USING A HYBRID WEIGHTING METHOD IN MULTI CRITERIA DECISION MAKING FOR THERMOPLASTIC MATERIAL SELECTION

Doctoral Thesis

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USING A HYBRID WEIGHTING METHOD IN MULTI CRITERIA DECISION MAKING FOR THERMOPLASTIC MATERIAL SELECTION

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DOCTORAL THESIS

Department of Business Administration

Program in Business Administration (English)

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ABSTRACT

USING A HYBRID WEIGHTING METHOD IN MULTI CRITERIA DECISION MAKING FOR THERMOPLASTIC MATERIAL SELECTION

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With the increasing competition in the production industry and the decrease in resources, the need for thermoplastic materials is increasing due to their low cost and design flexibility for mass production. The selection of the thermoplastic material to be used in the design phase is one of the most important points considered in the design. Usually, the designer decides on the material by considering his/her past experiences. However, this situation may cause critical points to be ignored. For example, focusing only on cost may cause the material strength to be ignored or the environmental effects of the material to be ignored. This situation may affect the business as field complaints, high investment costs or environmental negativities. This study was developed to provide designers with a general thermoplastic material selection methodology with the hybrid weighting method. The ten-stage multi criteria decision analysis proposed in the study is: approval of the project, then determination of the team of expert designers and informing the team about the details, determination of alternative and criterion sets, use of the weights obtained from AHP and Entropy as input to the SOWIA method, a hybrid weighting method, to determine the weights of the criteria, creation of material ranking with the TOPSIS method, evaluation of the selected material by experts, implementation of the material and regular checks. Thanks to this study, a general selection and evaluation system that will provide designers with a strong foundation in thermoplastic materials has been provided.

Keywords: AHP, Entropy, TOPSIS, Multiple Criteria Decision analysis

ÖZET

TERMOPLASTİK MALZEME SEÇİMİ İÇİN ÇOK KRİTERLİ KARAR VERME HİBRİT AĞIRLIKLANDIRMA YÖNTEMİNİN KULLANILMASI

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Üretim endüstrisinde rekabetin artması ve kaynakların azalmasıyla seri üretim için hem maliyetinin düşük olması hem de tasarım esnekliğine izin vermesi nedeniyle termoplastik malzemelere olan ihtiyaç artmaktadır. Tasarım aşamasında kullanılacak olan termoplastik malzemenin seçimi tasarımda dikkate alınan en önemli noktalardan biridir. Genellikle tasarımcı, geçmiş deneyimlerini göz önünde bulundurarak malzemeye karar verir. Ancak bu durum kritik noktaların göz ardı edilmesine neden olabilir. Örneğin, yalnızca maliyete odaklanmak, malzeme mukavemetinin göz ardı edilmesine veya malzemenin çevresel etkilerinin dikkate alınmamasına neden olabilir. Bu durum, işletmeyi saha şikayetleri, yüksek yatırım maliyetleri veya çevresel olumsuzluklar olarak etkileyebilir. Bu çalışma tasarımcılara hibrit ağırlıklandırma yöntemi ile genel bir termoplastik malzeme seçimi metodolojisi sağlamak için geliştirilmiştir. Çalışmada önerilen on aşamalı karar analizi: ilk projenin onaylanması, akabinde uzman tasarımcılardan oluşan ekibin belirlenmesi ve ekibin detaylar hakkında bilgilendirilmesi, alternatif ve kriter setlerinin belirlenmesi, kriterlerin ağırlıkların belirlenmesi için AHP ve Entropy'den elde edilen ağırlıkların hibrit bir ağırlıklandırma yöntemi olan SOWIA yöntemine girdi olarak kullanılması, TOPSIS yöntemiyle malzeme sıralamasının oluşturulması, seçilen malzemenin uzmanlar tarafından değerlendirilmesi , malzemenin implementasyonu ve düzenli olarak kontrollerin yapılmasıdır. Bu çalışma sayesinde, tasarımcılara termoplastik malzemelerde güçlü bir temel sağlayacak genel bir seçim ve değerlendirme sistemi sağlanmıştır.

Anahtar Sözcükler: AHP, Entropy, TOPSIS, Çok Kriterli Karar Analizi

04/07/2025

ETİK İLKE VE KURALLARA UYGUNLUK BEYANNAMESİ

Bu tezin bana ait, özgün bir çalışma olduğunu; çalışmamın hazırlık, veri toplama, analiz ve bilgilerin sunumu olmak üzere tüm aşamalarında bilimsel etik ilke ve kurallara uygun davrandığımı; bu çalışma kapsamında elde edilen tüm veri ve bilgiler için kaynak gösterdiğimi ve bu kaynaklara kaynakçada yer verdiğimi; bu çalışmanın Anadolu Üniversitesi tarafından kullanılan "Bilimsel İntihal Tespit Programı"yla tarandığını ve hiçbir şekilde "intihal içermediğini" beyan ederim. Herhangi bir zamanda, çalışmamla ilgili yaptığım bu beyana aykırı bir durumun saptanması durumunda, ortaya çıkacak tüm ahlaki ve hukuki sonuçları kabul ettiğimi bildiririm.

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I hereby truthfully declare that this thesis/dissertation is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with "Scientific Plagiarism Detection Program" used by Anadolu University, and that "it does not have any plagiarism" whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

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Lastly, I would like to thank my dear nephews Oğuz and İpek, whose cheerful presence has always brought me moments of happiness and relief.

DECLARATION OF PRODUCTIVE USE OF ARTIFICIAL INTELLIGENCE

I declare that I have not used productive artificial intelligence programs at any stage of the preparation, execution, data analysis, etc. of this study.

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(İmza)

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04/07/2025

DECLARATION OF GENERATIVE ARTIFICIAL INTELLIGENCE USAGE

I declare that I have not used generative artificial intelligence programs at any stage of the preparation, execution, data analysis, etc. of this study.

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(Raziye OKYAY DURMUŞ)

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INDEX OF SYMBOLS AND ABBREVIATION

MCDM	: Multi Criteria Decision Making
AHP	: Analytical Hierarchy Process
MARE	: Multi Attribute Range Evaluations
ELECTRE III	: Elimination Et Choix Traduisant La Realité Trois
TOPSIS	: Technique for Order Performance by Similarity to Ideal Solution
FAHP	: Fuzzy Analytical Hierarchy Process
DEMATEL	: Decision-Making Trial and Evaluation Laboratory
ANP	: Analytic Network Process
SWARA	: Step Wise Weight Assessment Ratio Analysis
SMART	: Simple Multi-Attribute Ranking Technique
CRITIC	: Criteria Importance Through Inter-Criteria Correlation
MACBETH	: Measuring Attractiveness by a Categorical Based Evaluation Technique
PAPRIKA	: Potentially All Pairwise Rankings of All Possible Alternatives
CA	: Conjoint Analysis
SOWIA	: Subjective and Objective Weight Integrated Approach
PDCA	: Plan Do Check Act

1 INTRODUCTION

People make many different decisions throughout their lives. These decisions can be very simple, for example, which outfit should I wear today, which restaurant should I eat dinner at, or these decisions can be more complex, for example, which kindergarten should I register my child in or how should I rank my university preference list. Or these decisions can be related to business life that affect more stakeholders and involve higher costs.

All of these are decision-making problems that need to be solved, and these contain various alternatives and criteria.

Decision making includes ranking of alternatives in line with criteria by decision maker (Saaty, 2008). To make these decisions, multicriteria decision methods are used. The multi criteria decision making (MCDM) is defined choosing of the best alternative within many alternatives to solve a decision problem (Güner and Yücel, 2007). In business life, the MCDM problems arise as supplier selection, project selection, financial evaluation method selection, strategic investment decisions such as equipment selection or new factory location selection problems. In the literature, there are many studies to solve these problems.

For example, Hodgett (2016) studied on an equipment selection problem using in a chemical manufacturing process by using three different MCDM methods which are Analytical Hierarchy Process (AHP), MultiAttribute Range Evaluations (MARE) and ELimination Et Choix Traduisant la REalité trois (ELECTRE III). Kiracı and Bakır (2018) studied on the selection of most suitable aircraft for airline companies with different flight networks and destination using Technique for Order Performance by Similarity to Ideal Solution (TOPSIS). Yadav and Sharma (2015) conducted a study about the procurement source determination using Fuzzy AHP (FAHP) method for an automobile company.

Dalalah, Hayajneh and Batieha (2011) studied on a fuzzy MCDM method for cans procurement source determination in Nutridar Factory in Jordan. Cristóbal (2011) applied VIKOR method on the selection of a Renewable Energy project for the Renewable Energy Plan launched by the Spanish Government. Liang and Wang (1991) handled a study about selection of facility site using fuzzy MCDM method.

MCDM methods are used to produce solutions in many different areas such as project selection, supplier selection. There are very valuable studies in the literature in these areas and studies that present very valuable systematic literature reviews. For example, De Souza et. al (2021) reviewed extensive literature and provided a systematic review of MCDM techniques in Research and Development project selection. Yildiz and Yayla (2015) presented a literature review on MCDM methods in supplier selection. Studies in supply chain by Momena et. al (2024), selection of suitable wave energy technology by Nasrollahi et. al. (2023), suitable site selection for urban green space development by Hailemariam (2021), selection of the most suitable blockchain platform for the healthcare sector by Erol et. al (2023) and sustainable supplier selection for a construction company by Matić (2019) use various MCDM methods for complex situations.

In the field of material selection, various MCDM methods are used to cope with complex situations. AHP, TOPSIS, Entropy methods provide effectiveness in determining the criteria weights and ranking the materials (Kumar and Kumar, 2019, Milani et. al, 2005 and, Hussain and Mandal, 2016). By examining the literature in depth, Emovon and Oghenenyerovwho (2020) provide a methodical review of studies applying the MCDM method in material selection for optimum design.

Chatterjee and Chakraborty (2021) focus on the application of decision-making trial and evaluation laboratory (DEMATEL) for gear material selection problem, a mechanical material. Anupam et. al (2014) and Singh et. al (2020) applied the TOPSIS multiple criteria decision-making design in the selection of raw material in pulping and papermaking industry.

With thermoplastic materials, complex designs can be easily made without thinking about production limits. Less energy is consumed in production processes compared to metal materials and they can be recycled more easily. It is also more advantageous in terms of cost. As technology develops, plastic materials are the solution of the future in terms of production as they become more durable and efficient. Today, many metal materials are being replaced by thermoplastics and this situation will increase in the future. There are various MCDM problems addressed for different sectors in the literature. Girubha and Vinodh (2012) presented fuzzy VIKOR for alternative material selection of instrument panel used in electric car. Gul et. al (2018) used a fuzzy PROMETHEE method for the material selection of an automotive instrument panel. Ilangkumaran et. al (2013) used

MCDM approach to evaluate optimum material to be used in automobile bumper manufacturing. The criteria weights are computed by fuzzy analytical hierarchy process. PROMETHEE I and PROMETHEE II are used in the ranking of the material. Mansor et. al (2014) applied AHP to calculate criteria weights and TOPSIS method to decide the best thermoplastic material in hybrid natural fiber composites formulation for the design of automotive parking brake lever component. Zhang et. al (2017) proposed a hybrid MCDM approach combining DEMATEL, ANP, GRA and TOPSIS for green material selection in an empirical application of rubbish bins. The criteria were weighted using the subjective methods DEMATEL and ANP, and the alternative ranking was done using the GRA and TOPSIS methods. Bulut et. al (2024) discusses a comparative MCDM approach for optimum thermoplastic material selection of hybrid vehicle battery packs in the automotive industry. Step-Wise Weight Assessment Ratio Analysis (SWARA) Approach is used to determine the weighting criteria. ARAS, EDAS and TOPSIS methods are used for the selection of optimum thermoplastic materials.

1.1 Research Motivation

With the industrial revolution and then the rapid progress of technology, a major increase in the world population has been observed. This increase in the population has increased the supply in the production sector. Large companies have started to carry out studies to increase production volumes to meet the demand in the market. However, from time to time, the crises in the world economy, natural resources reach the boundary, and the importance of the environment affects the consumer movements due to the size of the consumer perspective quality/long lifetime has gained value. The first critical step in producing long /high quality products is the correct selection of raw materials. The raw materials determined while the design phase of the product directly affect the whole process and consequently the production costs. Companies attach importance to the fact that raw materials used in production to reduce costs are as plastic as possible. However, at this point, the choice of plastic raw material becomes the most critical issue in design.

Mostly the wrong material can be selected because it contains too many criteria. Mold investments can cause a difficult and costly process as it can be realized according to the selection of material. The main purpose of this study is to provide designers with a generic selection and evaluation system that will provide a strong foundation in thermoplastic materials.

1.2 Research Significance

This study enriches the literature by applying MCDM in general thermoplastic material selection, which can guide designers by addressing various technical and environmental constraints (tensile strength, elongation at break etc.). It provides a new perspective on comparative thermoplastic material analysis by emphasizing the balance of criteria such as yield strength, tensile strength, elongation at break, density, coefficient of thermal expansion, cost, melting temperature and carbon dioxide effect. This research provides a detailed framework for materials selection, contributing to material science and supporting sustainable developments across all manufacturing industries. Although the selection of suitable thermoplastic materials has been addressed in recent studies, many of these studies focus on limited criteria, use a single criterion weighting method, or use a single decision-making method. This prevents designers from having to go through a generic material selection process. Specifically, it filled the gap in material selection with a hybrid weighting method that includes technical, financial, production and environmental effects of thermoplastic materials together with subjective and objective inputs. The study aims to address this gap and provide designers with a generic material selection methodology.

1.3 Research Objective

Determining the material to be selected is one of the most important points taken into consideration during design. Usually, the designer decides on the material by taking into account his/her past experiences. However, this situation may cause critical points to be ignored. For example, focusing only on cost may result in ignoring the material strength or the environmental effects of the material may not be taken into account. This situation may affect the business as field complaints, high investment costs or environmental negativities. For this reason, the main objective of the research includes:

Provide designers with a generic material selection methodology with hybrid weighting method.

The originality of the thesis is that it is made by using the hybrid weighting method with AHP and Entropy subjective and objective methods, also by benefiting from the experiences of experts, for the selection of thermoplastic raw materials to be used in industrial materials. There is no study in the literature with a general application area in the industry.

1.4 Research Questions

The research focuses on two basic questions. These are as follows.

Q1. What are the basic criteria for designers in selecting and evaluating thermoplastic raw materials?

Q2. How is the hybrid weighting method and MCDM method used in thermoplastic raw material selection and evaluation?

1.5 Thesis Structure

The first chapter of the thesis is Introduction which consists of brief history of the topics discussed in the thesis, research motivation, research significance, research objectives and research questions and structure of the thesis.

The second chapter is about brief history of MCDM, types of MCDM problems and MCDM methods.

The third chapter explains different weighting methods for multi criteria decision making methods and how the criteria are weighted under these different weighting methods.

In the fourth chapter, thermoplastic materials and their cost, technical and environmental properties are explained.

The fifth chapter is about the research methodology used in this thesis. It includes the framework for our decision-making model. It also includes of our criteria and the scale used to measure them.

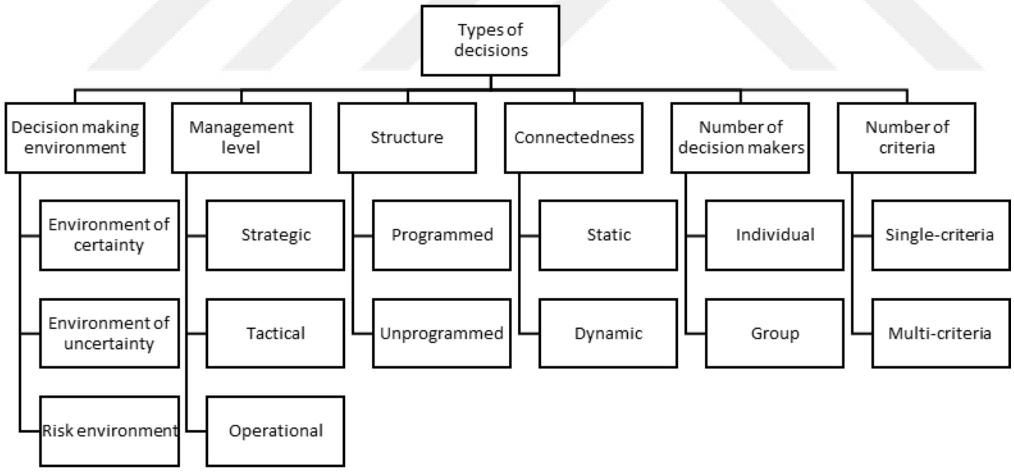
The sixth chapter is about the results and discussion of our application of SOWIA and TOPSIS to obtain the final rankings of the projects. Our analysis uses the weights generated by AHP and Entropy methods.

2 MULTI CRITERIA DECISION MAKING

In all areas of our life, the decision making takes place. The people decide at the all- time like which game should I buy, what time should I leave home for job or where should I celebrate my friend's birthday etc. And this type of decision occurs in business life like which machine should be chosen for new chemical process, which employee should be upgraded for vacant manager position etc. And the people must choose the best solution for their benefit or their company benefit.

Decision types are distinguished by focusing on different points such as the decision-making environment, management level, structures, interconnectedness, number of decision makers and number of criteria. Breakdowns of decision types are given in Figure 2.1.

Figure 2. 1
T*ype of decisions*



According to the decision-making environment, decisions are divided into three as decisions in a certainty, uncertainty and risk environment. A decision environment in which the decision maker knows for sure what situations he will face in the future is called a certainty decision environment. The exact opposite of this situation is called an uncertainty environment. The decision maker can define natural situations but does not have enough information to determine the probability of these situations occurring. In a risk environment, the decision maker has enough information to determine the probability of natural situations occurring.

According to the management level, decisions are divided into three as strategic, tactical and operational decisions. Strategic decisions are decisions that are complex in nature and given in an environment of uncertainty, where the results can be seen in the long term. Tactical decisions are decisions related to activities where the results can be seen in the medium term. Operational decisions are decisions that include daily activities.

According to their structure, decisions are divided into two as programmed and unprogrammed decisions. Programmed decisions refer to repetitive decisions, while unprogrammed refers to non-routine decisions.

Decisions are divided into two groups according to their connectedness: static and dynamic decisions. Static decisions refer to decisions that are made only once, while dynamic decisions refer to a series of decisions in which the outcome of one decision affects subsequent decisions.

Decisions are divided into two groups according to the number of decision makers: individual and group decisions. Decisions involving a single decision maker are individual decisions. In group decisions, more than one decision maker makes a joint decision.

Decisions are divided into two groups according to the number of criteria: single-criteria and multi-criteria. In single-criteria decisions, the number of criteria needed to achieve the desired goal is one, while in multi-criteria decisions, the number of criteria is more than one (Özdemir, 2016).

In this case, a decision making becomes harder as the options (alternatives) and criteria increase, and the best solution is overlooked. To avoid these situations, the MCDM methods should be used with weighting methods. Thanks to that, the most effective solution is selected by keeping the decision-making mechanism under control. Thus, the blockage between choices/options does not occur, the values/criteria that are important for the decision maker cannot be overlooked.

There are various MCDM methods used in solving decision making problems. According to Roy (1981), there are four main decision-making problems: sorting, description ranking and choice. MCDM problems and methods are shown in Table 1 (Roy, 1981).

Table 2. 1
MCDM Problems and Methods

MCDM Problems	MCDM Methods
Choice Problems	AHP, ANP, MAUT/UTA, MACBETH, PROMETHEE, ELECTRE I, TOPSIS, Goal Programming, DEA
Sorting Problems	AHPSort, UTADIS, FlowSort, ELECTRE- Tri
Ranking Problems	AHP, ANP, MAUT/UTA, MACBETH, PROMETHEE, ELECTRE III, TOPSIS, DEA
Description Problems	GAIA, FS-Gaia

Source: Roy, 1981

In choice problems, the aim is to select best option among all alternatives. For solving these problems, some MCDM methods such as AHP, ANP, MAUT/UTA, MACBETH, PROMETHEE, ELECTRE I, TOPSIS, Goal Programming or DEA can be used.

In the sorting problems, the alternative is sorted by specific criteria or preferences. For solving these problems, the several MCDM methods which are AHPSort, UTADIS, FlowSort or ELECTRE- Tri can be used.

In the ranking problems, all alternatives are sorted from best to worst with means of scores etc. To solve the ranking problems, the several MCDM method which are AHP, ANP, MAUT/UTA, MACBETH, PROMETHEE, ELECTRE III, TOPSIS or DEA can be used.

In the description problems, the options and their results are described for understanding of decision problem's characteristics. To solve such problems, the MCDM method which are GAIA, FS-Gaia is used.

In the literature, there are many studies which are related to MCDM problems. These problems were solved with different MCDM methods such as AHP, TOPSIS, PROMETHEE, ELECTRE and VIKOR etc.

3 WEIGHTING METHODS FOR MULTI CRITERIA DECISION MAKING

People encounter decision-making problems many times in their daily lives on different issues and try to find solutions to them. These decision problems may vary from business to business, such as supplier, material, machine, investment selection. More than one criterion is taken into account when evaluating alternatives. The most critical factor affecting the decision is determining the importance levels of the criteria on the alternative. Since each criterion has a different level of importance, the order of the decision to be made between the alternatives is affected by the weights of these criteria. There are many criterion weighting techniques in the literature. These criterion weighting methods are basically divided into three classes: subjective, objective and integrated weighting methods.

Subjective weighting methods include weighting techniques based on the decision maker's experiences and expert opinions. Many questions are asked to decision makers and the answers are analyzed. In cases where there is no agreement between decision makers or inconsistency in decisions, determining the weights takes a long time (Sałabun et al., 2020). There are many subjective weighting methods in the literature, such as Pairwise comparison (AHP), Ranking method, Point allocation, Direct rating, Ratio weighting method, Swing method, Delphi method, Nominal group technique, Simple Multi-attribute Ranking Technique (SMART).

The objective weighting method includes techniques in which the weight of each criterion is determined by mathematical models, without taking into account the decision maker's experiences and expert opinions. There are many objective weighting methods in the literature, such as Ideal point method, Entropy method, Criteria Importance Through Inter-criteria Correlation (CRITIC)).

The integrated weighting method includes techniques based on these two methods. Some weighting methods are shown in Table 3.1. (Odu, 2019). There are many criteria weighting techniques such as SMART, AHP, the measuring attractiveness by a categorical based evaluation technique (MACBETH), the potentially all pairwise rankings of all possible alternatives (PAPRIKA) methodology and conjoint analysis (CA) in the literature.

Table 3. 1
Classification of Weighting Methods

Subjective weighting methods	Pairwise comparison (AHP) Ranking method Point allocation Direct rating Ratio weighting method Swing method Delphi method Nominal group technique SMART
Objective weighting methods	Ideal point method Entropy method CRITIC

Source: Odu, 2019

3.1 Subjective Weighting Methods

In this part of the thesis, subjective weighting methods are going to be discussed.

3.1.1 Pairwise comparison (AHP)

When using the AHP in decision problem, determination of criterion weights is based on pairwise comparisons. Thanks to these pairwise comparisons, a preference matrix is occurred, and the weights of criteria are calculated with the eigenvector of the matrix. And then consistency ratio is defined and evaluated (Saaty, 2003).

The steps of pairwise comparison can be defined with three steps (Zardari et.al, 2015). The first step is to compare each criterion in pairs with the other criteria. The second step is to normalize the pairwise comparison matrix. The third step is to calculate the consistency ratio. If the ratio is larger than 0.10, pairwise comparisons are inconsistent. Otherwise, pairwise comparisons are consistent.

Ahmed (2012) presents the advantages and disadvantages of the pairwise comparison as follows:

+ It is useful when the decision maker is not able to rank the alternatives directly according to a criterion
+ It is easy for calculation and it has clear results
+ When the decision maker uses the method, the decision maker has to consider all elements of the problem (Hajkowicz et al. 2000).

+ It is widely used in estimating the preference values of finite alternatives based on a certain criterion.
+ The method's prioritization process assumes that decision makers can express the strength of their preferences by providing additional background.
+ The methodology used to assign weights to criteria is found to be the most transparent and scientifically sound methodology for the user.
+ It is used to determine the weights of top and bottom level criteria (Petridis, Drogalas, Zografidou, 2021).
- The decision makers choose between two choices, but they are not allowed to convey their sense of distance between these two choices.
- As the size of the problem increases, the number of pairs being compared increases, it becomes difficult for the decision maker to choose between two choices without contradiction and the completion of comparisons can become a difficult task
- Reconciling the inevitable inconsistency of the matrix obtained from decision makers in real life problems is one of the most important challenges.
- In many real-life problems, people's pairwise judgment is rather vague and ambiguous.
- It becomes impossible to make consistent pairwise comparisons as the size of the problem increases. In case of more than nine criteria, meaningless pairwise comparisons occur (Žižović and Pamucar, 2019).

Guo and Yu (2011) used the pairwise comparison method as a subjective weighting method to evaluate railway freight enterprises. Karaman and Çerçioğlu (2015) used the AHP method to determine the criteria weights in a hospital investment project selection problem. In the Üstün and Anagün's (2016) study, the importance weights of Istanbul's districts in terms of disaster management are determined by using the AHP. Şenyiğit and Demirel (2017) used the AHP method to determine seven criteria's weights in the material selection problem for the carbonated soft drink packaging. Mohammad, Anbari, Muhannad and Thameer (2015) compared the pairwise comparison, ranking and trade-off weighting methods in the landfill site selection problem.

3.1.2 Point allocation

In the point allocation method, the decision maker assigns points to all criteria so that the sum of the criteria values is equal to 100. A high value means that the criterion is of high importance (Golaszewski et al., 2012).

Ahmed (2012) presents the advantages and disadvantages of the Point Allocation Method as follows:

- \+ Thank to this method, the decision makers are forced to make trade-offs (Deng et al. 2000).
- \+ With this method, it is possible to assign more importance to one criterion and reduce the importance of the other.
- \+ Converting the information from the decision maker to a weight vector requires the least number of operations (Deng et al. 2000).
- \+ Weights obtained by this method are more reliable than weights obtained by direct rating in a test-retest situation (Von Winterfeldt and Edwards, 1986).
- − The decision maker has a restriction that the sum of all weights must be 100 when assigning weights, and it is difficult for the decision maker to assign weights under this constraint (Demirci et al. 2009).
- − The decision maker has to carefully consider the relative importance. Because increasing the importance of one criterion actually means decreasing the importance of the other criterion, and this evaluation is a difficult task for the decision maker (Deng et al. 2000).

3.1.3 Direct rating

In the direct rating method, the decision maker assigns numerical values to the criteria without trade-offs involved (Ribeiro, Ferreira and Araújo, 2013). There are slight differences between the point allocation and direct rating weighting methods. However, Bottomley, Doyle and Green (2000) stated in the comparison study that the directing rating method is more reliable than the point allocation method.

3.1.4 Ratio weighting method

First, the decision maker orders the criteria in accordance with their significance level, then the decision maker assigns 10 to the criterion with the lowest significance level, and the scoring continues as a multiple of 10 according to the order of significance. Then the values are normalized so that the sum of the weights of the criteria is 1 (Edwards, 1977). Delle and Filippi (2009) used the ratio weighting method as a subjective weighting method for transport projects evaluation problem.

3.1.5 Swing method

In the swing method, the decision maker first assumes that all the criteria are at the worst level and determines the criterion that will improve the general situation the most in case of improvement, selects this criterion as the most important and gives 100 points to that criterion, then continues this process and the value of the next most important criterion will be less than 100 (Von Winterfeldt and Edwards, 1986).

Ahmed (2012) presents the advantages and disadvantages of the Swing Method as follows:

+ This method is very efficient for evaluating, explaining and summarizing weights due to providing of a clear definition of importance, explicit consideration of variation in measurements, a framework for consistent swing weight assessments and a simple but effective framework for presenting and justifying weighting decisions (Von Winterfeldt and Edwards, 1986).
+ This technique involves less computation than techniques involving Pairwise comparisons such as AHP when weighting more than four criteria (Valiris et al. 2005).
+ It is quite fast and the decision makers respond immediately (Hayashi 2000).
− The main disadvantages of the method are that it is based on direct rating and does not include consistency checks.
− This method carries the risk of decision makers responding without considering the consequences of their responses (Hayashi 2000).

Joubert et al. (2003) used the Swing method to determine the weights of criteria to evaluate water supply augmentation and water demand management options.

3.1.6 Delphi method

The Delphi technique is a method of structuring a group communication process, enabling a group of individuals as a whole to deal effectively with a complex problem (Linstone and Turoff, 1975). Using a series of iterative questionnaires, information is collected from experts and this information is distilled (Adler and Ziglio, 1996). Results from previous questionnaires are returned to respondents, who are then allowed to change their answers. Experts are expected to reach a consensus in the second or third round (Angus et al., 2003).

The advantages and disadvantages of the Delphi technique are stated as follows (Ahmed, 2012):

+ One of the most important advantages of this technique is the avoidance of direct confrontation with experts (Afshar et al. 2011).
+ The resulting decision is a group decision and excessive judgments of individual decision makers are avoided (Chou et al. 2008).
- Selflessly designed questionnaires, wrong panelist selections, unreliable results analysis, insufficient feedback and instability of responses are the main disadvantages that can be found in the Delphi technique.
- If more than one round is needed, this causes time and cost (Chou et al. 2008).
- Fatigue occurs in decision makers when there are many topics or questions in the study or when the questions are difficult to understand (Peng and Zhou 2011).

The Delphi method was used to evaluate ecological quality, contaminated sediments, potential of ground water flow and water reservoir management by Wu et al. (2012), Kim et al. (2010), Aalianvari et al. (2010) and Taylor and Ryder (2003), respectively.

3.1.7 Nominal group technique

The nominal group technique is a brainstorming technique based that a team of at least 7 people experienced on the subject produces ideas and evaluates all the ideas. The generated ideas are prioritized by the group and the weights are determined (Abdullah and Islam, 2011).

3.1.8 Simple multi-attribute ranking technique

While determining the weights of the criteria with the SMART method, the decision maker first occurs the order of criteria's importance. Then, starting with the least important criterion, its relative importance is determined according to the next least important criterion. This value is higher than the value assigned to the previous one. Finally, these weights are normalized to give a sum of 100% (Herişçakar, 1999).

The advantages and disadvantages of the SMART are stated as follows:

+ It is useful for decision makers as it is a simple and fast technique (Gu et al. 2012).
+ This technique is widely used because it includes both quantitative and qualitative criteria (Chen and Hou 2004).
− Comparing the importance of the attributes has been determined to be meaningless if the attributes do not reflect the consequence ranges (Von Winterfeldt and Edwards 1986).
− This technique does not consider the interrelationships between parameters (Demirci et al. 2009).
− In this technique, the ratings of alternatives are not relative. Changing the number of alternatives in the problem alone does not change the decision scores of the original alternatives (Valiris et al. 2005).

Hayashi (2000) used the goal programming with SMART for the agricultural resources management and Chen et al. (2010) used the SMART as a subjective weighting method for construction method selection.

3.2 Objective Weighting Methods

In this part of the thesis, objective weighting methods are going to be discussed.

3.2.1 Entropy method

Rudolf Julius Emanuel Clausius (1865) suggested the concept of entropy, from the phonetic and etymological harmony of words, which comes from the Greek word τροπη (trope), meaning transformation, turning, change, and the Greek word ενεργεια (energeia), meaning activity, operation, work.

With the Entropy method, the entropy values of the criteria are calculated by (3.1) developed by Shannon (1948).

$$S(p_1, p_1, \ldots, p_1) = -k \sum_{j=1}^{n} p_j \ln p_j \tag{3.1}$$

where the $p_j$is the entropy of probability distribution and k is a constant.

The Entropy method basically consists of 5 steps: (Ömürbek and Aksoy, 2016)

- The first step of Entropy is the defining of the decision matrix.

- The second step is normalization of the decision matrix.
- The third step is calculation of the Entropy values of each criterion using (3.1).
- The fourth step is computation of the degree of differentiation (d_j) for each Entropy value (E_j) with (3.2).

$$d_j = 1 - E_j, \qquad \forall j \tag{3.2}$$

- Finally, the fifth step is to compute the weights for each criterion.

Advantages and disadvantages of the Entropy method are stated as follows (Ahmed, 2012):

+ With this method, unbiased relative criterion weights are calculated quite simply (Srdjevic et al. 2004).
+ Entropy method is a reliable method for determining both contrast intensity and conflict of criteria (Srdjevic et al. 2004).
+ It allows for quantitative evaluation of efficiency and benefit/cost parameters (Singh 2000).
+ It adequately takes into account the value information of all monitoring sections provided in order to maintain the balance in the evaluation. It weakens the false effect caused by some abnormal values and makes the evaluation result more accurate.
− One of the most important disadvantages of this method is that expert opinion is not taken into account when calculating the weights and it is only the determinant of entropy values.

The entropy method was used in the service evaluation of airlines (Bakır and Atalık, 2018), supplier selection (Shemshadi et al., 2011), tourism destination evaluation (Zhang et al., 2011), and groundwater sustainability evaluation (Chen et al., 2015).

3.2.2 Criteria importance through inter-criteria correlation

Diakoulaki et al. (1995) developed a method called CRITIC, which uses correlation analysis to determine contrasts between criteria. The method consists of four steps:

First step is to normalize the decision matrix.

Second step is that the contrast between the jth criteria and criteria is calculated by (3.3).

$$\sum_{k=1}^{m} 1 - l_{jk} \tag{3.3}$$

where l_{jk} shows the correlation coefficient between criterion values

The third step is computation of the amount of information C_j by jth the criteria by (3.4).

$$C_j = \sigma_j \sum_{k=1}^{m} (1 - l_{jk}) \tag{3.4}$$

where The C_j is amount of information.

The fourth step is calculation of the weights (w_j) of the criteria by (3.5).

$$w_j = C_j \frac{1}{\sum_{k=1}^{m} C_k} \tag{3.5}$$

where the w_j is weight of criteria.

The advantages and disadvantages of the CRITIC method are stated as follows:

+ This method determines weights taking into account contrast intensity and conflict (Jahan et al. 2012).
+ The weights determined include the information transmitted from all criteria. In addition, objective weights provide insight into the nature of dilemmas created by the existence of opposing criteria and allow the inclusion of interdependent criteria (Jahan et al. 2012).
− Complex modeling process; for example, there is no specific requirement for normalization in the Correlation coefficient and Standard deviation method (Mustajoki et al. 2004).

The CRITIC method was used in the air conditioner selection (Vujicic et al., 2017), laptop selection (Ulutaş and Cengiz, 2018) and an application on UPS Selection (Demircioğlu and Coşkun, 2018).

3.2.3 Mean weight

In the mean weight method used in the absence of any information from the decision maker, the weights of the criteria are calculated by (3.6). In this method, all criteria are of equal importance (Zardari et al., 2015).

$$w_j = \frac{1}{n} \tag{3.6}$$

where the w_j is weight of criteria and n is number of criteria.

3.2.4 Standard deviation method

The standard deviation method calculates the weights of criteria by (3.7) and (3.8) (Jahan et al., 2012)

$$w_j = \frac{\sigma_j}{\sum_{j=1}^{n} \sigma_j} \ , j = 1, \ldots, n \tag{3.7}$$

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m} (x_{ij} - \overline{x_j})^2}{m}} \ , j = 1, \ldots, n \tag{3.8}$$

where the w_j is weight of criteria and σ_j is standard deviation.

This method is not as precise as the entropy approach because the outcomes can be affected by the range of different criteria. The normalization approach in entropy prevents this situation (Jahan et al., 2012).

3.2.5 Statistical variance procedure

Statistical variance procedure is an objective weighting method (Zardari et al., 2015).. It consists of two steps. First step is calculation of statistical variance by using (3.9). Second step is calculation of the objective weight by (3.10).

$$V_j = \left({}^{1}\!/_{n}\right) \sum_{i=1}^{n} (x_{ij}^{*} - (x_{ij}^{*})_{mean})^2 \tag{3.9}$$

$$w_j^{o} = \frac{V_j}{\sum_{i=1}^{m} V_j} \tag{3.10}$$

where V_j is statistical variance, x_{ij} is average value of data set of points and w_j^o is the objective weight.

3.2.6 Potentially all pairwise rankings of all possible alternatives

PAPRIKA method includes the decision maker pairwise ranking all potentially undominated pairs of all possible alternatives (Hansen and Ombler, 2008).

3.3 Integrated Weighting Methods

Subjective and objective weighting methods have advantages as well as disadvantages. For example, in subjective weighting methods, error may be inevitable in the weights given in accordance with the decision of the decision maker. Likewise, in objective weighting methods, the weights may be inconsistent with the subjective preferences of the decision maker. For this reason, some scientists have developed various weighting methods by integrating both methods (Jahan et al., 2012).

3.3.1 Multiplication synthesis

In the Multiplication synthesis method, the combination weight is calculated by (3.11).

$$w_j = \frac{w_{1j} w_{2j}}{\sum_{j=1}^{n} w_{1j} w_{2j}} \tag{3.11}$$

where w_j is combination weight, $w_{1j}$is subjective weight and w_{2j} is objective weight of jth criteria (Wang, 2009).

3.3.2 Subjective and objective weight integrated approach method

In the SOWIA method, the combination weight is calculated by (3.12) (Zaher et.al, 2018).

$$w_{jb} = \propto O_j + (1 - \propto) S_j, \quad \propto \geq 0 \tag{3.12}$$

where w_j is combination weight, S_j is subjective weight and O_j is objective weight of jth criteria, $\propto$ is the objective decision weight.

In the context of the planned research, the hybrid weighting method represents a crucial element in addressing the MCDM problems.

4 THERMOPLASTIC MATERIALS USED IN PRODUCTION

The selection of materials used by businesses operating in various sectors such as White Goods, Automotive, Heating Ventilating and Air Conditioning, Sanitary Ware, Electronics is of vital importance for businesses. The right material selection can affect various factors such as cost, product durability, and customer satisfaction. With the development of technology, plastic materials have become more durable and efficient, and have become the solution of the future in terms of production. Complex designs can be easily made with thermoplastic materials without considering production limits. Less energy is consumed in production processes compared to metal materials and they can be recycled more easily. They are also more advantageous in terms of cost. Today, many metal materials are replaced with thermoplastics and this situation will increase in the future.

Polymers are solid, high molecular weight, long-chain substances formed by the combination of molecules called monomers. These substances are examined in two different classes, thermoplastics, and thermosets, separated according to their properties.

Thermoplastic materials exhibit the ability to become pliable upon heating and regain their rigidity once cooled. This behavior is both reversible and repeatable, allowing these materials to be reprocessed multiple times. Their production typically involves the combined use of heat and pressure. Common examples of thermoplastics include polyethylene, polystyrene, poly(ethylene terephthalate), and poly(vinyl chloride).

In contrast, thermosetting polymers form cross-linked structures during processing, which causes them to solidify permanently. Once set, they do not become soft again, even when exposed to high temperatures. Vulcanized rubbers, epoxies, phenolics and some polyester resins are examples of these thermosetting polymers (Callister and Rethwisch, 2020).

The use of thermoplastic materials is increasing day by day, thanks to their advantages such as lightness, reusability, superior ballistic performance, explosion resistance and easy shaping ability (Akkaya et. al., 2021). Thermoplastics, one of the widely used material types in the industry, are today used in the interior and exterior parts of vehicles in the automotive industry (Ünal, 2013), in wall roof coverings, installation pipes, window glass in the construction industry thanks to their various strengths (Demirarslan,2019), and in control panels, belt pulley mechanisms, and filtering systems in the white goods industry (Vasić and Schiesser, 2010). Characteristics, and typical applications for a number of thermoplastics are shown in Annex-1a. For applications where electrical properties are excellent, fluorocarbons, polypropylenes and polystyrenes are particularly suitable. These materials are used in a variety of components. For example, polypropylenes are used in packaging film, automotive kick panels, fibers, and luggage.

The mechanical features of polymeric materials are commonly described through features such as elastic modulus, yield strength, and tensile strength. These characteristics are determined by performing standard stress strain tests. A summary of the mechanical features at room temperature for several widely used polymers is presented in Annex-1b.

The melting temperature and glass transition temperature are critical thermal properties that influence how polymers are utilized in various usages. In particular, the glass transition temperature marks the maximum use temperature for amorphous polymers in their glassy state (Callister and Rethwisch, 2020). In Annex-1c, these thermal properties are presented for several commonly used polymeric materials is provided.

Most polymers are insulating materials at room temperature. Insulating materials, electrical conductivity increases with increasing temperature. Typical room temperature electrical conductivities for thirteen polymers are shown in Annex-1d.

Thermal properties describe how a material responds when exposed to heat. Heat capacity, thermal expansion, and thermal conductivity are important criteria for solids. $\propto_l$ and $\mathbf{c_p}$ represent the linear coefficient of thermal expansion that indicates how much a material expands when heated and the constant external pressure, respectively. (Callister and Rethwisch, 2020). Thermal properties for various polymers are shown in Annex-1e. Cp represents the constant external pressure.

The ratio of substance's mass in a unit volume is called density. Density is an important parameter in the design of parts where the weight of the material is critical. Room temperature density values for various polymers are shown in Annex-1f.

Modules of elasticity that is the measurement of a material's elasticity, is a critical property in polymers. The values of elastic modulus at room temperature for various polymers are shown in Annex-1g.

Poisson's ratio is a parameter that expresses the ratio of lateral and axial stresses (Callister and Rethwisch, 2020). Room temperature Poisson’s ratio values for various polymers are shown in Annex-1h.

The yield strength is the maximum stress that a material can carry without exceeding its elastic limit. When a material encounters a load above this value, irreversible deformation begins to occur. Tensile strength is the highest tensile stress that a material can withstand without yielding or breaking. Ductility is a measure of the degree of plastic deformation that continues at the moment of fracture (Callister and Rethwisch, 2020). Typical room temperature yield strength, tensile strength, and ductility (percent elongation) values for various polymers are shown in Annex-1i.

Fracture toughness is a critical mechanical term, especially for structural materials, that indicates the resistance of a material to fracture when a crack is present (Callister and Rethwisch, 2020). Room temperature plane strain fracture toughness and strength values for various polymers are shown in Annex-1j.

The coefficient of thermal expansion is a material property that measures how much a material expands or contracts when its temperature changes (Callister and Rethwisch, 2020). Room temperature linear coefficient of thermal expansion values for various polymers are shown in Annex-1k.

Thermal conductivity refers to a material's ability to conduct heat through its structure. The Annex-1l presents the thermal conductivity values at room temperature for a selection of commonly used polymeric materials.

The Annex-1m provides specific heat values of various polymer materials measured at room temperature.

Electrical resistivity is a parameter that represents a material’s electrical resistance, or how strongly it resists electric current. The Annex-1n provides electrical resistivity values of various polymer materials measured at room temperature.

Costs for various polymers are shown in Annex-1o. Pricing information was collected by Callister and Rethwisch (2020) from at least three distributors/manufacturers through January 2007. Costs are in US dollars per kilogram.

In a world where our resources are limited and more resources are used with growth, and we directly affect the environment with more production and more consumption, a sustainable lifestyle is important. The way to minimize the environmental impact of growth that accelerated after the Second World War is green sustainable growth.

At this point, the United Nations (UN) Conference on Human Environment held in Stockholm, Sweden in 1972 pioneered international environmental management. Then, in 1972, the United Nations Environmental Program (UNEP) was established within the UN in order to protect the environment and ensure sustainable development (Türk and Erciş, 2019).

In 1985, the World Commission on Environment and Development (WCED) was established (IISD and UNEP, 2014). In 1990, the International Institute for Sustainable Development (IISD) under the auspices of the UN began its activities. In 1992, the Rio Conference (United Nations Conference on the Human Environment –UNCHE) was held in Rio, Brazil. The concepts of environment and development were brought together in this conference (Clémençon, 2012). The decisions taken at the Rio Conference in 1992 were reviewed and updated at the United Nations Conference on Sustainable Development (UNCSD), which was held in Rio in 2012 (IISD and UNEP, 2014).

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal dated 1989, the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade dated 1998 and the Stockholm Convention on Persistent Organic Pollutants dated 2001 contain provisions regulating international trade. The Kyoto Protocol of 1997 and the Paris Climate Agreement of 2015 are more related to production and production methods (Parıltı, 2019).

The use of internationally standardized Environmental Management Systems for environmental planning in manufacturing companies (Graedel et al., 1995). The declaration published in the World Business Council for Sustainable Development in 1990 formed the basis for an international ISO 14001 standard published by the International Organization for Standardization (ISO) in Switzerland in 1996 (Marcus and Willing, 1997). At this point, with global growth, there is a lot of production and this situation causes a large amount of carbon emissions to the world due to industrial reasons. With the development of technology, the significance of plastics is raising day by day. At this point, it is closely related to the selection of materials during design and the carbon dioxide emissions accordingly. Carbon Dioxide ($kg\ CO_2e$) amounts for various thermoplastics are shown in Table 4.16.

Table 4. 1
Carbon Dioxide ($\boldsymbol{kg\ CO_2e}$*) for Various Thermoplastics*

Material	**Carbon Dioxide (kg $\mathbf{CO_2}$e)**
ABS (Acrylonitrile butadiene styrene)	2.690
ABS 30% glass fibre	2.255
Ionomer	11.582
PA 6 (Nylon 6, Polyamide 6)	4.520
PA 6 30% glass fibre	3.536
PA 66 (Nylon 66, Polyamide 6-6)	6.400
PA 66 30% glass fibre	4.852
PB-1 (Polybutylene)	1.630
PC (Polycarbonate)	3.400
PC 30% glass fibre	2.752
PE (HDPE)	1.800
PE (LDPE)	1.870
PE (LLDPE)	1.790
PE (Polyethylene) expanded	2.449
PET (Polyethylene terephthalate) amorphous	2.068
PMMA (Polymethyl methacrylate)	3.900
POM (Polyoxymethyleen, polyacetaal)	3.200
PP (Polypropylene)	1.630
PP GF30	1.513
PS (EPS, expandable polystyrene, white)	2.280
PTFE (Teflon, Polytetrafluoroethylene)	12.000
PTT (Polyltrimethylene terephthalate)	3.324
PVOH and PVA	3.251
PVC (Polyvinylchloride suspension polymerised)	2.220
PVDC (Polyvinyliden chloride)	4.577
PAN Polyacrylonitrile fibres	5.130

Source: Sustainability Impact Metrics, 2024

5 RESEARCH METHODOLOGY

In this chapter, the proposed decision analysis is introduced. Up to this stage of the thesis, information about the subject is given. The content of this chapter examines the methodology used in this thesis and focuses extensively on the proposed decision analysis and details. By examining these topics comprehensively, Chapter 5 provides the basis for the subsequent analyses performed in the thesis and the interpretation of the results. For the analyses performed in this thesis, SOWIA is the primary method along with AHP and Entropy.

5.1 Proposed Decision Analysis

In this section of the thesis, the steps of the proposed decision analysis proposed to guide structural designers in material selection are defined. The first steps after the project is approved are to establish the team and share information about the project with the team. The third step includes the determination of alternatives and criteria by brainstorming by the team. Then, in the fourth step, the criteria weights are determined with the hybrid approach. This hybrid approach, SOWIA, consists of 2 basic methods. In this study, the first method is the subjective method AHP, and the second method is the objective method Entropy. In the fifth step, the criteria values of the alternatives are clarified. In the sixth step, the ranking of the alternative materials is obtained by using the TOPSIS method. The seventh and eighth steps include the re-evaluation of the results by team and the implementation of the selected material. The last step includes regular updates about the status of the selected material. The steps of the proposed decision analysis are as follows and the details are specified in this section of the thesis.

Step 1: Approval of the project

Step 2: Determination of a team including expert designers in accordance with the project schedule

Step 3: Informing the team about the details of the project by the project designer.

Step 4: Conducting the brainstorming session by the team to determine the criteria with alternatives.

Step 5: Determination of criterion weights using the hybrid method

Step 6: Clarifying the criteria values of usable material alternatives.

Step 7: Using the TOPSIS method to rank the materials to be used in the design.

Step 8: Evaluation of results by the team.

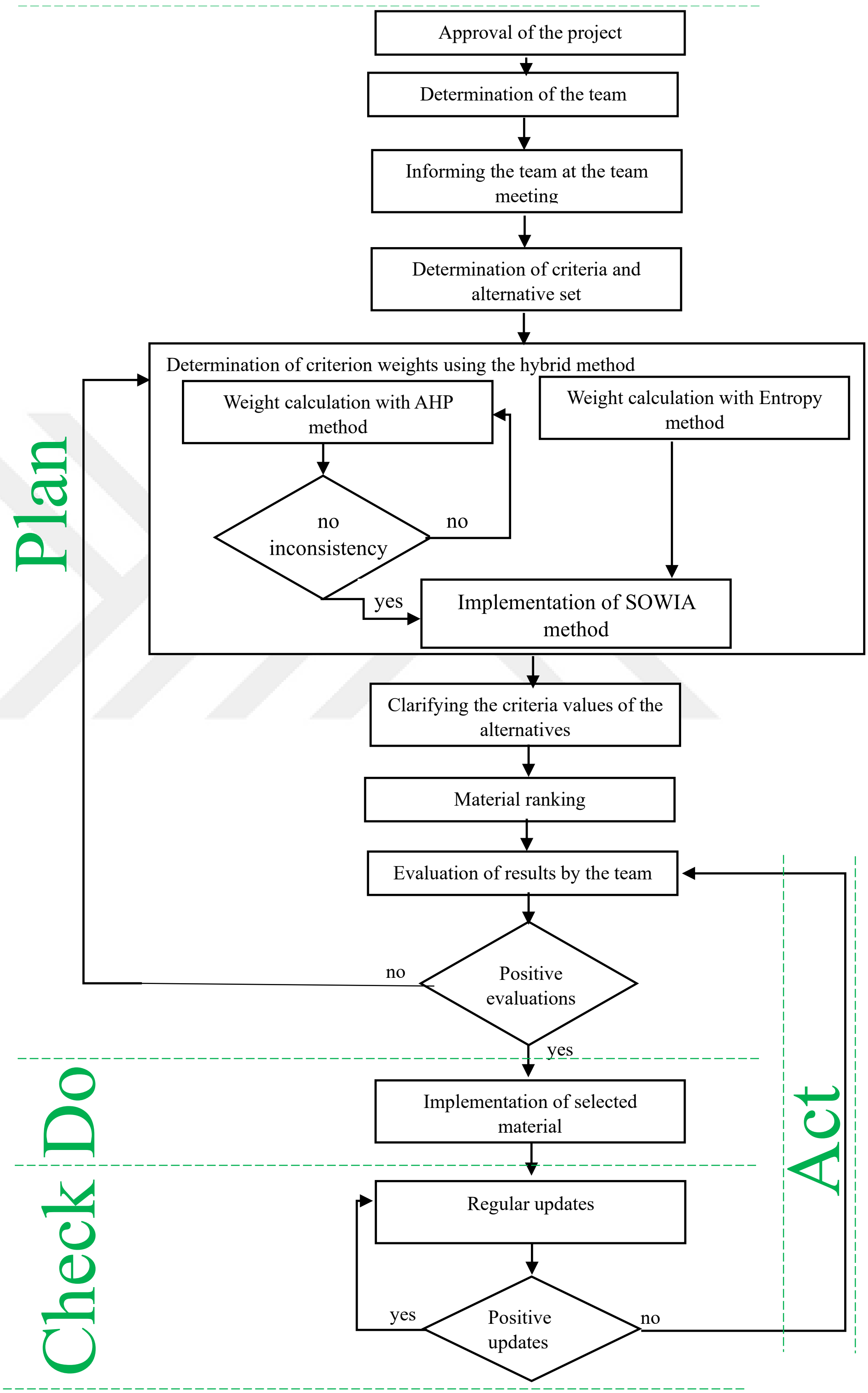
Step 9: Implementation of selected material.

Step 10: Regular updates on the status of selected material.

The proposed decision analysis process is given in Figure 5.1.

Figure 5. 1

Process of Proposed Decision Analysis Integrated with PDCA Cycle



5.2 Determination of the Team

In the context of the research, firstly the records of the chamber of industry and commerce in Eskişehir province were examined and the companies working in the relevant field were determined. The reports produced by the companies were examined and the people who had experience in the subject were determined and invitations were sent to these people. AHP method does not require a large sample size because it is a subjective method (Doloi, 2008; Dias and Ioannou, 1996; Lam and Zhao, 1998). Saaty & Özdemir (2014) state that it is sufficient to have one or more experts who are experts in their field of expertise in the sample. Cheng and Li (2002) stated in their study that using a large sample may be useless in AHP, that experts may give arbitrary answers, and that this situation will affect its consistency. For this reason, this study, which was carried out with the people who accepted the invitation, was completed with 4 experts. These expert designers are named Expert 1, Expert 2, Expert 3 and Expert 4. In the study, the experts' backgrounds are given in Table 5.1.

Table 5. 1
Experts' Backgrounds

Name	**Background**		
	Major of the expert	**Years of experience**	**Area of expertise**
Expert 1	Mechanical Engineering	13	Structural Design
Expert 2	Mechanical Engineering	5	Structural Design
Expert 3	Mechanical Engineering	6	Structural Design
Expert 4	Mechanical Engineering	10	Structural Design

5.3 Team Meeting

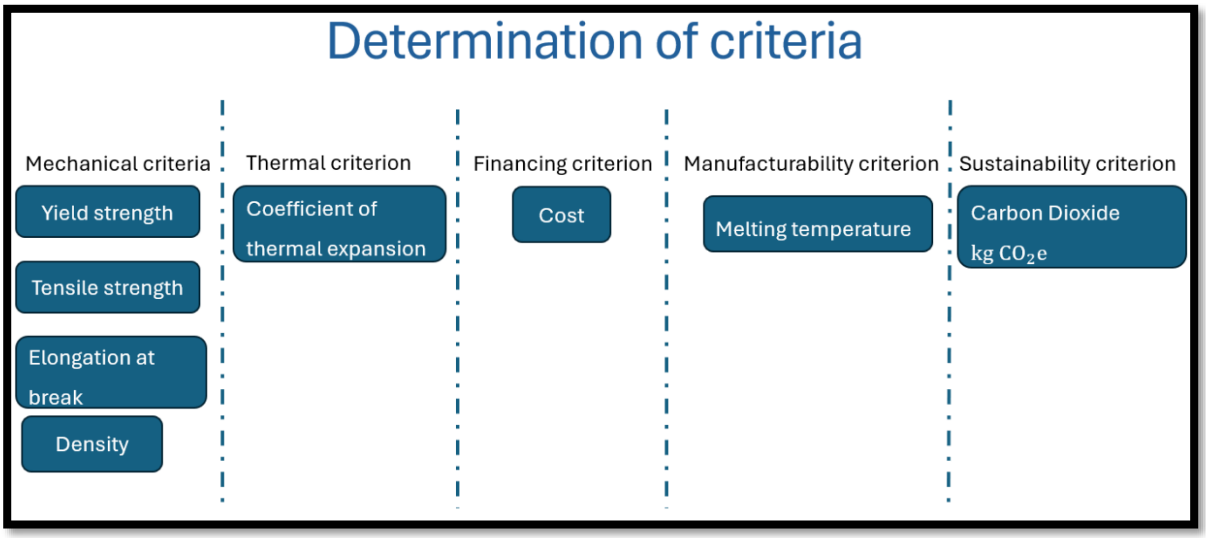
In the team meeting to be organized by the project designer; the project designer informs the experts in the team about the details and schedule of the project and leads the meeting. In this study, the project designer role is undertaken by the thesis author. The team is informed about the details of the project by the project designer. In the study, the design of a mechanically stressed functional part exposed to temperature difference is discussed. The team meeting was held online and the interviews were conducted in this meeting.

5.4 Determination of Criteria and Alternative Set

In this study, a brainstorming session in a group setting to determine the criteria and alternative sets. In the group brainstorming session, group members (the expert team) list all the (sub) criteria and alternatives that they consider important for the project. The group facilitator (the project designer) groups similar sub-criteria and relates each sub-criteria cluster to an overarching criterion. The proposed decision hierarchy is discussed and modified in the group until each level consists of mutually exclusive, clear, comprehensive and equally important (sub)criteria (Hummel et al, 2014).

A brainstorming session was carried out with a group of four experts that working in the sector. During this process, the identified criteria were divided into categories, and overlapping elements were consolidated to form unified items. The criteria were categorized into mechanical, thermal, financing, manufacturability and sustainability. The output of brainstorming with 8 criteria is given in Figure 5.2. For the criteria selection, after discussion and brainstorming with experts we have short listed the Yield strength, Tensile strength, Elongation at break, Density, Coefficient of thermal expansion, Cost, Melting temperature and Carbon Dioxide kg CO_2e.

Figure 5. 2
Output of Brainstorming with 8 Criteria



The material selection criteria in the proposed decision analysis are given in Table 5.2.

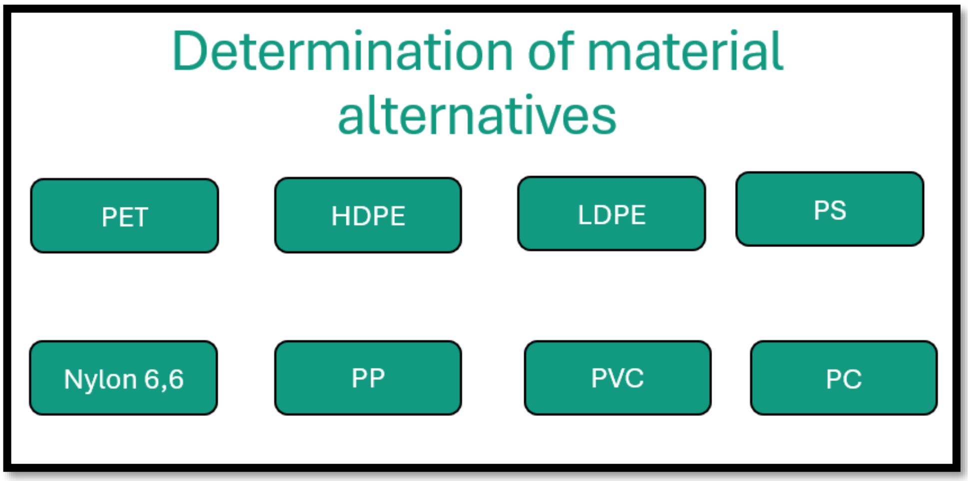
Table 5. 2
Material Selection Criteria

Group	Representation of criterion	Criteria
Mechanical criteria	Me1	Yield strength
	Me2	Tensile strength
	Me3	Elongation at break
	Me4	Density
Thermal criterion	T1	Coefficient of thermal expansion
Financing criterion	F1	Cost
Manufacturability criterion	Ma1	Melting temperature
Sustainability criterion	S1	Carbon Dioxide kg CO_2e

Brainstorming was conducted for determination of alternatives too. The output of brainstorming with 8 alternatives is given in Figure 5.3. For the alternative selection, after discussion and brainstorming with experts we have short listed PET, HDPE, LDPE, PS, PP, Nylon6,6, PVC and PC.

Figure 5. 3

Output of Brainstorming with 8 Alternatives



5.4.1 Yield strength

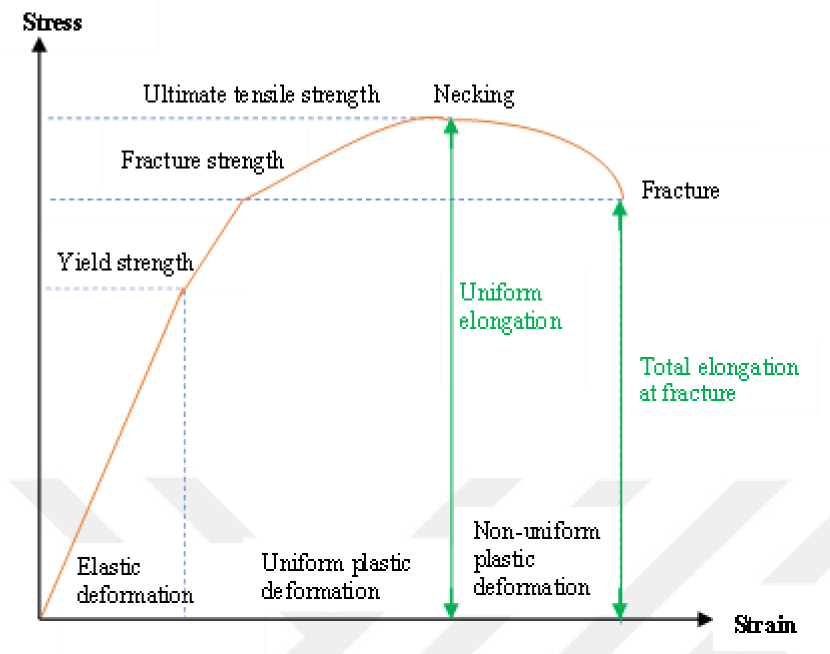
Yield strength refers to the load resistance of the material corresponding to the end of the elastic deformation phase before it transitions to the plastic deformation phase under a certain load. For this reason, yield strength is considered as a critical criterion in designs where material strength is important.

5.4.2 Tensile strength

Tensile strength refers to the load strength of the material corresponding to the end of the plastic deformation phase before it passes to the rupture (irreversible deformation) phase under a certain load. Figure 5.4 shows the stress strain relationship under uniaxial tensile load.

Figure 5. 4

Stress Strain Relationship



5.4.3 Elongation at break

Elongation at break is the percentage expression of the elongation amount of the material under tensile load. Figure 5.4 shows the uniform elongation and total elongation at fracture under uniaxial tensile load.

5.4.4 Density

Density is an important factor that expresses the weight of a material in a given volume, which affects the performance of the material.

5.4.5 Coefficient of thermal expansion

Thermal expansion coefficient is the amount of elongation of the material per unit temperature.

5.4.6 Cost

Cost refers to the material's process, logistics and raw material costs. Costs are affected by transportation method differences (air, sea, rail, road), customs rules, and taxes. In this research; the costs of various polymers are shown in Annex-1o. Pricing information was collected by Callister and Rethwisch (2020) from at least three distributors/manufacturers up to January 2007. Costs are in US dollars per kilogram.

5.4.7 Melting temperature

Melting temperature refers to the temperature that the raw material must reach in order to be shaped. As the melting temperature of a material increases, its formability tends to decrease due to the greater amount of energy required for processing.

5.4.8 Carbon dioxide $kg\ CO_2e$

Another important point in material selection is the environmental impact of the material. At this point, Carbon Dioxide Equivalent is taken into consideration. The equivalent refers to the unit of measure of the warming effect of greenhouse gases.

5.5 Determination of Criterion Weights

Criterion weights are determined using the hybrid weighting method. The SOWIA method calculates the weights of criteria by (5.13).

$$w_{jb} = \propto O_j + (1 - \propto) S_j, \qquad 0 \leq \propto \leq 1 \tag{5.13}$$

where the O_j is objective criterion weights (ENTROPY), the S_j is subjective criterion weights (AHP) and $\propto$ is objective factor decision weight (0.4). The steps of ENTROPY and AHP methods are explained in Chapter 3.

5.6 Clarifying the Criteria Values of Usable Material Alternatives

The values of the criteria determined for the alternatives were determined by examining the tables in Chapter 4. Criterion values of the determined material alternatives are given in Table 5.3.

Table 5. 3

Criterion Values of the Determined Material Alternatives

Representation of criterion	***Criteria***	***LDPE***	***HDPE***	***PVC***	***PP***	***PS***	***Nylon 6,6***	***PET***	***PC***
Me1	Yield Strength	11.75	29.65	42.75	34.1	47	63.8	59.3	62.1
Me2	Tensile Strength	19.85	26.55	46.2	36.2	58.8	85.2	60.35	67.6
Me3	Elongation at break	375	605	60	350	1.85	157.5	165	130
Me4	Density	0.925	0.959	1.44	0.905	1.05	1.14	1.35	1.34
T1	Coefficient of thermal expansion	290	152	135	163	120	144	117	122
F1	Cost	1.725	1.475	1.475	1.375	1.75	3.6	1.625	3.85
Ma1	Melting temperature	115	137	212	175	240	265	265	265
S1	Carbon Dioxide	1.870	1.800	2.220	1.630	2.280	6.400	2.068	3.400

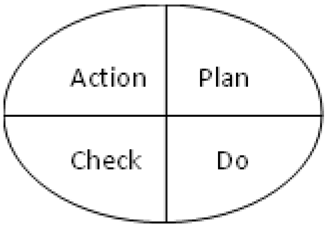
5.7 Material Ranking

The TOPSIS method is used in ranking the materials to be used in the design. Calculations and results of the method are included in Chapter 6.

5.8 Evaluation, implementation and monitoring of selected material

The TOPSIS method is used in ranking the materials to be used in the design. The suitability of the first material in the obtained ranking for the project is evaluated by experts. Following the evaluation, the selected material is implemented into the project and the status of the selected material is regularly observed as part of the Plan-Do-Check-Act (PDCA) cycle. Imai (1886) stated that Japanese managers transformed the Deming wheel into the current PDCA cycle in Figure 5.4.

Figure 5. 5
PDCA Cycle



6 RESULTS AND DISCUSSION

In this last section of the study, firstly the calculations and results of the proposed decision analysis defined in Chapter 5 are given. Then these results are evaluated. In the following sections, the contributions to the literature and notes on possible future studies are given.

6.1 AHP

AHP method does not require a large sample size because it is a subjective method (Doloi, 2008; Dias and Ioannou, 1996; Lam and Zhao, 1998). Saaty & Özdemir (2014) state that it is sufficient to have one or more experts who are experts in their field of expertise in the sample. Some researchers state that the judgments of even a single qualified expert may be sufficient, citing the method's reliance on expert judgments (Golden et al., 1989; Tavares et al., 2008; Abudayyeh et al., 2007). In addition to this situation, Cheng and Li (2002) stated in their study that using a large sample may be useless in AHP, that experts may give arbitrary answers, and that this situation will affect its consistency.

The study was carried out by a team consisting of 4 structural designer experts: Expert 1, Expert 2, Expert 3 and Expert 4. Experts were used to calculate the criterion weights using the AHP method. When using the method, pairwise comparison was based on Saaty's scale. Saaty's scale of pairwise comparison is given in Table 6.1.

Table 6. 1
Saaty's Scale of Pairwise Comparison

Numerical Value: Definition	***Explanation***
1: Equal Significance	Both activities are considered to contribute equally toward achieving the objective
3: Moderate Significance	Experience and Judgements slightly favor one activity over another
5: Strong Significance	Judgments and past experiences strongly indicate a preference for one activity over the other.
7: Very Strong	One activity is heavily favored based on practical relevance and clear dominance.
9: Extreme Significance	The preference for one activity is supported by the highest level of evidence and justification.
2, 4, 6, 8: Intermediate Values	These values are used to express a compromise between the importance levels listed above.

6.1.1 Pairwise comparison matrix

In the AHP method, which is carried out in order to compute the weights of the criteria, first of all, a survey was presented to the experts so that they could compare the criteria in pairs. The survey template is included in ANNEX-1. Table 6.2-5 was created with the scores given by the experts for the criteria. The scores of the experts' criteria relative to each other are important from the pairwise comparison matrixes. For example, it is seen in Table 6.2 that there is no difference between Criteria Me2 and Me1 according to Expert-1. The situation that should be noted in these matrixes is that if the score of a criterion is exactly the opposite compared to another criterion, it is expressed as 1 divided by 1. In addition to this situation, the diagonal elements of these matrices are equal to 1. Pairwise comparison matrixes of experts' are given in Table 6.2-5.

Table 6. 2
Pairwise Comparison Matrix of Expert-1

Expert-1	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
Me2	1	1	7	3	2	2	9	3
Me1	1	1	4	3	2	2	9	3
Me3	0.1428	0.25	1	0.3333	0.125	0.125	2	0.125
Ma1	0.3333	0.3333	3	1	0.2	0.1428	7	0.1666
F1	0.5	0.5	8	5	1	2	9	3
T1	0.5	0.5	8	7	0.5	1	6	3
Me4	0.1111	0.1111	0.5	0.1428	0.1111	0.1666	1	0.2
S1	0.3333	0.3333	8	6	0.3333	0.3333	5	1
Sum	3.9206	4.0277	39.5	25.4761	6.2694	7.7678	48	13.4916

Table 6. 3
Pairwise Comparison Matrix of Expert-2

Expert-2	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
Me2	1	1	9	3	1	2	9	1
Me1	1	1	9	3	1	2	8	1
Me3	0.1111	0.1111	1	0.3333	0.1111	0.25	6	0.125
Ma1	0.3333	0.3333	3	1	0.2	0.3333	6	0.1666
F1	1	1	9	5	1	4	7	3
T1	0.5	0.5	4	3	0.25	1	9	0.25
Me4	0.1111	0.125	0.1666	0.1666	0.1428	0.1111	1	0.1111
S1	1	1	8	6	0.3333	4	9	1
Sum	5.0555	5.0694	43.1666	21.5	4.0373	13.6944	55	6.6527

Table 6. 4
Pairwise Comparison Matrix of Expert-3

Expert-3	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
Me2	1	1	5	3	0.1428	0.5	8	0.5
Me1	1	1	5	2	0.125	0.3333	8	0.3333
Me3	0.2	0.2	1	0.3333	0.1111	0.2	5	0.1428
Ma1	0.3333	0.5	3	1	0.1111	0.2	3	0.25
F1	7	8	9	9	1	6	9	4
T1	2	3	5	5	0.1666	1	7	3
Me4	0.125	0.125	0.2	0.3333	0.1111	0.1428	1	0.1428
S1	2	3	7	4	0.25	0.3333	7	1
Sum	13.6583	16.825	35.2	24.6666	2.0178	8.7095	48	9.3690

Table 6. 5
Pairwise Comparison Matrix of Expert-4

Expert-4	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
Me2	1	2	5	5	0.25	0.3333	8	1
Me1	0.5	1	3	2	0.1666	0.2	8	0.5
Me3	0.2	0.3333	1	0.3333	0.125	0.1428	5	0.1428
Ma1	0.2	0.5	3	1	0.125	0.1666	3	0.2
F1	4	6	8	8	1	5	9	4
T1	3	5	7	6	0.2	1	5	2
Me4	0.125	0.125	0.2	0.3333	0.1111	0.2	1	0.1428
S1	1	2	7	5	0.25	0.5	7	1
Sum	10.025	16.9583	34.2	27.6666	2.2277	7.5428	46	8.9857

6.1.2 Normalized matrix

In order to normalize the pairwise comparison matrices constructed in the previous section, each element is divided by the sum of its corresponding column. The sum of each column of the normalized matrix is equal to 1. Normalized matrixes of the comparison matrixes are shown in Table 6.6-9. The purpose of normalizing the matrix is to convert the criteria, each with a different unit, to a common scale and comparable units.

Table 6. 6
Normalized Matrix of Expert-1

Expert-1	Me2	Me1	Me3	Ma1	F1	T1	Me4	**S1**	**wi**
Me2	0.255	0.2482	0.1772	0.1177	0.3190	0.2574	0.1875	0.2223	0.2230
Me1	0.255	0.2482	0.1012	0.1177	0.3190	0.2574	0.1875	0.2223	0.2135
Me3	0.0364	0.0620	0.0253	0.0130	0.0199	0.0160	0.0416	0.0092	0.0279
Ma1	0.0850	0.0827	0.0759	0.0392	0.0319	0.0183	0.1458	0.0123	0.0614
F1	0.1275	0.1241	0.2025	0.1962	0.1595	0.2574	0.1875	0.2223	0.1846
T1	0.1275	0.1241	0.2025	0.2747	0.0797	0.1287	0.125	0.2223	0.1606
Me4	0.0283	0.0275	0.0126	0.0056	0.0177	0.0214	0.0208	0.0148	0.0186
S1	0.0850	0.0827	0.2025	0.2355	0.0531	0.0429	0.1041	0.0741	0.1100
Sum	1	1	1	1	1	1	1	1	1

Table 6. 7
Normalized Matrix of Expert-2

Expert-2	Me2	Me1	Me3	Ma1	F1	T1	Me4	**S1**	**wi**
Me2	0.1978	0.1972	0.2084	0.1395	0.2476	0.1460	0.1636	0.1503	0.1813
Me1	0.1978	0.1972	0.2084	0.1395	0.2476	0.1460	0.1454	0.1503	0.1790
Me3	0.0219	0.0219	0.0231	0.0155	0.0275	0.0182	0.1090	0.0187	0.0320
Ma1	0.0659	0.0657	0.0694	0.0465	0.0495	0.0243	0.109	0.0250	0.0569
F1	0.1978	0.1972	0.2084	0.2325	0.2476	0.2920	0.1272	0.4509	0.2442
T1	0.0989	0.0986	0.0926	0.1395	0.0619	0.0730	0.1636	0.0375	0.0957
Me4	0.0219	0.0246	0.0038	0.0077	0.0353	0.0081	0.0181	0.0167	0.0170
S1	0.1978	0.1972	0.1853	0.2790	0.08256	0.29208	0.1636	0.1503	0.1935
Sum	1	1	1	1	1	1	1	1	1

Table 6. 8
Normalized Matrix of Expert-3

Expert-3	Me2	Me1	Me3	Ma1	F1	T1	Me4	**S1**	**wi**
Me2	0.0732	0.0594	0.1420	0.1216	0.0707	0.0574	0.1666	0.0533	0.0930
Me1	0.0732	0.0594	0.1420	0.0810	0.0619	0.0382	0.1666	0.0355	0.0822
Me3	0.0146	0.0118	0.0284	0.0135	0.0550	0.0229	0.1041	0.0152	0.0332
Ma1	0.0244	0.0297	0.0852	0.0405	0.0550	0.0229	0.0625	0.0266	0.0433
F1	0.5125	0.4754	0.2556	0.3648	0.4955	0.6889	0.1875	0.4269	0.4259
T1	0.1464	0.1783	0.1420	0.2027	0.0825	0.1148	0.1458	0.3202	0.1666
Me4	0.0091	0.0074	0.0056	0.0135	0.0550	0.0164	0.0208	0.0152	0.0179
S1	0.146	0.1783	0.1988	0.1621	0.1238	0.0382	0.1458	0.1067	0.1375
Sum	1	1	1	1	1	1	1	1	1

Table 6. 9

Normalized Matrix of Expert-4

Expert-4	Me2	Me1	Me3	Ma1	F1	T1	Me4	**S1**	**wi**
Me2	0.0997	0.1179	0.1461	0.1807	0.1122	0.0441	0.1739	0.1112	0.1232
Me1	0.0498	0.0589	0.0877	0.0722	0.0748	0.0265	0.1739	0.0556	0.0749
Me3	0.0199	0.0196	0.0292	0.0120	0.0561	0.0189	0.1086	0.0158	0.0350
Ma1	0.0199	0.0294	0.0877	0.0361	0.0561	0.0220	0.0652	0.0222	0.0423
F1	0.3990	0.3538	0.2339	0.2891	0.4488	0.6628	0.1956	0.4451	0.3785
T1	0.2992	0.2948	0.2046	0.2168	0.0897	0.1325	0.1086	0.2225	0.1961
Me4	0.0124	0.0073	0.0058	0.0120	0.0498	0.0265	0.0217	0.0158	0.0189
S1	0.0997	0.1179	0.2046	0.1807	0.1122	0.0662	0.1521	0.1112	0.1306
Sum	1	1	1	1	1	1	1	1	1

As you will recall from Chapter 3, the matrix must be consistent for the AHP method to be valid. Therefore, the λ_{max} and CI values are calculated by (6.14) and (6.15), respectively. The value of consistency ratio is calculated by Eq. (16) (Özdemir, 2002). To calculate the Consistency Ratio (CR), Random Consistency Indices (RI) values are needed. Random Consistency Indices are given in Table 6.10.

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{\sum_{j=1}^{n} a_{ij}w_j}{w_i} \tag{6.14}$$

$$CI = {}^{\lambda_{max} - n}/_{n-1} \tag{6.15}$$

$$CR = {}^{CI}/_{RI} \tag{6.16}$$

Table 6. 10
Random Consistency Indices (RI)

n	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Source: Saaty, 1980

6.1.3 Consistency of pairwise comparison matrix

Consistency matrixes of Pairwise Comparison Matrix are given in Table 6.11-14. λ_{max} is the largest or principal eigenvalue of the matrix that can be computed from the matrix by (6.14). The Consistency Ratio of experts is expressed as CR and the Consistency Ratio (CR) is calculated with (6.16).

The consistency matrix of Expert 1 is given in Table 6.11. The consistency ratio is 0.0969 and since this value is less than 0.1, it appears that the matrix of Expert 1 is consistent.

Table 6. 11
Consistency Matrix of Expert-1

Expert-1	$a_{ij}w_j$	$a_{ij}w_j/w_i$		
Me2	2.0051	8.9882	$\lambda_{max} =$	8.9568
Me1	1.9211	8.9947		
Me3	0.2278	8.1438	$CI =$	0.1366
Ma1	0.4995	8.1317	$CR =$	0.0969
F1	1.7529	9.4927		Consistent
T1	1.5670	9.7570		
Me4	0.1592	8.5463		
S1	1.0562	9.6003		

The consistency matrix of Expert 2 is given in Table 6.12. The consistency ratio is 0.0772 and since this value is less than 0.1, it appears that the matrix of Expert 2 is consistent.

Table 6. 12
Consistency Matrix of Expert-2

Expert-2	$a_{ij}w_j$	$a_{ij}w_j/w_i$		
Me2	1.6025	8.8367	$\lambda_{max} =$	8.7627
Me1	1.5854	8.8535		
Me3	0.2687	8.3926	$CI =$	0.1089
Ma1	0.4886	8.5785	$CR =$	0.0772
F1	2.2607	9.2554		Consistent
T1	0.8381	8.7543		
Me4	0.1414	8.2838		
S1	1.7700	9.1469		

The consistency matrix of Expert 3 is given in Table 6.13. The consistency ratio is 0.0975 and since this value is less than 0.1, it appears that the matrix of Expert 3 is consistent.

Table 6. 13
Consistency Matrix of Expert-3

Expert-3	$a_{ij}w_j$	$a_{ij}w_j/w_i$		
Me2	0.8279	8.8961	$\lambda_{max} =$	8.9627
Me1	0.7262	8.8267		
Me3	0.2726	8.2031	$CI =$	0.1375
Ma1	0.3840	8.8515	$CR =$	0.0975
F1	4.1364	9.7115		Consistent
T1	1.5918	9.5536		
Me4	0.1517	8.4688		
S1	1.2641	9.1898		

The consistency matrix of Expert 4 is given in Table 6.14. The consistency ratio is 0.0941 and since this value is less than 0.1, it appears that the matrix of Expert 4 is consistent. The matrices of all experts in the study are consistent.

Table 6. 14
Consistency Matrix of Expert-4

Expert-4	$a_{ij}w_j$	$a_{ij}w_j/w_i$		
Me2	1.1028	8.9459	$\lambda_{max} =$	8.9290
Me1	0.6459	8.6165		
Me3	0.2876	8.2040	$CI =$	0.1327
Ma1	0.3727	8.7973	$CR =$	0.0941
F1	3.6150	9.5495		Consistent
T1	1.8723	9.5451		
Me4	0.1648	8.6894		
S1	1.1866	9.0841		

6.2.4 Overall comparison matrix

The Overall Comparison Matrix calculated with the help of geometric mean after consistency check is given in Table 6.15.

Table 6. 15
The Overall Comparison Matrix

	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
Me2	1	1.1892	6.2997	3.4086	0.5169	0.9036	8.4852	1.1066
Me1	0.8408	1	4.8205	2.4494	0.4518	0.7186	8.2390	0.8408
Me3	0.1587	0.2074	1	0.3333	0.1178	0.1728	4.1617	0.1336
Ma1	0.2933	0.4082	3	1	0.1535	0.1996	4.4093	0.1930
F1	1.9343	2.2133	8.4852	6.5135	1	3.9359	8.4519	3.4641
T1	1.1066	1.3915	5.7850	5.0099	0.2540	1	6.5934	1.4564
Me4	0.1178	0.1213	0.2402	0.2267	0.1183	0.1516	1	0.1459
S1	0.9036	1.1892	7.4833	5.1800	0.2886	0.6865	6.8525	1
Sum	**2.7184**	**4.7974**	**21.144**	**15.8509**	**17.6916**	**5.7019**	**39.4032**	**34.4936**

In order to convert criteria, each with a different unit, to a common scale and comparable units, the normalized overall comparison matrix is given in Table 6.16. The last column of Table 6.16 shows the weights of the criteria. These weights are calculated by taking the average of the row.

Table 6. 16
Normalized Matrix of the Overall Comparison Matrix

	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1	**wi**
Me2	0.1573	0.1540	0.1697	0.1413	0.1781	0.1163	0.1760	0.1326	0.1532
Me1	0.1323	0.1295	0.1298	0.1015	0.1557	0.0924	0.1709	0.1008	0.1266
Me3	0.0249	0.0268	0.0269	0.0138	0.0406	0.0222	0.0863	0.0160	0.0322
Ma1	0.0461	0.0528	0.0808	0.0414	0.0529	0.0256	0.0914	0.0231	0.0518
F1	0.3043	0.2866	0.2286	0.2700	0.3446	0.5066	0.1753	0.4153	0.3164
T1	0.1741	0.1802	0.1558	0.2076	0.0875	0.1287	0.1368	0.1746	0.1557
Me4	0.0185	0.0157	0.0064	0.0094	0.0407	0.0195	0.0207	0.0174	0.0185
S1	0.1421	0.1540	0.2016	0.2147	0.0995	0.0883	0.1421	0.1198	0.1453
	1	1	1	1	1	1	1	1	1

Then, the consistency of the normalized overall comparison matrix is calculated with Eq. (14)-(16). Consistency matrix of overall comparison matrix is given in Table 6.17. The consistency ratio is 0.0504 and since this value is less than 0.1, it appears that the matrix is consistent.

Table 6. 17
Consistency Matrix of Overall Comparison Matrix

	$a_{ij}w_j$	$a_{ij}w_j/w_i$		
Me2	1.3063	8.5266	$\lambda_{max} =$	8.4982
Me1	1.0680	8.4321		
Me3	0.2610	8.1000	$CI =$	0.0711
Ma1	0.4348	8.3911	$CR =$	0.0504
F1	2.7775	8.7768		Consistent
T1	1.3622	8.7484		
Me4	0.1537	8.2737		
S1	1.2696	8.7370		

Since the matrix is consistent, the weights in Table 6.16 are given in descending order in Table 6.18. Cost has the highest weight with 0.3164, followed by Coefficient of thermal expansion with 0.1557, Tensile Strength with 0.1532, Carbon Dioxide with 0.1453, Yield Streght with 0.1266, Melting temperature with 0.0518, Elongation at break with 0.0322 and Density with 0.0185.

Table 6. 18
The Ranking of Criterion Weights Calculated with the AHP

Rank	Weights	Description
1	0.3164	Cost
2	0.1557	Coefficient of thermal expansion
3	0.1532	Tensile Strength
4	0.1453	Carbon Dioxide
5	0.1266	Yield Streght
6	0.0518	Melting temperature
7	0.0322	Elongation at break
8	0.0185	Density

After the AHP method, Entropy, an objective criterion weighting method, was applied.

6.2 Entropy

The entropy method calculates the entropy values of the criteria by (6.17) and (6.18) (Shannon, 1948)

$$S(p_1, p_1, \dots, p_1) = -k \sum_{j=1}^{n} p_j \ln p_j \tag{6.17}$$

$$d_j = 1 - E_j, \qquad \forall j \tag{6.18}$$

where the p_j is the entropy of probability distribution, k is a constant and d_j is the degree of differentiation.

The values gathered regarding the thermoplastics based on the eight criteria are given in Table 6.19.

Table 6. 19
Entropy Input Decision Matrix

	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
LDPE	19.85	11.75	375	115	1.725	290	0.925	1.87
HDPE	26.55	29.65	605	137	1.475	152	0.959	1.8
PVC	46.2	42.75	60	212	1.475	135	1.44	2.22
PP	36.2	34.1	350	175	1.375	163	0.905	1.63
PS	58.8	47	1.85	240	1.75	120	1.05	2.28
Nylon 6,6	85.2	63.8	157.5	265	3.6	144	1.14	6.4
PET	60.35	59.3	165	265	1.625	117	1.35	2.068
PC	67.6	62.1	130	265	3.85	122	1.34	3.4

The normalized matrix is shown in Table 6.20 so that values with different units can be converted to a common scale and comparable units.

Table 6. 20
Normalized Matrix of Decision Matrix

	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
LDPE	0.0495	0.0335	0.2033	0.0686	0.1022	0.2333	0.1015	0.0863
HDPE	0.0662	0.0846	0.3280	0.0818	0.0874	0.1222	0.1052	0.0830
PVC	0.1152	0.1219	0.0325	0.1266	0.0874	0.1086	0.1580	0.1024
PP	0.0903	0.0973	0.1897	0.1045	0.0814	0.1311	0.0993	0.0752
PS	0.1467	0.1341	0.0010	0.1433	0.1037	0.0965	0.1152	0.1052
Nylon 6,6	0.2126	0.1820	0.0853	0.1583	0.2133	0.1158	0.1251	0.2953
PET	0.1505	0.1692	0.0894	0.1583	0.0962	0.0941	0.1482	0.0954
PC	0.1686	0.1772	0.0704	0.1583	0.2281	0.0981	0.1471	0.1569
Sum	1	1	1	1	1	1	1	1

The Entropy values of each criterion and the degree of differentiation calculated by (6.17) and (6.18) are given in Table 6.21.

Table 6. 21

The Entropy Values of Each Criterion and the Degree of Differentiation

$p_j \ln p_j$	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
LDPE	-0.1488	-0.1138	-0.3238	-0.1839	-0.2331	-0.3395	-0.2322	-0.2114
HDPE	-0.1798	-0.2089	-0.3656	-0.2048	-0.2130	-0.25696	-0.2369	-0.2066
PVC	-0.2490	-0.2566	-0.1114	-0.2616	-0.2130	-0.2411	-0.2916	-0.2334
PP	-0.2171	-0.2267	-0.3153	-0.2360	-0.2043	-0.2664	-0.2294	-0.1946
PS	-0.2815	-0.2694	-0.0069	-0.2784	-0.2350	-0.2256	-0.2490	-0.2369
Nylon 6,6	-0.3291	-0.3101	-0.2101	-0.2917	-0.3295	-0.2497	-0.2600	-0.3602
PET	-0.2850	-0.3006	-0.2159	-0.2917	-0.2253	-0.2224	-0.2829	-0.2242
PC	-0.3002	-0.3066	-0.1869	-0.2917	-0.3371	-0.2278	-0.2819	-0.2906
$k = 1/ln(m)$ → $m = 8$ →0.4808								
E_j	-0.9574	-0.9584	-0.8349	-0.9812	-0.9572	-0.9760	-0.9927	-0.9416
d_j	1.9574	1.9584	1.8349	1.9812	1.9572	1.9760	1.9927	1.9416
w_j	**0.1254**	**0.1255**	**0.11762**	**0.1270**	**0.1254**	**0.1266**	**0.1277**	**0.1244**

The descending order of criterion weights calculated with the Entropy is given in Table 6.22. The weights of density, melting temperature, coefficient of thermal expansion, yield strength, tensile strength, cost, carbon dioxide and elongation at break criteria are 0.1277, 0.1270, 0.1266, 0.1255, 0.12547, 0.12546, 0.1244 and 0.1176, respectively.

Table 6. 22
The Ranking of Criterion Weights

Rank	Weights	Description
1	**0.1277**	Density
2	**0.1270**	Melting temperature
3	**0.1266**	Coefficient of thermal expansion
4	**0.1255**	Yield strength
5	**0.12547**	Tensile strength
6	**0.12546**	Cost
7	**0.1244**	Carbon dioxide
8	**0.1176**	Elongation at break

6.3 SOWIA

The criterion weights are calculated with the subjective method AHP in Section 6.2, and the weights are calculated with the objective method Entropy in Section 6.2. These calculated weights are integrated into the hybrid weighting method, SOWIA method. The SOWIA method calculates the weights of criteria by (6.19).

$$w_{jb} = \propto O_j + (1-\propto)S_j, \qquad 0 \leq \propto \leq 1 \tag{6.19}$$

where the O_j is objective criterion weights (ENTROPY), the S_j is subjective criterion weights (AHP) and $\propto$ is objective factor decision weight (0.4).

The ranking of criterion weights calculated with the SOWIA (Entropy & AHP) method is given in Table 6.23. The weights of cost, coefficient of thermal expansion, tensile strength, carbon dioxide, yield strength, melting temperature elongation at break and density are 0.2400, 0.1440, 0.1421, 0.1369, 0.1262, 0.0818, 0.0663 and 0.0622, respectively.

Table 6. 23
Ranking of Criterion Weights Calculated with the SOWIA Method

Rank	Weights	Description
1	0.2400	Cost
2	0.1440	Coefficient of thermal expansion
3	0.1421	Tensile strength
4	0.1369	Carbon dioxide
5	0.1262	Yield strength
6	0.0818	Melting temperature
7	0.0663	Elongation at break
8	0.0622	Density

After the weighting was done using SOWIA method, the TOPSIS method was applied.

6.4 TOPSIS

The TOPSIS method is an MCDM method developed by Hwang and Yoon (1981). The assessment of alternatives relies on two key reference points: the positive ideal solution and the negative ideal solution. The objective of the TOPSIS approach is to identify the alternative that is closest to the positive ideal and farthest from the negative ideal, based on calculated distances.

The steps of the TOPSIS method are given as followed:

Step 1: The decision matrix is created.

Step 2: The normalized decision matrix is calculated by (6.20).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \quad ,\mathrm{j} \;=\; 1,2, \dots, \mathrm{m} \;; \;\; \mathrm{i} \;=\; 1,2, \dots, \mathrm{n} \tag{6.20}$$

Step 3: Weighted normalized matrix (V_{ij}) is determined using (6.21).

$$V_{ij} = w_j \; x \; r_{ij} \tag{6.21}$$

Step 4: Positive (A^{+}) and Negative Ideal (A^{-}) solutions are calculated by (6.22) and (6.23).

$$A^{+} = \{(\max V_{ij} \mid j \in J), (\min V_{ij} \mid j \in J'), i = 1,2,\dots,n\} \tag{6.22}$$
$$= \{V_1^{+}, V_2^{+}, \dots, V_j^{+}, \dots, V_m^{+}\}$$

$$A^{-} = \{(min\, V_{ij} \mid j \in J), (max\, V_{ij} \mid j \in J'), i = 1,2,\dots,n\} \tag{6.23}$$
$$= \{V_1^{-}, V_2^{-}, \dots, V_j^{-}, \dots, V_m^{-}\}$$

Step 5: Calculate the distance to the Positive Ideal Solution (D_i^*) and distance to the Negative Ideal Solution (D_i^-) using (6.24).

$$D_i^* = \sqrt{\sum_{j=1}^{n}(V_{ij} - V_j^*)^2} \quad \mathrm{i} = 1, \dots\dots, \mathrm{n} \tag{6.24}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}(V_{ij} - V_j^-)^2} \quad \mathrm{i} = 1, \dots\dots, \mathrm{n} \tag{6.25}$$

Step 6: Calculate the relative closeness value to the ideal solution by (6.26).

$$C_i^* = \frac{D_i^-}{D_i^* + D_i^-}, \quad \mathrm{i} = 1, \dots, \mathrm{n} \tag{6.26}$$

Step 7: Rank the options to obtain the best alternative with the highest C_i^* value.

In this study, the input decision matrix to be used in the TOPSIS method are given in Table 6.24.

Table 6. 24
Input Decision Matrix

Alternatives\Criteria	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
LDPE	19.85	11.75	375	115	1.725	290	0.925	1.87
HDPE	26.55	29.65	605	137	1.475	152	0.959	1.8
PVC	46.2	42.75	60	212	1.475	135	1.44	2.22
PP	36.2	34.1	350	175	1.375	163	0.905	1.63
PS	58.8	47	1.85	240	1.75	120	1.05	2.28
Nylon 6,6	85.2	63.8	157.5	265	3.6	144	1.14	6.4
PET	60.35	59.3	165	265	1.625	117	1.35	2.068
PC	67.6	62.1	130	265	3.85	122	1.34	3.4

The normalized matrix is calculated by (6.20). Overall normalized decision matrix was created according to this formula. The matrix is given in the Table 6.25.

Table 6. 25
Overall Normalized Decision Matrix

Alternatives\Criteria	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
LDPE	0.1295	0.0884	0.4476	0.1875	0.2639	0.6244	0.2829	0.2140
HDPE	0.1732	0.2231	0.7222	0.2234	0.2257	0.3272	0.2933	0.2060
PVC	0.3015	0.3216	0.0716	0.3458	0.2257	0.2906	0.4404	0.2541
PP	0.2362	0.2566	0.4178	0.2854	0.2104	0.3509	0.2768	0.1865
PS	0.3837	0.3536	0.0022	0.3914	0.2677	0.2583	0.3211	0.2609
Nylon 6,6	0.5561	0.4800	0.1880	0.4322	0.5508	0.3100	0.3487	0.7326
PET	0.3939	0.4462	0.1969	0.4322	0.2486	0.2519	0.4129	0.2367
PC	0.4412	0.4673	0.1551	0.4322	0.5891	0.2626	0.4098	0.3891

Using (6.21), weighted normalized matrix (V_{ij}) was created by multiplying the elements in each column of the normalized decision matrix with the relevant weight (w_j) value calculated by the SOWIA method. The matrix is shown in the Table 6.26.

Table 6. 26
The Weighted Normalized Matrix

Alternatives\Criteria	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
LDPE	0.0184	0.0111	0.0297	0.0153	0.0633	0.0899	0.0176	0.0293
HDPE	0.0246	0.0281	0.0479	0.0183	0.0541	0.0471	0.0182	0.0282
PVC	0.0428	0.0406	0.0047	0.0283	0.0541	0.0418	0.0274	0.0348
PP	0.0335	0.0323	0.0277	0.0233	0.0505	0.0505	0.0172	0.0255
PS	0.0545	0.0446	0.0001	0.0320	0.0642	0.0372	0.0199	0.0357
Nylon 6,6	0.0790	0.0605	0.0124	0.035	0.1322	0.0446	0.0217	0.1003
PET	0.0559	0.0563	0.0130	0.035	0.0596	0.0362	0.0257	0.0324
PC	0.0627	0.0589	0.0103	0.0353	0.1414	0.0378	0.0255	0.0533

Positive (A^{+}) and Negative Ideal (A^{-}) solutions were calculated by (6.22) and (6.23). The relevant values are stated in the Table 6.27.

Table 6. 27
Positive and Negative Ideal Solutions

	+	+	-	-	-	+	-	-
Alternatives\Criteria	Me2	Me1	Me3	Ma1	F1	T1	Me4	S1
Ideal Solution (A^{+})	0.0790	0.0605	0.0001	0.0153	0.0505	0.0899	0.0172	0.0255
Negative Ideal Solution (A^{-})	0.0184	0.0111	0.0479	0.0353	0.1414	0.0362	0.0274	0.1003

In the TOPSIS method, the Euclidean Distance Approach is used, and in this approach, the deviations of the evaluation factor values of the decision points from the positive ideal and negative ideal solution set are determined (Özdemir, 2014). The values obtained here are called distance from the Positive Ideal Solution (D_i^{*}) and distance from the Negative Ideal Solution (D_i^{-}). (6.24) was used to calculate D_i^{*}, and (6.25) was used to calculate D_i^{-}. Positive ideal and negative ideal distances are listed in Table 6.28.

Table 6. 28
Positive Ideal and Negative Ideal Distances

LDPE	D1 +	0.0846	D1 -	0.1218
HDPE	D2 +	0.0903	D2 -	0.1167
PVC	D3 +	0.0664	D3 -	0.1237
PP	D4 +	0.0723	D4 -	0.1241
PS	D5 +	0.0649	D5 -	0.1220
Nylon 6,6	D6 +	0.1220	D6 -	0.0869
PET	D7 +	0.0648	D7 -	0.1263
LDPE	D8 +	0.1122	D8 -	0.0887

Distances from Positive ideal and negative ideal solutions are used to compute the relative closeness of decision points to the ideal solution (C_i^*) (Akyüz, Bozdoğan and Hantekin, 2011). How the relative closeness value to the ideal solution is calculated is stated in (6.26). Relative closeness values according to the ideal solution found according to this formula are given in Table 6.29.

Table 6. 29
Relative Closeness Values

Materials	**Relative Closeness**	**Rank**
LDPE	0.5899	5
HDPE	0.5638	6
PVC	0.6507	3
PP	0.6316	4
PS	0.6527	2
Nylon 6,6	0.4160	8
PET	0.6609	1
PC	0.4417	7

According to the ideal solution, when the relative closeness values (C_i^*) are sorted from largest to smallest, the values is listed in Table 6.30.

Table 6. 30
Ranking of Relative Closeness Values

Rank	Materials	Relatives Closeness
1	PET	0.6609
2	PS	0.6527
3	PVC	0.6507
4	PP	0.6316
5	LPDE	0.5899
6	HPDE	0.5638
7	PC	0.4417
8	Nylon 6,6	0.4160

In this study, PET is ranked as the top most raw material with regard to the eight criteria that are used for the selection and evaluation of the thermoplastic raw materials followed by PS which secured the 2nd largest value for the relative closeness to the ideal solution. The analysis shows that PET is the closest to the positive ideal solution with the value of 0.0648 which is the lowest value among the rest of the materials' value for the distance from the PIS. Results also show that the PET secures the highest value for the distance from the negative ideal solution with the value of 0.1263. TOPSIS usually ranks the raw materials in order of how close the raw materials are to the positive ideal solution and how far it is from the negative ideal solution.

Before the study, the project designer Expert-1 chose PP material because the expert thought the material was cheap and had average strength and had used it in previous similar designs. However, PET material was at the top of the list as a result of the analysis. It turned out to be a 173% more durable material with only an 18% cost increase. Since the increase was within the budget, the life of the design could be increased by choosing a more durable material.

The Likert scale, developed by Rensis Likert (1932), is frequently used in studies because it is relatively easy to create, largely reliable, and successful in measuring many affective qualities (Gable and Wolf, 2012). The application of the results obtained with the TOPSIS method was evaluated by experts using 5-point Likert type scale. The question asked to the experts are given in Table 6.31 and Experts' answer matrix is given in Table 6.32.

Table 6. 31
The 5-point Likert Type Scale

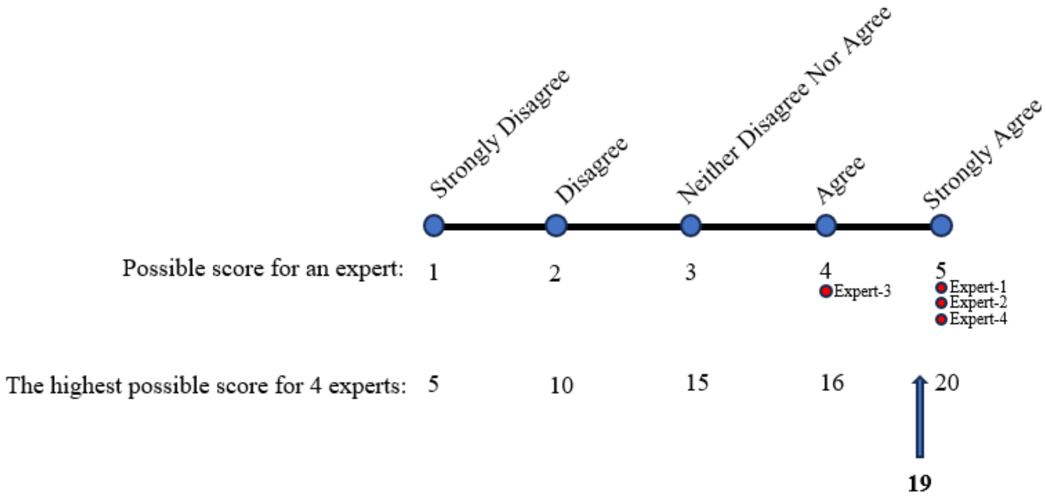
	Strongly Agree	Agree	Neither Disagree Nor Agree	Disagree	Strongly Disagree
The ranking obtained from the analysis is quite suitable for application in the project.					

Table 6. 32
Experts' Answer Matrix

	Strongly Agree	Agree	Neither Disagree Nor Agree	Disagree	Strongly Disagree
Expert-1:					
The ranking obtained from the analysis is quite suitable for application in the project.	x				
Expert-2:					
The ranking obtained from the analysis is quite suitable for application in the project.	x				
Expert-3:					
The ranking obtained from the analysis is quite suitable for application in the project.		x			
Expert-4:					
The ranking obtained from the analysis is quite suitable for application in the project.	x				

The answers given by the experts were scored as 5 for Strongly Agree and 1 for Strongly Disagree, as shown in Figure 6.1. In this study, three experts chose Strongly Agree, while one expert chose Agree. If all experts chose Strongly Agree, the highest score could have been 20, but in this study, it is 19. All experts (100%) agreed that the ranking obtained from TOPSIS was quite appropriate in terms of application. When considered in detail, 75% of the experts strongly agree, while 25% agree.

Figure 6. 1
The Answers Given by the Experts



6.5 Discussion

In the designs of plastic parts used in the white goods, automotive and all electronic equipment sectors, designers usually decide on the material according to their past experiences while making part designs. In some cases, the raw materials of similar parts are checked, and the same raw material is used, while in other cases, the focus is completely on durability and important points such as cost for businesses can be overlooked. Another point that can be overlooked is the sustainability, which is becoming more and more important with global warming. The concept of green product has emerged in the manufacturing sector, and the selection of raw materials of all materials used in the product, especially the raw materials of packaging materials, should be evaluated in terms of sustainability.

The aim of the study was to provide designers with a framework for thermoplastic raw material selection that can be used in other businesses. If other businesses follow this framework during the design phase, their contribution to the environment can reach an undeniable level. The proposed model will help designers evaluate thermoplastic raw materials. The hybrid weighting method uses the subjective judgments of decision makers and converts them into weights for each criterion using objective judgments. While the significance of each criterion varies from decision maker to decision maker, it is also combined with data based on objective calculations. Subjective calculations obtained from the AHP method may cause differences in weights due to the change of decision-making experts. In some cases, in business life, employees may create pressure on other employees due to their characters or positions. However, since the decision-maker does not influence other decision-makers while using his/her vote in the AHP method, indifference will be preserved. This method, which is applied in the selection and evaluation of raw materials, offers a detailed evaluation opportunity for all criteria, not just one.

6.6 Future Work

The criteria set in this study can be changed and applied to the raw material selection of metal materials. In the future, this study can be generalized to allow the simultaneous evaluation of different types of materials. Thus, if the material to be selected is a plastic material, the current criteria set can be used, while a different set of criteria can be used for metal materials. In this way, a general picture can be obtained for the raw material selections in the design.

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APPENDICES

ANNEX-1a. Major application characteristics, and their typical applications for various thermoplastics

Material Type	Major Application Characteristics	Typical Applications
ABS	Outstanding strength and toughness, resistant to heat distortion; good electrical properties; flammable and soluble in some solvents	Under-the-hood automotive applications, refrigerator linings, computer and television housings, toys, highway safety devices
Acrylics	Outstanding light transmission and resistance to weathering; only fair mechanical properties	Lenses, transparent aircraft enclosures, drafting equipment, bathtub and shower enclosures
Polyesters (PET or PETE)	One of the toughest of plastic films; excellent fatigue and tear strength, and resistance to humidity, acids, greases, oils, and solvents	Oriented films, clothing, automotive tire cords, beverage containers
Fluorocarbons (PTFE or TFE)	Chemically inert in almost all environments, excellent electrical properties; low coefficient of friction; may be used to 260C (500F); relatively weak and poor cold-flow properties	Anticorrosive seals, chemical pipes and valves, bearings, wire and cable insulation, antiadhesive coatings, high-temperature electronic parts
Polyamides (nylons)	Good mechanical strength, abrasion resistance, and toughness; low coefficient of friction; absorbs water and some other liquids	Bearings, gears, cams, bushings, handles, and jacketing for wires and cables, fibers for carpet, hose, and belt reinforcement
Polycarbonates	Dimensionally stable; low water absorption; transparent; very good impact resistance and ductility; chemical resistance not outstanding	Safety helmets, lenses, light globes, base for photographic film, automobile battery cases
Polyethylenes	Chemically resistant and electrically insulating; tough and relatively low coefficient of friction; low strength and poor resistance to weathering	Flexible bottles, toys, tumblers, battery parts, ice trays, film wrapping materials, automotive gas tanks

Polypropylenes	Resistant to heat distortion; excellent electrical properties and fatigue strength; chemically inert; relatively inexpensive; poor resistance to ultraviolet light	Sterilizable bottles, packaging film, automotive kick panels, fibers, luggage
Polystyrenes	Excellent electrical properties and optical clarity; good thermal and dimensional stability; relatively inexpensive	Wall tile, battery cases, toys, indoor lighting panels, appliance housings, packaging
Vinyls	Good low-cost, general-purpose materials; ordinarily rigid, but may be made flexible with plasticizers; often copolymerized; susceptible to heat distortion	Floor coverings, pipe, electrical wire insulation, garden hose, shrink wrap

Source: Callister and Rethwisch, 2020

ANNEX-1b. Summary of the mechanical properties at room temperature for several widely used polymers

Material	**Specific Gravity**	**Tensile Modulus [GPa (ksi)]**	**Tensile Strength [MPa (ksi)]**	**Yield Strength [MPa (ksi)]**	**Elongation at Break (%)**
Polyethylene (low density)	0.917–0.932	0.17–0.28 (25–41)	8.3–31.4 (1.2–4.55)	9.0–14.5 (1.3–2.1)	100–650
Polyethylene (high density)	0.952–0.965	1.06–1.09 (155–158)	22.1–31.0 (3.2–4.5)	26.2–33.1 (3.8–4.8)	10–1200
Poly(vinyl chloride)	1.30–1.58	2.4–4.1 (350–600)	40.7–51.7 (5.9–7.5)	40.7–44.8 (5.9–6.5)	40–80
Polytetrafluoroethylene	2.14–2.20	0.40–0.55 (58–80)	20.7–34.5 (3.0–5.0)	13.8–15.2 (2.0–2.2)	200–400
Polypropylene	0.90–0.91	1.14–1.55 (165–225)	31–41.4 (4.5–6.0)	31.0–37.2 (4.5–5.4)	100–600
Polystyrene	1.04–1.05	2.28–3.28 (330–475)	35.9–51.7 (5.2–7.5)	25.0–69.0 (3.63–10.0)	1.2–2.5
Poly(methyl methacrylate)	1.17–1.20	2.24–3.24 (325–470)	48.3–72.4 (7.0–10.5)	53.8–73.1 (7.8–10.6)	2.0–5.5
Phenol-formaldehyde	1.24–1.32	2.76–4.83 (400–700)	34.5–62.1 (5.0–9.0)	—	1.5–2.0
Nylon 6,6	1.13–1.15	1.58–3.80 (230–550)	75.9–94.5 (11.0–13.7)	44.8–82.8 (6.5–12)	15–300
Polyester (PET)	1.29–1.40	2.8–4.1 (400–600)	48.3–72.4 (7.0–10.5)	59.3 (8.6)	30–300
Polycarbonate	1.20	2.38 (345)	62.8–72.4 (9.1–10.5)	62.1 (9.0)	110–150

Source: Callister and Rethwisch, 2020

ANNEX-1c. Melting and glass transition temperatures for several widely used polymers

Material	**Glass Transition Temperature [C (F)]**	**Melting Temperature [C (F)]**
Polyethylene (low density)	—110 (—165)	115 (240)
Polytetrafluoroethylene	—97 (—140)	327 (620)
Polyethylene (high density)	—90 (—130)	137 (279)
Polypropylene	—18 (0)	175 (347)
Nylon 6,6	57 (135)	265 (510)
Poly(ethylene terephthalate) (PET)	69 (155)	265 (510)
Poly(vinyl chloride)	87 (190)	212 (415)
Polystyrene	100 (212)	240 (465)
Polycarbonate	150 (300)	265 (510)

Source: Callister and Rethwisch, 2020

ANNEX-1d. Electrical conductivities at room temperature for six polymers

Material	**Electrical Conductivity** $[(\Omega..\mathbf{m})^{-1}]$
Phenol-formaldehyde	10^{-9}-10^{-10}
Poly(methyl methacrylate)	<10^{-12}
Nylon 6,6	110^{-12}- 10^{-13}
Polystyrene	<10^{-14}
Polyethylene	10^{-15}-10^{-17}
Polytetrafluoroethylene	<10^{-17}

Source: Callister and Rethwisch, 2020

ANNEX-1e. Thermal properties for various polymers

Material	$\mathbf{c_p}$ $\mathbf{(J/kg.K)^a}$	$\propto_l$ $\mathbf{[(°C)^{-1} x10^{-6}]^b}$	$\mathbf{k}$ $\mathbf{(W/m.K)^c}$
Polyethylene (high density)	1850	106–198	0.46–0.50
Polypropylene	1925	145–180	0.12
Polystyrene	1170	90–150	0.13
Polytetrafluoroethylene (Teflon)	1050	126–216	0.25
Phenol-formaldehyde, phenolic	1590–1760	122	0.15
Nylon 6,6	1670	144	0.24
Polyisoprene	—	220	0.14

aTo convert to cal/g.K, multiply by 2.39 × 10—4; to convert to Btu/lbm.°F, multiply by 2.39 × 10—4.

bTo convert to (°F)—1, multiply by 0.56.

cTo convert to cal/s cm K, multiply by 2.39 × 10—3; to convert to Btu/ft h °F, multiply by 0.578.

Source: Callister and Rethwisch, 2020

ANNEX-1f. Density values at room temperature for various polymers

Material	Density	
	g/cm^3	$lb_m/in.^3$
Elastomers		
• Butadiene–acrylonitrile (nitrile)	0.98	0.0354
• Styrene–butadiene (SBR)	0.94	0.0339
• Silicone	1.1–1.6	0.040–0.058
Epoxy	1.11–1.40	0.0401–0.0505
Nylon 6,6	1.14	0.0412
Phenolic	1.28	0.0462
Poly(butylene terephthalate) (PBT)	1.34	0.0484
Polycarbonate (PC)	1.20	0.0433
Polyester (thermoset)	1.04–1.46	0.038–0.053
Polyetheretherketone (PEEK)	1.31	0.0473
Polyethylene • Low density (LDPE)	0.925	0.0334
• High density (HDPE)	0.959	0.0346
• Ultrahigh molecular weight (UHMWPE)	0.94	0.0339
Poly(ethylene terephthalate) (PET)	1.35	0.0487
Poly(methyl methacrylate) (PMMA)	1.19	0.0430
Polypropylene (PP)	0.905	0.0327
Polystyrene (PS)	1.05	0.0379
Polytetrafluoroethylene (PTFE)	2.17	0.0783
Poly(vinyl chloride) (PVC)	1.30–1.58	0.047–0.057

Source: Callister and Rethwisch, 2020

ANNEX-1g. Modulus of elasticity values at room temperature for various polymers

Material	**Modules of Elasticity**	
	GPa	**10^6psi**
Elastomers • Butadiene–acrylonitrile (nitrile) • Styrene–butadiene (SBR)	 0.0034^b $0.002 - 0.010^b$	 0.00049^b $0.0003 - 0.0015^b$
Epoxy	2.41	0.35
Nylon 6,6	1.59-3.79	0.230-0.550
Phenolic	2.76-4.83	0.40-0.70
Poly(butylene terephthalate) (PBT)	1.93-3.00	0.280-0.435
Polycarbonate (PC)	2.38	0.345
Polyester (thermoset)	2.06-4.41	0.30-0.64
Polyetheretherketone (PEEK)	1.10	0.16
Polyethylene Low density (LDPE) High density (HDPE) Ultrahigh molecular weight (UHMWPE)	 0.172-0.282 1.08 0.69	 0.025-0.041 0.157 0.100
Poly(ethylene terephthalate) (PET)	2.76-4.14	0.40-0.60
Poly(methyl methacrylate) (PMMA)	2.24-3.24	0.325-0.470
Polypropylene (PP)	1.14-1.55	0.165-0.225
Polystyrene (PS)	2.28-3.28	0.330-0.475
Polytetrafluoroethylene (PTFE)	0.40-0.55	0.058-0.080
Poly(vinyl chloride) (PVC)	2.41-4.14	0.35-0.60

Source: Callister and Rethwisch, 2020

ANNEX-1h. Poisson’s ratio values at room temperature for various polymers

Material	**Possion's Ratio**
Nylon 6,6	0.39
Polycarbonate (PC)	0.36
Polyethylene • Low density (LDPE) • High density (HDPE)	 0.33–0.40 0.46
Poly(ethylene terephthalate) (PET)	0.33
Poly(methyl methacrylate) (PMMA)	0.37–0.44
Polypropylene (PP)	0.40
Polystyrene (PS)	0.33
Polytetrafluoroethylene (PTFE)	0.46
Poly(vinyl chloride) (PVC)	0.38

Source: Callister and Rethwisch, 2020

ANNEX-1i. Yield strength, tensile strength, and ductility (percent elongation) values at room temperature for various polymers

Material	**Yield Stregth (Mpa[ksi])**	**Tensile Stregth (Mpa[ksi])**	**Percent Elongation**
Elastomers • Butadiene–acrylonitrile (nitrile)	—	6.9–24.1 (1.0–3.5)	400–600
• Styrene–butadiene (SBR)	—	12.4–20.7 (1.8–3.0)	450–500
• Silicone	—	10.3 (1.5)	100–800
Epoxy	— 27.6–90.0 (4.0–13)	27.6–90.0 (4.0–13)	3–6
Nylon 6,6 • Dry, as molded • 50% relative humidity	55.1–82.8 (8–12) 44.8–58.6 (6.5–8.5)	94.5 (13.7) 75.9 (11)	15–80 150–300
Phenolic	—	34.5–62.1 (5.0–9.0)	1.5–2.0
Poly(butylene terephthalate) (PBT)	56.6–60.0 (8.2–8.7)	56.6–60.0 (8.2–8.7)	50–300
Polycarbonate (PC)	62.1 (9)	62.8–72.4 (9.1–10.5)	110–150
Polyester (thermoset)	—	41.4–89.7 (6.0–13.0) <2.6	<2.6
Polyetheretherketone (PEEK)	91 (13.2)	70.3–103 (10.2–15.0) 30–150	30-150
Polyethylene • Low density (LDPE	9.0–14.5 (1.3–2.1)	8.3–31.4 (1.2–4.55)	100–650
Polyethylene • High density (HDPE) • Ultrahigh molecular weight (UHMWPE)	26.2–33.1 (3.8–4.8) 21.4–27.6 (3.1–4.0)	22.1–31.0 (3.2–4.5) 38.6–48.3 (5.6–7.0)	10–1200 350–525
Poly(ethylene terephthalate) (PET)	59.3 (8.6)	48.3–72.4 (7.0–10.5)	30–300
Poly(methyl methacrylate) (PMMA)	53.8–73.1 (7.8–10.6)	48.3–72.4 (7.0–10.5)	2.0–5.5
Polypropylene (PP)	31.0–37.2 (4.5–5.4)	31.0–41.4 (4.5–6.0)	100–600
Polystyrene (PS)	25.0–69.0 (3.63–10.0)	35.9–51.7 (5.2–7.5)	1.2–2.5
Polytetrafluoroethylene (PTFE)	13.8–15.2 (2.0–2.2)	20.7–34.5 (3.0–5.0)	200–400

Poly(vinyl chloride) (PVC)	40.7–44.8 (5.9–6.5)	40.7–51.7 (5.9–7.5)	40–80

Source: Callister and Rethwisch, 2020

ANNEX-1j. Plane strain fracture toughness and strength values at room temperature for various polymers

Material	***Fracture Toughness***		***Strength***
	$\boldsymbol{MPa\sqrt{m}}$	$\boldsymbol{ksi\sqrt{in.}}$	***(Mpa)***
Epoxy	0.6	0.55	—
Nylon 6,6	2.5–3.0	2.3–2.7	44.8–58.6
Polycarbonate (PC)	2.2	2.0	62.1
Polyester (thermoset)	0.6	0.55	—
Poly(ethylene terephthalate) (PET)	5.0	4.6	59.3
Poly(methyl methacrylate) (PMMA)	0.7–1.6	0.6–1.5	53.8–73.1
Polypropylene (PP)	3.0–4.5	2.7–4.1	31.0–37.2
Polystyrene (PS)	0.7–1.1	0.6–1.0	—
Poly(vinyl chloride) (PVC)	2.0–4.0	1.8–3.6	40.7–44.8

Source: Callister and Rethwisch, 2020

ANNEX-1k. Linear coefficient of thermal expansion values at room temperature for various polymers

Material	**Coefficient of Thermal Expansion**	
	$\mathbf{10^{-6}(°C)^{-1}}$	$\mathbf{10^{-6}(°F)^{-1}}$
Elastomers • Butadiene–acrylonitrile (nitrile) • Styrene–butadiene (SBR) • Silicone	 235 220 270	 130 125 150
Epoxy	81–117	45–65
Nylon 6,6	144	80
Phenolic	122	68
Poly(butylene terephthalate) (PBT)	108–171	60–95
Polycarbonate (PC)	122	68
Polyester (thermoset)	100–180	55–100
Polyetheretherketone (PEEK)	72–85	40–47
Polyethylene • Low density (LDPE) • High density (HDPE) • Ultrahigh molecular weight(UHMWPE)	 180–400 106–198 234–360	 100–220 59–110 130–200
Poly(ethylene terephthalate) (PET)	117	65
Poly(methyl methacrylate) (PMMA)	90-162	50-90
Polypropylene (PP)	146-180	81-100
Polystyrene (PS)	90-150	50-83
Polytetrafluoroethylene (PTFE)	126-216	70-120
Poly(vinyl chloride) (PVC)	90-180	50-100

Source: Callister and Rethwisch, 2020

ANNEX-11. Thermal conductivity values at room temperature for various polymers

Material	Thermal Conductivity	
	W/m.K	**$Btu/ft.h.°F$**
Elastomers • Butadiene-acrylonitrile (nitrile)	0.25	0.14
• Styrene-butadiene (SBR)	0.25	0.14
• Silicone	0.23	0.13
Epoxy	0.19	0.11
Nylon 6,6	0.24	0.14
Phenolic	0.15	0.087
Poly(butylene terephthalate) (PBT)	0.18–0.29	0.10–0.17
Polycarbonate (PC)	0.20	0.12
Polyester (thermoset)	0.17	0.10
Polyethylene • Low density (LDPE)	0.33	0.19
• High density (HDPE) • Ultrahigh molecular weight (UHMWPE)	0.48 0.33	0.28 0.19
Poly(ethylene terephthalate) (PET)	0.15	0.087
Poly(methyl methacrylate) (PMMA)	0.17–0.25	0.10–0.15
Polypropylene (PP)	0.12	0.069
Polystyrene (PS)	0.13	0.075
Polytetrafluoroethylene (PTFE)	0.25	0.14
Poly(vinyl chloride) (PVC)	0.15-0.21	0.08-0.12

Source: Callister and Rethwisch, 2020

ANNEX-1m. Specific heat values at room temperature for various polymers

Material	***Spesific Heat***	
	J/kg.K	$\mathbf{10^{-2} Btu/lb_m.°F}$
Epoxy	1050	25
Nylon 6,6	1670	40
Phenolic	1590-1760	38-42
Poly(butylene terephthalate) (PBT)	1170-2300	28-55
Polycarbonate (PC)	840	20
Polyester (thermoset)	710-920	17-22
Polyethylene • Low density (LDPE) • High density (HDPE) • Ultrahigh molecular weight (UHMWPE)	 2300 1850	 55 44.2
Poly(ethylene terephthalate) (PET)	1170	28
Poly(methyl methacrylate) (PMMA)	1460	35
Polypropylene (PP)	1925	46
Polystyrene (PS)	1170	28
Polytetrafluoroethylene (PTFE)	1050	25
Poly(vinyl chloride) (PVC)	1050-1460	25-35

Source: Callister and Rethwisch, 2020

ANNEX-1n. Electrical resistivity values at room temperature for various polymers

Material	**Electrical Resistivity, $\Omega.\mathrm{m}$**
Elastomers • Butadiene–acrylonitrile (nitrile) • Styrene–butadiene (SBR) • Silicone	 3.5×10^{8} 6×10^{11} 10^{13}
Epoxy	$10^{10} - 10^{13}$
Nylon 6,6	$10^{12} - 10^{13}$
Phenolic	$10^{9} - 10^{10}$
Poly(butylene terephthalate) (PBT)	4×10^{14}
Polycarbonate (PC)	2×10^{14}
Polyester (thermoset)	10^{13}
Polyetheretherketone (PEEK)	6×10^{14}
Polethlene •Low density (LDPE) • High density (HDPE) • Ultrahigh molecular weight (UHMWPE)	 $10^{15} - 5 \times 10^{16}$ $10^{15} - 5 \times 10^{16}$ $> 5 \times 10^{14}$
Poly(ethylene terephthalate) (PET)	10^{12}
Poly(methyl methacrylate) (PMMA)	$> 10^{12}$
Polypropylene (PP)	$> 10^{14}$
Polystyrene (PS)	$> 10^{14}$
Polytetrafluoroethylene (PTFE)	10^{17}
Poly(vinyl chloride) (PVC)	$> 10^{14}$

Source: Callister and Rethwisch, 2020

ANNEX-1o. Costs for various polymers

Material	**Cost ($US/kg)**
Butadiene-acrylonitrile (nitrile) rubber • Raw and unprocessed • Extruded sheet (14–18 in. thick) Calendered sheet (14–18 in. thick)	4.00 8.25 5.25-7.40
Styrene-butadiene (SBR) rubber • Raw and unprocessed • Extruded sheet (14–18 in. thick) Calendered sheet (14–18 in. thick)	1.70 5.05 3.25-3.75
Silicone rubber • Raw and unprocessed • Extruded sheet (14–18 in. thick) Calendered sheet (14–18 in. thick)	9.90-14.00 28.00-29.50 7.75-12.00
Epoxy resin, raw form	2.20-2.80
Nylon 6,6 Raw form	3.20-4.00
Nylon 6,6 • Extruded	12.80
Phenolic resin, raw form	1.65-1.90
Poly(butylene terephthalate) (PBT) • Raw form • Sheet	4.00-7.00 40.00-100.00
Polycarbonate (PC) • Raw form • Sheet	3.00-4.70 10.50

Polyester (thermoset), raw form	3.10-4.30
Polyetheretherketone (PEEK), raw form	90.00-105.00
Polethlene • Low density (LDPE), raw form • High density (HDPE), raw form • Ultrahigh molecular weight (UHMWPE), raw form	 1.60-1.85 1.20-1.75 2.20-3.00
Poly(ethylene terephthalate) (PET) • Raw form Sheet	 1.50-1.75 3.30-5.40
Poly(methyl methacrylate) (PMMA) • Raw form Extruded sheet (14 in. thick)	 2.60-5.40 4.65-6.05
Polypropylene (PP), raw form	1.05-1.70
Polystyrene (PS), raw form	1.55-1.95
Polytetrafluoroethylene (PTFE) • Raw form Rod	 14.80-16.90 21.00
Poly(vinyl chloride) (PVC), raw form	1.10-1.85

Source: Callister and Rethwisch, 2020

ANNEX-2. AHP Survey

Aim of the Survey:

The aim of this survey is to provide relevant data from expert designers in order to calculate the weights of the criteria for the material ranking to be used in the design of a functional part that is exposed to temperature difference and mechanically stressed, using the AHP criterion weighting method.

Saaty's scale is used to compare criteria

Numerical Value: Definition	***Explanation***
1: Equal Significance	Both activities are considered to contribute equally toward achieving the objective
3: Moderate Significance	Experience and Judgements slightly favor one activity over another
5: Strong Significance	Judgments and past experiences strongly indicate a preference for one activity over the other.
7: Very Strong	One activity is heavily favored based on practical relevance and clear dominance.
9: Extreme Significance	The preference for one activity is supported by the highest level of evidence and justification.
2, 4, 6, 8: Intermediate Values	These values are used to express a compromise between the importance levels listed above.

Pairwise comparison survey for weighting criteria

Expert No:																		
Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Yield Strength
Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Elongation at break
Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Melting temperature
Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Cost
Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Yield Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Elongation at break
Yield Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Melting temperature
Yield Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Cost
Yield Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Yield Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Yield Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Melting temperature
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Cost
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Cost
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Coefficient of thermal expansion	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Coefficient of thermal expansion	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Density	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide

ANNEX-3. Experts Pairwise Preferences for AHP weighting method

Expert No: 1																		
Tensile Strength	9	8	7	6	5	4	3	2	✓	2	3	4	5	6	7	8	9	Yield Strength
Tensile Strength	9	8	✓	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Elongation at break
Tensile Strength	9	8	7	6	5	4	✓	2	1	2	3	4	5	6	7	8	9	Melting temperature
Tensile Strength	9	8	7	6	5	4	3	✓	1	2	3	4	5	6	7	8	9	Cost
Tensile Strength	9	8	7	6	5	4	3	✓	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Tensile Strength	✓	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Tensile Strength	9	8	7	6	5	4	✓	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Yield Strength	9	8	7	6	5	✓	3	2	1	2	3	4	5	6	7	8	9	Elongation at break
Yield Strength	9	8	7	6	5	4	✓	2	1	2	3	4	5	6	7	8	9	Melting temperature
Yield Strength	9	8	7	6	5	4	3	✓	1	2	3	4	5	6	7	8	9	Cost
Yield Strength	9	8	7	6	5	4	3	✓	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Yield Strength	✓	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Yield Strength	9	8	7	6	5	4	✓	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Elongation at break	9	8	7	6	5	4	3	2	1	2	✓	4	5	6	7	8	9	Melting temperature
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	✓	9	Cost
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	✓	9	Coefficient of thermal expansion
Elongation at break	9	8	7	6	5	4	3	✓	1	2	3	4	5	6	7	8	9	Density
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	✓	9	Carbon Dioxide
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	✓	6	7	8	9	Cost
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	5	6	✓	8	9	Coefficient of thermal expansion
Melting temperature	9	8	✓	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	5	✓	7	8	9	Carbon Dioxide
Cost	9	8	7	6	5	4	3	✓	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Cost	✓	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Cost	9	8	7	6	5	4	✓	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Coeffient of thermal expansion	9	8	7	✓	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Coeffient of thermal expansion	9	8	7	6	5	4	✓	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Density	9	8	7	6	✓	4	3	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide

Expert No: 2

Tensile Strength	9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9	Yield Strength
Tensile Strength	~~9~~	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Elongation at break
Tensile Strength	9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9	Melting temperature
Tensile Strength	9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9	Cost
Tensile Strength	9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Tensile Strength	~~9~~	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Tensile Strength	9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9	Carbon Dioxide
Yield Strength	~~9~~	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Elongation at break
Yield Strength	9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9	Melting temperature
Yield Strength	9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9	Cost
Yield Strength	9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Yield Strength	9	~~8~~	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Yield Strength	9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9	Carbon Dioxide
Elongation at break	9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9	Melting temperature
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	~~9~~	Cost
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	~~4~~	5	6	7	8	9	Coefficient of thermal expansion
Elongation at break	9	8	7	~~6~~	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	~~8~~	9	Carbon Dioxide
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9	Cost
Melting temperature	9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9	Coefficient of thermal expansion
Melting temperature	9	8	7	~~6~~	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	5	~~6~~	7	8	9	Carbon Dioxide
Cost	9	8	7	6	5	~~4~~	3	2	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Cost	9	8	~~7~~	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Cost	9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Coeffient of thermal expansion	~~9~~	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Coeffient of thermal expansion	9	8	7	6	5	4	3	2	1	2	3	~~4~~	5	6	7	8	9	Carbon Dioxide
Density	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	~~9~~	Carbon Dioxide

Expert No: 3																		
Tensile Strength	9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9	Yield Strength
Tensile Strength	9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9	Elongation at break
Tensile Strength	9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9	Melting temperature
Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	~~7~~	8	9	Cost
Tensile Strength	9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9	Coefficient of thermal expansion
Tensile Strength	9	~~8~~	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Tensile Strength	9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9	Carbon Dioxide
Yield Strength	9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9	Elongation at break
Yield Strength	9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9	Melting temperature
Yield Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	~~8~~	9	Cost
Yield Strength	9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9	Coefficient of thermal expansion
Yield Strength	9	~~8~~	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Yield Strength	9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9	Carbon Dioxide
Elongation at break	9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9	Melting temperature
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	~~9~~	Cost
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9	Coefficient of thermal expansion
Elongation at break	9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9	Density
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	~~7~~	8	9	Carbon Dioxide
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	~~9~~	Cost
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9	Coefficient of thermal expansion
Melting temperature	9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9	Density
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	~~4~~	5	6	7	8	9	Carbon Dioxide
Cost	9	8	7	~~6~~	5	4	3	2	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Cost	~~9~~	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Cost	9	8	7	6	5	~~4~~	3	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Coeffient of thermal expansion	9	8	~~7~~	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Coeffient of thermal expansion	9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Density	9	8	7	6	5	4	3	2	1	2	3	4	5	6	~~7~~	8	9	Carbon Dioxide

Expert No: 4

Tensile Strength	9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9	Yield Strength
Tensile Strength	9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9	Elongation at break
Tensile Strength	9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9	Melting temperature
Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	~~4~~	5	6	7	8	9	Cost
Tensile Strength	9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9	Coefficient of thermal expansion
Tensile Strength	9	~~8~~	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Tensile Strength	9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9	Carbon Dioxide
Yield Strength	9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9	Elongation at break
Yield Strength	9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9	Melting temperature
Yield Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	~~6~~	7	8	9	Cost
Yield Strength	9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9	Coefficient of thermal expansion
Yield Strength	9	~~8~~	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Density
Yield Strength	9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9	Carbon Dioxide
Elongation at break	9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9	Melting temperature
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	~~8~~	9	Cost
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	~~7~~	8	9	Coefficient of thermal expansion
Elongation at break	9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9	Density
Elongation at break	9	8	7	6	5	4	3	2	1	2	3	4	5	6	~~7~~	8	9	Carbon Dioxide
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	~~8~~	9	Cost
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	5	~~6~~	7	8	9	Coefficient of thermal expansion
Melting temperature	9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9	Density
Melting temperature	9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9	Carbon Dioxide
Cost	9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9	Coefficient of thermal expansion
Cost	~~9~~	8	7	6	5	4	3	2	1	2	3	4	5	5	7	8	9	Density
Cost	9	8	7	6	5	~~4~~	3	2	1	2	3	4	5	5	7	8	9	Carbon Dioxide
Coeffient of thermal expansion	9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9	Density
Coeffient of thermal expansion	9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9	Carbon Dioxide
Density	9	8	7	6	5	4	3	2	1	2	3	4	5	6	~~7~~	8	9	Carbon Dioxide

ANNEX-4. Survey

Aim of the Survey:

The aim of this survey is to provide relevant data from expert designers in order to evaluate the raw material ranking to be used in the design of a functional part that is exposed to temperature difference and mechanically stressed, using the TOPSIS method.

Rank	**Materials**	**Relatives Closeness**
1	PET	0.660911168
2	PS	0.65279054
3	PVC	0.650737984
4	PP	0.631603977
5	LPDE	0.589973492
6	HPDE	0.563831659
7	PC	0.441704643
8	Nylon 6,6	0.416045425

Expert No:	Strongly Agree	Agree	Neither Disagree Nor Agree	Disagree	Strongly Disagree
The ranking obtained from the analysis is quite suitable for application in the project.					

ANNEX-5. Experts' answer matrix

Expert No: 1	Strongly Agree	Agree	Neither Disagree Nor Agree	Disagree	Strongly Disagree
The ranking obtained from the analysis is quite suitable for application in the project.	X				

Rank	Materials	Relatives Closeness
1	Nylon 6,6	0.636387
2	PC	0.585228
3	PET	0.58199
4	PS	0.56916
5	PVC	0.503742
6	PP	0.410912
7	LDPE	0.390029
8	HDPE	0.322988

Expert No: 2	Strongly Agree	Agree	Neither Disagree Nor Agree	Disagree	Strongly Disagree
The ranking obtained from the analysis is quite suitable for application in the project	X				

Rank	Materials	Relatives Closeness
1	Nylon 6,6	0.636387
2	PC	0.585228
3	PET	0.58199
4	PS	0.56916
5	PVC	0.503742
6	PP	0.410912
7	LDPE	0.390029
8	HDPE	0.322988

Expert No: 3	Strongly Agree	Agree	Neither Disagree Nor Agree	Disagree	Strongly Disagree
The ranking obtained from the analysis is quite suitable for application in the project.		✓			

Rank	Materials	Relatives Closeness
1	Nylon 6.6	0.636387
2	PC	0.585228
3	PET	0.58199
4	PS	0.56916
5	PVC	0.503742
6	PP	0.410912
7	LDPE	0.390029
8	HDPE	0.322988

Expert No: A	Strongly Agree	Agree	Neither Disagree Nor Agree	Disagree	Strongly Disagree
The ranking obtained from the analysis is quite suitable for application in the project	/				

Rank	**Materials**	**Relatives Closeness**
1	Nylon 6.6	0.636387
2	PC	0.585228
3	PET	0.58199
4	PS	0.56916
5	PVC	0.503742
6	PP	0.410912
7	LDPE	0.390029
8	HDPE	0.322988

ANNEX-5. Ethics Committee Decision Letter

Evrak Kayıt Tarihi: 16.04.2025 | Protokol No: 879455

Tarih: 22.07.2025

ANADOLU ÜNİVERSİTESİ

SOSYAL VE BEŞERÎ BİLİMLER BİLİMSEL ARAŞTIRMA VE YAYIN ETİĞİ KURULU

KARAR BELGESİ

ÇALIŞMANIN TÜRÜ:	Doktora Tez Çalışması
KONU:	Sosyal Bilimler
BAŞLIK:	Using a Hybrid Weighting Method in Multi Criteria Decision Making for Thermoplastic Material Selection Termoplastik Malzeme Seçimi için Çok Kriterli Karar Verme Hibrit Ağırlıklandırma Yönteminin Kullanılması
~~PROJE/~~TEZ YÜRÜTÜCÜSÜ:	Prof. Dr. Fikret ER
TEZ YAZARI:	Raziye OKYAY DURMUŞ
ALT KOMİSYON GÖRÜŞÜ:	-
KARAR:	Olumlu

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Scientific Activities (Congress, Symposium, Workshop, etc.):

Topaloğlu, Ş., & Okyay, R. (2016, December). ASSEMBLY LINE HIERARCHICAL WORKER ASSIGNMENT AND BALANCING PROBLEM WITH POSITIONAL CONSTRAINTS, TASK ASSIGNMENT RESTRICTIONS AND PARALLEL STATIONS. In *LM-SCM 2016 XIV. INTERNATIONAL LOGISTICS AND SUPPLY CHAIN CONGRESS* (p. 70).

Rewards:

Mahindra Group Global Synergy Award, 2019, India