | 49000 | | 40000 | | | | | | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer134** | **ROAD** | 110000 | 150000 | 103000 | 80000 | 50000 | 176000 | 180000 | 210000 | 170000 | 210000 | 40000 | |
| **POLYESTER** | **FACTORY 1** | **Customer137** | **SEA** | 20730 | 42336 | | | | | | | | 20929 | | |
| **POLYESTER** | **FACTORY 1** | **Customer139** | **SEA** | | | | 36000 | | | | 39700 | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer15** | **ROAD** | 160000 | | 40000 | 60000 | | | | | 111000 | | 59000 | 60000 |
| **POLYESTER** | **FACTORY 1** | **Customer150** | **ROAD** | | 126808 | 127006 | 108864 | 72576 | 90721 | 91125 | 54790 | | 127330 | | |
| **POLYESTER** | **FACTORY 1** | **Customer155** | **ROAD** | | 58932 | 59835 | | 177882 | | 99046 | 59488 | 59143 | | | 178184 |
| **POLYESTER** | **FACTORY 1** | **Customer156** | **SEA** | | | 26850 | | | | | | | 25540 | 25700 | 24600 |
| **POLYESTER** | **FACTORY 1** | **Customer163** | **ROAD** | | 70290 | | | | | | 39660 | 58400 | 92780 | | |
| **POLYESTER** | **FACTORY 1** | **Customer165** | **ROAD** | | | 20000 | | | | | 28000 | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer170** | **SEA** | | | 21500 | | | | | | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer19** | **SEA** | | | 50300 | | | 46500 | | | 29050 | 48500 | 77850 | 27850 |
| **POLYESTER** | **FACTORY 1** | **Customer190** | **SEA** | | | | | | | | 35600 | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer197** | **SEA** | | | 60000 | 64000 | | | | | | 39000 | | 60000 |
| **POLYESTER** | **FACTORY 1** | **Customer201** | **SEA** | | | 39000 | | | | | | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer21** | **ROAD** | 27300 | | | | | | | | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer210** | **SEA** | | | | 21000 | | | | | | | | 21300 |

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| **POLYESTER** | **FACTORY 1** | **Customer216** | **SEA** | | 66025 | 61554 | | | | 39507 | 58552 | 41080 | | 41203 | |
| **POLYESTER** | **FACTORY 1** | **Customer222** | **ROAD** | | 54000 | 21000 | | | | 92000 | 59200 | | 36000 | 38000 | 60000 |
| **POLYESTER** | **FACTORY 1** | **Customer224** | **ROAD** | 20400 | | 41100 | | | | | 40000 | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer225** | **ROAD** | | | | 20747 | | | | | | | | 20016 |
| **POLYESTER** | **FACTORY 1** | **Customer228** | **ROAD** | | | | 19958 | | | | 39366 | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer231** | **SEA** | | | | | | 31226 | 47753 | | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer256** | **SEA** | | | | | | 27933 | | 34717 | | 40915 | 30094 | 40092 |
| **POLYESTER** | **FACTORY 1** | **Customer258** | **SEA** | | | | | 28748 | 25463 | 68497 | | | | | 31795 |
| **POLYESTER** | **FACTORY 1** | **Customer260** | **SEA** | | | 21281 | | | | | | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer270** | **SEA** | | | | | | | 107959 | 37195 | 339800 | 108000 | 216000 | 197500 |
| **POLYESTER** | **FACTORY 1** | **Customer281** | **ROAD** | | | | | | | | 33000 | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer30** | **ROAD** | 33250 | | 25900 | | 23250 | 30850 | | 30300 | | 23000 | | |
| **POLYESTER** | **FACTORY 1** | **Customer326** | **SEA** | | | | | | | | 41908 | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer327** | **SEA** | | | | | | | | | | | | 37531 |
| **POLYESTER** | **FACTORY 1** | **Customer334** | **SEA** | | | | | | | | 24000 | | | 36000 | |
| **POLYESTER** | **FACTORY 1** | **Customer336** | **SEA** | | | | | | | | | | 25140 | | 20000 |
| **POLYESTER** | **FACTORY 1** | **Customer35** | **SEA** | | 25100 | | | | 43500 | | | 78000 | | 24000 | |
| **POLYESTER** | **FACTORY 1** | **Customer39** | **SEA** | | | | 20250 | 22170 | | | | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer58** | **ROAD** | | 37700 | | | | | | 30500 | | | | |
| **POLYESTER** | **FACTORY 1** | **Customer75** | **SEA** | | | 35000 | | | | | 30000 | | | | |
| **POLYESTER** | **FACTORY 2** | **Customer10** | **SEA** | 36740 | | | | | | | | | | | |
| **POLYESTER** | **FACTORY 2** | **Customer150** | **SEA** | 126160 | | | | | | | | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer1** | **RAIL** | 120000 | 55000 | 91400 | 143000 | 191000 | 96500 | | 57000 | | 100000 | 29000 | 124450 |
| **METALLIZED** | **FACTORY 1** | **Customer132** | **ROAD** | 64000 | | | | | | | | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer133** | **ROAD** | | | | | | | | 25579 | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer148** | **ROAD** | | | 87000 | | | | | | | | | |

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| **METALLIZED** | **FACTORY 1** | **Customer156** | **SEA** | | 33450 | | | | | 30400 | 41000 | | | | 39030 |
| **METALLIZED** | **FACTORY 1** | **Customer183** | **ROAD** | | 20000 | | 60000 | | | | | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer19** | **SEA** | 72650 | 95850 | 50750 | 36450 | 37550 | 44450 | | 24000 | 37700 | 48250 | 80050 | 98800 |
| **METALLIZED** | **FACTORY 1** | **Customer191** | **SEA** | | | | 34170 | | | | | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer193** | **SEA** | | 20000 | | | | | 40325 | 40600 | 20000 | | | |
| **METALLIZED** | **FACTORY 1** | **Customer2** | **ROAD** | | 20000 | | | 56600 | | | | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer200** | **RAIL** | | 29225 | 28348 | | | | | | | 42741 | | |
| **METALLIZED** | **FACTORY 1** | **Customer226** | **ROAD** | | | | | | | 26000 | | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer23** | **ROAD** | | 54000 | 78500 | 69000 | | | | | 31000 | | 51000 | |
| **METALLIZED** | **FACTORY 1** | **Customer232** | **SEA** | | | 36000 | | | | | | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer25** | **ROAD** | | | | | | | | 23400 | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer3** | **ROAD** | | | | | | | | | | 76500 | 86000 | 110800 |
| **METALLIZED** | **FACTORY 1** | **Customer306** | **SEA** | | | | | | | 51358 | | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer309** | **SEA** | | | | | | 36000 | 89000 | | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer32** | **SEA** | | | | | | | 24260 | | | 32325 | 32000 | |
| **METALLIZED** | **FACTORY 1** | **Customer35** | **SEA** | 41000 | | | | | | 29750 | 50050 | 45100 | | | |
| **METALLIZED** | **FACTORY 1** | **Customer5** | **ROAD** | 26000 | | | | | | | | 12000 | | | |
| **METALLIZED** | **FACTORY 1** | **Customer60** | **ROAD** | | | | | | | 35250 | | 35750 | | | |
| **METALLIZED** | **FACTORY 1** | **Customer63** | **ROAD** | | | | | | | 26500 | | | | | |
| **METALLIZED** | **FACTORY 1** | **Customer68** | **ROAD** | 49000 | 50000 | 70750 | 88000 | 95250 | 144000 | 60000 | 84000 | 62000 | 88000 | 90000 | 50900 |
| **METALLIZED** | **FACTORY 2** | **Customer148** | **SEA** | 49000 | 69000 | | 89000 | 89000 | | | | | 49000 | 58000 | 69000 |
| **METALLIZED** | **FACTORY 2** | **Customer60** | **SEA** | 23500 | | | | | | | | | | | |
| **CAST** | **FACTORY 1** | **Customer102** | **ROAD** | | | | 102000 | 145000 | | 139000 | | | 134250 | 117000 | 24500 |
| **CAST** | **FACTORY 1** | **Customer14** | **SEA** | | | | | | | | | 40000 | | | |
| **CAST** | **FACTORY 1** | **Customer149** | **ROAD** | | | | 20000 | | | | | | | | |
| **CAST** | **FACTORY 1** | **Customer175** | **ROAD** | | | | | | 42000 | | 60000 | | | 20000 | 53500 |

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| **CAST** | **FACTORY 1** | **Customer20** | **RAIL** | | | | | | | | 16000 | | | | 21000 |
| **CAST** | **FACTORY 1** | **Customer202** | **SEA** | | | | 20250 | | | | | | | | |
| **CAST** | **FACTORY 1** | **Customer214** | **SEA** | | | | 20000 | | | | 18000 | | | 36000 | |
| **CAST** | **FACTORY 1** | **Customer22** | **SEA** | | 75500 | 109500 | | | 55000 | 55000 | 50000 | | 75000 | | |
| **CAST** | **FACTORY 1** | **Customer23** | **ROAD** | | | | 23250 | | | | | | | | 26000 |
| **CAST** | **FACTORY 1** | **Customer35** | **SEA** | | 60000 | | | | 54700 | | | | | | |
| **CAST** | **FACTORY 1** | **Customer38** | **RAIL** | 40000 | | 88000 | | | | | 40000 | 43000 | | | |
| **CAST** | **FACTORY 1** | **Customer39** | **SEA** | 50000 | | | | | | | 21200 | | | 53550 | 27750 |
| **CAST** | **FACTORY 1** | **Customer50** | **ROAD** | 148000 | 155000 | 138000 | 92000 | 84000 | 81000 | 50000 | 92000 | 90500 | 95000 | 40000 | 57000 |
| **CAST** | **FACTORY 1** | **Customer53** | **SEA** | 92500 | | 71700 | 60000 | 48000 | 37250 | 46900 | 42400 | 73400 | 35000 | 39360 | 36315 |
| **CAST** | **FACTORY 1** | **Customer65** | **ROAD** | | | | | | | | | 22400 | | | |
| **PEARLIZED** | **FACTORY 1** | **Customer10** | **ROAD** | | | | | | | | | 23400 | | | |
| **PEARLIZED** | **FACTORY 1** | **Customer135** | **SEA** | | 16000 | | | | | | | | | | |
| **PEARLIZED** | **FACTORY 1** | **Customer19** | **SEA** | 72350 | 63900 | 62750 | | 60650 | 55450 | | 124700 | 20050 | 95200 | 46250 | 58800 |
| **PEARLIZED** | **FACTORY 1** | **Customer220** | **SEA** | | | | | | | | | | | | 48000 |
| **PEARLIZED** | **FACTORY 1** | **Customer237** | **SEA** | | | | | | | 37900 | | | | | |
| **PEARLIZED** | **FACTORY 1** | **Customer261** | **SEA** | | | | 17000 | | | | | | | | |
| **PEARLIZED** | **FACTORY 1** | **Customer3** | **ROAD** | | 24000 | 32400 | 45000 | 52000 | | | | | | 14500 | |
| **PEARLIZED** | **FACTORY 1** | **Customer30** | **ROAD** | | | | | | | | | | | 30000 | |
| **PEARLIZED** | **FACTORY 1** | **Customer35** | **SEA** | | | | 63500 | | 26000 | | | | | | |
| **PEARLIZED** | **FACTORY 1** | **Customer48** | **ROAD** | | | 60000 | 25500 | 20000 | | | | | | 20000 | |
| **PEARLIZED** | **FACTORY 1** | **Customer60** | **ROAD** | | | | | | 43000 | | | | | | |
| **PEARLIZED** | **FACTORY 1** | **Customer68** | **ROAD** | 71500 | 17000 | 51000 | | 75000 | 40000 | 43700 | 42500 | 72000 | 75500 | 15000 | 100000 |
| **PEARLIZED** | **FACTORY 2** | **Customer3** | **SEA** | 34800 | | | | | | | | | | | |
| **PEARLIZED** | **FACTORY 2** | **Customer48** | **SEA** | 30000 | | | | | | | | | | | |
| **LABEL** | **FACTORY 1** | **Customer102** | **ROAD** | | | | | | | | | | | 13750 | 12000 |

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| **LABEL** | **FACTORY 1** | **Customer172** | **SEA** | | | | | | | 20000 | 40000 | | | | |
| **LABEL** | **FACTORY 1** | **Customer277** | **SEA** | | | | | | 20000 | | | | | | |
| **LABEL** | **FACTORY 1** | **Customer288** | **ROAD** | | | | | | | 25000 | | | | | |
| **LABEL** | **FACTORY 1** | **Customer322** | **SEA** | | | | | | | | | | 35800 | | 21000 |
| **LABEL** | **FACTORY 1** | **Customer35** | **SEA** | | | | | | 25000 | 30000 | | | | | |
| **LABEL** | **FACTORY 1** | **Customer44** | **SEA** | 23000 | | | | | | | | | | | |
| **LABEL** | **FACTORY 1** | **Customer45** | **SEA** | 85500 | 114500 | 63000 | 159000 | 146000 | 103000 | | | | | | |
| **LABEL** | **FACTORY 1** | **Customer46** | **ROAD** | | | | | | | | | 10000 | | 10500 | |
| **LABEL** | **FACTORY 1** | **Customer90** | **ROAD** | | | 20000 | 30000 | 105000 | | | | | | | |
| **LABEL** | **FACTORY 2** | **Customer148** | **SEA** | | | | | | | 29000 | | 18000 | | | 38000 |
| **TAPE** | **FACTORY 1** | **Customer127** | **ROAD** | 144275 | 56610 | 72330 | 51715 | 124530 | 62220 | 81950 | 133880 | 82250 | 82960 | 84160 | 103700 |
| **TAPE** | **FACTORY 1** | **Customer75** | **SEA** | 1250 | 1750 | | | | | | | | | | |
| **TAPE** | **FACTORY 1** | **Customer85** | **ROAD** | | | | | | 10000 | | | | | | |
| **TAPE** | **FACTORY 1** | **Customer89** | **ROAD** | | | | | | | | | 7000 | | | |
| **BARRIER** | **FACTORY 1** | **Customer117** | **RAIL** | | | | 27000 | | | | | | | | |
| **BARRIER** | **FACTORY 1** | **Customer122** | **RAIL** | | | | | | 18500 | | | | 15000 | | |
| **BARRIER** | **FACTORY 1** | **Customer16** | **SEA** | 15000 | | 11000 | | | 11500 | | | | 11500 | | 13500 |
| **BARRIER** | **FACTORY 1** | **Customer43** | **SEA** | 17450 | | 19630 | | 41500 | | | | 13000 | | 14000 | 16500 |
| **BARRIER** | **FACTORY 1** | **Customer64** | **ROAD** | | | | | | | | | | 8500 | | |
| **BARRIER** | **FACTORY 1** | **Customer80** | **ROAD** | 10500 | 28000 | 13500 | 17700 | 62540 | | 55000 | 42500 | 34500 | 6385 | | |
| **BARRIER** | **FACTORY 1** | **Customer9** | **RAIL** | | | | | | | | | | | 10500 | |
| **CAST-ANTIFOG** | **FACTORY 1** | **Customer72** | **SEA** | 6500 | | | | | 1400 | | | | | | |
| **CAST-ANTIFOG** | **FACTORY 1** | **Customer86** | **ROAD** | | 176 | | | | | | | | | | |
| **CAST-ANTIFOG** | **FACTORY 2** | **Customer360** | **SEA** | | | | | | | | | 200 | | | |
| **CAST-ANTIFOG** | **FACTORY 2** | **Customer56** | **ROAD** | | | | 545 | 350 | | 350 | 350 | | | 450 | |
| **CAST-ANTIFOG** | **FACTORY 2** | **Customer72** | **ROAD** | | | | | | 600 | | | | | | |

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| **COATED** | **FACTORY 1** | **Customer147** | **ROAD** | | | | | | 5136 | | | | | | |
| **COATED** | **FACTORY 1** | **Customer173** | **SEA** | 2900 | | | | | | | | | | | |
| **COATED** | **FACTORY 1** | **Customer19** | **SEA** | | | | 9000 | | 10250 | | | 9500 | | 7000 | |
| **COATED** | **FACTORY 1** | **Customer216** | **SEA** | | 8468 | | | | | | | | | | |
| **COATED** | **FACTORY 1** | **Customer30** | **ROAD** | | 7500 | | | | | | 4250 | | 1000 | | |
| **COATED** | **FACTORY 1** | **Customer44** | **SEA** | 500 | | | | | | | | | | | |
| **COATED** | **FACTORY 1** | **Customer49** | **ROAD** | 400 | | | | | | | | | | | |
| **COATED** | **FACTORY 1** | **Customer65** | **ROAD** | | | | | 10000 | | | 10000 | | | | |
| **COATED** | **FACTORY 1** | **Customer68** | **ROAD** | 300 | | 3000 | 3500 | | | | | | | 3700 | |
| **COATED** | **FACTORY 1** | **Customer7** | **RAIL** | | | | | | | 500 | | | | | |

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