AN INTEGRATED METHOD USING FUZZY DECISION MAKING AND MULTI-OBJECTIVE OPTIMIZATION FOR SUSTAINABLE SUPPLIER SELECTION AND ORDER ALLOCATION IN AUTOMOTIVE INDUSTRY

(OTOMOTİV ENDÜSTRİSİNDE BÜTÜNLEŞİK BULANIK KARAR VERME VE ÇOK AMAÇLI OPTİMİZASYON METHODUYLA SÜRDÜRÜLEBİLİR TEDARİKÇİ SEÇİMİ VE SİPARİŞ MİKTARININ BELİRLENMESİ)

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İpek ELDEM

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LIST OF SYMBOLS

AHP	:	Analytic Hierarchy Process
ANP	:	Analytic Network Process
BWM	:	Best and Worst Method
CAPA	:	Corrective and Preventive Actions
CI	:	Consistency Index
CR	:	Consistency Ratio
DEA	:	Data Envelopment Analysis
DEMATEL	:	Decision-Making Trial and Evaluation Laboratory
EFA	:	Explanatory Factor Analysis
EMS	:	Environmental Management System
FIS	:	Fuzzy Inference Systems
FP	:	Fuzzy Programming
GP	:	Goal Programming
GRI	:	Global Reporting Initiative
IFS	:	Intuitionistic Fuzzy Sets
IIFWA	:	Interval-Valued Intuitionistic Fuzzy Weighted Average
IP	:	Integer Programming
IVIF	:	Interval-Valued Intuitionistic Fuzzy
IVIFs	:	Interval-Valued Intuitionistic Fuzzy Sets

LEWM	**:**	Linguistic Entropy Weight Method
LP	**:**	Linear Programming
MCDM	**:**	Multi-Criteria Decision Making
MILP	**:**	Mixed Integer Linear Programming
MOORA	**:**	Multi-Objective Optimization on the basis of Ratio Analysis
NLP	**:**	Non-Linear Programming
OEM	**:**	Original Equipment Manufacturer
OHS	**:**	Occupational Health and Safety
QFD	**:**	Quality Function Deployment
QMS	**:**	Quality Management System
RI	**:**	Random Index
SEM	**:**	Structural Equation Modelling
SP	**:**	Stochastic Programming
SSOA	**:**	Supplier selection and order allocation
SWOT	**:**	Strengths-Weaknesses-Opportunities-Threats
TOPSIS	**:**	Technique for Order Preference by Similarity to Ideal Solution

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ABSTRACT

Along with the increasing factors influencing global markets, companies become more motivated to seek an optimum strategy for achieving competitive advantage covering the whole supply chain. Also, due to the excessive use of natural resources and increasing consumers' awareness, the regulations have become stricter and the pressure of stakeholders' has increased. This has stimulated companies to incorporate environmental and social aspects into their strategy in addition to economical aspect in order to achieve long-term competitiveness. This study aims to develop an integrated two-phase sustainable supplier selection and order allocation model considering the experiences and observations of decision makers, corrective and preventive action and product development rate. In the first phase, the weight of each alternative supplier is obtained through interval-valued intuitionistic fuzzy analytical hierarchy process method based on the economic, environmental, and social dimensions of sustainability. In the second phase, these weights are incorporated into a multi-product and multi-objective mixed integer linear programming model to obtain optimum number of suppliers and order quantities. Lastly, the model is empirically tested on an original equipment manufacturer parts supplier company in automotive industry. As a result, it was ensured that all factors originating from the supplier and product in the company and the experiences and observations of experts who faced with the problems of the system were included in the decision making process and optimum number of suppliers and ordering quantity is determined for each product types.

ÖZET

Küresel pazarları etkileyen faktörlerin artmasıyla birlikte, şirketler tüm tedarik zincirini kapsayan rekabet avantajı elde etmeyi sağlayan optimum bir strateji aramak için daha fazla motive olmaktadır. Ayrıca, doğal kaynakların aşırı kullanımı ve tüketicilerin bilinçlenmesi nedeniyle, yönetmelikler daha katı hale gelmiş ve paydaşların baskısı artmıştır. Bu, şirketleri uzun vadeli rekabet elde etmek için stratejilerine ekonomik boyutlara ek olarak çevresel ve sosyal boyutları da dahil etmeye teşvik etmiştir. Bu çalışma, karar vericilerin deneyim ve gözlemlerini, düzeltici ve önleyici faaliyet ve ürün geliştirme oranını dikkate alarak entegre iki aşamalı sürdürülebilir bir tedarikçi seçimi ve sipariş tahsis modeli geliştirmeyi amaçlamaktadır. İlk aşamada, sürdürülebilirliğin ekonomik, çevresel ve sosyal boyutlarına dayalı aralık-değerli sezgisel bulanık analitik hiyerarşi prosesi yöntemi ile her bir alternatif tedarikçinin ağırlığı elde edilir. İkinci aşamada, bu ağırlıklar, optimum tedarikçi sayısını ve sipariş miktarlarını elde etmek için çok ürünlü ve çok amaçlı bir karma tamsayılı doğrusal programlama modeline dahil edilir. Son olarak model, otomotiv endüstrisinde faaliyet gösteren bir orijinal ekipman üreticisi parçaları tedarikçisi firma üzerinde ampirik olarak test edilmiştir. Sonuç olarak, firmada tedarikçi ve ürün kaynaklı tüm faktörlerin ve sistemin sorunları ile karşılaşan uzmanların deneyim ve gözlemlerinin karar verme sürecine dahil edilmesi ve her ürün tipi için optimum tedarikçi sayısı ile sipariş miktarının belirlenmesi sağlanmıştır.

1. INTRODUCTION

Managing complexity and uncertainty turns into a more challenging task as the number of factors influencing global markets increases. Thus, companies become more motivated to seek the optimum strategy which creates competitive advantage covering the whole supply chain. Among the various functions of supply chain, purchasing function plays a strategic role as it deploys tremendous amount of financial resources. Considering the major impact of suppliers on the final production cost and product design, a preferred supplier selection provides substantial savings for the companies in terms of cost, quality and service (Govindan and Sivakumar, 2016). Also, in recent years, along with the excessive use of natural resources and increasing consumers' awareness, the regulations have become stricter and the pressure of stakeholders' has increased. This has stimulated companies to incorporate environmental and social aspects into their strategy and supply chains in addition to economical aspect in order to achieve long-term competitiveness (Zimmer et. al., 2016). Thus, there is an increasing requirement of robust decision support models that effectively incorporate diverse supplier selection criteria covering these aspects.

However, diversity of criteria has further complicated the evaluation and decision making process. Extensive decisions making techniques have been proposed in the literature to overcome this problem. There are several review articles that summarize these techniques based on the prioritized aspects and use different methods to categorize them. Govindan et. al. (2015), for example, considered studies which concentrated on environmental aspects of supplier selection. Karsak and Dursun (2016), on the other hand, focused only on non-deterministic analytical methods. Also, Simic et. al. (2017) reviewed articles which examined supplier selection and evaluation based on fuzzy sets theory, fuzzy models and fuzzy hybridization. Considering the method categorization, Ho et. al. (2010) and Zimmer et. al. (2016) classified the modelling approaches as single and combined. Single modelling approaches cover qualitative methods, mathematical programming methods, mathematical analytical methods and artificial intelligent methods. Combined modelling approaches further gather one or more of these methods for solving the problem. Naqvi and Amid (2021) analyzed the existing techniques under deterministic and uncertain optimization models. Additionally, Aouadni (2019) categorized a wide range of related articles based on their methodology such as pre-selection methods, multi-criteria selection methods, order allocation methods and hybrid methods. The common results of these studies show that analytical hierarchy process (AHP) is the most utilized method for the supplier selection problem.

Supplier selection and evaluation problem can be either single or multiple sourcing. While at the single sourcing; the problem is to define only one supplier from alternative suppliers for satisfying all buyer's requirements, at the multiple sourcing; buyer's requirements are split among several suppliers based on pre-determined criteria. Thus, not only the most preferred supplier is identified, but also the product, the quantity and the period can be determined at multiple sourcing models. Because of this property multiple sourcing is defined as supplier selection and order allocation (SSOA) problem. Multiple sourcing allows eliminating the supplier related disruption risk but incurs more cost due to loss of economies of scale and complexity of managing multiple suppliers. For these reasons, the modelling and techniques used in SSOA problems changes according to the number of products, period and objective. Independent from the number of objectives, the optimization methods are mainly used in SSOA problems such as linear programming (LP), non-linear programming (NLP) and their extensions such as integer programming (IP), dynamic programming (DP), goal programming (GP), stochastic programming (SP), fuzzy programming (FP) and data envelopment analysis (DEA). Also, for tackling the problem from several aspects and being able to incorporate qualitative judgements into the model, variety of studies combined multi-criteria selection methods with optimization methods. According to the result of mentioned review studies, the AHP and multi-objective optimization methods has been the most utilized integrated method so far.

Because of the conflicting objectives in selection, the complex and hierarchical structure of the selection criteria and the limitation of each method, integration of AHP and multi-objective optimization methods allows to achieve a healthier solution for SSOA problem. The greatest advantage of the AHP method is that it handles both the qualitative and quantitative factors. It can also be revised according to changing needs over time. Also, consistency verification operation ensures the judgements of decision makers to be consistent. Hence, it is a flexible and consistent solution approach. Nevertheless, AHP provides only the relative importance of weightings of criteria and sub-criteria. In SSOA problem, resource limitations, additionally, need to be considered. Therefore, multi-objective optimization can not only compensate for AHP but also provides the most appropriate solution according to the importance level of conflicting objectives. As a result of these advantages, an integrated AHP and multi-objective optimization method will be used to solve SSOA problem in this study.

Although there are numerous studies about SSOA using integrated AHP and multi-objective optimization, any study which considers the corrective and predictive actions (CAPA) and product development in the modelling of SSOA problem could not be encountered. In this study, the CAPA and product development rates are incorporated into the model in addition to defect and late delivery rate. Moreover, in order to cope with the uncertainty of decision makers' judgements, interval-valued intuitionistic fuzzy sets (IVIFs) are combined with AHP method. At the present time, few if any study about the SSOA using IVIF-AHP have been published. So, the ultimate goal of this study is to provide an optimum SSOA strategy under uncertainty at decision makers' judgements, CAPA and product development rate. The key contributions of this study can be summarized as below:

- The main criteria and sub-criteria influencing the selection of sustainable supplier and the methods used in solving the order allocation problem is determined through a wide literature search.
- A multi-item and single period model is established and intergraded with IVIF-AHP and a multi-objective optimization method is purposed for finding the optimal SSOA strategy.
- The model is applied to an OEM part supplier company in automotive industry and the results are discussed.

The remainder of this study is organized as follows. A detailed literature review about sustainable SSOA is provided in Section 2. The proposed integrated IVIF-AHP and multi-objective optimization method is introduced in Section 3. Section 4 includes the proposed method with the case company and the discussion of results. Finally, the conclusion and suggestions for future studies are presented in Section 5.

2. LITERATURE REVIEW

The increasing pace of competition and constant changes in customer demands require companies to embrace innovation that produces new and improved designs, providing good customer service at highest quality and minimum cost. Since it becomes essential to increase customer satisfaction in the competitive market, companies seek ways to improve their processes and products, meet the environmental regulations while keeping their businesses in a sustainable working environment as well as creating new techniques and design options for surviving in the competitive environment of globalizing world. Hence, a series of recent studies has incorporated, classified and prioritized a wide range of criteria in order to capture the level of operationalization of sustainability. Also, over time, an extensive literature has been developed on tackling different purchasing situations in order to better reflect the real-world problems and requirements peculiar to organizations and industries. Parallel to the complexity of models, several solution approaches have been suggested and verified for achieving an optimum SSOA strategy with the lowest effort and shortest time.

In this section, to determine the best model configuration and most reliable method, a systematic literature review has been caried out on SSOA applications. The systematic literature review is designed according to the guidelines set by Kitchenham (2004). Hence, instead of examining all supplier selection studies, it rigorously reviews studies which combines order allocation with supplier selection. The aim of this section is bringing forward different views, approaches, limitations about SSOA applications and presenting a criteria analysis and content analysis in the existing literature, thus providing a point of view to grasp the trends in decision support modelling in sustainable SSOA.

2.1. Systematic Literature Review on SSOA

In order to reduce the likelihood of bias when analysing the relevant literature, systematic reviews need a clearly established process. Through comprehensive explanation and documentation of the search process, the methodology should be made accessible to the readers. (Kitchenham, 2004). To this end, the research questions being addressed in this section, the search process, the inclusion and exclusion criteria for the studies, and the procedures for data collection and analysis have been explained in the following sections.

This section aims to answer the following research questions:

- What are the key performance criteria that allow to develop a common understanding on capturing the suppliers' level of operationalization of sustainability?
- What are the major modelling and solution approaches for providing an optimum SSOA strategy?
- What are the understudied and unexplored research fields in SSOA?

2.2. Search Process

In the search process, an electronic search utilizing eight major electronic databases, namely, ScienceDirect, SpringerLink, Taylor & Francis, Wiley Online Library, Emerald and IEEE Xplore, was carried out. The studies were extracted with a search on the titles and the abstracts by using keywords, with their suffix variations and spelling variations, "supplier selection and order allocation" for focusing on the research field. The timespan for the literature review was established from January 1st, 2008, to January 1st, 2023, covering a 15 year of literature. A constraint index was established in order to increase the reliability of methodologies of extracted papers. Only papers published on journals indexed in Science Citation Index-Expanded and Social Sciences Citation Index were taken into consideration. The proceeding papers, dissertations and other manuscripts are not included. The initial search with the above mentioned search terms brought 72 results in total. After the removal of duplicates, 64 articles were analysed, in which after removal of 24 unrelated articles, the remaining 44 articles were determined for the systematic analysis.

2.2.1. Inclusion and Exclusion Criteria

The main purpose of this study is to evaluate SSOA application in automotive industry, hence, certain studies are excluded from the initial search results for keeping the focus on the main purpose. The exclusion is conducted according to the following criteria:

- Studies that do not focus on order allocation,
- Studies that focus merely on supplier selection.

Furthermore, certain inclusion criteria have been set:

- Studies that focus on decision support systems, performance measurement sustainable supply chain management,
- Studies that focus on model and method development for sustainable SSOA while providing cases in the automotive industry.

2.2.2. Data collection

From the research, the following data is extracted:

- The sources (full reference),
- Application area of the studies,
- Methodology used in the studies,
- Criteria used in the studies.

Collected data is analyzed and presented in the tabulated form and as graphics in the following sections. The tabulated data scope is as follows referring to the research questions:

- Number of studies published regarding the performance criteria,
- Number of studies published regarding the methodology.
- Number of studies published in different sources
- Number of studies published in different application areas

2.3. Systematic Literature Review Results

2.3.1. Criteria Analysis

An effective supplier selection and evaluation needs to consider several criteria simultaneously. There are numerous studies in literature which concentrates on measuring the suppliers' performance according to the selected criteria. While majority of studies examines the impact of traditional economic criteria such as cost, quality, delivery etc., recent studies incorporate sustainability features into their models. Environmental, social, and economic dimensions are the three pillars of sustainability which are extensively used in performance measurement frameworks. Based on the review study of Kravchenko et. al (2019), most frequently used criteria at global sustainability performance measurement and reporting frameworks such as GRI and EcoVadis are resource consumption, waste and pollution generation, gaseous emissions, land use, material safety, product architecture with respect to environmental dimension; community relationships, employee empowerment, employee health and safety, employee training and education, employment conditions with respect to social dimension; costs, revenues, investments, quality, innovation and technologies, knowledge with respect to economical dimension. Even though there are several studies on the performance measurement frameworks, this section concentrates on criteria used only in SSOA applications. The review is systematized by classifying criteria based on sustainability context. So, the name of the criteria and the frequency of recurrence in literature is determined based on economic, environmental and social aspects of sustainability. Lastly, a discussion is made about the result of the criteria analysis.

Among the 44 articles in which the data is extracted, only 28 articles of SSOA application use criteria in their model to select and evaluate the preferred supplier according to the concentrated dimension(s). Within these articles, 30 criteria related with economical dimension, 24 criteria related with environmental dimension and 14 criteria related with social dimension are identified. When the frequency of usage is taken into consideration, it is observed that cost, quality, delivery, flexibility and technical capability are the most used criteria in economical dimension. Also, resource (energy, water, material) consumption, environmental management system (EMS), waste and pollution management and green resource utilization are the highest number of criteria used in environmental dimension. Occupational health and safety system (OHS), information disclosure, and training and community development are the most employed criteria in social dimension.

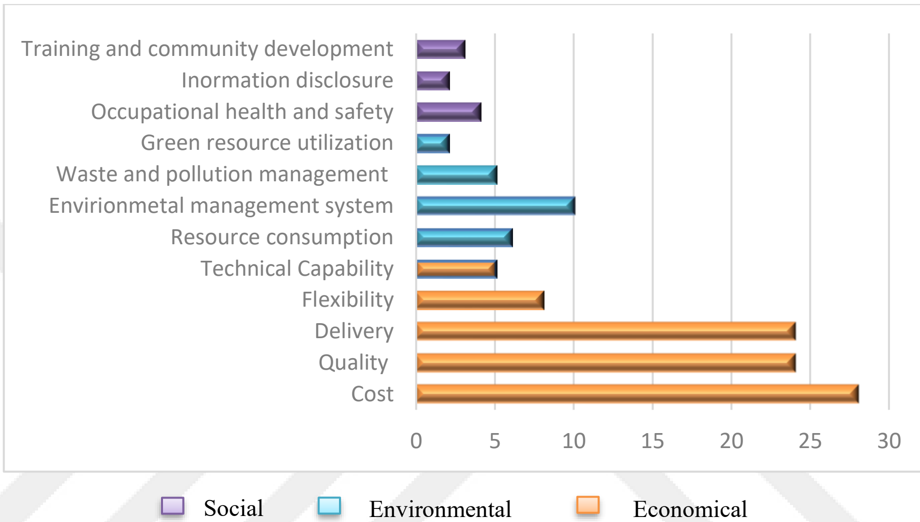

Figure 2.1: Distribution of the most used sustainability criteria in the reviewed studies

Figure 2.1 shows that economical dimension has the highest impact on the selection and evaluation of supplier. The main reason might be the time range of reviewed studies is too wide. Although the latest studies highly use sustainability dimensions, their time range is shorter compared to studies which utilize traditional economic dimension. Also, the figure 2.1 displays that social dimension covers the least number of criteria compared to the economical and environment dimensions. Since most criteria of social dimension are employee-related, measurement and quantification of this dimension with sufficient precision is difficult compared to other sustainability dimensions. Apart from these comparisons, it is, also, important to mention that some criteria are cross-dimensional which means the dimension class of a criteria might change according to its process origin. To avoid this misclassification, some studies use same criteria in different dimensions simultaneously. Thus, although a wide range of criteria identified, there is not a common performance measurement framework in the reviewed literature.

2.3.2. Content Analysis

Methodological approaches to SSOA literature can be classified as single and combined. While single approach utilizes only one method to solve the problem, combined approach incorporates two or more methods. In the combined approach, the output of one method is used as input in other method. The main purpose of the combining methods is to prioritize or reduce the number alternative suppliers. Hence, first multi-criteria decision making (MCDM) methods such as AHP, ANP, BWM, TOPSIS etc. are used in the selection of supplier, then optimization methods such as LP, NLP considering resource constraints are used for determining the order quantity. Moreover, the model specifications of optimization methods change based on the number of objectives, products and periods. Lastly, the uncertainty has been tackled either by employing fuzzy logic or stochastic.

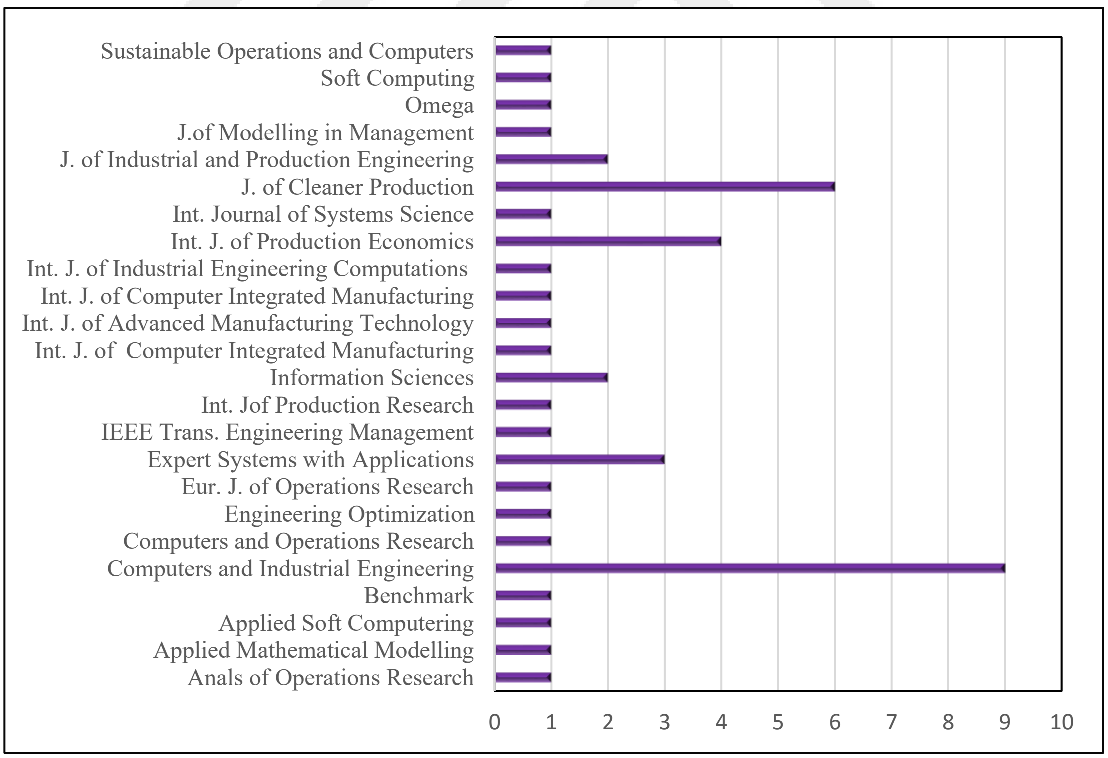

Figure 2.2: The distribution of the reviewed studies sources

Table 2.1: Methodology approaches to SSOA in the literature

Method	Technique	Model			References
		Multi-Objective	Multi-Product	Multi-Period	
Single	MILP	-	*	-	Bohner and Minner (2017)
	LP	*	*	-	Bai, et. al.(2022)
	MILP	-	*	*	Sona and Hopa (2021)
	MILP	-	*	*	Cui, et. al.(2015)
	Stochastic-MINLP	-	-	-	Guo and Li (2015)
	F-GP	*	-	-	Hashmi, et. al.(2021)
	F-GP	*	*	*	Mirzaee, et. al.(2018)
	Weighted GP	*	-	-	Jadidi, et. al.(2014)
	MILP	*	*	*	Hosseini, et. al.(2022)
	Stochastic DP	-	-	*	Zhou, et. al.(2011)
Combined	F-AHP, LP	*	*	*	Azadnia, et. al.(2015)
	F-AHP, LP	-	-	-	Laosirihongthong, et. al.(2019)
	F-TOPSIS, F-LP	*	*	-	Govindan and Sivakumar (2016)
	F-AHP, F-TOPSIS, F-LP	*	-	*	Kannan, et. al.(2013)
	F-AHP, TOPSIS, MILP	-	*	*	Kaur and Singh (2021)
	IF-AHP, F-LP	*	*	-	Kaviani, et. al.(2020)
	ANP, MILP	*	-	-	Demirtas and Ustün (2008)
	AHP, F-MOLP	*	*	-	Ozgen, et. al.(2008)
	F-ANP, F-DEMANTEL, F-TOPSIS, MILP	*	*	*	Tirkolaee, et. al.(2020)
	AHP, MINLP	*	*	*	Almasi, et. al.(2021)
	BWM, MILP	*	*	*	Li, et. al.(2021)
	AHP, F-MILP	*	*	-	Gupta, et. al.(2016)
	MILP, DEA	*	*	*	Alizadeh and Handfield (2019)
	F-TOPSIS, AHP, MILP	*	-	*	Hamdan and Cheaitou (2016)
	F-AHP, F-TOPSIS, MILP	*	-	*	Hamdan and Cheaitou (2017)
	TYPE 2 IF-EDAS, LP	*	-	-	Keshavar, et. al.(2017)
	F-AHP, MILP	-	*	*	Khoshfetrat, et. al.(2020)
	IF-TOPSIS, GP	*	*	*	Kilic and Yalcin (2020)
	F-AHP, FLP	*	-	-	Kumar, et. al.(2017)
	TOPSIS, LP	*	*	-	Jia, et. al.(2020)
	F-BWM, MILP	*	*	*	Tavana, et. al.(2020)
	AHP, MINLP	*	*	*	Almasi, et. al.(2021)
	F-AHP, QFD, MINLP	*	-	*	Azadnia, et. al.(2018)
	QFD, MILP	*	*	*	Babbar and Amin (2018)
	LEWM, MILP	*	*	*	Beiki, et. al.(2021)
	Type-2 F-AHP, LP	*	*	-	Alegoz and Yapicioglu (2019)
	F-AHP, F-DEMANTEL, MILP	*	*	-	Govindan, et. al.(2020)
	SWOT-QFD, MILP	*	*	-	Vahidi, et. al.(2018)
	AHP, DP	-	-	*	Mafakheri , et. al.(2011)
	FIS, LP	*	*	*	Ghadimi, et. al.(2018)
	F-DEMANTEL, TLF, LP	*	*	*	Goren (2018)
	BWM, MILP	*	*	*	Cheraghalipour and Farsad (2018)
	F-Multi MOORA, F-GP	*	*	-	Çebi and Otay (2016)
	F-Cmean, Stochastic LP	*	-	*	Hosseini, et. al.(2019)
	Monte carlo simulation F-GP	*	*	-	Moghaddam (2015)

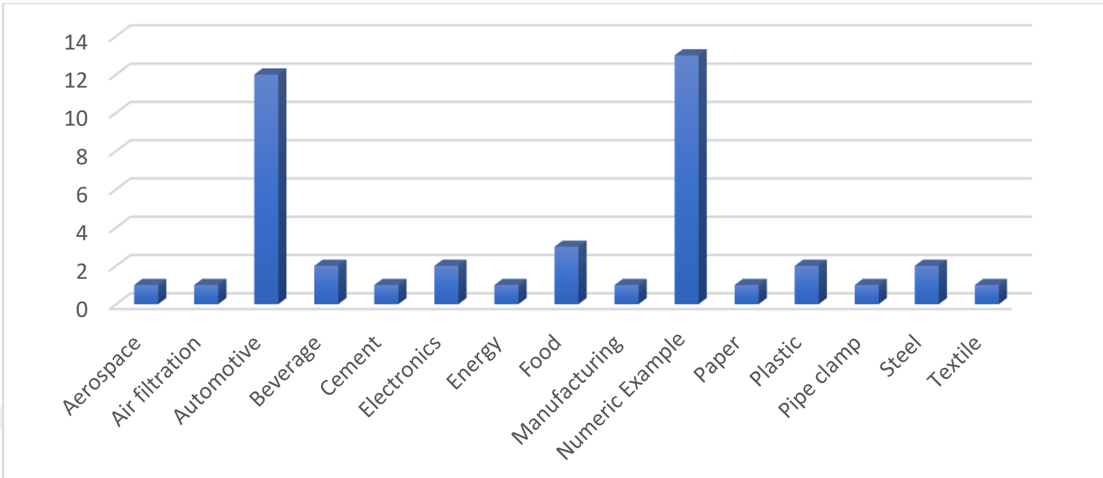

Figure 2.3: The distribution of the reviewed studies application fields

Table 2.1 summarizes the methodological approaches and the model specifications of the reviewed studies. The analysis of the reviewed studies showed that the number of studies utilizing from combined methodological approach is greater than single approach. It is observed that the most preferred combined methods are AHP and multi-objective LP. Also, the uncertainty mostly tackled by incorporating fuzzy logic on MCDM methods. Apart from the methodological approach, it is noticed that model formulations are concentrated mainly on factors that impact the cost, quality and undesired environmental effects such as quantity discounts, disruption risks, inflation rate, defect rate, carbon emission rate and sustainability score. Also, the main resource constraint of the reviewed studies are demand and capacity. On the other hand, the application fields of the review studies are mostly automotive industry and numeric examples. Figure 2.2 and Figure 2.3 depict the distribution of application fields and the source of the reviewed studies. Computers and Industrial Engineering journal covers the highest number of studies related with SSOA. Lastly, the analysis showed that the frequency of studies related with sustainability is increased but the number of these studies is lower compared to studies concentrate solely on economical dimension. Thus, there is a need for studies that further explore optimum sustainable SSOA strategy with different model configurations and methods.

3. RESEARCH METHODOLOGY

A two-phase research methodology is purposed to solve the sustainable SSOA problem. Figure 3.1 exhibits the steps in each of these two phases explicitly. In the first phase, the weight of each alternative supplier is obtained through IVIF-AHP method considering the pre-determined main and sub-criteria. In the second phase, these weights are incorporated into a multi-product and multi-objective mixed integer linear programming (MO-MILP) model to obtain optimum number of suppliers and order quantities. The rest of this section elaborates steps of these two phases by providing necessary information about IVIFS, computational steps of IVIF-AHP and MILP model, respectively.

3.1. Preliminaries

Zadeh (Zadeh, 1965) developed fuzzy set theory to describe circumstances when the data are ambiguous or imprecise. Fuzzy sets assign a membership degree to each object that belongs to a set in order to handle the uncertainty. Atanassov (1986) improved the theory by adding a non-membership function to the conventional fuzzy set which does not take hesitation in membership degrees into account and proposing the intuitionistic fuzzy set (IFS). Furthermore, by introducing an interval for both membership and non-membership functions, Atanassov and Gargov (1989) extended the IFS to Interval-Valued Intuitionistic Fuzzy Set (IVIFS) in order to more accurately capture the uncertainty. (Verma and Chandra, 2021). This benefit leads to the combination of IVIFS with AHP, a structured decision-making method for determining relative weights for criteria and sub-criteria. This section explains the prelaminar information needed to convert linguistic terms into IVIFS.

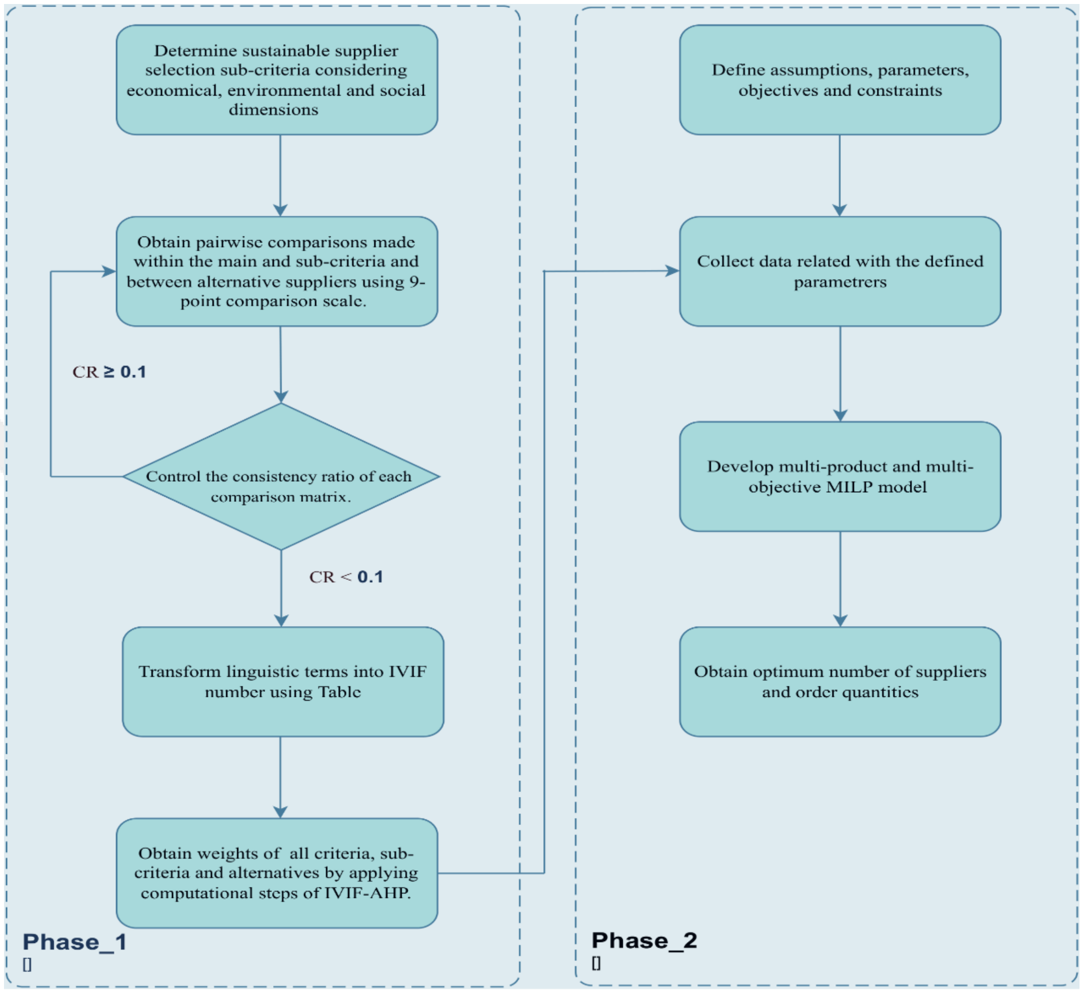

Figure 3.1: Two-phase approach for the sustainable SSOA

Definition 1: Considering that X is a non-empty set and $\tilde{A}$ over X is an intuitionistic fuzzy set (IFS) which is an object with the form:

$$\tilde{A} = \{x, \mu_{\tilde{A}}(x), v_{\tilde{A}}(x);\ x \in X\}, \tag{1}$$

where $\mu_{\tilde{A}}(x): X \to [0,1]$ is the function of membership degree and $v_{\tilde{A}}(x): X \to [0,1]$ is the function of non-membership degree of element to the set $\tilde{A}$ representing intervals which satisfy the condition of $0 \leq \mu_{\tilde{A}}(x) + v_{\tilde{A}}(x) \leq 1$ for $\forall x \in X$.

Let X be the universe of discourse and $D \subseteq [0,1]$ be the set of all closed sub-intervals of the interval. An object with the following form is known as an interval-valued intuitionistic fuzzy set (IVIFS) in $\tilde{A}$ over X (Wu, 2013):

$$\tilde{A} = \{< x, \tilde{\mu}_{\tilde{A}}(x), \tilde{v}_{\tilde{A}}(x) > \mid x \in X\}, \tag{2}$$

where $\tilde{\mu}_{\tilde{A}}(x): D \to [0,1]$ and $\tilde{v}_{\tilde{A}}(x): D \to [0,1]$ where they represent function of membership and non-membership degree of element to the set $\tilde{A}$ with the condition of $0 \leq sup\, \tilde{\mu}_{\tilde{A}}(x) + sup\, \tilde{v}_{\tilde{A}}(x) \leq 1$ for $\forall x \in X$. Thus, for each $x \in X$, $\tilde{\mu}_{\tilde{A}}(x)$ and $\tilde{v}_{\tilde{A}}(x)$ are close intervals and their lower and upper ending points are denoted by $\tilde{\mu}_{\tilde{A}}{}^{L}(x)$, $\tilde{\mu}_{\tilde{A}}{}^{U}(x)$, $\tilde{v}_{\tilde{A}}{}^{L}(x)$ and $\tilde{v}_{\tilde{A}}{}^{U}(x)$, respectively. This means that IVIFS in $\tilde{A}$ can be formed as follows:

$$\tilde{A} = \left\{< x, \left[\tilde{\mu}_{\tilde{A}}{}^{L}(x), \tilde{\mu}_{\tilde{A}}{}^{U}(x)\right], \left[\tilde{v}_{\tilde{A}}{}^{L}(x), \tilde{v}_{\tilde{A}}{}^{U}(x)\right] > \mid x \in X\right\}, \tag{3}$$

where $0 \leq \tilde{\mu}_{\tilde{A}}{}^{L}(x) + \tilde{v}_{\tilde{A}}{}^{U}(x) \leq 1$, $\tilde{\mu}_{\tilde{A}}{}^{L}(x) \geq 0$ and $\tilde{v}_{\tilde{A}}{}^{L}(x) \geq 0$. The following equation can be used to express the unknown degree (hesitancy degree) of an IVIFS for each element x:

$$\pi_{\tilde{A}}(x) = \left[1 - \tilde{\mu}_{\tilde{A}}{}^{L}(x) - \tilde{\mu}_{\tilde{A}}{}^{L}(x)\right], \left[1 - \tilde{v}_{\tilde{A}}{}^{U}(x) - \tilde{v}_{\tilde{A}}{}^{U}(x)\right], \tag{4}$$

Definition 2: Let $\tilde{\alpha} = \left[\tilde{\mu}_{\tilde{\alpha}}{}^{L}(x), \tilde{\mu}_{\tilde{\alpha}}{}^{U}(x)\right], \left[\tilde{v}_{\tilde{\alpha}}{}^{L}(x), \tilde{v}_{\tilde{\alpha}}{}^{U}(x)\right]$ be a IVIF number. The following represents the of the score function of $\tilde{\alpha}$.

$$s(\tilde{\alpha}) = \tilde{\mu}_{\tilde{\alpha}}(x) - \tilde{v}_{\tilde{\alpha}}(x) = \left[\tilde{\mu}_{\tilde{\alpha}}{}^{L}(x) - \tilde{v}_{\tilde{\alpha}}{}^{U}(x), \tilde{\mu}_{\tilde{\alpha}}{}^{U}(x) - \tilde{v}_{\tilde{\alpha}}{}^{L}(x)\right], \tag{5}$$

Definition 3: Let $\tilde{\alpha} = \left[\tilde{\mu}_{\tilde{\alpha}}{}^{L}(x), \tilde{\mu}_{\tilde{\alpha}}{}^{U}(x)\right], \left[\tilde{v}_{\tilde{\alpha}}{}^{L}(x), \tilde{v}_{\tilde{\alpha}}{}^{U}(x)\right]$ be a IVIF number. The following definition applies to the accuracy function of $\tilde{\alpha}$:

$$s(\tilde{\alpha}) = \tilde{\mu}_{\tilde{\alpha}}(x) + \tilde{v}_{\tilde{\alpha}}(x) = \left[\tilde{\mu}_{\tilde{\alpha}}{}^{L}(x) + \tilde{v}_{\tilde{\alpha}}{}^{L}(x), \tilde{\mu}_{\tilde{\alpha}}{}^{U}(x) + \tilde{v}_{\tilde{\alpha}}{}^{U}(x)\right], \tag{6}$$

Definition 4: Let $\tilde{\alpha}_J = \left[\tilde{\mu}_{\tilde{\alpha}_J}{}^{L}(x), \tilde{\mu}_{\tilde{\alpha}_J}{}^{U}(x)\right], \left[\tilde{v}_{\tilde{\alpha}_J}{}^{L}(x), \tilde{v}_{\tilde{\alpha}_J}{}^{U}(x)\right]$ be a group of IVIFNs. The interval-valued intuitionistic fuzzy weighted averaging ($IIFWA$) operator is represented as

$$IIFWA_w\,(\tilde{\alpha}_1, \tilde{\alpha}_2, .., \tilde{\alpha}_n) = w_1\,\tilde{\alpha}_1 \oplus w_2\,\tilde{\alpha}_2 \dots \oplus w_n\,\tilde{\alpha}_n, \tag{7}$$

where $w = (w_1, w_2, \dots, w_n)$ is the weight vector of the $IVIFNs$ $\tilde{\alpha}_J$ $(j = 1, 2, \dots, n)$, and $w_j > 0$, $\sum_{j=1}^{n} w_j = 1$. The $IIFWA$ operator can be further transformed into the following form:

$$IIFWA_w\,(\tilde{\alpha}_1, \tilde{\alpha}_2, .., \tilde{\alpha}_n) = \left(\begin{bmatrix} 1 - \left(\prod_{i=1}^{n}(1 - \tilde{\mu}_{\tilde{\alpha}_i}{}^{L}(x)\right)^{w_i}, \\ 1 - \left(\prod_{i=1}^{n}(1 - \tilde{\mu}_{\tilde{\alpha}_i}{}^{U}(x)\right)^{w_i} \end{bmatrix}, \begin{bmatrix} 1 - \left(\prod_{i=1}^{n}(1 - \tilde{v}_{\tilde{\alpha}_i}{}^{L}(x)\right)^{w_i}, \\ 1 - \left(\prod_{i=1}^{n}(1 - \tilde{v}_{\tilde{\alpha}_i}{}^{U}(x)\right)^{w_i} \end{bmatrix}\right), \tag{8}$$

Also, if $w = ({}^{1}/_{n}, {}^{1}/_{n}, \dots, {}^{1}/_{n})$, then the $IIFWA$ operator reduces to an interval-valued intuitionistic fuzzy averaging operator, where

$$IIFA_w\,(\tilde{\alpha}_1, \tilde{\alpha}_2, .., \tilde{\alpha}_n) = \frac{1}{n}(\tilde{\alpha}_1 \oplus \tilde{\alpha}_2 \oplus \dots \oplus \tilde{\alpha}_n)$$
$$= \left(\begin{bmatrix} 1 - \left(\prod_{i=1}^{n}(1 - \tilde{\mu}_{\tilde{\alpha}_i}{}^{L}(x)\right)^{1/n}, \\ 1 - \left(\prod_{i=1}^{n}(1 - \tilde{\mu}_{\tilde{\alpha}_i}{}^{U}(x)\right)^{1/n} \end{bmatrix}, \begin{bmatrix} 1 - \left(\prod_{i=1}^{n}(1 - \tilde{v}_{\tilde{\alpha}_i}{}^{L}(x)\right)^{1/n}, \\ 1 - \left(\prod_{i=1}^{n}(1 - \tilde{v}_{\tilde{\alpha}_i}{}^{U}(x)\right)^{1/n} \end{bmatrix}\right), \tag{9}$$

At the rest of this section, $\tilde{A}$ will be denoted $\tilde{A} = ([\mu^-, \mu^+], [v^-, v^+])$ as where $\tilde{\mu}_{\tilde{A}}(x) = [\mu^-, \mu^+]$ *and* $\tilde{v}_{\tilde{A}}(x) = [v^-, v^+]$, for convenience.

3.2. Computational Steps of IVIF-AHP

The computational steps of the interval-valued intuitionistic fuzzy AHP (IVIF-AHP), proposed by Kahraman et. al. (2020), are as follows:

Step 1: Linguistic pairwise comparison matrices are formed with respect to goal, criteria and sub-criteria based on the modeled hierarchical structure. The evaluation process is conducted by the decision makers using the linguistic scale given in Table 3.1.

Table 3.1: Linguistic scale and its corresponding IVIFS.

Linguistic terms	Membership and non-membership values
Absolutely low (AL)	([0,10], [0,25]), ([0,65], [0,75])
Very low (VL)	([0,15], [0,30]), ([0,60], [0,70])
Low (L)	([0,20], [0,35]), ([0,55], [0,65])
Medium low (ML)	([0,25], [0,04]), ([0,50], [0,60])
Exactly Equal (EE)	([0,50], [0,50]), ([0,50], [0,50])
Medium high (MH)	([0,50], [0,60]), ([0,25], [0,40])
High (H)	([0,55], [0,65]), ([0,20], [0,35])
Very high (VH)	([0,60], [0,70]), ([0,15], [0,30])
Absolutely high (AH)	([0,65], [0,75]), ([0,10], [0,25])

Step 2: Consistency of comparison matrix is controlled by using crisp values and method purposed by Saaty (1977). In the method, first, deviation of consistency, which is also named as Consistency Index (CI), is measured using the Eq. (10). Here, n is the size of the matrix of reciprocal comparison, and λ_{max} is the largest eigenvalue. The Consistency Ratio (CR) is then determined by subtracting the value of the Comparison Index (CI) from the value of the Random Index (RI) in the comparison matrix size Eq. (11).

Table 3.2: Random consistency index

n	1	2	3	4	5	6	7	8	9	10
RI	0,00	0,00	0,58	0,90	1,12	1,24	1,32	1,41	1,45	1,49

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{10}$$

$$CR = \frac{CI}{RI} \tag{11}$$

Step 3: Utilizing the scale shown in Table 3.1, filled matrices are transformed from IVIF to their corresponding IVIFSs to obtain an intuitionistic pairwise comparison matrix. Using the Eq. (9), it is converted into an aggregated pairwise comparison matrix ($\tilde{R}_g$).

$$\tilde{R}_g = \begin{bmatrix} ([\mu_{g_{11}}{}^{-}, \mu_{g_{11}}{}^{+}], [\nu_{g_{11}}{}^{-}, \nu_{g_{11}}{}^{+}]) & \cdots & ([\mu_{g_{1n}}{}^{-}, \mu_{g_{1n}}{}^{+}], [\nu_{g_{1n}}{}^{-}, \nu_{g_{1n}}{}^{+}]) \\ \vdots & \ddots & \vdots \\ ([\mu_{g_{n1}}{}^{-}, \mu_{g_{n1}}{}^{+}], [\nu_{g_{n1}}{}^{-}, \nu_{g_{n1}}{}^{+}]) & \cdots & ([\mu_{g_{nn}}{}^{-}, \mu_{g_{nn}}{}^{+}], [\nu_{g_{nn}}{}^{-}, \nu_{g_{nn}}{}^{+}]) \end{bmatrix}, \tag{12}$$

Step 4: Score judgement matrix $\tilde{S} = (\tilde{S}_{ij})_{nxn}$ are calculated using the scoring function given in Eq. (5):

$$\tilde{S} = \begin{bmatrix} ([\mu_{g_{11}}{}^{-} - \nu_{g_{11}}{}^{+}], [\mu_{g_{11}}{}^{+} - \nu_{g_{11}}{}^{-}]) & \cdots & ([\mu_{g_{1n}}{}^{-} - \nu_{g_{1n}}{}^{+}], [\mu_{g_{1n}}{}^{+} - \nu_{g_{1n}}{}^{-}]) \\ \vdots & \ddots & \vdots \\ ([\mu_{g_{n1}}{}^{-} - \nu_{g_{n1}}{}^{+}], [\mu_{g_{n1}}{}^{+} - \nu_{g_{n1}}{}^{-}]) & \cdots & ([\mu_{g_{nn}}{}^{-} - \nu_{g_{nn}}{}^{+}], [\mu_{g_{nn}}{}^{+} - \nu_{g_{nn}}{}^{-}]) \end{bmatrix}, \tag{13}$$

Step 5: Interval exponential matrices $\tilde{A} = (\tilde{a}_{ij})_{nxn}$ are formed where $a_{ij} = e^{\tilde{S}_{ij}}$.

$$\tilde{A} = \begin{bmatrix} e^{(\mu_{g_{11}}{}^{-} - \nu_{g_{11}}{}^{+})}, e^{(\mu_{g_{11}}{}^{+} - \nu_{g_{11}}{}^{-})} & \dots & e^{(\mu_{g_{1n}}{}^{-} - \nu_{g_{1n}}{}^{+})}, e^{(\mu_{g_{1n}}{}^{+} - \nu_{g_{1n}}{}^{-})} \\ \vdots & \ddots & \vdots \\ e^{(\mu_{g_{n1}}{}^{-} - \nu_{g_{n1}}{}^{+})}, e^{(\mu_{g_{n1}}{}^{+} - \nu_{g_{n1}}{}^{-})} & \dots & e^{(\mu_{g_{nn}}{}^{-} - \nu_{g_{nn}}{}^{+})}, e^{(\mu_{g_{nn}}{}^{+} - \nu_{g_{nn}}{}^{-})} \end{bmatrix}, \tag{14}$$

Step 6: Interval exponential matrices $\tilde{A} = (\tilde{a}_{ij})_{nxn}$ has a priority vector and are determined using Eq. (14).

$$\widetilde{w}_i = \left[\frac{\sum_{j=1}^{n} \tilde{a}_{ij}^{-}}{\sum_{i=1}^{n}\sum_{j=1}^{n} \tilde{a}_{ij}^{+}}, \frac{\sum_{j=1}^{n} \tilde{a}_{ij}^{+}}{\sum_{i=1}^{n}\sum_{j=1}^{n} \tilde{a}_{ij}^{-}}\right] = \left[\widetilde{w}_i^{-}, \widetilde{w}_i^{+}\right],\ i \in N \tag{15}$$

Step 7: Possibility degree matrices $P = (p_{ij})_{nxn}$, where $p_{ij} \geq 0,\ p_{ij} + p_{ji=}$ 1 and $p_{ij} = \frac{1}{2}$ $i, j \in N,$ are constructed by comparing each $\widetilde{w}_i$ with all the $\widetilde{w}_i$ which and by using Eq. (16) and Eq. (17).

$$P(\widetilde{w}_i > \widetilde{w}_j\ ) = p_{ij} = \frac{max(0, w_i^{+} - w_j^{-}\ ) - max(0, w_i^{-} - w_j^{+}\ )}{(\ w_i^{+} - w_i^{-}\ ) + (\ w_j^{+} - w_j^{-}\ )} \tag{16}$$

$$P(\widetilde{w}_j > \widetilde{w}_i\ ) = p_{ji} = \frac{max(0, w_j^{+} - w_i^{-}\ ) - max(0, w_j^{-} - w_i^{+}\ )}{(\ w_i^{+} - w_i^{-}\ ) + (\ w_j^{+} - w_j^{-}\ )} \tag{17}$$

Step 8: Possibility degree matrices $P = (p_{ij})_{nxn}$ are prioritized and the obtained values are normalized to rank them by using Eq. (18) and Eq. (19), respectively.

$$w_i = \frac{\sum_{j=1}^{n} p_{ij} - 1}{n} + 0.5 \tag{18}$$

$$w_i^{T} = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{19}$$

3.3. Multi-objective MILP model

The objective of MO-MILP, which includes various items and suppliers, is to evaluate suppliers and distribute order quantities in accordance with suppliers' sustainability performance as determined by IVIF-AHP. The model was built on a number of assumptions. Firstly, demand is constant and known with certainty. Secondly, no shortage of material is allowed for any supplier. Lastly, $O_{ij_{min}}, O_{ij_{max}}, U_{ij}, P_{ij}, B_{ij}, R_{ij}$ parameters are considered equal for each product type as the data related with suppliers' products are not collected. Companies generally identify their suppliers as a collection of all their products.

Index

i Index for products; $i = 1,2,\ldots,n$

j Index for suppliers; $j = 1,2,\ldots,m$

Decision variables

X_{ij} Order quantity of product i from supplier j

Y_{ij} 1 if product i is ordered from supplier j, otherwise 0

Parameters

n_i Minimum number of suppliers selected for product i

k_i Maximum number of suppliers selected for product i

$O_{ij_{min}}$ Minimum number of product i ordered from supplier j

$O_{ij_{max}}$ Maximum number of product i ordered from supplier j

D_i Demand of product i

U_{ij} Sustainability score of supplier j for product i

F_{ij} Price of the product i purchased from supplier j

T_{ij} Late delivery rate of product i from supplier j

Q_{ij} Partial delivery rate of product i from supplier j

G_{ij} Defect rate at incoming quality control of product i from supplier j

I_{ij} Defect rate at in-process quality control of product i from supplier j

M_{ij} Defect rate at customer quality control of product i from supplier j

P_{ij} Quality audit score of supplier j

H_{ij} 1 if supplier j has CAPA for product i which is not closed on-time, otherwise 0

B_{ij} New product development project rate of supplier j which is not completed on-time

R_{ij} Customer revision rate of product i for supplier j which is not completed on-time

Objective functions

$$Min(Defect\ rate_{incoming})\ Z_1 = \sum_{i=1}^{5}\sum_{j=1}^{4} G_{ij}\, X_{ij} \tag{20}$$

$$Min(Defect\ rate_{in-prosess})\ Z_2 = \sum_{i=1}^{5}\sum_{j=1}^{4} I_{ij}\, X_{ij} \tag{21}$$

$$Min(Defect\ rate_{Customer})\ Z_3 = \sum_{i=1}^{5}\sum_{j=1}^{4} M_{ij}\, X_{ij} \tag{22}$$

$$Max(Audit\ score\ )\ Z_4 = \sum_{i=1}^{5}\sum_{j=1}^{4} P_{ij}\, X_{ij} \tag{23}$$

$$Min(Late\ delivery)\ Z_5 = \sum_{i=1}^{5}\sum_{j=1}^{4} T_{ij}\, X_{ij} \tag{24}$$

$$Min(Partial\ delivery)\ Z_6 = \sum_{i=1}^{5}\sum_{j=1}^{4} Q_{ij}\, X_{ij} \tag{25}$$

$$Min(Price)\ Z_7 = \sum_{i=1}^{5}\sum_{j=1}^{4} F_{ij}\, X_{ij} \tag{26}$$

$$Min(Late\ product\ development\ project)\ Z_8 = \sum_{i=1}^{5}\sum_{j=1}^{4} B_{ij}\, X_{ij} \tag{27}$$

$$Min(Late\ customer\ revision)\ Z_9 = \sum_{i=1}^{5}\sum_{j=1}^{4} R_{ij}\, X_{ij} \tag{28}$$

$$Max(Sustainability\ score)\ Z_{10} = \sum_{i=1}^{5}\sum_{j=1}^{4} U_{ij}\, X_{ij} \tag{29}$$

Subject to

$$X_{ij} \leq O_{ij_{max}}(1 - H_{ij}) \tag{30}$$

$$\sum_{i=1}^{5} X_{ij} = D_i \tag{31}$$

$$O_{ij_{min}} Y_{ij} \leq X_{ij} \tag{32}$$

$$O_{ij_{max}} Y_{ij} \geq X_{ij} \tag{33}$$

$$\sum_{1}^{4} Y_{ij} \geq n_i \tag{34}$$

$$\sum_{1}^{4} Y_{ij} \leq k_i \tag{35}$$

$$X_{ij} \geq 0,\ X_{ij} \in Z^{+},\ Y_{ij} \in \{0, 1\} \qquad \forall\, i, j \tag{36}$$

The purposed MILP model consists of ten conflicting objective functions which are represented with Eq. (20) to (29). The first four objective functions focus on the quality performance. Supplier-related quality problems can be detected at the incoming and in-process controls and by the customer returns. Hence, Eq. (20) to Eq. (22) ensure the order allocation is made to the supplier with the lowest defect rate. Eq. (23) aims to maximize the audit score of suppliers. So, the order can be allocated to the supplier which has the highest audit score. Eq. (24) and Eq. (25) minimize the late delivery rate and partial delivery rate. Eq. (26) aims to minimize the price of the product to be ordered. So, the supplier with lowest price can be selected. Eq.(27) and Eq. (28) ensure the order allocated supplier which has the lowest late product development and late customer revision rates. Lastly, Eq. (29) ensures that the sustainability score which is obtained from the IVIF-AHP is maximized.

The constraints of the model are formulated by Eq. (30) to Eq. (36). Eq. (30) ensures that the order is not allocated to a supplier which has an open CAPA. Eq. (31) implies that the sum of the quantity purchased from each supplier must be equal the demand. Eq. (32) requires that the order quantity from each supplier should not be higher than its minimum ordering quantity. Likewise, Eq. (33) indicates that the order quantity from each supplier should not be lower than its maximum ordering quantity. Eq. (34) and Eq. (35) satisfy the number of order allocated supplier which is not lower and higher than the predetermined min. and max number of suppliers. Finally, Eq. (36) indicates that X_{ij} is a non-negative and integer number and Y_{ij} is a binary variable, respectively.

4. EMPRICAL STUDY

In this study, considering the literature research, the structure of the automotive industry and the discussions with the experts of the case company, three main criteria and twelve sub-criteria are determined to select the most preferred sustainable supplier company. These are cost, quality, delivery, technical capability and flexibility under economical dimension; environmental management system, resource consumption, waste and pollution management and green resource utilization under environmental dimension; and occupational health and safety, wages and working hours, training and community development under social dimension, respectively. Based on the determined criteria and sub-criteria, an AHP model is formed. For the measurement of these criteria, three experts in Input Quality Control, Purchasing and Manufacturing departments were asked to make pairwise comparisons by indicating their preference levels. The pairwise comparisons using 9-point comparison scale, which assigns a numerical value between 1 and 9 to the different preference levels, are made both within the main and sub-criteria and between the four alternative suppliers for each criterion. The linguistic terms are converted into the IVIF numbers as given in Table 3.1 for constructing pairwise matrices. The weights of each sustainability criteria and the total weight of each alternative supplier is obtained by applying the computational steps of IVIF-AHP method. Then, the weight of each supplier is incorporated into proposed multi-product, multi-source and MO-MILP model, which satisfies CAPA and demand constraints, in order to determine the optimum number of suppliers and the order quantity.

4.1. Application of IVIF-AHP

Since the scope of main criteria is wide, sub-criteria of each criterion that are important for the company have been determined in terms of ease of measurement. The definitions of criteria and the hierarchical structure of AHP model is depicted as follows:

Table 4.1: Definitions of the selected sustainability criteria

Criterion			Definition
(C11)	Cost	:	Level of cost incurred due to product price.
(C12)	Quality	:	Level of compliance to quality requirements, standards and defect rate.
(C13)	Delivery	:	Ability to deliver orders on-time and complete.
(C14)	Technical capability	:	Ability of responding requirements about product development and customer revisions on-time.
(C15)	Flexibility	:	Ability of responding changes at production, delivery and market requirements.
(C21)	Environmental Management System	:	Level of implementing continuous improvement framework for the compliance with environmental policies.
(C22)	Resource consumption	:	Level of material, water and energy consumption during the production process.
(C23)	Environmental pollution	:	Level of air pollutants, harmful materials, solid/water waste released at all supply chain processes.
(C24)	Green resource utilization	:	Level of green material usage throughout all supply chain processes.
(C31)	Occupational Health and Safety System	:	Level of implementing continuous improvement framework for the maintenance of worker's health and working capacity.
(C32)	Wages and working hours	:	Level of arrangements to promote a living wage to the workers and reduce working hours.
(C33)	Training and community development	:	Training hour per employee to develop their skills in improving standard of living in their community.

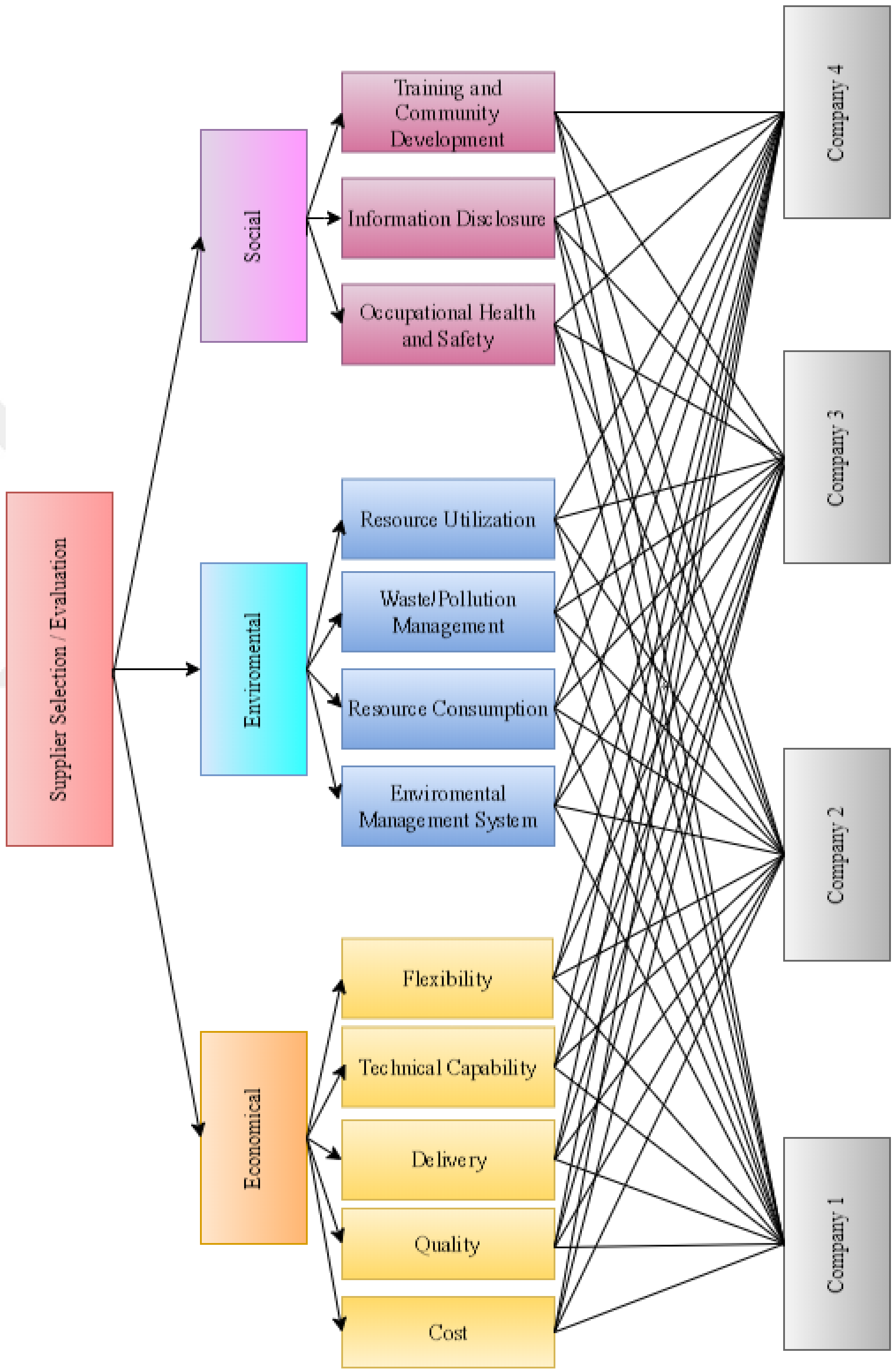

Figure 4.1: AHP model for the sustainable supplier selection and evaluation

Table 4.2: Linguistic pairwise comparisons with respect to goal

	Expert 1			Expert 2			Expert 3		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
C1	EE	MH	VH	EE	MH	H	EE	ML	MH
C2		EE	H		EE	MH		EE	H
C3			EE			EE			EE

Table 4.3: Consistency of linguistic pairwise comparisons with respect to goal

EXPERT 1					EXPERT 2				EXPERT 3			
	C1	C2	C3	Priority vector	C1	C2	C3	Priority vector	C1	C2	C3	Priority vector
C1	1.00	3.00	7.00	0.65	1.00	3.00	5.00	0.64	1.00	0.33	3.00	0.26
C2	0.33	1.00	5.00	0.28	0.33	1.00	3.00	0.26	3.00	1,00	5.00	0.64
C3	0.14	0.20	1.00	0.07	0.20	0.33	1.00	0.10	0.33	0.20	1.00	0.10
				1.00				1.00				1.00
λmax = 3.06, CI = 0.03, CR = 0.06					λmax = 3.04, CI = 0.02, CR = 0.03				λmax = 3.04, CI = 0.02, CR = 0.03			

Table 4.4: Pairwise comparisons using IVFN with respect to goal

Expert 1			
	C1	C2	C3
C1	[0.50, 0.50] [0.50, 0.50]	[0.50, 0.60] [0.25, 0.40]	[0.60, 0.70] [0.15, 0.30]
C2	[0.25, 0.40] [0.50, 0.60]	[0.50, 0.50] [0.50, 0.50]	[0.55, 0.65] [0.20, 0.35]
C3	[0.15, 0.30] [0.60, 0.70]	[0.20, 0.35] [0.55, 0.65]	[0.50, 0.50] [0.50, 0.50]

Expert 2			
	C1	C2	C3
C1	[0.50, 0.50] [0.50, 0.50]	[0.50, 0.60] [0.25, 0.40]	[0.55, 0.65] [0.20, 0.35]
C2	[0.25, 0.40] [0.50, 0.60]	[0.50, 0.50] [0.50, 0.50]	[0.50, 0.60] [0.25, 0.40]
C3	[0.20, 0.35] [0.55, 0.65]	[0.25, 0.40] [0.50, 0.60]	[0.50, 0.50] [0.50, 0.50]

Expert 3			
	C1	C2	C3
C1	[0.50, 0.50] [0.50, 0.50]	[0.25 0.40] [0.5 0.60]	[0.50, 0.60] [0.25, 0.40]
C2	[0.5 0.60] [0.25 0.40]	[0.50, 0.50] [0.50, 0.50]	[0.55, 0.65] [0.20, 0.35]
C3	[0.25, 0.40] [0.50, 0.60]	[0.20, 0.35] [0.55, 0.65]	[0.50, 0.50] [0.50, 0.50]

Table 4.5: Aggregated pairwise comparison matrix with respect to goal

	C1	C2	C3
C1	[0.50, 0.50] [0.50, 0.50]	[0.43, 0.54] [0.32, 0.46]	[0.55, 0.65] [0.20, 0.35]
C2	[0.34, 0.48] [0.40, 0.52]	[0.50, 0.50] [0.50, 0.50]	[0.53, 0.63] [0.22, 0.37]
C3	[0.20, 0.35] [0.55, 0.65]	[0.22, 0.37] [0.53, 0.63]	[0.50, 0.50] [0.50, 0.50]

Table 4.6: Score judgment matrix with respect to goal

	C1	C2	C3
C1	[0.00, 0.00]	[-0.03, 0.23]	[0.20, 0.46]
C2	[-0.18, 0.08]	[0.00, 0.00]	[0.17, 0.42]
C3	[0.45,-0.20]	[-0.42,-0.17]	[0.00, 0.00]

Table 4.7: Interval exponential matrix with respect to goal

	C1	C2	C3
C1	[1.00, 1.00]	[0.97, 1.25]	[1.23, 1.58]
C2	[0.84, 1.08]	[1.00, 1.00]	[1.18, 1.52]
C3	[0.64, 0.82]	[0.66, 0.85]	[1.00, 1.00]

Table 4.8: Possibility degree matrix and normalized weights with respect to goal

	C1	C2	C3	Prioritization	Normalized Weights
C1	0.50	0.59	0.99	0.87	0.43
C2	0.41	0.50	0.93	0.78	0.39
C3	0.01	0.07	0.50	0.35	0.18

A total of 276 pairwise comparisons are made by each expert for 3 main criteria, 12 sub-criteria and 4 alternative companies. Then, the computational steps are applied to the extracted data for obtaining weights of each criterion and total weights of each alternative. First, the consistency of each comparison matrix is controlled by using the crisp values proposed by Saaty (1977). The consistency ratio (CR) is calculated as in Eq (10). It is ensured that all comparison matrices' CR values are less than 0.1. Next, each linguistic pairwise matrices are converted to the IVIF values using the scale presented in Table 3.1. At the rest of this section, the computational steps are exemplified only on comparison matrix with respect goal, for convenience. Table 4.2 to Table 4.8 show each step accordingly. Lastly, the weights of each main criteria, sub-criteria and alternative companies are summarized at the Table 4.9.

Table 4.9: Weights of all criteria and alternatives with respect to each sub-criterion

	Normalized Weights
C1	0.43
C2	0.39
C3	0.18
C11	0.30
C12	0.25
C13	0.14
C14	0.16
C15	0.14
C21	0.38
C22	0.29
C23	0.19
C24	0.14
C31	0.44
C32	0.39
C33	0.17

	A1	A2	A3	A4
C11	0.38	0.29	0.19	0.14
C12	0.45	0.22	0.17	0.16
C13	0.42	0.33	0.10	0.15
C14	0.35	0.28	0.16	0.21
C15	0.38	0.29	0.19	0.14
C21	0.35	0.38	0.12	0.15
C22	0.29	0.24	0.25	0.22
C23	0.42	0.33	0.10	0.15
C24	0.33	0.26	0.20	0.21
C31	0.37	0.21	0.26	0.16
C32	0.45	0.22	0.17	0.16
C33	0.33	0.42	0.15	0.10

The results of IVIF-AHP show that economical dimension is the most important main criteria for the company at the selection of sustainable supplier. It is followed by environmental and social dimensions, respectively. Also, it is observed that cost is the most influential sub-criteria in economical dimension. Although quality is the second most influential sub-criteria, its weight is much higher compared to delivery, technical capability and flexibility. Moreover, delivery and flexibility criteria have the same influence on sustainable supplier selection considering the economical perspective. On the other hand, among the four sub-criteria of environmental dimension, the results show that existing of an environmental management system has the highest impact on sustainable supplier selection. It is followed by resource consumption, waste/pollution management and green resource utilization. Further, it is found that occupational health and safety has higher impact on sustainable supplier selection compared to information disclosure and training and community development. Finally, the weights of alternative suppliers are calculated as on Table 4.10. Based on the IVIF-AHP results, A1 supplier is found to be the most preferred supplier that meets the company's requirements considering the sustainability context.

Table 4.10: Weights of alternative suppliers

	Weights
A1	0,39
A2	0,30
A3	0,18
A4	0,18

4.2. Application of the MO-MILP Model

After finding the weights of each supplier sustainability score, the multi-objective optimization model formulation listed from Eq. (20) to Eq. (36) is employed for 5 products and 4 alternative suppliers in order to calculate the optimum number of supplier and order quantity. The data required for building model is depicted on Table 4.11. Also, the capacity of each supplier covering all product types are 200000, 180000, 300000 and 285000, respectively. Model is solved with weighted sum method. For the calculations, CPLEX solver within the GAMS software package is used. Following elaborates the multi-objective optimization solution methods, weighted sum method structure and the results are summarized on Table 4.13 and Table 4.14.

Table 4.11: Data used in MILP model

i	j	F_{ij}	T_{ij}	Q_{ij}	G_{ij}	I_{ij}	M_{ij}	P_{ij}	H_{ij}	B_{ij}	R_{ij}	n_i	k_i	D_i	$O_{ij_{min}}$	$O_{ij_{max}}$	U_{ij}
1	1	9,00	4,70	4,20	0,80	0,60	0,40	9,50	0	0,25	0,10	2	4	40000	2000	135000	0,39
	2	8,90	4,80	4,00	1,10	0,90	0,70	9,00	0	0,20	0,15	2	4	40000	1500	145000	0,30
	3	8,85	3,50	4,80	0,95	0,75	0,00	9,30	0	0,30	0,15	2	4	40000	500	150000	0,18
	4	7,80	4,60	5,00	1,20	1,00	0,80	8,50	1	0,35	0,20	2	4	40000	500	185000	0,18
2	1	100	4,80	4,90	0,95	0,75	0,55	9,50	0	0,20	0,15	2	4	75000	2000	135000	0,39
	2	9,90	4,90	5,00	1,20	1,00	0,80	9,00	0	0,15	0,20	2	4	75000	1500	145000	0,30
	3	9,85	3,60	4,70	1,15	0,95	0,00	9,30	0	0,25	0,10	2	4	75000	500	150000	0,18
	4	8,80	4,70	5,20	1,25	1,05	0,85	8,50	0	0,30	0,15	2	4	75000	500	185000	0,18
3	1	9,85	4,85	4,70	0,70	0,50	0,00	9,50	0	0,35	0,10	2	4	15000	2000	135000	0,39
	2	9,75	4,95	4,80	0,80	0,60	0,40	9,00	0	0,30	0,15	2	4	15000	1500	145000	0,30
	3	9,70	3,65	3,50	0,90	0,70	0,50	9,30	0	0,40	0,05	2	4	15000	500	150000	0,18
	4	8,65	4,75	4,60	0,90	0,70	0,50	8,50	0	0,45	0,10	2	4	15000	500	185000	0,18
4	1	9,89	4,60	5,00	0,10	0,00	0,00	9,50	0	0,15	0,25	2	4	230000	2000	135000	0,39
	2	9,78	4,70	4,95	0,70	0,50	0,30	9,00	0	0,20	0,20	2	4	230000	1500	145000	0,30
	3	9,72	3,40	4,80	0,90	0,70	0,50	9,30	1	0,10	0,30	2	4	230000	500	150000	0,18
	4	8,60	4,50	4,85	0,60	0,40	0,20	8,50	0	0,15	0,35	2	4	230000	500	185000	0,18
5	1	9,90	4,90	5,00	0,25	0,05	0,00	9,50	0	0,10	0,25	2	4	95000	2000	135000	0,39
	2	9,75	5,00	5,00	0,20	0,00	0,00	9,00	0	0,80	0,20	2	4	95000	1500	145000	0,30
	3	9,65	3,70	3,90	0,10	0,00	0,00	9,30	0	0,10	0,30	2	4	95000	500	150000	0,18
	4	8,70	4,80	4,95	0,30	0,10	0,00	8,50	0	0,05	0,35	2	4	95000	500	185000	0,18

For the solution of the multiple objective optimization problems, scalarization methods have been used in the literature to convert them into a single objective problem. Hwang and Masud (1979) and Lieberman (1991 a, b) defined these methods under four classes which are no-preference methods, a priori methods, a posteriori methods and interactive methods. The main difference between these scalarization methods is the way of decision makers participation in decision making process. In the a priori methods, for example, the decision maker involves at the beginning of the decision process and the collected data is reflected on the model. In the posteriori methods, on the other hand, the decision maker participates the process after scanning the Pareto fronts efficiently. In the interactive methods, the decision maker and the analyst or solution interface interact sequentially. At each period Pareto effective sets are generated according to the decision maker preference. The process ends when a satisfactory result is achieved. Although these methods are superior to each other, an ideal solution does not exist. Table 4.12 shows some related scalarization methods under each class and a more detailed comparison of these methods can be found in Ozden (2007).

Table 4.12: Multi-objective optimization solution methods

No-preference methods	• Unweighted compromise programming methods
A priori methods	• Weighted sum method • Goal programming methods • Lexicographic ordering based methods • Utility theory based methods • Conic scalarization method
A posteriori methods	• ε-Constraint method • Weighted compromise programming methods • Elastic constraint method • Benson's method
Interactive methods	• Tchebycheff metric based interactive methods • Reference point algorithms

In this study, weighted sum method is used to solve the multi-objective SSOA optimization problem. This method scalarizes all objective functions by multiplying each objective function with a weight which reflects their relative importance and summing them. Here, the summation of the of weights is equal to 1 and each of them needs to be greater than or equal to 0. The goal of weighted sum method is to identify Pareto optimal solutions which refers to the solutions that optimize one objective without deteriorating another objective. Eq. (37) to Eq. (39) describe the general form of the method and the formulation of the problem is provided in Appendix B.

$$z_1 = Min\, f_1(x)\ ,\ z_2 = Min\, f_2(x), \ldots, z_n = Min\, f_n(x) \tag{37}$$

$$Z = w_1 z_1 + w_2 z_2 + \cdots + w_n z_n \tag{38}$$

$$\text{where } \textstyle\sum_1^n w_i = 1\ ,\ w_i \geq 0 \tag{39}$$

Since the solution highly depends on the defined weights, equal weights are first defined for each objective function for making consistent and objective evaluation. Also, anchor points, which are special reference points that attain a specific value to each weight, are identified for comparison. They describe the extremes of Pareto frontier by minimizing one of the objective functions while ignoring all others. Thus, while 1 is attained to minimized objective function's weight, all other objective functions' weights are given 0. In other words, the anchor points are obtained by setting the weight values to $(1,0,0,0,0,0,0,0,0,0)$, $(0,1,0,0,0,0,0,0,0,0), \ldots, (0,0,0,0,0,0,0,0,0,1)$, respectively. Table 4.13 shows the order quantities of each product type of all alternative suppliers that is achieved through giving the weight of 0.1 simultaneously and 1 separately to ten objective functions, respectively. Also, Table 4.14 depicts the value of each objective function for defined weights.

Several results can be drawn from Table 4.13. Firstly, if ten objective functions are kept equally important, orders should not be placed to supplier A2. Also, it is observed that supplier A3 has overall the highest order but not in product type 4. It is followed by supplier

A4 and orders of product type 4 is mostly met by this supplier. Secondly, it is seemed that supplier A1 has the highest overall order if the decision maker wants to minimize the defect rate at the incoming, in-process and late customer revision. If minimum defect rate detected by customer, late delivery, partial delivery, late product development rate and maximum sustainability score is crucial for the decision maker, then supplier A3 gets the highest overall order. Lastly, if minimizing the product price and maximizing quality audit score is demanded, then supplier A4 gets the highest overall order. Considering these results, supplier A3 not only best meets half of the objectives separately, but also satisfies all objectives simultaneously.

Table 4.13: Order quantities of each product type for all alternative supplier and weights

		Weights										
Supplier A1		Wz = 0.1	Wz1 = 1	Wz2 = 1	Wz3 = 1	Wz4 = 1	Wz5 = 1	Wz6 = 1	Wz7 = 1	Wz8 = 1	Wz9 = 1	Wz10 = 1
Product Types	1	0	2000	2000	0	0	0	2000	0	0	39500	0
	2	0	63000	63000	0	0	0	0	0	0	0	0
	3	0	0	0	14500	0	0	0	0	0	0	0
	4	45000	135000	135000	135000	0	0	0	0	80000	135000	0
	5	0	0	0	0	0	0	0	0	0	10000	0
Total		45000	200000	200000	149500	0	0	2000	0	80000	184500	0
Supplier A2		Wz = 0.1	Wz1 = 1	Wz2 = 1	Wz3 = 1	Wz4 = 1	Wz5 = 1	Wz6 = 1	Wz7 = 1	Wz8 = 1	Wz9 = 1	Wz10 = 1
Product Types	1	0	0	0	0	1500	0	38000	0	39500	0	0
	2	0	0	0	0	1500	0	0	0	74500	0	0
	3	0	14500	14500	0	1500	0	0	0	14500	0	0
	4	0	0	0	0	71000	0	0	0	0	95000	0
	5	0	0	1500	0	94500	0	0	0	0	85000	0
Total		0	14500	16000	0	170000	0	38000	0	128500	180000	0
Supplier A3		Wz = 0.1	Wz1 = 1	Wz2 = 1	Wz3 = 1	Wz4 = 1	Wz5 = 1	Wz6 = 1	Wz7 = 1	Wz8 = 1	Wz9 = 1	Wz10 = 1
Product Types	1	39500	38000	38000	39500	0	500	0	500	500	500	500
	2	74500	12000	12000	74500	0	40500	74500	15500	500	74500	40500
	3	14500	500	500	500	0	14500	14500	14500	500	14500	14500
	4	0	0	0	0	0	150000	116500	45000	150000	0	150000
	5	94500	94500	93500	94500	0	94500	94500	94500	500	0	94500
Total		223000	145000	144000	209000	0	300000	300000	170000	152000	89500	300000
Supplier A4		Wz = 0.1	Wz1 = 1	Wz2 = 1	Wz3 = 1	Wz4 = 1	Wz5 = 1	Wz6 = 1	Wz7 = 1	Wz8 = 1	Wz9 = 1	Wz10 = 1
Product Types	1	500	0	0	500	38500	39500	0	39500	0	0	39500
	2	500	0	0	500	73500	34500	500	59500	0	500	34500
	3	500	0	0	0	13500	500	500	500	0	500	500
	4	185000	95000	95000	95000	159000	80000	113500	185000	0	0	80000
	5	500	500	0	500	500	500	500	500	94500	0	500
Total		187000	95500	95000	96500	285000	155000	115000	285000	94500	1000	155000

Table 4.14: Objective function value for each weight

	Objectives										
Weights	Z	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10
Wz = 0.1	1301437	263025	185975	45342	4090900	1857950	2091175	4189000	80800	118850	91350
Wz1 = 1	203500	203500	135450	60520	4190750	1962150	2134025	4317150	76025	114275	125640
Wz2 = 1	135400	203550	135400	60519	4190700	1963550	2135150	4317775	77100	114100	125820
Wz3 = 1	20102	215125	147075	20102	4184200	1883800	2121525	4307800	80050	110550	113295
Wz4 = 1	3952500	319025	228035	155985	3952500	2132750	2255075	4094205	156250	109750	102300
Wz5 = 1	1768750	343675	262125	159430	4107500	1768750	2101725	4222300	76950	119500	81900
Wz6 = 1	2046900	325750	244200	116284	4128500	1776550	2046900	4264155	71050	117400	86880
Wz7 = 1	4078450	314675	233125	149178	4003500	1911750	2119475	4078450	83450	126000	81900
Wz8 = 1	55675	317350	234400	168317	4133350	1965250	2196325	4320850	55675	121375	114120
Wz9 = 1	84575	231375	153884	52256	4213600	2054750	2194350	4435125	143075	84575	142245
Wz10 = 1	81900	343675	262125	159430	4107500	1768750	2101725	4222300	76950	119500	81900

In addition to order quantities among alternative suppliers, the objective functions' values depicted on Table 4.14 shows the trade-off between ten objectives according to the weight combinations. While the first column shows the values where each objective is equally weighted, rest provides the values where only one objective is prioritized at each column. Results show that each separately prioritized objective have better value compared to equally weighted objectives. In other words, all objectives are better satisfied when separately minimized so that each has lower values then equally weighted objectives. For example, when the first objective is prioritized, the acceptable minimum number of products with defect detected at in-coming control is 203500. On the other hand, when there is not a priority relation among objectives, this value is calculated as 263025. Also, when this value is compared with all other separately prioritized objectives, it is observed that all of the first objective function values are greater than 203500. Likewise, when the second objective is prioritized, the acceptable minimum number of products with defect detected at in-process control is 135400 and this value is the lowest among all other separately prioritized objectives. Thus, these outcomes confirm that when an objective is prioritized alone, it reaches its lowest value. However, it is also observed that prioritizing an objective causes compromising from other objective. Considering prioritization of first objective, for instance, causes the value of third, fourth, fifth, sixth, seventh and tenth objectives to increase. Thus, these objectives could not be so well satisfied compared to equally weighted objectives. Likewise, same trade-off is valid for comparing it with the outcomes of second objective prioritization. The lowest acceptable number of defected products with in-process control is achieved as 135400 which is very close to the outcome achieved at first objective prioritization. Also, first, eighth and ninth objective functions are better satisfied while the rest of the objective functions' values are worsened by prioritizing the second objective function. Considering the prioritization of the third objective, the lowest acceptable number of products with defect detected at customer site is 20102. This is the minimum achievable among all other prioritizations, but the decrement at prioritization of third objective deteriorates fourth, fifth, sixth, seventh and tenth objective functions values compared to equal weighting.

Moreover, the first three weighting depicts similar sensitivity although each prioritizes different objectives. Thus, prioritizing one of the objectives does not considerably impact other objectives. However, first, second, third and eight objectives have strong sensitivity to prioritization of fourth, fifth, sixth, seventh, eighth and tenth objectives. Third objective, for example, takes values between 116284 and 168317 considering these weighting while the value achieved through equal weighting is 45342 and the minimum value among all weighting is 20102. Similarly, second objectives' values spread between 228035 and 262125 with the mentioned weighting while it's minimum is 135400 and value derived from equal weighting is 185975. Due to these reasons, the decision maker should critic the importance of the first, second, third and eight objectives if either fourth, fifth, sixth, seventh, eighth or tenth objectives is needed to be prioritized as these objectives depict huge variation.

5. CONCLUSION

In this study, a two-phase optimization model is developed for sustainable SSOA problem and applied to a company which operates in automotive industry. In the first phase, the sustainability weights of alternative suppliers are determined through IVIF-AHP. AHP is a practical technique which allows to prioritize the alternatives based on the pre-determined criteria. IVIF, on the other hand, allow to cope with ambiguity and impreciseness in the judgements of decision makers. In the second phase, a multi-product and multi-objective optimization model is suggested for finding the optimum number of suppliers and order quantity with the objective of minimizing cost, late and incomplete delivery, defect and late product development rate and maximizing quality audit and sustainability score. Also, unlike the previous studies, CAPA, which is an effective QMS tool in tracking supplier quality performance, is involved as a model constraint along with demand and order quantity constraints. As a result of the study, it was ensured that all factors originating from the supplier and product in the company and the experiences and observations of experts who faced the problems of the system were included in the decision making process.

There are several limitations of this study. Firstly, a better representation of SSOA needs to tackle the problem by incorporating several stimulating effects together which has a huge impact on decision. The demand, capacity and price, for example, are kept constant in this study. However, in real-world situation these parameters cannot be known certainly and shortages might appear due to several disruption impact. Also, these parameters can be time-varying and/or situation-varying. Thus, a better representation of real-world situation can be achieved by considering these cases in establishing the model. Secondly, the problem only solved with eleven different weighting which represent different prioritizations. However, this is not enough to display an evenly spaced Pareto frontier which causes information gaps. Another limitation of this study is reliance on limited number of decision maker in making decision. In this study, only three expert decisions are involved in making supplier selection. Also, although a diversity is reached by selecting the experts from different department, a common decision that represents the company's needs and requirements from a sustainable supplier can be revealed by incorporating more decision makers.

Further studies can take into consideration the limitations of these study and provide solution approaches as incorporating additional variables into the model and changing the variable setting will further complicate the problem. Several methodological approaches such as dynamic programming, stochastic programming and meta-heuristic methods can be utilized for the solving the sustainable SSOA problem with different analyzing methods. On the other hand, the AHP method in itself has some limitations. For example, the potential problem of AHP is that decision makers evaluate each cluster based on their own observations. Due to the hierarchical structure, sub-criteria are not evaluated with respect to the goal. Thus, Explanatory Factor Analysis (EFA) can be used to select criteria and sub-criteria to be included in supplier evaluation. Also, whether the criteria and sub-criteria constitute the supplier selection decision can be tested by Structural Equation Modelling (SEM). Moreover, multi-objective optimization methods such as ε-Constraint method, Benson's method and conic scalarization method can be used to solve the problem and their performances can be compared. Last but not least, the membership degree can be tacked as interval type-2 fuzzy sets, pythagorean fuzzy sets, circular fuzzy sets, spherical fuzzy or neutrosophic fuzzy sets and their impact on final decision can be analyzed in the further studies.

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APPENDICES

Appendix A

Table 4.15: Pairwise comparisons with respect to economical dimension

	Expert 1					Expert 2					Expert 3				
	C11	C12	C13	C14	C15	C11	C12	C13	C14	C15	C11	C12	C13	C14	C15
C11	EE	H	H	MH	VH	EE	ML	H	ML	MH	EE	ML	VH	MH	H
C12		EE	H	MH	H		EE	VH	MH	H		EE	VH	MH	H
C13			EE	VL	ML			EE	VL	L			EE	L	ML
C14				EE	MH				EE	MH				EE	MH
C15					EE					EE					EE

Table 4.16: Pairwise comparisons with respect to environmental dimension

	Expert 1				Expert 2				Expert 3			
	C21	C22	C23	C24	C21	C22	C23	C24	C21	C22	C23	C24
C21	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H
C22		EE	H	MH		EE	MH	H		EE	MH	H
C23			EE	ML			EE	MH			EE	MH
C24				EE				EE				EE

Table 4.17: Pairwise comparisons with respect to social dimension

	Expert 1			Expert 2			Expert 3		
	C31	C32	C33	C31	C32	C33	C31	C32	C33
C31	EE	MH	VH	EE	MH	H	EE	ML	MH
C32		EE	H		EE	MH		EE	H
C33			EE			EE			EE

Table 4.18: Pairwise comparisons of all alternatives with respect to each sub-criterion

	Expert 1				Expert 2				Expert 3					Expert 1				Expert 2				Expert 3			
C11	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4	**C12**	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H	A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H
A2		EE	H	MH		EE	MH	H		EE	MH	H	A2		EE	H	MH		EE	MH	H		EE	MH	H
A3			EE	ML			EE	MH			EE	MH	A3			EE	ML			EE	MH			EE	MH
A4				EE				EE				EE	A4				EE				EE				EE
	Expert 1				**Expert 2**				**Expert 3**					**Expert 1**				**Expert 2**				**Expert 3**			
C13	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4	**C14**	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H	A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H
A2		EE	H	MH		EE	MH	H		EE	MH	H	A2		EE	H	MH		EE	MH	H		EE	MH	H
A3			EE	ML			EE	MH			EE	MH	A3			EE	ML			EE	MH			EE	MH
A4				EE				EE				EE	A4				EE				EE				EE
	Expert 1				**Expert 2**				**Expert 3**					**Expert 1**				**Expert 2**				**Expert 3**			
C15	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4	**C21**	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H	A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H
A2		EE	H	MH		EE	MH	H		EE	MH	H	A2		EE	H	MH		EE	MH	H		EE	MH	H
A3			EE	ML			EE	MH			EE	MH	A3			EE	ML			EE	MH			EE	MH
A4				EE				EE				EE	A4				EE				EE				EE
	Expert 1				**Expert 2**				**Expert 3**					**Expert 1**				**Expert 2**				**Expert 3**			
C22	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4	**C23**	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H	A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H
A2		EE	H	MH		EE	MH	H		EE	MH	H	A2		EE	H	MH		EE	MH	H		EE	MH	H
A3			EE	ML			EE	MH			EE	MH	A3			EE	ML			EE	MH			EE	MH
A4				EE				EE				EE	A4				EE				EE				EE
	Expert 1				**Expert 2**				**Expert 3**					**Expert 1**				**Expert 2**				**Expert 3**			
C24	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4	**C31**	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H	A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H
A2		EE	H	MH		EE	MH	H		EE	MH	H	A2		EE	H	MH		EE	MH	H		EE	MH	H
A3			EE	ML			EE	MH			EE	MH	A3			EE	ML			EE	MH			EE	MH
A4				EE				EE				EE	A4				EE				EE				EE
	Expert 1				**Expert 2**				**Expert 3**					**Expert 1**				**Expert 2**				**Expert 3**			
C32	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4	**C33**	A1	A2	A3	A4	A1	A2	A3	A4	A1	A2	A3	A4
A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H	A1	EE	MH	H	H	EE	MH	H	VH	EE	MH	H	H
A2		EE	H	MH		EE	MH	H		EE	MH	H	A2		EE	H	MH		EE	MH	H		EE	MH	H
A3			EE	ML			EE	MH			EE	MH	A3			EE	ML			EE	MH			EE	MH
A4				EE				EE				EE	A4				EE				EE				EE

Appendix B

- GAMS code for weighted sum method with equal importance

```
SupplierCapacity1.. X11 + X21 + X31 + X41 + X51 =L= 200000;

SupplierCapacity2.. X12 + X22 + X32 + X42 + X52 =L= 180000;

SupplierCapacity3.. X13 + X23 + X33 + X43 + X53 =L= 300000;

SupplierCapacity4.. X14 + X24 + X34 + X44 + X54 =L= 285000;

CAPA11.. X11 =L= (1 - H11) * 135000;

CAPA21.. X21 =L= (1 - H21) * 135000;

CAPA31.. X31 =L= (1 - H31) * 135000;

CAPA41.. X41 =L= (1 - H41) * 135000;

CAPA51.. X51 =L= (1 - H51) * 135000;

CAPA12.. X12 =L= (1 - H12) * 145000;

CAPA22.. X22 =L= (1 - H22) * 145000;

CAPA32.. X32 =L= (1 - H32) * 145000;

CAPA42.. X42 =L= (1 - H42) * 145000;

CAPA52.. X52 =L= (1 - H52) * 145000;

CAPA13.. X13 =L= (1 - H13) * 150000;

CAPA23.. X23 =L= (1 - H23) * 150000;

CAPA33.. X33 =L= (1 - H33) * 150000;

CAPA43.. X43 =L= (1 - H43) * 150000;

CAPA53.. X53 =L= (1 - H53) * 150000;
```

```
CAPA14.. X14 =L= (1 - H14) * 185000;

CAPA24.. X24 =L= (1 - H24) * 185000;

CAPA34.. X34 =L= (1 - H34) * 185000;

CAPA44.. X44 =L= (1 - H44) * 185000;

CAPA54.. X54 =L= (1 - H54) * 185000;

DemandP1.. X11 + X12 + X13 + X14 =E= 40000;

DemandP2.. X21 + X22 + X23 + X24 =E= 75000;

DemandP3.. X31 + X32 + X33 + X34 =E= 15000;

DemandP4.. X41 + X42 + X43 + X44 =E= 230000;

DemandP5.. X51 + X52 + X53 + X54 =E= 95000;

MinOrder11.. 2000 * Y11 =L= X11;

MinOrder21.. 2000 * Y21 =L= X21;

MinOrder31.. 2000 * Y31 =L= X31;

MinOrder41.. 2000 * Y41 =L= X41;

MinOrder51.. 2000 * Y51 =L= X51;

MinOrder12.. 1500 * Y12 =L= X12;

MinOrder22.. 1500 * Y22 =L= X22;

MinOrder32.. 1500 * Y32 =L= X32;

MinOrder42.. 1500 * Y42 =L= X42;

MinOrder52.. 1500 * Y52 =L= X52;

MinOrder13.. 500 * Y13 =L= X13;

MinOrder23.. 500 * Y23 =L= X23;
```

MinOrder33.. 500 * Y33 =L= X33;

MinOrder43.. 500 * Y43 =L= X43;

MinOrder53.. 500 * Y53 =L= X53;

MinOrder14.. 500 * Y14 =L= X14;

MinOrder24.. 500 * Y24 =L= X24;

MinOrder34.. 500 * Y34 =L= X34;

MinOrder44.. 500 * Y44 =L= X44;

MinOrder54.. 500 * Y54 =L= X54;

MaxOrder11.. 135000 * Y11 =G= X11;

MaxOrder21.. 135000 * Y21 =G= X21;

MaxOrder31.. 135000 * Y31 =G= X31;

MaxOrder41.. 135000 * Y41 =G= X41;

MaxOrder51.. 135000 * Y51 =G= X51;

MaxOrder12.. 145000 * Y12 =G= X12;

MaxOrder22.. 145000 * Y22 =G= X22;

MaxOrder32.. 145000 * Y32 =G= X32;

MaxOrder42.. 145000 * Y42 =G= X42;

MaxOrder52.. 145000 * Y52 =G= X52;

MaxOrder13.. 150000 * Y13 =G= X13;

MaxOrder23.. 150000 * Y23 =G= X23;

MaxOrder33.. 150000 * Y33 =G= X33;

MaxOrder43.. 150000 * Y43 =G= X43;

MaxOrder53.. 150000 * Y53 =G= X53;

MaxOrder14.. 185000 * Y14 =G= X14;

MaxOrder24.. 185000 * Y24 =G= X24;

MaxOrder34.. 185000 * Y34 =G= X34;

MaxOrder44.. 185000 * Y44 =G= X44;

MaxOrder54.. 185000 * Y54 =G= X54;

MinSupplierP1.. Y11 + Y12 + Y13 + Y14 =G= 2;

MinSupplierP2.. Y21 + Y22 + Y23 + Y24 =G= 2;

MinSupplierP3.. Y31 + Y32 + Y33 + Y34 =G= 2;

MinSupplierP4.. Y41 + Y42 + Y43 + Y44 =G= 2;

MinSupplierP5.. Y51 + Y52 + Y53 + Y54 =G= 2;

MaxSupplierP1.. Y11 + Y12 + Y13 + Y14 =L= 4;

MaxSupplierP2.. Y21 + Y22 + Y23 + Y24 =L= 4;

MaxSupplierP3.. Y31 + Y32 + Y33 + Y34 =L= 4;

MaxSupplierP4.. Y41 + Y42 + Y43 + Y44 =L= 4;

MaxSupplierP5.. Y51 + Y52 + Y53 + Y54 =L= 4;

DefectIncomingMin.. Z1 =E= 0.8*X11 + 0.95*X21 + 0.7*X31 + 0.1*X41 + 0.25*X51 + 1.1*X12 + 1.2*X22 + 0.8*X32 + 0.7*X42 + 0.2*X52 + 0.95*X13 + 1.15*X23 + 0.9*X33 + 0.9*X43 + 0.1*X53 + 1.2*X14 + 1.25*X24 + 0.9*X34 + 0.6*X44 + 0.3*X54;

DefectInprocessMin.. Z2 =E= 0.6*X11 + 0.75*X21 + 0.5*X31 + 0*X41 + 0.05*X51 + 0.9*X12 + 1*X22 + 0.6*X32 + 0.5*X42 + 0.0001*X52 + 0.75*X13 + 0.95*X23 + 0.7*X33 + 0.7*X43 + 0*X53+1*X14 + 1.05*X24 + 0.7*X34 + 0.4*X44 + 0.1*X54;

DefectCusmoterMin.. Z3 =E= 0.4*X11 + 0.55*X21 + 0.0001*X31 + 0.0001*X41 + 0.0001*X51 + 0.7*X12 + 0.8*X22 + 0.4*X32 + 0.3*X42 + 0.0001*X52 + 0.0001*X13 + 0.0001*X23 + 0.5*X33 + 0.5*X43 + 0.00001*X53 + 0.8*X14 + 0.85*X24 + 0.5*X34 + 0.2*X44 + 0.0001*X54;

AuditScoreMax.. Z4 =E= 9.5*X11 + 9.5*X21 + 9.5*X31 + 9.5*X41 + 9.5*X51 + 9*X12 + 9*X22 + 9*X32 + 9*X42 + 9*X52 + 9.3*X13 + 9.3*X23 + 9.3*X33 + 9.3*X43 + 9.3*X53 + 8.5*X14 + 8.5*X24 + 8.5*X34 + 8.5*X44 + 8.5*X54;

LateDeliveryMin.. Z5 =E= 4.7*X11 + 4.8*X21 + 4.85*X31 + 4.6*X41 + 4.9*X51 + 4.8*X12 + 4.9*X22 + 4.95*X32 + 4.7*X42 + 5*X52 + 3.5*X13 + 3.6*X23 + 3.65*X33 + 3.4*X43 + 3.7*X53 + 4.6*X14 + 4.7*X24 + 4.75*X34 + 4.5*X44 + 4.8*X54;

IncompleteDeliveryMin.. Z6 =E= 4.2*X11 + 4.9*X21 + 4.7*X31 + 5*X41 + 5*X51 + 4*X12 + 5*X22 + 4.8*X32 + 4.95*X42 + 5*X52 + 4.8*X13 + 4.7*X23 + 3.5*X33 + 4.8*X43 + 3.9*X53 + 5*X14 + 5.2*X24 + 4.6*X34 + 4.85*X44 + 4.95*X54;

ProductPriceMin.. Z7 =E= 9*X11 + 10*X21 + 9.85*X31 + 9.89*X41 + 9.9*X51 + 8.9*X12 + 9.9*X22 + 9.75*X32 + 9.78*X42 + 9.75*X52 + 8.85*X13 + 9.85*X23 + 9.7*X33 + 9.72*X43 + 9.65*X53 + 7.8*X14 + 8.8*X24 + 8.65*X34 + 8.6*X44 + 8.7*X54;

LateProductDevelopmentMin.. Z8 =E= 0.25*X11 + 0.2*X21 + 0.35*X31 + 0.15*X41+ 0.1*X51+ 0.2*X12 + 0.15*X22 + 0.3*X32 + 0.2*X42 + 0.8*X52 + 0.3*X13 + 0.25*X23 + 0.4*X33 + 0.1*X43 + 0.1*X53 + 0.35*X14 + 0.3*X24 + 0.45*X34 + 0.15*X44 + 0.05*X54;

LateCustomerRevisionMin.. Z9 =E= 0.1*X11 + 0.15*X21 + 0.1*X31 + 0.25*X41 + 0.25*X51 + 0.15*X12 + 0.2*X22 + 0.15*X32 + 0.2*X42 + 0.2*X52 + 0.15*X13 + 0.1*X23 + 0.05*X33 + 0.3*X43 + 0.3*X53 + 0.2*X14 + 0.15*X24 + 0.1*X34 + 0.35*X44 + 0.35*X54;

SustainabilityScoreMax.. Z10 =E= 0.39*X11 + 0.39*X21 + 0.39*X31 + 0.39*X41 + 0.39*X51 + 0.30*X12 + 0.30*X22 + 0.30*X32 + 0.30*X42 + 0.30*X52 + 0.18*X13 + 0.18*X23 + 0.18*X33 + 0.18*X43 + 0.18*X53 + 0.18*X14 + 0.18*X24 + 0.18*X34 + 0.18*X44 + 0.18*X54;

```
Objective.. Z =E= 0.1*Z1 + 0.1*Z2 + 0.1*Z3+ 0.1*Z4 + 0.1*Z5 + 0.1* Z6+ 0.1*Z7 +
0.1*Z8 + 0.1*Z9 + 0.1*Z10

model   project/all/;

solve  project using mip minimizing Z;
```

BIOGRAPHICAL SKETCH

İpek ELDEM studied at Terakki Vakfı Özel Şişli Terakki Highschool. She received her B.Sc degree in Geomatic Engineering from Istanbul Technical University and M.Sc degree in Business and Engineering Management from University of Warwick. She received her second M.Sc degree in Logistics and Financial Management at Galatasaray University. She is the recipient of distinction degree from M.Sc dissertation in University of Warwick, Warwick Manufacturing Group (WMG) scholarship, Dean’s High Honor List and second raked student at the department in Istanbul Technical University. Her research interests include optimization, statistics, information theory and machine learning. In addition to her academic studies, she has eight years of working experience in automotive and chemical industries serving in purchasing and sales departments.