



**REPUBLIC OF TURKEY
ADANA ALPARSLAN TÜRKER SCIENCE AND TECHNOLOGY
UNIVERSITY**

**INSTITUTE OF GRADUATE SCHOOL
DEPARTMENT OF INDUSTRIAL ENGINEERING**

**IDENTIFICATION AND IMPROVEMENT OF COMFORT
PARAMETERS FOR MILITARY VEHICLES THROUGH TOTAL
QUALITY MANAGEMENT, RISK ANALYSIS, AND MULTI-CRITERIA
DECISION-MAKING**

**YASİN AYTAÇ BALKIR
MASTER OF SCIENCE**

ADANA, 2023



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YASİN AYTAÇ BALKIR

MASTER OF SCIENCE

SUPERVISOR

ASSOC. PROF. CANSU DAĞSUYU

ADANA, 2023

I hereby declare that all information in this thesis has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all information that is not original to this work.

[Signature]

Yasin Aytaç BALKIR

ABSTRACT

IDENTIFICATION AND IMPROVEMENT OF COMFORT PARAMETERS FOR MILITARY VEHICLES THROUGH TOTAL QUALITY MANAGEMENT, RISK ANALYSIS, AND MULTI-CRITERIA DECISION-MAKING

Yasin Aytaç BALKIR

Department of Industrial Engineering

Supervisor: Assoc. Prof. Dr. Cansu DAĞSUYU

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Quality Function Deployment (QFD) is a total quality management tool that focuses on the voice of customers in the early stages of the product/service development process in order to identify the customer requirements clearly and increase the profitability of the sales returns by achieving the maximum customer satisfaction levels possible. Combined with the Failure Modes and Effect Analysis (FMEA), which is a risk analysis methodology, the efficiency of the design stage of the product/service development can be increased by identifying the most crucial technical specifications affiliated with the customer requirements. Sometimes, during the design stage, there can be some caveats while trying to meet the technical specifications. For instance, when a technical parameter is being improved another one can be worsened, simultaneously. This causes a technical contradiction. TRIZ (Theory of Inventive Problem Solving) is a comprehensive set of tools to resolve these kinds of contradictions by offering several potential solutions. And, Analytic Hierarchy Process (AHP) methodology, one of the most popular and useful multi-criteria decision-making (MCDM) tools, can be used to make a consistent and useful selection among those solutions.

In this study, the integrated combination of QFD, FMEA, TRIZ, and AHP was made used to identify and improve the comfort characteristics of military vehicles. Materials for the study are gathered from a subject company that is based in the automotive and defense systems industry. Based on the interviews conducted with the company, the elements related to in-cab air conditioning were defined as the most important criteria that affect the comfort parameter inside the vehicle. These elements were taken into consideration during the identification

process of customer requirements. Technical specifications and their importance values were evaluated with respect to the customer requirements. Technical contradictions were identified between the technical specifications. Later, an FMEA application was conducted in order to identify potential failure modes regarding the technical specifications. At the end of the FMEA application, the calculated RPN values were integrated into the relative score values of technical specifications in the House of Quality matrix. This resulted in the identification of new technical contradictions among the technical specifications. By using the Contradiction Matrix and the 40 Inventive Principles of TRIZ, various inventive solutions were identified for these contradictions. At the end of the study and through the AHP application the most suitable one among the potential solutions was selected and suggested to the company.

Keywords: Quality Function Deployment (QFD), Failure Modes and Effect Analysis (FMEA), Theory of Inventive Problem Solving (TRIZ), Analytic Hierarchy Process (AHP), Automotive Industry, Defense Systems Industry

ÖZET

ASKERİ ARAÇLAR İÇİN KONFOR PARAMETRELERİNİN TOPLAM KALİTE YÖNETİMİ, RİSK ANALİZİ VE ÇOK KRİTERLİ KARAR VERME YOLUYLA BELİRLENMESİ VE İYİLEŞTİRİLMESİ

Yasin Aytaç BALKIR

Endüstri Mühendisliği Anabilim Dalı

Danışman: Doç. Dr. Cansu DAĞSUYU

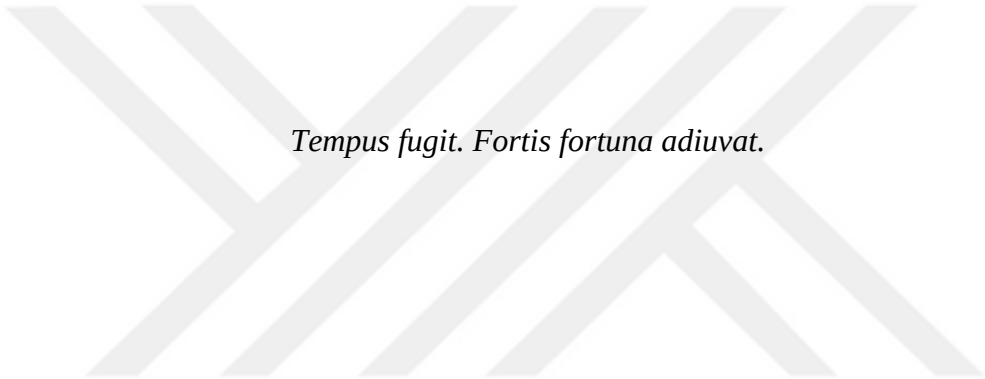
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Kalite Fonksiyon Yayılımı (KFY), müşteri gereksinimlerini net bir şekilde belirlemek ve satış getirilerinin kârlılığını en yüksek müşteri memnuniyet düzeyine ulaşıarak artırmak için ürün/hizmet geliştirme sürecinin erken aşamalarında müşterilerin beklentilerine odaklanan bir toplam kalite yönetim aracıdır. Bir risk analizi metodu olan Hata Türleri ve Etkileri Analizi (HTEA) ile birlikte, ürün/hizmet geliştirmenin tasarım aşamasının etkinliği, müşteri gereksinimlerine bağlı en önemli teknik özelliklerin belirlenmesiyle artırılabilir. Bazen tasarım aşamasında teknik özellikleri karşılamaya çalışırken bazı çelişkiler ile karşılaşılabilir. Örneğin, bir teknik parametre iyileştirilirken, aynı anda bir diğeri kötüleştirilebilir. Bu, teknik bir çelişkiye neden olur. TRIZ (Yaratıcı Problem Çözme Teorisi), çeşitli potansiyel çözümler sunarak bu tür çelişkileri çözmek için kapsamlı bir araç setidir. En popüler ve kullanışlı çok kriterli karar verme (ÇKKV) araçlarından biri olan Analitik Hiyerarşi Süreci (AHS) metodu da de bu çözümler arasında tutarlı ve kullanışlı bir seçim yapmak için kullanılabilir.

Bu çalışmada, askeri araçların konfor parametrelerini belirlemek ve iyileştirmek için KFY, HTEA, TRIZ ve AHS'nin entegre kombinasyonu kullanılmıştır. Çalışmanın materyalleri otomotiv endüstrisi ve savunma sanayiinde faaliyet gösteren bir firmadan temin edilmiştir. Çalışma sonunda söz konusu firmaya çeşitli yaratıcı çözümler önerilmiş ve AHP uygulaması ile bunlardan en uygun olanı belirlenmiştir. Firma ile yapılan görüşmelerden yola çıkılarak araç içi konfor parametresini etkileyen en önemli kriter olarak kabin içi iklimlendirme ile ilgili unsurlar belirlenmiştir. Müşteri gereksinimlerinin belirlenmesi sürecinde başta bu unsurlar dikkate alınmıştır. Teknik özellikler ve önem değerleri müşteri istekleri

doğrultusunda belirlenip değerlendirilmiştir. Teknik özellikler arasında teknik çelişkiler tespit edilmiştir. Daha sonra, teknik özelliklerle ilgili olası arıza modlarını belirlemek için HTEA uygulaması yapılmıştır. HTEA uygulaması sonunda hesaplanan Risk Öncelik Sayısı (RÖS) değerleri, Kalite Evi matrisindeki teknik özelliklerin bağıl puan değerlerine entegre edilmiştir. Bu, teknik şartnameler arasında yeni teknik çelişkilerin tanımlanmasına neden olmuştur. Çelişki Matrisi ve TRIZ'in 40 Yaratıcı Problem Çözme İlkesi kullanılarak bu çelişkiler için çeşitli yaratıcı çözümler belirlenmiştir. Çalışma sonunda AHP uygulaması ile olası çözümler arasından en uygun olanı seçilerek söz konusu firmaya önerilmiştir.

Anahtar Kelimeler: Kalite Fonksiyon Yayılımı (KFY), Hata Türleri ve Etkiler Analizi (HTEA), TRIZ (Yaratıcı Problem Çözme Teorisi), Analitik Hiyerarşi Süreci (AHS), Otomotiv Endüstrisi, Savunma Sanayii



Tempus fugit. Fortis fortuna adiuvat.

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NOMENCLATURE

QFD:	Quality Function Deployment
TRIZ:	Theory of Inventive Problem Solving
FMEA:	Failure Modes and Effect Analysis
AHP:	Analytic Hierarchy Process
MCDM:	Multi-Criteria Decision-Making
TQM:	Total Quality Management
SERVQUAL:	Service Quality
VSM:	Value Stream Mapping
LM:	Lean Manufacturing
FMEAA:	Failure Mode and Effects Anticipation Analysis
PFMEA:	Process Failure Mode and Effects Analysis
R&D:	Research and Development
RPN:	Risk Priority Number
CRs:	Customer Requirements
TSs:	Technical Specifications
VOC:	Voice of Customers
TCM:	Technical Correlation Matrix
S:	Severity
O:	Occurrence Probability
D:	Detection/Detectability
CI:	Consistency Index
CR:	Consistency Ratio
RI:	Random Consistency Index

1. INTRODUCTION

Since its very first interaction with the environment, mankind has always looked for new ways to discover and make their daily life easier. This fundamental series of course of actions gave birth to a new term called "technology", eventually.

Today, technology is ever-developing and evolving at an unprecedented rate. New application methodologies and tools are developed day by day by so many inventors, engineers, and companies. As a result, with every further technological advancement, problems arise as well, as a part of the nature of the causality of technology and its interaction with mankind. This interaction between mankind and technology can be considered a closed-loop system. To briefly explain, while accomplishing their daily goals people come across new kinds of problems. And to come up with solutions for these problems they tend to look into their already-existing potential resolutions. Sometimes, these potential resolutions won't be sufficient and so they won't apply to such new kinds of problems. It is at this point, we make full use of our cumulative intellectual knowledge to come up with new and better ways to approach our problems, and hopefully find suitable resolutions for them. As a matter of fact, most of the technological advancements, methodologies, and inventions were introduced with this approach.

New problems bring different questions. Some of these questions can be related to the methodology to tackle such problems, while others can be related to the instruments to be used to resolve the problems. Even though the methodology and the instruments are already defined, the applicability of the methodology and the safety of the approach should be taken into consideration. Because, at the end of the day, the theoretical approach that emerged from the cumulative intellectual knowledge has to be approved and confirmed by practical applicability.

Sometimes, instead of defining problems in the already existing technology, companies ask for feedback from their customers. This logical approach not only helps the companies to hear the voice of customers but also enables the customers' expectations to be directly taken into consideration in the production or revision process of the internal teams of the companies. Quality Function Deployment (QFD) and House of Quality (HOQ), which is the fundamental methodology of QFD, directly help this purpose for the companies. It puts the voice of

customers at the center and early stages of the company and its product development process so that the production teams can better understand the customer expectations and define their technical requirements to meet those expectations while developing their new service or product (Chan and Wu, 2002b; Prasad, 1998).

Defining and meeting technical requirements according to customer expectations can be a bit problematic from time to time. For instance, customers may be expecting from an automobile brand a new car that is faster than its previous generation models. To meet this specific customer expectation, the company may decide to go with a new and more powerful engine. The physical space required for the new engine can be larger than the previous engine and because of that the production teams might have to revise their product development process due to technical contradictions, e.g, larger engine space might cause larger body parts of the car, and this increases the total weight of the car. At this point, it can be said that the larger motor space is considered to be a positive technical characteristic whereas the increase in the total weight of the car can be considered a negative or unwanted technical characteristic. In order to solve these kinds of conflicts that arise from the interaction between the technical specifications and customer requirements, TRIZ (Theory of Inventive Problem Solving) can be a powerful tool. It has various application tools, e.g, the Contradiction Matrix, 40 Inventive Principles, Substance-Field Analysis, etc. Specifically, for this technical contradiction, the Contradiction Matrix of TRIZ tools can be used. Its fundamental working principle is based on identifying the increasing and decreasing characteristics of a system, simultaneously. With that approach, specific pre-determined applications from the 40 Inventive Principles can be applied and the technical contradiction can be resolved. TRIZ helps these kinds of technical contradictions to be eliminated in practice besides making use of cumulative intellectual technological knowledge and inventing new application methodologies as well (Ekmekci and Koksall, 2015; Ilevbare et al., 2013).

During the product development process, customer expectations can be identified via various methodologies. Afterward, based on customer expectations technical specifications are determined by internal teams of the company that is executing the product development process. By various approaches, e.g., TRIZ, technical contradictions can be eliminated and technical requirements/specifications can clearly be determined. In order to serve the new product to the customers, firstly, a risk analysis should be conducted not only to see the applicability of the new methodology or production in practice but also to identify any

potential risks that can harm the safety of the customers while experiencing this new product or service. Risk analysis can also be conducted for the product development process to identify and eliminate any potential faulty and hazardous parameters that can affect the safety and efficiency of the internal teams, e.g., the production department, research, and development department, etc. At that point, the Failure Modes and Effect Analysis (FMEA) methodology can be benefited. It helps identify any possible failures, hazardous parameters, or dangerous elements in the process or product and eliminate them proactively. FMEA methodology involves not only one individual but many people from different departments of the company so that more knowledge sharing is encouraged and that can help the teams to have a better perspective on the process making them capable of determining, evaluating, and eliminating the risk factors easily (Sharma and Srivastava, 2018).

Also, there can always be more than possible solution, criterion, methodology, application, or approach to a service, process, or problem. And when the number of elements related to a subject increased, that subject gets more complex to be evaluated. For these kinds of situations, the resolutions must be unbiased and based on analytical thinking. Through that approach objective decision-making can be possible. And objective decision-making inspires the most suitable solutions. The Analytic Hierarchy Process (AHP), a multi-criteria decision-making (MCDM) tool, works with that principle. It examines complex problems or situations with many criteria, identifies the problem, evaluates the interrelationship between criteria, and determines the most suitable one among them related to the problem or situation. In other words, it can be said that AHP is a very useful methodology to reduce complex problems to simplified ones by evaluating each criterion of them (T. L. Saaty, 1990b).

1.2. Problem Definition of the Study

Based on the information above, determining customer requirements, identifying respective technical specifications regarding those customer requirements, conducting a risk analysis to determine and eliminate any potential risk factors before they occur, according to these data determining various technical contradictions between the technical specifications, eliminating these contradictions through various possible and inventive solutions, and selecting the most suitable and efficient solution among all the suggested possible solutions can all be part of a new product/process/service development operation. Because of that, it is possible to make use of QFD, FMEA, TRIZ, and AHP all together in one single operation. However, the literature review conducted for this study, presented in the next section, shows that there was

not any joint application of these methodologies. Another observation regarding the scope of the literature review is that there was no study in which this kind of joint application was used in the automotive and defense systems industry.

According to these findings, it can be said that in order to improve the overall customer satisfaction levels and develop new solutions for the common product/process/service development stages in the automotive and defense systems industry the joint application of QFD, FMEA, TRIZ, and AHP can be used, effectively.

Based on the information gathered from the subject company, there was a need for the deployment of a group of engineering methodologies in order to improve the comfort parameter inside military vehicles. This need was specifically indicated by the customers of the company. QFD methodology directly deals with the voice of customers and puts them at the center of its applications. So, it was determined to be one of the key components of this study. Since there can be several potential design and parameter changes during the conduction of the study a risk assessment application for design characteristics of military vehicles was required. The FMEA methodology was selected to be used in that manner. Also, due to the nature of design improvements/changes, there can be some technical contradictions that might occur during product/service development stages. In order to come up with several potential solutions for eliminating those contradictions the TRIZ tools can be made use of for creative solution providing. So, the Contradiction Matrix and 40 Inventive Principles of TRIZ tools were selected as other tools of application. Considering the budget expenses and project timelines of the company, among all the potential and creative solutions the most suitable and effective one needed to be determined. Also, for the sake of the benchmarking of the study, an MCDM method was needed. In that matter, the AHP application was chosen to be deployed in the final stage of the study. the AHP method was also beneficial to order the potential solutions hierarchically, so that if the need arose more than one solution could be deployed in order to further improve the comfort parameter for the product portfolio of military vehicles of the company. Further details about the subject company are provided in section 3.

1.3. The Purpose of the Study

This study examines the previous studies, applications, and research in the literature to identify the interrelationship of QFD, FMEA, TRIZ, and AHP when they are made use of in a joint methodology.

In this study, QFD, FMEA, TRIZ, and AHP methodologies are taken into consideration as a synthesis to see their applicability in practice, more specifically in the automotive and defense systems industry. This study aims to identify the gap in the literature and use all four methodologies in one single product/process/service development operation to contribute to the cumulative knowledge library of the specific area in the literature. Another purpose of the study is the identification of key elements that affect the comfort parameter in military vehicles based on customer expectations, evaluation of these elements in terms of risk assessment, and determination of possible technical conflicts with their possible solutions arising from the technical specifications related to customer expectations, and finally choosing the most suitable solution option among them. With that approach, it is aimed to improve the comfort parameter of the military vehicles product line of the subject company by reducing the problem definition from a complex situation to a simple one.

The rest of the paper is as follows: Literature review in section 2, materials and methods in section 3, results and discussions in section 4, conclusion in section 5, recommendations in section 6, references, and appendices in the final section.

2. LITERATURE REVIEW

In this section, research that included QFD, TRIZ, FMEA, and AHP methodologies in different industries in recent years is presented and discussed. A literature review was conducted methodically, so in the first step, the articles and research that only use one of the four tools are presented. In the second step, the research that only uses two of the four tools together are presented. In the third step, the research that use three of the four tools together are presented. And finally, in the last step of the literature review, the articles and research that use all four tools together are presented.

2.1. Quality Function Deployment (QFD) Studies

QFD is a useful tool to understand customer desires, needs, and requirements, and determine the corresponding technical requirements and specifications to help its user operate more easily to meet the end user requirements of a service or product (Morrell, 1987). It is, like TRIZ, a flexible tool that can be applied in various industries, e.g., automotive, food, and service. For instance, in a recent study, it was employed to understand the expectations of the customers from the car seat industry. In the research, the aim was to identify the key characteristics that hold the car seat industry to improve its design specifics by having the customers at the very center of the research. As a result, a win-win situation was created for both the customers and the participating company(-ies) in the study. Also, the overall product and production quality were improved (Purba et al., 2020). An example of QFD being used in the service sector can be given from a study conducted in 2013. In a private hospital located in Istanbul, a combination of QFD and SERVQUAL was employed to understand the expectations of patients and their requirements from the hospital management. The study was stated to be unique in terms of combining QFD with SERVQUAL in the service, more specifically the healthcare, sector. According to the study's findings, QFD was very beneficial for determining patient requirements and evaluating key characteristics to improve the hospital's overall service quality and operational effectiveness (Sinha et al., 2013).

2.2. Failure Modes and Effect Analysis (FMEA) Studies

Failure Modes and Effect Analysis (FMEA) is a well-known risk analysis and total quality management (TQM) tool its origin dates back to 1949. It was first used in the United States military applications. Later, its scope of applications spread widely around the world based on the companies' need for product and process improvement and safety regulations (Sharma and Srivastava, 2018). Although its main purpose is to identify the possible root causes of failures and problems before they occur and give insights to act proactively (Eryürek and Tanyaş, 2003), it has become a very diversified tool so that it can be used for many other purposes as well, e.g., cost reduction operations for the production of high-quality products, supply chain operations, product and process quality improvement, occupational health and safety regulations, etc. (Çevik and Aran, 2010). Today, FMEA is widely used across various industries, e.g., automotive, aerospace, defense systems, furniture, healthcare, etc.

Çevik and Aran (2010) focused on identifying critical failure modes for the production stages of engine pistons in the automotive industry. Based on their study, results seemed promising to ensure improved product quality and increased customer satisfaction levels. Another study conducted in the automotive industry focused on supply chain management activities and identified some procedural applications in order to improve supplier quality and eliminate any potential failures during transportation activities (Özkan Tez et al., 2012). In the early 90s, Kara-Zaitri et al. (1991) conducted their FMEA operations in order to identify the potential failure modes and their root causes and store them in a digital environment for cumulative knowledge gathering and proactive action-taking to eliminate risk factors in the British railway and automotive industry. Ramere and Laseinde (2021) preferred a different approach and tried to improve maintenance equipment efficiency in the same industry.

If we shift the focus from the automotive industry, there still can be many different application industries for FMEA. For instance, one study aims to identify and evaluate the risk factors for accommodation situations (Altın et al., 2018), whereas the others tried to determine the cause of the failure modes and potential risk factors in the healthcare industry (Eraslan et al., 2018; Chiozza and Ponzetti, 2009). Chanamool and Naenna (2016) used FMEA to provide emergency services help for determining the employee action plans based on healthcare risk factors and circumstantial prioritization. Ookalkar et al. (2009) based their FMEA study on improving the operational effectiveness of renal care applications and patient conditions.

The FMEA methodology is also proved to be beneficial for the supply chain industry. Dagsuyu et al. (2021) studied identifying the potential harmful factors for both the environment and human health in the cold chain industry and provided necessary suggestions to reduce the effects of these factors by combining the FMEA methodology with various approaches. Curkovic et al. (2015) indicated the lack of usage of risk assessment approaches in the supply chain industry. Based on their research, they presented a collection of data that shows the inclination of companies to the usage of risk analysis methods for managing supply chain operations. They also proposed some methodologies on how to choose suppliers while also evaluating the risk factors. Mangla et al. (2018) shared the same idea as Curkovic et al. (2015) indicating the reluctance of companies to make use of risk assessment methods in the supply chain industry. They based their research on eco-friendly supply chain operations, integrating a fuzzy approach to FMEA. They aimed to make an improvement on the already existing FMEA methodology, while also identifying the risk components in the aforementioned industry.

2.3. Theory of Inventive Problem Solving (TRIZ) Studies

TRIZ can be used in various application areas, e.g., the automobile industry, aviation and space industries, agronomy, food industry, composite material studies, healthcare, service industry, and even the entertainment industry.

In a recent study, Yang et al. (2018) benefited from TRIZ to improve mechanical attributes and the overall performance of the current state sowing machines. They identified the key characteristics of the machine that needed to be improved and later determined the matching conflicting characteristics that may potentially cause a contradiction. They also used the Substance-Field Analysis methodology, one of the tools of TRIZ, to dive deeper into the subject. According to their observation, the results were promising and the aim of the project was met without any divergence and incompatibility from their national standards. Tian and Liu (2019) tackled a common problem of seedling transplanting mechanisms by using the Contradiction Matrix of Altshuller. They stated that by following the path that the matrix laid down for them it became easier for the authors to develop a more efficient machine. The authors also stated that by benefiting from the contradiction matrix and 40 inventive principles the time of the design stage was decreased conspicuously.

If the scope is changed to the automotive industry, there are also many examples of TRIZ usage. Whenever a new technology is invented and ready to be served to the community, most individuals tend to be hesitant to use it because of their natural inclination not wanting to leave their comfort zones. In that matter, one of the researches focuses on the new energy automobile manufacturing market. The study's authors intended to make future-based research and provide statistically proven guidelines for the manufacturers, distributors, and customers interested in being involved in the new energy vehicle technology. They also aimed to make transitioning to a new energy vehicle industry comfortable enough not only for individuals but also for the governments as well. The research took concepts and tools like Ideal Final Result (IFR), Ideality, Contradiction Matrix, and Substance-Field Analysis into account and proposed a perspective on how to build a structure for the new energy vehicle industry and the service derivatization considering the industrial, social, and governmental elements (Wan et al., 2020).

Another case study that is based on the automotive industry combines TRIZ applications with tribology. In this specific article, a common problem, degradation of electrical connectors in motors due to constantly changing vibration and temperature exposure/exchange between the surfaces was investigated. The authors of the article tackled the problem by making use of the TRIZ trend roadmap combined with the various tribological methodologies. The study determines how to design an electrical motor that can resist vibration and temperature exposures and the fundamentals of know-how of the surface design for the electrical motor. With this approach, it was stated that the life cycle of the electric motors can be extended and more importantly controlled (Liskiewicz et al., 2020).

If the scope is changed to the aviation and space industry, many examples of TRIZ applications can be identified in the literature. One of the studies based on the aforementioned industry aims to improve the overall customer satisfaction level while also maintaining safety standards. As the authors of the research stated, the aim to meet customer requirements may conflict with the industry's flight safety standards and technical regulations. They also provided three case studies to better explain those conflicts. The authors made use of the TRIZ contradiction matrix to come up with respective solutions for these issues. Their approach was commercially based and customer-oriented suggesting ways to maintain and improve the profitability of airline service quality (Jeeradist et al., 2016).

In the healthcare sector, which is a less technical but still useful area for TRIZ applications (Zlotin et al., 2000), one of the studies focuses on increasing the response time of hospital employees while also maintaining the safeness of the workplace and ensuring the treatment quality of the patients is not affected negatively. Service Quality (SERVQUAL), a commonly used methodology to measure the expectations of patients and relatives of patients in light of various components in the healthcare sector (Buttle, 1996), was also benefited from and combined with the contradiction matrix of the TRIZ (Yener and Altuntaş, 2012).

2.4. Analytic Hierarchy Process (AHP) Studies

AHP is one of the multicriteria decision-making tools that has been created and used since the mid-1970s in various application areas for critical and analytics-based decision-making, resolving contradictions, planning studies, etc. It is based on a pair-wise comparison of multiple criteria or elements and their dependency relationship of them with each other. It is a useful tool to come up with an objective conclusion when the problems of a system become more complex to interpret with the increased number of subjective criteria (R. W. Saaty, 1987).

AHP has been used for nearly 50 years since its creation. So, it has been continuously improved upon, integrated into different methodologies, and commonly used for different applications in various industries. The banking industry is one of the popular industries for AHP and AHP-combined applications (Haghighi et al., 2010; Seçme et al., 2009). Customer requirement identification, rating, and hierarchical ordering can also benefit from AHP-included methodologies in various industries (Y. L. Li et al., 2010; Lin et al., 2010). Product/service development systems and operations are another application area for AHP methodology (İç and Yurdakul, 2009; T. S. Li and Huang, 2009; C. L. Yang et al., 2009). AHP can also be benefited from organizational activities, e.g., evaluation for operators, performance reviewing of organizations, and hiring processes (Celik et al., 2009; Khosla et al., 2009; Şen and Çınar, 2010; Tseng and Lee, 2009).

2.5. QFD-TRIZ Combined Studies

As can be understood from the information presented above, QFD and TRIZ can be combined and used together in both theory and practice. As a matter of fact, many technical and administrative contradictions in various industries can be resolved with that approach since each tool has its unique advantages. Yamashina et al. (2002) stated that until the date their

study was published no other research or study made effective use of a combination of QFD and TRIZ. The authors took that opportunity to create a new methodology, named it, and applied it to a fully functioning washing machine. They aimed to find better, easier, and more innovative approaches for manufacturers to take the next steps in the innovation life-cycle of washing machines and lay a foundation for manufacturers in all industries. As a result of their research, it was stated that using QFD and the HOQ matrix made determining key elements that need improvement and innovation easier. It was also stated that using TRIZ after determining the respective elements made solving technical conflicts made easier. In the electronic devices industry, research regarding the production of an energy-efficient and environmentally friendly notebook was conducted. What made this study unique was that it created several stages, and repetitively used the QFD-TRIZ application. At each stage, customer needs and technical requirements were evaluated and the contradictory elements regarding these parameters were identified and resolved. So, from a wider perspective, it can be said that the study got deeper at every stage of the application. As a result, proper ways to save energy on an operating notebook were identified. Also, the study laid a foundation for many laptop manufacturers by introducing a new composite material to be used in the frames of laptops (Yeh et al., 2011).

QFD-TRIZ combination was also used in the product-service systems (PSS). In a 2012 study, the authors of the respective research study investigated various PSS cases to evaluate to chances to apply the 40 Inventive Principles of TRIZ and to come up with a unique PSS concept for a car-service system. In addition, they included QFD in the equation to determine the interactions and relationships between customer requirements and sub-systems on both the product and service sides (Kim and Yoon, 2012).

If the scope is changed to the additive manufacturing industry, the QFD-TRIZ combination can be used to create more efficient product manufacturing at every step of the application area e.g., raw material usage, total manufacturing time, and energy and waste consumption. One of the studies aimed to obtain the above objectives while also offering a statistically proven new design concept for open mold processes (Caligiana et al., 2017).

Another combination of QFD-TRIZ was applied in the service design applications. Service QFD combined with the contradiction matrix of TRIZ resulted in an efficient, digital, re-adjustable self-service meal ordering system. The proposed approach increased the general

satisfaction of the employees with the menus and service and reduced many costs (Y. H. Wang et al., 2017).

In the urban transportation sector, the research used the QFD-TRIZ combination to attend to customers' expectations and requirements for a publicly usable hoverboard (Donnici et al., 2021).

2.6. QFD-FMEA Combined Studies

One of the early discussions of FMEA combined with QFD suggested the similarities of both tools in terms of their application and effectiveness area. It is stated that QFD attends to the voice of customers, requirements, and expectations from a product, company, or manufacturer whereas the FMEA puts the voice of the internal and external responsible of those companies, manufacturers, or the creators of the products, e.g., executives, engineers, sales teams (Ginn et al., 2006). Since QFD and FMEA can complement each other in such an effective and comprehensive way, this synthesis can be deployed in various sectors as well. Almannai et al. (2008) pursued that objective by aiming to cover different aspects of a manufacturing process, e.g, technological and organizational matters on one hand, and issues concerning human resources or people management on the other. They aimed to make use of these valuable tools to bring many different components of the manufacturing industry, as stated above, and come up with new creative and applicable approaches for each component, eventually leading to an improvement in both product quality and customer satisfaction.

Tanik (2010) took the QFD-FMEA combination and applied it to the food packaging industry. In the study, it was stated that QFD was an effective tool to build a bridge between customer expectations and engineering applications, but sometimes there might be a probability of severe production faults due to misunderstandings between customers and engineering teams. He stated that FMEA can be a complementary tool to prevent this proactively and provide statistical data based on a case study from a food packaging production company.

T. Wang et al. (2018) based their research study on ship power plant design solutions. Their study aimed to propose a unique approach to QFD-FMEA synthesis to implement a new design methodology for ship power plants. It was suggested that AHP can also be implemented in the study to further investigate the possibilities of the proposed approach.

Bhuvanesh Kumar and Parameshwaran (2018) preferred a fuzzy QFD-FMEA approach combined with Value Stream Mapping (VSM) in the manufacturing industry. They aimed to

integrate this approach into the lean manufacturing (LM) technique and get as many different perspectives and experts' opinions involved in the process to increase the profitability and effectiveness of the approach.

Despite using the QFD-FMEA combination to improve key areas in various industries and applications, one quality improvement tool can be used to improve the functionality of the other. In that matter, Shaker et al. (2019) concentrated on improving the operability of FMEA by deploying a two-stages QFD application on it. Each stage had a different purpose for identifying key characteristics of FMEA applications and building upon the current functionality of the FMEA process. The authors also conducted a case study on a company based in the steel-manufacturing industry to prove the effectiveness of their proposed approach.

2.7. TRIZ-FMEA Combined Studies

Since FMEA is a well-known application tool for identifying risk factors, theoretically TRIZ can be combined with the FMEA to chase creative undertakings and actions to eliminate such risk factors that are identified with FMEA.

Yen and Chen (2005) examined the design specifications of a vacuum cleaner and applied the FMEA to the current design of the equipment. Then, they determined various risk factors that may potentially be harmful to both customers and the environment. Afterward, they deployed the TRIZ application on the already determined key risk factors and came up with possible creative solutions for the respective issues. One of the many aspects of their study was the belief that the combination of such application tools requires many different professional perspectives to be shared. But, it was also stated that since eliminating idea-generation techniques, e.g., brainstorming, was possible via TRIZ, the time consumption in the idea-generation process decreased dramatically.

Regazzoni and Russo (2011) suggested a similar idea to Yen and Chen (2005), focusing on the creation of a more precise risk management FMEA. They also benefited from various TRIZ tools, e.g., Su-Fields Analysis, 76 standard solutions. They believed that by their approach the overall functionality and precision of FMEA could be increased exponentially and the tool can be used more frequently and confidently by designers, engineers, and alike.

Thurnes et al. (2015) followed a different approach than the aforementioned authors. They used TRIZ to invent failures and risks despite calculating the risk priority number (RPN) of

them using standard FMEA techniques in the first place. They also made use of Anticipatory Failure Determination (AFD), a methodology that benefits from TRIZ, to come up with a unique combination called Failure Mode and Effects Anticipation and Analysis (FMEAA) technique. Although a case study was presented in the research, the authors stated that the respective methodology was in the early stages of its usefulness and needed to be deployed in wider areas of application.

Awad and Yusof (2012) proposed a different approach incorporating Process Failure Mode and Effects Analysis (PFMEA) combined with application tools of TRIZ, e.g., contradiction matrix and 40 inventive principles.

2.8. QFD-TRIZ-FMEA Combined Studies

As can be understood from the information given so far up to this point; FMEA, like QFD and TRIZ, can be made use of separately in various application areas and industries for many different purposes. Also, as stated above, some quality improvement tools, like QFD, can be combined with inventive problem-solving techniques (TRIZ) to come up with innovative, resilient, and user-friendly solutions, final products, or actions. Besides, it can be understood that both QFD and TRIZ can be combined with the FMEA methodology separately. In that matter, since QFD puts the voice of customers at the center of its application, the conclusive results obtained from the QFD approach can be put to test by using the FMEA methodology to evaluate the applicability possibilities of the results in terms of risk assessment. Likewise, if TRIZ is combined with the FMEA in a case study, the practical applicability of the potential innovative solutions, including the contradictions determined at the very beginning of the operation, can be evaluated based on their risk factors. With that approach, safety becomes the number one priority in the operations playbook and this can lead to a more healthy innovative working environment.

Considering these three different methodologies and their advantages altogether, it can be said that it would be convenient to combine the three of them and come up with safety-based, customer-centric, innovative solutions. In the literature, some studies made use of this approach in various application areas. However, based on the scope of the literature review of this study, not many academic articles related to the combination of QFD, TRIZ, and FMEA could be identified. Below, the content of the identified academic articles and the scope of their aim are explained briefly.

Hu et al. (2014) applied the combination of QFD, TRIZ, and FMEA to the design stage of control valves. They tried to explain the advantages of the combination by approaching the design stage from various starting points. For instance, it was explained if the FMEA process took place first the results can be slightly different than those that were obtained if QFD or TRIZ had been used first. It was also stated that the QFD-TRIZ combination can improve the overall effect of the FMEA methodology on the customers positively. Vysotskaya (2020), on the other hand, applied these tools in the aviation industry. The authors applied a four-level QFD methodology and then used FMEA with TRIZ, simultaneously. The authors made use of FMEA to determine the technical contradictions in the process and identify the key elements that are helpful to improve the overall life cycle of a life support system used in the aviation industry.

2.9. AHP-TRIZ Combined Studies

Based on the nature of TRIZ, there can be more than one solution offered via the Contradiction Matrix, 40 Inventive Principles, and other tools of TRIZ. And since, the AHP can be used for identifying and evaluating the degree of dependency of more than one criterion in a hierarchical order, simultaneously, the combination of AHP and TRIZ can be an effective methodology to determine the best possible solutions for complex problems in any application area. Below, the literature review results for AHP-TRIZ combined applications and studies are indicated.

In the automotive industry, there have been some studies identified that focus on the identification of various parameters and their ideal design specifications in order to improve the overall car design specifics via the AHP-TRIZ combination (M. U. Rosli et al., 2013a, 2013b; U. Rosli et al., 2014). Some other studies based on the automotive industry used the AHP-TRIZ combination for the development of conceptual braking systems for automobiles (Mansor et al., 2014). Another study focuses on the determination of ideal design specifics of automated production lines by identifying the technical contradictions occurring in the product/process development stage and their possible solutions and then selecting the most ideal solution for the ideal design. (T. S. Li and Huang, 2009). One study benefits this combination in order to improve the remote handling systems design (Di Gironimo et al., 2013) whereas another study is conducted in the supply chain industry aiming to improve the overall effectiveness of lean manufacturing and eco-friendly activities (Essaber et al., 2021). There are also some studies that incorporate the AHP-TRIZ combination in health care to

improve overall service quality and equipment provided to patients (Desai et al., 2019; Kose and Guner, 2020).

2.10. AHP-QFD Combined Studies

The methodology of QFD is based on the identification of customer expectations. As a result of a QFD application, more than one technical specification can be identified as the key parameter to fulfill customer expectations. From that perspective, it can be said that the AHP methodology can be used at this point to select the best technical specification in order to achieve the maximum customer satisfaction level possible. Below, some findings regarding the literature review conducted for AHP-QFD combined applications are presented to indicate the variability of such applications for different purposes in different industries.

One study indicates that the AHP-QFD combination can be used for selecting the best-automated equipment under specific conditions (Bhattacharya et al., 2005). Another study shows the applicability of the AHP-QFD combination for complex location allocation situations (Chadawada et al., 2013). To increase the sustainability parameter in the supply chain industry and evaluate the supplier ratings to identify the best supplier options the AHP-QFD combination can also be used (Dai and Blackhurst, 2012; Rajesh and Malliga, 2013). Another study based on the supply chain industry aimed to improve the benefits of decision-making criteria for sourcing (W. Ho et al., 2011). In terms of material selection, one study benefited from this combination in order to prove its usefulness (Mayyas et al., 2011). The AHP-QFD combined application can also be used for evaluating and ranking customer expectations to increase overall customer satisfaction and market share (De Felice & Petrillo, 2011). There is also one study identified that benefits the AHP-QFD combination in the tourism industry (Das and Mukherjee, 2008).

2.10. AHP-FMEA Combined Studies

As a result of an FMEA application, various high-value risk factors for potential failure modes can be identified. Based on the value of the risk priority numbers of potential failure modes, the respective hierarchical actions can be determined, accordingly. But, in terms of risk assessment, since more than one criterion is involved in real-life practices, the AHP integration into the FMEA methodology can be beneficial to make the best and safest action planning possible. There are some studies, mentioned below, from different industries that incorporate the combination of AHP and FMEA.

In terms of determining occupational health and safety parameters, one study benefits the AHP-FMEA combined application in the construction industry (Mete, 2019). Another study, also in the construction industry, focuses on determining the key parameters and action plans in order to deliver projects on time while also giving insight to the workers and managers for establishing proper risk assessment methods and applications in construction sites (Abdelgawad and Fayek, 2010). The combined study of AHP-FMEA is beneficial in terms of lean activities for maintenance departments for various purposes of overall equipment effectiveness operations (Shahrabi and Shojaei, 2014). The alternative energy industry is one of the sectors that benefit from the combination as well (Karatop et al., 2021). A recent study focused on the identification of risk factors that occurred due to the COVID-19 pandemic and provide possible supply chain solutions for logistics firms to decrease the effects of the pandemic (Jin et al., 2022). Also in the agriculture industry, the AHP-FMEA combination can be used for the identification of various risk parameters and their possible preventive actions regarding agricultural operations (Zandi et al., 2020).

2.11. AHP-TRIZ-QFD Combined Studies

There are also some studies that make use of the triple combination of AHP-TRIZ-QFD methodologies to provide ideal solutions in various industries. In that matter, Hou and Su (2007) aimed to define various parameters that affect the life cycle of products and evaluate the key components of these parameters. A study conducted for organizations in the automotive industry aimed to identify the key parameters of adaptability and sustainability based on customer expectations in order to stay competitive in the market (Vinodh et al., 2014). Another study focused on the improvement of current product designs based on ever-changing customer expectations (Zhang et al., 2009). Also, an optimization study was conducted for the process improvement operations by incorporating the AHP-TRIZ-QFD combined application.

2.12. AHP-QFD-FMEA Combined Studies

In the literature, some studies incorporate the joint applications of AHP-QFD-FMEA methodologies. Hsiao (2002) made use of QFD, FMEA, and AHP, respectively to identify the various customer expectations with their potential risk factors that could prevent fulfilling these expectations, and propose the best approach in order to come up with the best possible product design. Bhuvanesh Kumar and Parameshwaran (2020), on the other hand, used the

combination of AHP-QFD-FMEA methodologies for the evaluation of the most beneficial lean tools that could be incorporated into the manufacturing industry resulting in various advantageous outputs.

2.13. Literature Review Criticism

Based on the literature review conducted for this study, it has been observed that the use of QFD, FMEA, TRIZ, and AHP applications, independent of one another, are very common in many industries with different approaches and for various purposes. Besides, the combined use of these methodologies also proved to be beneficial based on the data obtained from the literature review. These tools possess valuable cumulative knowledge and unique approaches in their nature in order to resolve many issues and propose advantageous resolutions. However, it was observed that when the number of tools combined for the joint applications increased, the number of conducted studies in the literature decreased, dramatically. For instance, based on the literature review conducted for this study, there was no study identified that incorporated the combined use of QFD, FMEA, TRIZ, and AHP. So, this study aimed to provide a joint application of these four methodologies together to fill the gap in the literature and suggest new approaches for future studies.

To be more specific, the QFD method can be used to identify the most important customer requirements and their respective technical specifications. The FMEA method can be deployed to identify the potential risk factors regarding the technical specifications and several technical contradictions occurring as a result of these applications can be resolved by using TRIZ. In fact, a lot of inventive resolutions can be generated via TRIZ tools and among these resolutions, the most effective and suitable one can be selected by using the AHP methodology. This proposed approach can be used in the automotive and defense systems industry in order to identify and improve the various elements that affect the comfort parameter for military vehicles.

In the next section, the details about the material gathered for this study and the subject company, and the methodology used are explained in detail.

3. MATERIALS AND METHODS

3.1. Materials

As mentioned earlier, although the various combinations of QFD, TRIZ, FMEA, and AHP applications have been made use of in various research papers and case studies in different industries, there is a significant gap identified in the automotive and defense industries. In this paper, this gap was tried to be filled by working closely with a company that is positioned in these specific sectors to contribute to the literature.

The aforementioned company is one of the group companies, that has been operating in the automotive and defense systems industry for more than 20 years, of a holding company that is established nearly 57 years ago. It possesses valuable cumulative knowledge and experience at its core, making it one of the most well-known and successful companies in the automotive and defense industry sectors in the Mediterranean region of Turkey and the whole country. The company manufactures upper structures for semi-trailers and tactical vehicles within military projects for transportation and logistics operations, and the defense industry, respectively. The product family of the company consists of upper structures of various trailers, concrete pumps, and sweeper group variations for the semi-trailer category as well as 4x4, 6x6, and 8x8 vehicle projects for the defense industry. The company has established import-export channels throughout its 57-year-long journey. It also possesses the "main dealer" title for one of the most popular automotive brands in the world and provides sales and after-sales services for the vehicles of this brand. So, it is considered to be one of the best retailers in its geographical region in terms of semi-trailer manufacturing, and sales/after-sales services.

In 2016, the company established its research and development (R&D) center, focusing on new inventions, patents, continuous improvement methodologies for current and new product developments, etc. to be used both in military and civilian projects.

As part of an ongoing solution for the current military projects, the R&D center of the company handled one of the most common feedback from the customers. According to the data gathered from the company's recent customer meetings and design and production teams of the company, the most common generalized parameter that is expected to be improved was defined as "comfort". As mentioned, the parameter "comfort" is a very generalized term. So,

to be more specific, a detailed approach to the design specifics of the upper structure of military vehicles needed to be inspected. The "Comfort" parameter can be related to many elements, e.g, damping characteristics of the vehicle or equipment in the cabin, in-cab temperature, dashboard, and various component locations and dimensional characteristics of the cabin components in accordance with the international military standards.

In this study, all the data had been gathered by working closely with the military projects section of the R&D center of the company. Based on the data, various methodologies had been applied to obtain an increase in the "comfort" parameter in military vehicles. The methodologies used in this study are explained in Section 3.2.

3.2. Methods

In this study, QFD, FMEA, TRIZ, and AHP methodologies were made use of, respectively. During the material gathering process, a company based in the automotive and defense systems industry had been worked closely. While pursuing the main purpose of the study, the identification, and evaluation of the key comfort parameters for the military vehicles of the subject company, in the first step, the QFD method was used to identify various customer expectations with their respective technical specifications and the potential technical conflicts among these specifications. In the second step, the technical specifications were treated as the potential failure modes in an FMEA application and their risk priority number (RPN) values were evaluated. In the third step, the calculated RPN values were integrated into the HOQ matrix in order to identify new technical conflicts among the technical specifications. At this point, it is important to state that the integration of RPN values to the HOQ matrix via a specific approach was one of the elements that helped this study establish a unique methodology. The details about this step and the methodology used at it are indicated further in section 4. In the fourth step, the identified technical conflicts were evaluated and their respective possible resolutions were provided. In the final step, together with a team of specialists from the subject company's R&D section, an AHP application was conducted in order to select the most suitable and profitable solution for the subject company.

3.2.1. Quality Function Deployment (QFD) Application

Quality Function Deployment (QFD) is a total quality management (TQM) tool that is believed to be originated between the late 1960s and early 1970s in Japan. Its methodology emphasizes the importance of the customers' perspective and expectations on product and process development. It puts the customer requirements at its center at the very beginning of the application, enabling a company's internal design teams to develop their product or process design specifications accordingly. One way to increase the market share of a company is to design its product line based on customer requirements. So, QFD is a systematic quality development/improvement methodology in that regard (Morrell, 1987).

QFD methodology uses a complex matrix called the House of Quality (HOQ). Its name comes from the similarity of its design shape with a house. Although its fundamental design never changes there can be different implementations of the HOQ (Chan and Wu, 2002b). It consists of several components, e.g., customer requirements (CRs), the importance level of customer requirements, technical specifications (TSs), technical correlation matrix for TSs, company satisfaction level, planned quality level, improvement rate, sales advantage, absolute weight, relative weight, absolute importance, and relative score. In Figure 3.1, a version of the HOQ used in this study is given.

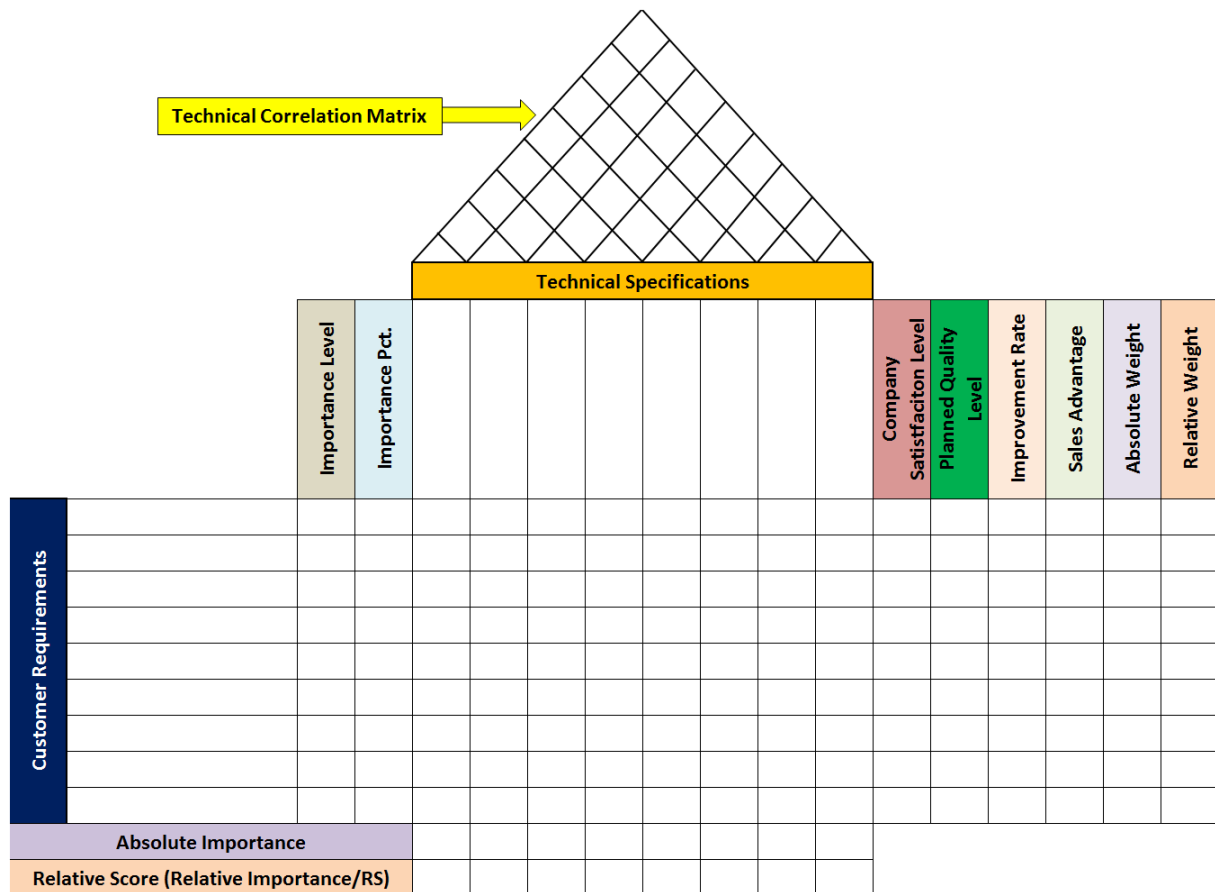


Figure 3. 1 House of Quality Matrix

As can be seen from Figure 3.1, customer requirements (CRs) are positioned on the left section of the HOQ matrix, whereas the technical specifications (TSs) are located on the top section. On the rooftop section of the matrix, the technical correlation matrix is positioned. This matrix helps evaluate the correlation and strength of the relationship of TSs with each other. In the right section, company satisfaction level, planned quality level, improvement rate, sales advantage, absolute weight, and relative weight parameters are given. This section is considered the strategic planning section of the HOQ and in different builds of the matrix, cross-referencing the various CRs and their company satisfaction level values with other companies that are in the same industry as the subject company can be made (Sireli et al., 2007). Each component of the matrix serves a purpose in order to achieve the optimum results of a QFD application. Fundamental explanations of these components are provided in the application steps of the methodology (Güllü and Ulcay, 2002).

As mentioned above, although there can be different implementations of the HOQ matrix, its original structure does not change and these different versions of the matrix do not affect the fundamental purpose and operation road map of the QFD methodology (Chan and Wu, 2002b). In the following pages, the steps of building a HOQ matrix are given. Note that at some stages there are analytical analyses and calculations required. So, in that matter, the related formulations are also provided in their respective order as well.

Step 1: Identification of Customer Requirements

CRs are also known as the voice of customers (VOC). Since QFD puts the VOC at its core, it is essential for CRs to be determined clearly and effectively in order for QFD to succeed. CRs can be identified both internally and externally. In that manner, one way to identify the CRs is through various company surveys, questionnaires, and focus group studies in cooperation with the customers. The subject company evaluates the data gathered from these operations conducted with the customers and identifies what the customers expect from the company to improve the overall product-user experience.

On the other hand, the second way to identify the CRs is through various interdepartmental studies conducted within the subject company. On occasion, the company that applies QFD may want to conduct its product/process development operations discreetly. And they only present the final product that is ready to be serviced to customers. While using this methodology, different departments of the subject company are gathered together and they exchange cumulative, experience-based knowledge to determine what the customers might expect from the new product/service of the company. In this study, CRs are determined by the internal departments of the subject company.

At this step, not only the customers' expectations are identified, but also the target market of the subject company's product and the potential market share of the opponent companies that produce similar products or services are determined, giving the subject company an insight for the steps to be taken during the process.

In Figure 3.2, the location of the CRs is shown on the HOQ matrix.

Customer Requirements	

Figure 3. 2 Customer Requirements Section of HOQ Matrix

Step 2: Determination of Importance Levels of Customer Requirements

The importance levels of CRs are numerical values assigned for each CR as a result of the evaluation of VOC through various customer surveys, questionnaires, focus group studies, or interdepartmental studies of the subject company in order to determine customers' perspectives for each CR in terms of criticality and importance degree. In this study, the 5-point Likert scale is used by the subject company to rate the importance levels of CRs. So, the CRs are rated from 1 to 5, and according to the importance level ratings of the customer requirements their respective importance percentage ratings are determined, respectively. On the other hand, the importance percentage values of the CRs can be determined as the equivalent of each importance level of CR in percentile expression. Based on the feedback that is received from customers via various approaches or interdepartmental studies of the subject company, the identified CRs are rated accordingly.

In Figure 3.3, the importance levels and importance percentage sections of the HOQ matrix are given.

Customer Requirements		Importance Level	Importance Pct.

Figure 3. 3 Importance Level and Importance Percentage Sections of CRs

Step 3: Determination of the Strategic Planning Parameters for Customer Requirements

For each CR, company satisfaction levels and planned quality levels are determined respectively based on the evaluation made interdepartmentally in the subject company. It is important to state that since the 5-point Likert scale is used in the importance rating section of CRs, company satisfaction levels and planned quality levels are similarly rated numerically from 1 to 5.

The company satisfaction level parameter is a numerical expression of the subject company's current self-completeness level for each CR in terms of quality and customer satisfaction. It is rated from 1 to 5. 1 means that the subject company is not satisfied with the quality level of the respective CR and the aforementioned CR is the most problematic parameter on the list. On the other hand, 5 stands for the subject company is fully satisfied with the current state of the respective CR and the aforementioned CR is the least problematic one to meet.

The planned quality level is the determined level of quality of the subject company for each CR. Like company satisfaction level, planned quality levels of CRs are rated from 1 to 5. 1 stands for the lowest quality, whereas 5 means the best quality targeted possible.

The improvement rate is the parameter that defines how much improvement each CR need to achieve the planned quality level and satisfy the company expectations in that regard. Higher the value the more prioritized that respective CR needed to be.

In Figure 3.4, the strategic planning section of the HOQ matrix is given.

Company Satisfaction Level	Planned Quality Level	Improvement Rate	Sales Advantage	Absolute Weight	Relative Weight

Figure 3. 4 The Strategic Planning Section of the HOQ Matrix

As can be seen from Figures 3.1 and 3.4, for each CR, each parameter of the strategic planning section needed to be taken into consideration, separately.

Based on the numerical values that are assigned to the company satisfaction level and planned quality level sections, the improvement rate values are identified by evaluating the ratio of planned quality levels to company satisfaction levels, respectively for each CR.

In Equation (3.1), the improvement rate calculation and its parameters are indicated (Sireli et al., 2007).

$$IR_i = \frac{P_i}{S_i} \quad (3.1)$$

where;

IR_i : The improvement rate value for the customer requirement on the i^{th} row,

P_i : Planned quality level for the customer requirement on the i^{th} row,

S_i : Company satisfaction level that applies QFD for the customer requirement on the i^{th} row,

i : The row number which the customer requirement is located on

After that, the sales advantage values are determined based on the sales return potential of each CR considering the necessary improvements/changes made to them by the company. There can be three different numerical sales advantage values that can be assigned to each CR. These values and their meaning are stated below (Güllü and Ulcay, 2002):

- i. If the sales advantage is defined as 1,0, this means that there is no change expected in the sales return considering the improvements to be made on the respective CR.
- ii. If the sales advantage is defined as 1,2, this means that the improvements and changes on the respective CR may have the potential to increase the sales return.
- iii. If the sales advantage is defined as 1,5, this means that the improvements and changes on the respective CR may have the high potential to increase the sales return very much.

As the final step of the strategic planning section, the absolute weight and relative weight values of CRs are calculated. Absolute weight means the sum of the products of the relationship between the CRs and TSs and the importance of the CRs. It is a numerical value that helps determine the importance of each CR considering their importance level, improvement rate, and sales advantage values. Relative weight, on the other hand, is the ratio of each CR to the total sum of absolute weight values of all the CRs in percentile expression. This parameter can also clarify the hierarchical distribution of CRs considering their importance degree, planned quality level, and sales return advantage. So, the relative weight section of the HOQ is one the most strategic components of the matrix and helps the company in various stages, i.e., identification, prioritization, decision-making, and action phases. The

formulations for absolute and relative weight parameters are given respectively in Equations (3.2) and (3.3) (Sireli et al., 2007).

$$AW_i = \prod_{i=1}^n I_i IR_i SA_i \quad (3.2)$$

where;

AW_i : Absolute weight of the customer requirement on the i^{th} row,

n : The total number of customer requirements on the HOQ matrix,

i : The row number on which the customer requirement is located,

I_i : Importance level for the customer requirement on the i^{th} row,

SA_i : Sales advantage value for customer requirement on the i^{th} row

$$RW_i = \frac{AW_i}{\sum_{i=1}^n AW_i} \times 100 \quad (3.3)$$

where;

RW_i : Relative weight of the customer requirement on the i^{th} row

Step 4: Determination of Technical Specifications

TSs are another crucial component of the HOQ matrix since with the CRs, they directly affect the roadmap of the product/service development process during and after the QFD application.

The TSs are determined based on the CRs. Unlike the CRs, the TSs are needed to be determined only by the inner departments of the subject company, e.g., the production department, quality department, research and development department, etc. It is, at this point, important to state that the key characteristic of this step is gathering as many departments and attendants as possible in order to ensure objective decision-making with cumulative knowledge sharing and prevent biased evaluations.

The TSs section and its location on the HOQ matrix are given both in Figure 3.1 and Figure 3.5.

		Technical Specifications									
Importance Level	Importance Pct.									Company Satisfaction Level	

Figure 3. 5 The Technical Specifications Section of The HOQ Matrix

Step 5: Establishment of the Technical Correlation Matrix

Positioned at the rooftop section of the HOQ matrix, the technical correlation matrix (TCM) allows users to investigate and evaluate the strength of the relationship of TSs with each other so that in the design and product/process development stage importance and interdependence degree of TSs can be determined clearly. After the TSs are identified, their interrelationship with each other is needed to be evaluated. This step is one of the critical factors in the design stage of the product/service development since it helps users identify which TS can be related to another one and to what degree.

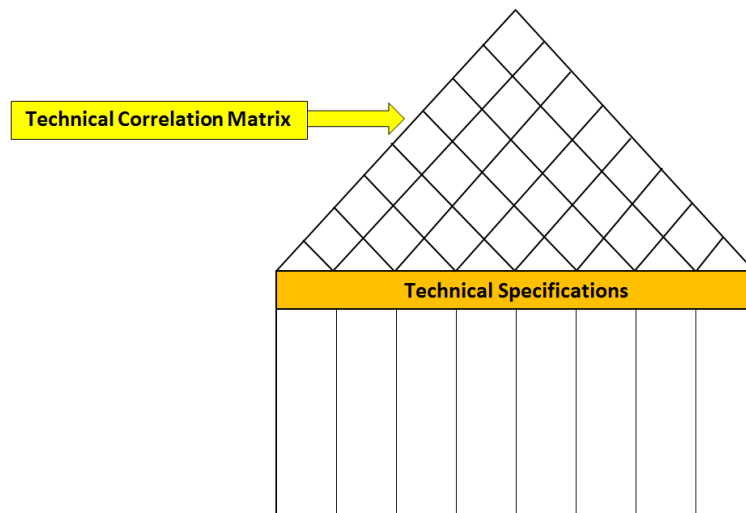


Figure 3. 6 The Technical Correlation Matrix

As can be seen from Figures 3.1 and 3.6, the TCM is positioned on top of the HOQ matrix and just on the technical specifications section.

The interrelationship of the TSs are evaluated by assigning a symbol for each intersecting cell of the two TS column on the TCM. There are 4 symbols used in the correlation matrix to determine the strength of the relationship between the TSs. These symbols and their meanings are stated below (Chan and Wu, 2002a).

- ☉: A positive and strong relationship between two TSs
- ○: A positive but weak relationship between two TSs
- ☆☆: A negative and strong relationship between two TSs
- ☆: A negative but weak relationship between two TSs

Step 6: Evaluation of the Interrelationships Between the Customer Requirements and Technical Specifications

After the completion of the evaluation stage on the TCM, each CR's relationship with each TS needed to be investigated. This process is carried out on the large middle section of the HOQ matrix which can be seen in Figure 3.1, or Figure 3.7.

		Technical Specifications										Company Satisfaction Level
		Importance Level	Importance Pct.									
Customer Requirements												

Figure 3. 7 Evaluation Area for Interrelationships Between CRs and TSs

At this point, the strength of relationships between the CRs and TSs can be determined numerically or symbolically. Each symbol stands for a degree of relationship. Those symbols and their equivalent degree of relationship value are given below. Please note that, in this study, numerical values are used in order to determine the relationship between the CRs and TSs (Sireli et al., 2007; Güllü and Ulcay, 2002).

- $\triangle$ or 1: Weak relationship between the CR and TS
- $\bigcirc$ or 3: Average relationship between the CR and TS
- $\odot$ or 9: Strong relationship between the CR and TS

Step 7: The Evaluation of the Absolute Importance and Relative Score Values for the Technical Specifications

Before proceeding to the design stage of the product/process development, the absolute importance and relative score values for each TS are needed to be determined. This step is the last and the most insightful stage of the creation of the HOQ matrix since it gives a perception to the company, which applies QFD, to mostly focus on which design parameter in order to obtain the most profitable customer satisfaction.

The absolute importance is the parameter that focuses on the TSs and evaluates their relationship with each CR and the absolute weight values of all CRs. On the other hand, the

relative score parameter is the ratio of the absolute importance of each TS to the total absolute importance value of TSs in percentile expression. These two parameters are the two key components to identify the criticality of TSs and prioritize them in hierarchical order in the planning stage of product/process development.

The formulations for the calculation of absolute importance and relative score values are given in Equations (3.4) and (3.5), respectively (Sireli et al., 2007).

$$AI_j = \sum_{i=1}^n (AW_i R_{ij}) \quad (3.4)$$

where;

AI_j : Absolute importance value of technical specification on the j^{th} column,

$i = 1, 2, 3, \dots, n$, where n is the total number of customer requirements,

$j = 1, 2, 3, \dots, m$, where m is the total number of technical specifications,

AW_i : Absolute weight of the customer requirement on the i^{th} row,

R_{ij} : Degree of the strength of the relationship between customer requirement on the i^{th} row and the technical specification on the j^{th} column

$$RS_j = \frac{AI_j}{\sum_{j=1}^m AI_j} \times 100 \quad (3.5)$$

where;

RS_j : Relative score (relative importance) value of the technical specification on the j^{th} column

Absolute importance and relative score values are positioned on the bottom section of the HOQ matrix. After the evaluation of these parameters, a clear perspective of which technical specification should have a higher priority in the design stage of the product/service

development process can be determined more clearly. The locations of the absolute importance and relative score parameters are shown in Figure 3.1, and below in Figure 3.8.

[illegible]

Figure 3. 8 Absolute Importance and Relative Score Values of the HOQ Matrix

3.2.2. Failure Modes and Effect Analysis (FMEA) Application

As mentioned earlier, in section 2, the FMEA methodology is a very common risk assessment tool that has been used widely in various industries (Sharma and Srivastava, 2018). It not only identifies the potential risk factors before they occur in an environment or during production in order to increase the safety parameters, but also helps achieve a higher quality level with maximum customer satisfaction. So, it can be said that the FMEA is a tool for both risk identification and quality improvement (Hassan et al., 2010; Jegadheesan et al., 2007; Dale and Shaw, 1990).

There are three important parameters for the FMEA applications while determining potential risk factors. These parameters are the fundamental elements of any FMEA process. These are severity (S), occurrence probability (O), and detectability/detection (D). Each parameter is assigned a numerical value from 1 to 10 depending on their strength of relationship with the respective failure mode they are associated with (Goddard, 2000).

Severity is associated with the intensity of the risk factor. The intensity of the risk factor is directly proportional to the potential damage that might be caused as a result of the occurrence of that risk factor. So, the higher the damage or cost of the risk factor the more intense it gets, naturally, and the higher the value of the severity parameter. In short, if a failure mode is determined to have a high impact in light of its possible occurrence, then the numerical value

that will be assigned to the severity parameter will be bigger (Sharma and Srivastava, 2018). Table 3.1 represents the stated relationship between the severity parameter and its possible numerical value assignments.

Table 3. 1 Severity Scale for FMEA (Curkovic et al., 2015)

The Intensity of the Effect	Description	Severity Rating
None/Minor	No recordable customer dissatisfaction or decrease in operational effectiveness, and safety/product/service parameters are not affected	1
Low	Low-level customer dissatisfaction caused by the failure during operations	2
		3
Moderate	Customer dissatisfaction, decrease in operation effectiveness, and potential equipment/service quality	4
		5
		6
High	The effect causes noncompliance with local governmental regulations, customer dissatisfaction, and decreased human factor performance	7
	The effect causes noncompliance with local governmental regulations, customer dissatisfaction, and decreased human factor performance, requiring warning	8
Very High	Can be dangerous for human factors or product/service quality. There can be a warning before the failure occurs	9
	Can be dangerous for human factors or product/service quality. There will be no warning before the failure occurs	10

Occurrence probability is associated with the frequency of the risk factor. The frequency of the risk factor is linked to how frequent the failure mode is in real life. So, if a failure mode happens to occur frequently, then its numerical value for occurrence rate will be higher. On the contrary, if a failure mode occurs every once in a while or very seldom, then its

occurrence rate will be assigned a lower value (Sharma and Srivastava, 2018). In Table 3.2, the occurrence rates of a potential failure mode and their associated meanings are given.

Table 3. 2 The Occurrence Scale for FMEA (Xu et al., 2002)

Occurrence Probability of the Failure Mode	Frequency of Occurrence	Occurrence Rating
Not likely/Distant	1 in 1500000	1
Very Low	1 in 150000	2
Low	1 in 15000	3
Average	1 in 2000	4
	1 in 400	5
	1 in 80	6
High	1 in 20	7
	1 in 8	8
Very High	1 in 3	9
	1 in 2	10

The detectability parameter of a risk factor is associated with how difficult it is for that risk factor to be noticeable. In other words, if a failure mode is easy to detect independent of how severe or frequent it is, then its detectability rate will be evaluated with a lower value. On the other hand, if a risk factor is hard to be noticed or cannot be detected easily then its detectability rate will be higher (Sharma and Srivastava, 2018). In Table 3.3, the detectability rates of a possible failure mode and their respective definitions are given.

Table 3. 3 The Detection Scale for FMEA (Xu et al., 2002)

Detectability of the Failure Mode	Description	Detection Rating
Impossible to miss	Failure can certainly be detected	1
Very easy	Failure can very easily be detected	2
Easy	Failure can easily be detected	3
Relatively easy	Failure detection is relatively easy	4
Moderate	Failure detection difficulty is medium	5
Above moderate	Failure detection difficulty is above medium	6
Relatively hard	Failure detection difficulty is relatively difficult	7
Hard	It is difficult to detect the failure	8
Very hard	It is very difficult to detect the failure	9
Impossible to detect	It is impossible to detect the failure	10

As can be seen from Tables 3.1, 3.2, and 3.3, severity, occurrence, and detection rates are all ranked from 1 to 10 depending on their respective relationship with the risk factors or failure modes. However, the detection parameter rating systems work a little differently than the ranking systems of severity and occurrence parameters. To be more specific, in terms of severity and occurrence rating, the higher the value the more intense or frequent the failure mode is. But, in terms of detection, the higher the rating value the harder the failure mode to be detected. In this regard, it can be said that the rating system for detection works inversely proportional to the ranking systems of severity and occurrence parameters in terms of rating increment.

The determination of severity, occurrence, and detection ratings lead to the evaluation of risk factors in the FMEA process. During the conduction of the FMEA process, each risk factor, or failure mode, is assigned a Risk Priority Number (RPN). These numerical values are related to risk factors in terms of prioritization. In other words, depending on the RPN value there can be different precautions, action plans, and corrective actions for each risk factor with different degrees of importance. The RPN value is equivalent to the multiplication of severity, occurrence, and detection ratings. In terms of precautions and prioritization, the RPN

results can be examined in three categories (Janakiram and Keats, 1995; Sharma and Srivastava, 2018; Xu et al., 2002).

- i. If $RPN < 40$, there is no need to take measures
- ii. If $40 \leq RPN \leq 100$, it is suggested to take measures
- iii. If $RPN > 100$, Strong measures must be taken

As a result of the RPN determination, depending on the numerical results, there can be different proactive or corrective measures to be taken. After the determination of necessary measures, new action plans are established based on these. The failure modes are inspected, observed, and evaluated under the circumstances of those new action plans. So, once again, their severity, occurrence, and detection rates are determined, and based on the numerical assignments for these parameters new RPN values are obtained. The difference between the two RPN values stands for the effectiveness of the new measures and the action plans. In short words, the effectiveness of the measures can be observed after the second RPN determination. If the second RPN value is decreased under the limit of 40, or between the limit between 40 and 100, depending on which limit the RPN is located and the severity of the failure mode the effectiveness of the measures can be observed. Stages of a fundamental application of an FMEA process are given below step by step to explain the whole operation briefly (Sharma and Srivastava, 2018; Ho and Teng, 1996).

- i. Establishment of the FMEA team
- ii. Definition of the subject of the FMEA applications
- iii. Determination of the potential failure modes regarding the FMEA subject
- iv. Determination of the effects of the potential failure modes
- v. Severity rating evaluation of the potential failure modes
- vi. Determination of the potential causes of the failure modes
- vii. Occurrence frequency rating evaluation of the potential failure modes
- viii. Identification of the current process/service controls to prevent the failure modes from occurring or detect them should they occur
- ix. Detection rating evaluation for the potential failure modes
- x. RPN calculations for the potential failure modes
- xi. Determination of the action plans and measures based on RPN values
- xii. Re-evaluation of severity, occurrence, and detection ratings and calculation of new RPN values based on action plans and measures

At this point, it is important to indicate that, in this study, more than one RPN value was determined for some of the TSs due to potential effects, causes, and current process controls of the failure modes. In order to assign one RPN value for each TS, the triangular distribution approach was benefited from. The aim and methodology of this approach are provided in detail in section 4 of the study.

After the determination of the new RPN values for each TS, these new RPN values were integrated into the bottom section of the HOQ matrix. The relationship between the RPN values and the relative score parameters of the TSs was investigated by the multiplication of each RPN value with the relative score result of the TSs. This process is indicated in Equation (3.6).

$$RS_{FMEA} = RS_j RPN_j \quad (3.6)$$

where;

RS_{FMEA} : The result of the multiplication of RPN and relative score value for each TS,

RS_j : The calculated relative score value of the TS on the j^{th} column of the HOQ matrix,

RPN_j : The calculated RPN value of the TS on the j^{th} column of the HOQ matrix,

$j = 1, 2, 3, \dots, m$, where m is the total number of technical specifications

3.2.3. Theory of Inventive Problem Solving (TRIZ) Application

Theory of Inventive Problem Solving (TRIZ), the English equivalent of the Russian term "Teoriya Resheniya Izobretatelskikh Zadatch", is a useful engineering methodology that incorporates various tools in its arsenal for designing, inventing, and problem-solving. It was discovered by Genrikh Saulovich Altshuller in the mid-1940s. Although its fundamental purpose was to derive resolutions for problems that came across in the field of technology, today its field of applications is widely spread across many areas, i.e., product development, problem-solving, quality management and improvement, customer satisfaction, and inventive designing. Today it is being widely used in many industries, e.g., automotive, aerospace, supply chain, computer manufacturing, furniture, health care, fast-moving consumer goods, etc. (Ilevbare et al., 2013).

TRIZ is a combination of various application tools. Each tool serves a different purpose in terms of problem-solving. These tools are the products and culmination of cumulative knowledge in the years of development. So, it can be said that TRIZ has been an ever-developing and improving set of tools for engineering applications. Some of the tools of this set are the Contradiction Matrix, 40 Inventive Principles, Substance-Field Analysis, and 76 Standard Solutions (Ilevbare et al., 2013). In order to increase the methodic use of TRIZ tools and ease the problem definition with resolution derivation, some studies were conducted to determine the field of application of these tools. Moehrle (2005) defined 5 groups in total and conducted the classification of these tools, accordingly. These fields of application groups are:

- "Current state" definition of the problem or product
- "Intended state" to define the state for the problem or product to be achieved
- "Goals" to be achieved and the degree of achievement of the goals while improving the current state to the intended state
- "Transformation" definition of modification from the "current stage" to the "intended state"
- "Resources" to be used during the improvement or resolution stage

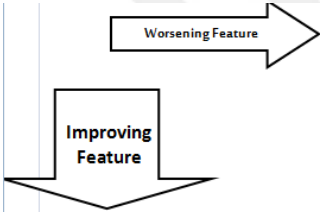
In this study, only two tools of TRIZ, the Contradiction Matrix, and 40 Inventive Principles were to be used. In the use of TRIZ, the aim was to resolve the technical contradictions for improving the comfort parameter in military vehicles. So, based on this definition and according to the classification of Moehrle (2005), it can be said that the Contradiction Matrix and 40 Inventive Principles fall into the categories of "Goals" and "Intended State". The following will be explaining the use of these two tools in detail in two phases.

Phase 1: The Contradiction Matrix Application

The Contradiction Matrix deals with providing resolution for the technical contradictions, conflicts, or problems that come across mostly during the design stages of product or service development/improvement operations. It is a 39 x 39 matrix and its rows and columns consist of 39 engineering parameters. The matrix is based upon these engineering parameters that are fundamentally the resulting conflicts of improvement and unintentional deterioration of various characteristics of a product or service, simultaneously. The rows of the matrix are associated with the features that are aimed to be improved, whereas the columns of the matrix

are linked to the simultaneously decreasing or deteriorating features. So, after the identification of the parameters that desired to be improved, and, in response to this, the respective worsening parameters, the equivalents of those two parameters are identified in the matrix. The cells where the rows of the improving features and the columns of the worsening features intersect house several probable solutions of the 40 Inventive Principles. In short, the stages of the contradiction matrix application can be determined in four steps (Moehrle, 2005a).

- Determination of the technical contradiction and the parameters that cause the contradiction
- Identification of the improving feature among those conflict parameters
- Identification of the worsening feature among those conflict parameters
- Evaluation of possible solutions from the 40 Inventive Principles



		1	2	3	4	5	6	7	8	9	10	11
		Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Speed	Force	
1	Weight of moving object	+		15, 8, 29, 34		29, 17, 38, 34		29, 2, 40, 28		2, 8, 15, 38	8, 10, 18, 37	10, 37
2	Weight of stationary object		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2		8, 10, 19, 35	13, 10
3	Length of moving object	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35		13, 4, 8	17, 10, 4	1, 8
4	Length of stationary object		35, 28, 40, 29		+		17, 7, 10, 40		35, 8, 2, 14		28, 10	1, 13
5	Area of moving object	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2	10, 36
6	Area of stationary object		30, 2, 14, 18		26, 7, 9, 39		+				1, 18, 35, 36	10, 36
7	Volume of moving object	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17		+		29, 4, 38, 34	15, 35, 36, 37	6, 36
8	Volume of stationary object		35, 10, 19, 14	19, 14	35, 8, 2, 14				+		2, 18, 37	24
9	Speed	2, 28, 13, 38		13, 14, 8		29, 30, 34		7, 29, 34		+	13, 28, 15, 19	6, 138
10	Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12	+	18, 1

Figure 3. 9 The Contradiction Matrix (10x10 Section) (Livotov, n.d.)

In Figure 3.9, the 10 x 10 section of the Contradiction Matrix is provided. As can be seen from Figure 3.9, the improving features are positioned on the rows of the matrix, whereas the worsening features are located on the columns of the matrix. The sequence of the features is identical to one another. This is mainly due to the nature of technical contradictions and their possible resolutions connected to the 40 Inventive Principles, whose elements are located in

the cells of the matrix. The complete version of the Contradiction Matrix is provided in the Appendices section of this study.

Phase 2: Identification of Potential Solutions Among 40 Inventive Principles

After the intersecting cell of improving and worsening features of the Contradiction Matrix is located, the potential solutions indicated inside the cell are investigated through the 40 Inventive Principles. The 40 Inventive Principles, as can be understood from the name, is another tool of TRIZ methodology consisting of 40 different solutions in total, created by Altshuller and his friends. The principles are distributed to the cells of the Contradiction Matrix in a way that makes them available and useful for any conflict caused by technical contradictions. The 40 Inventive Principles are categorized into 4 different groups by Separation Principles, another tool of TRIZ that groups the 40 Inventive Principles in order to ease the determination of the technical contradictions and the identification of the potential solutions. The working principle of the Separation Principles is based on simplifying the problem definition and identification of the ideal cluster of inventive principles that the problem is also included in. There are 4 separation principles/clusters in total, and each of them possesses several solutions from the 40 Inventive Principles. These aforementioned Separation Principles and some of the inventive principles included within their cluster are explained in detail, below (Chechurin and Borgianni, 2016; Moehrle, 2005a, 2005b).

a. Separation in Time

This principle focuses on resolving the technical contradictions of a situation, service, or product by enabling the parameters that cause contradiction to take place at different times. With that approach, it is aimed to make the situation, system, or product keep functioning without any failure by also resolving the contradictions. Some of the principles that belong to this category are given below.

- Principle 1 (Segmentation)
- Principle 15 (Dynamicity)
- Principle 34 (Rejecting and Regenerating Parts)

b. Separation in Space

According to this principle, the technical contradictions of a system are resolved by dividing the system into subsystems and resolving those respective contradictions in the subsystems without interfering with the structure or working principle of the system. With that approach, the system keeps functioning without any loss, but with improved parameters thanks to the resolved contradictions in each subsystem. Some of the principles that fall into this category are given below.

- Principle 3 (Local Quality)
- Principle 7 (Nesting)
- Principle 26 (Copying)

c. Separation in Structure

This principle aims to divide the main structure of a system into one or more subsystems, similar to separation in space, and assign one or all of the contradictory conditions to the subsystems leaving the main system as a whole functioning with the rest of the conditions. Some of the 40 Inventive Principles that belong to this group are given below.

- Principle 8 (Counterweight)
- Principle 23 (Feedback)
- Principle 40 (Composite Materials)

d. Separation in State

State separation works by identifying the contradictions in a system, in accordance with the contradictions changing the state of the system or the state of the system's environment in a way letting only positive features or processes occur. Some of the 40 Inventive Principles that belong to this category are given below.

- Principle 28 (Replacement of Mechanical System)
- Principle 35 (Transformation of Properties)

- Principle 39 (Inert Environment)

3.2.4 Analytic Hierarchy Process (AHP) Application

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making (MCDM) tool initially suggested by Myers and Alpert in the late 1960s and further developed and expanded as a model by Thomas Lorie Saaty in 1977. Since then, even though it has been continually developed, improved, and integrated into different applications, the main purpose of the AHP methodology has been providing solutions to complex problems with various criteria by resolving decision-making issues. AHP deals with the decisions and criteria including the factors that affect the decision-making process, evaluates them based on hierarchical order, and further establishes the decisions. AHP displays judgments as pairwise comparisons and offers a basic scale of relative magnitudes represented in dominance units. Then, from each set of comparisons, a ratio scale of relative magnitudes represented in priority units is generated. The options are then ranked using an overall priority scale that is subsequently synthesized (R. W. Saaty, 1987).

AHP is based on making comparisons between different criteria, to figure out which is the most important. Then, it uses a scale to determine how important each criterion is. This means that the different criteria will have different importance degrees assigned to them. A fundamental AHP application and its requirements are explained below in detail (T. L. Saaty, 1990a; Vaidya and Kumar, 2006).

Step 1: Hierarchical Structure Creation

This step includes the determination of the decision-making problem, the aim of the decision-making problem, and its criteria. It is, at this point, important to stay that the problem determination and its various criteria that affect the decision-making process should be identified clearly and in a logical manner.

Step 2: Creation of Pairwise Comparison Matrix

The Pairwise Comparison Matrix consists of all the criteria affecting the decision-making process and is based on their interrelationship in terms of importance degree. In Table 3.4, the

importance degree values and their equivalent descriptive meanings are given (T. L. Saaty, 1990b).

Table 3. 4 The AHP Scale of Importance Degrees (T. L. Saaty, 1990b)

Importance Degree	Description
1	Equal/same importance
3	Average importance of one over another criterion
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	The importance of two adjacent values (average values)

During a decision-making evaluation process in AHP with n criteria, as a result of pairwise comparison between the i^{th} criterion and j^{th} criterion; where $i = j$ is $a_{ij} = 1$, otherwise $a_{ij} = \frac{1}{a_{ji}}$.

Based on these data, matrix A , indicated in Equation (3.6), is created.

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \dots & \dots & 1 & \dots \\ a_{n1} & a_{n2} & \dots & 1 \end{bmatrix} \quad (3.6)$$

Step 3: Relative Importance Value Determination

This step includes the calculation of relative importance values of the pairwise comparison matrix. In this step, Equation (3.7) is evaluated via the use of column parameters of matrix A and vector B , given in Equation (3.8). Both of these equations are given below.

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad (3.7)$$

$$B_i = \begin{bmatrix} b_{11} \\ b_{21} \\ \vdots \\ b_{n1} \end{bmatrix} \quad (3.8)$$

The evaluation of n times the B column vectors equals the n x n-dimensional C matrix, given in Equation (3.9).

$$C = \begin{bmatrix} c_{11} & c_{12} & \dots & c_{1n} \\ c_{21} & c_{22} & \dots & c_{2n} \\ \dots & \dots & \dots & \dots \\ c_{n1} & c_{n2} & \dots & c_{nn} \end{bmatrix} \quad (3.9)$$

If the row components of the C matrix are taken into consideration, the evaluation of the W vector, the priority vector, that represents the importance value distributions of the criteria is made through Equations (3.10) and (3.11) below.

$$w_i = \frac{\sum_{j=1}^n c_{ij}}{n} \quad (3.10)$$

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \quad (3.11)$$

Step 4: Evaluation of Consistency Ratio

There may be some inconsistencies due to subjectivity during the evaluation of the priority values of the criteria. To assess this specific condition, the consistency ratio is evaluated. Based on the result of the consistency ratio evaluation, if the obtained value is lower than 0,1 then in this situation the obtained solutions are identified to be consistent. Otherwise, re-

evaluation must be done. Below, the calculation of the consistency ratio is explained step by step.

- i. Matrix A is multiplied by the priority vector W.

$$D = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \quad (3.12)$$

- ii. Every element of the D vector is divided by the respective elements of the priorities vector, W. The formulation for this step is given in Equation (3.13).

$$E_i = \frac{d_i}{w_i} \quad (3.13)$$

where;

$i = 1, 2, 3, \dots, n$

n = Total number of criteria

- iii. $\lambda_{\max}$ is evaluated through Equation (3.14), given below.

$$\lambda_{\max} = \frac{\sum_{i=1}^n g_i}{n} \quad (3.14)$$

- iv. The consistency index (CI) is calculated through Equation (3.15).

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (3.15)$$

- v. The consistency ratio (CR) is calculated by evaluating the ratio of consistency index (CI) to random consistency index (RI) through Equation (3.16).

$$CR = \frac{CI}{RI} \quad (3.16)$$

It is important to state that the random consistency index (RI) varies depending on the number of criteria included in the decision-making process. Table 3.5 shows the corresponding RI values based on the number of criteria.

Table 3. 5 Random Consistency Index Values Based on the Number of Criteria (Piantanakulchai and Saengkhao, 2003)

Number of criteria (n)	3	4	5	6	7	11	12	13	14	14
Random consistency index (RI)	0,58	0,90	1,12	1,24	1,32	1,51	1,48	1,56	1,57	1,59

3.2.5. The Development Approach of the Study

This study consists of 4 main steps. First, the QFD application was used to identify various customer requirements and their respective technical specifications regarding the comfort parameters inside military vehicles. According to the results of QFD, technical contradictions between the technical specifications were identified. In the second step, an FMEA application was conducted in order to define the potential risk factors and failure modes regarding the technical specifications that were determined in the QFD stage. In this step, more than one RPN value was assigned for some of the technical specifications. So, the triangular distribution methodology was used in order to assign one RPN value for each technical specification. In the end, the final RPN values were integrated into the HOQ matrix of the study, and their relationship with the importance parameters of the technical specifications was evaluated numerically. It is important to state that this specific approach was considered to be one of the key characteristics that differentiate this study from others, based on the literature review. At the end of the second step, as a result of the QFD-FMEA integration more possible technical contradictions between other technical specifications were identified. In the third step, the Contradiction Matrix and the 40 Inventive Principles of TRIZ were benefited from in order to provide possible solutions for all the technical contradictions identified up to this point. As a result, several solutions were determined. In the final step, the AHP methodology was used to select the most suitable one among those identified solutions

and suggested to the subject company. Figure 3.11 represents the mentioned development approach of this study, briefly.

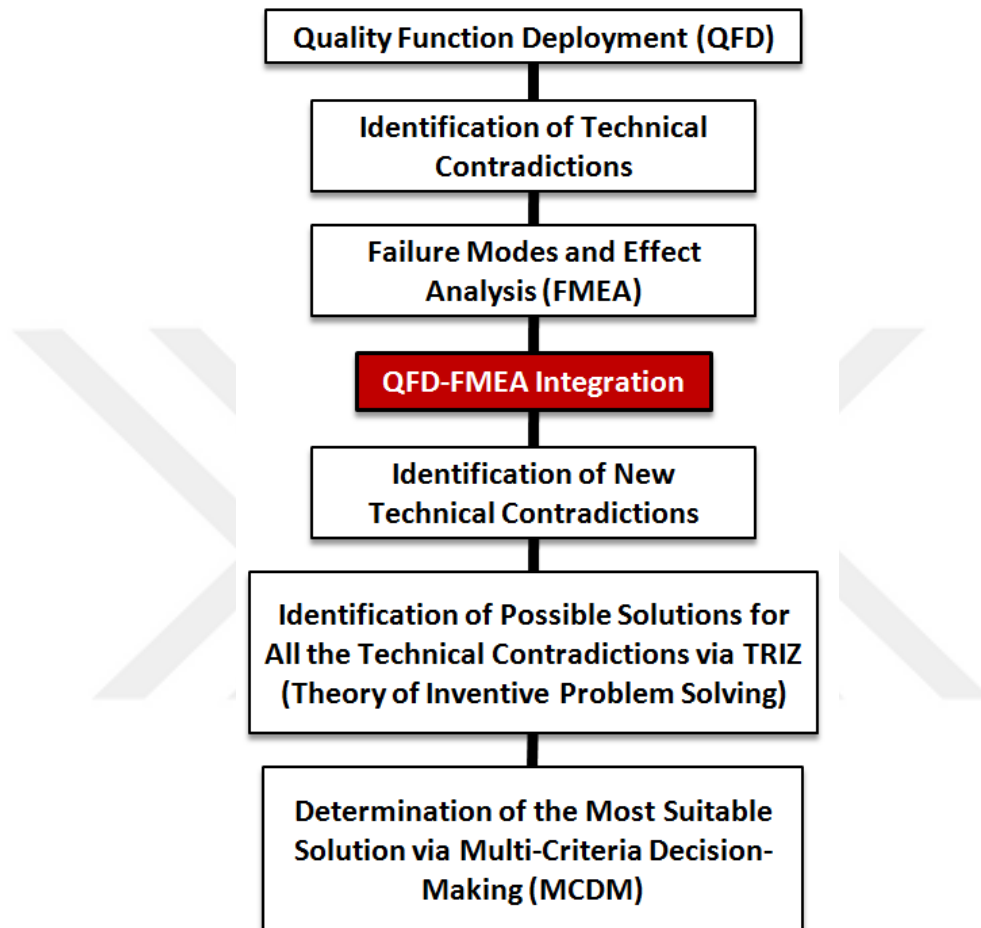


Figure 3. 10 The Development Approach of This Study

4. RESULTS AND DISCUSSION

The aforementioned methodologies and approaches indicated in detail in the previous section are deployed in this section in cooperation with the subject company on which the case study was based.

As mentioned earlier in the previous sections, the company is conducting its operations in the automotive and defense systems industry and intends to improve the comfort parameter of its various military vehicles product line. This aim was identified by the company following the feedback that was gathered from its customers. So, this study focuses on identifying customer expectations, determining their degree of criticality, and based on that, proposing various potential resolutions that can eliminate any technical contradiction which can occur during the product/service development stage. To fulfill both the customer expectations and respective technical specifications of the company's new product/service development process QFD, FMEA, TRIZ, and AHP methodologies were used respectively. In the following parts of this section, detailed explanations for the roadmap and the methodology of this study are given in stages.

Stage 1: Identification of Comfort Parameters

In the first step of the study, QFD methodology and its HOQ matrix were used in order to determine the CRs and their respective TSs. As mentioned earlier, there are two ways to identify the CRs: Through various customer surveys, questionnaires, and control/focus group studies that all of which are conducted externally, or by gathering inner departments of the company and making them share knowledge, and establish their own unique CRs.

The company identified the CRs through its departments, i.e., production, quality, research and development, project, marketing and communications departments. There were 9 CRs identified in total. These CRs and their detailed explanations are given in Table 4.1.

Table 4. 1 Customer Requirements for the House of Quality Matrix

Customer Requirements (CRs)	Descriptions
CR1	Vehicle air conditioner cooling performance
CR2	Vehicle air conditioner heating performance
CR3	Cabin temperature to reach the desired state within the expected time
CR4	Effective operation of the vehicle air conditioner regardless of environmental factors
CR5	Fuel consumption performance of the vehicle
CR6	Innovative filter design
CR7	Availability of digital control panel for air conditioning system
CR8	Interior material selection and layout in terms of warmth, ergonomics, and comfort
CR9	Ease of directing in-cab airflow

CR1: According to the company and various international military standards, i.e., MIL-STD-810G and MIL-STD-1472G, air conditioner performance is one of the most important key characteristics of military vehicles. That is a logically defined customer requirement since these kinds of vehicles are deployed and used in various difficult conditions in terms of terrain and weather variations. So, considering the air conditioner performance, two customer requirements were identified, one focusing on the cooling and the other focusing on the heating performance. The first one, in this case, which is CR1, focuses on the cooling performance of the air conditioner of the military vehicle. Based on the subject company statements and the aforementioned military standards, the air conditioner units of the military vehicles of the company are expected to cool the cabin air from 50°C to 20°C in 10 minutes.

CR2: This is the second category for the air conditioner performance and just like it is mentioned in CR1, CR2 focuses on the heating performance of the air conditioner. According

to the subject company and the aforementioned military standards, the air conditioner units of the military vehicles of the company are expected to heat the cabin air from -30°C to 20°C in 15 minutes.

CR3: Cabin temperature is directly affected by the air conditioner unit performance of the vehicle. But, material usage, component and personnel layout inside the cabin are other key parameters in order to achieve and maintain the desired temperature levels inside the cabin. So, considering all these parameters, the third customer requirement was identified as the cabin temperature to reach the desired state within the expected time.

CR4: As mentioned earlier, military vehicles are deployed and used in such hard terrain and weather conditions. So, environmental factors can directly affect the air conditioner performance of the vehicle. In light of that, the fourth customer requirement was identified as the effective operation of the vehicle air conditioner regardless of environmental factors.

CR5: As the fifth customer requirement, the fuel consumption of the vehicles was identified. To be more specific, based on the current and previous product performance reviews and the aforementioned international military standards, the company set a limit for vehicle fuel consumption not to exceed 5 liters/hour.

CR6: In order to increase the energy consumption efficiency of the air conditioner unit in the vehicle, the subject company stated that it focuses on an innovative filter design specifically for the air conditioning unit system and identified this parameter as another customer requirement.

CR7: The subject company stated that the availability of a digital control panel for the air conditioning system inside the vehicle cabin can directly improve the overall user experience since the operators inside the cabin will be able to monitor and change the data regarding air quality.

CR8: According to the subject company, one of the parameters that not only affect the cabin temperature but also ergonomics and overall comfort is the material selection and equipment layout inside the cabin. The company stated that if material selection and equipment layout aren't carefully constructed, then it can negatively affect the operators' effectiveness and comfort inside the cabin.

CR9: In-cab air flow was identified as the ninth customer requirement by the subject company. In detail, many parameters can affect the airflow inside the cabin, e.g., material selection, equipment layout, the number of operators in the vehicle, etc.

After the identification of CRs was complete, as the second step of QFD, the same teams of the subject company rated the importance levels for those CRs. It is, once again, important to state that in this study a 5-point Likert scale was used. So, the maximum rating value for a CR can be 5, whereas the minimum rating value for a CR can be 1. The importance level ratings of the 9 identified CRs are given in Table 4.2.

Table 4. 2 Importance Level and Importance Percentage Ratings of Customer Requirements

Customer Requirements (CRs)	Importance Level	Importance Level Percentage
CR1	5	14,29%
CR2	5	14,29%
CR3	5	14,29%
CR4	4	11,43%
CR5	3	8,57%
CR6	3	8,57%
CR7	2	5,71%
CR8	4	11,43%
CR9	4	11,43%

Based on the importance rating results indicated in Table 4.2, the following comments can be made.

- CR1 (Vehicle air conditioner cooling performance), CR2 (Vehicle air conditioner heating performance), and CR3 (Cabin temperature to reach the desired state within expected time) are the three and the most important customer requirements with the 5th degree of importance rating and 14,29% importance value share.

- CR4 (Effective operation of the vehicle air conditioner regardless of environmental factors), CR8 (Interior material selection and layout in terms of warmth, ergonomics, and comfort), and CR9 (Ease of directing in-cab air flow) are the second most important customer requirements with the 4th degree of importance rating and 11,43% importance value share.
- CR5 (Fuel consumption performance of vehicle) and CR6 (Innovative filter design) are the third most important requirements with the 3rd degree of importance rating and 8,43% importance value share.
- CR7 is determined to be the least important customer requirement with the 2nd degree of importance rating and 5,71% importance value share.

After the identification and importance rating evaluation of CRs had been completed, the strategic planning stage was initiated. At this stage, company satisfaction levels, planned quality levels, improvement rates, sales advantage values, absolute weights, and relative weights for each CR were determined. In Table 4.3, the company satisfaction levels, planned quality levels, and sales advantage values determined for each CR are indicated.

Table 4. 3 The Strategic Planning Parameters for Each Customer Requirements

Customer Requirements	Company Satisfaction Level	Planned Quality Level	Sales Advantage
CR1	4	5	1,50
CR2	4	5	1,50
CR3	4	5	1,50
CR4	3	5	1,50
CR5	3	5	1,20
CR6	2	5	1,20
CR7	3	5	1,20
CR8	3	5	1,50
CR9	2	5	1,20

Based on the results given in Table 4.3, the following comments can be made.

- The subject company is satisfied most with the performance of the vehicle air conditioner system (CR1, CR2, CR3), but still believes that there is room for

improvement in that regard. The company also believes that the air conditioner system performance has a very high sales return potential.

- The subject company is satisfied least with the CR6 (innovative filter design) and CR9 (ease of directing in-cab air flow) and believes that these customer requirements needed to be improved the most. However, the company believes that these two parameters have the potential to have a considerable amount of sales return potential. So, it can be said that there is a lot of room for improvement in those two CRs.

On the rest of the strategic planning section of the HOQ matrix, the improvement rates, absolute weights, and relative weights of the defined customer requirements were also calculated. These calculations were made according to Equations (3.1), (3.2), and (3.3), respectively, that were given in section 3 of the study. The results of these calculations are given in Table 4.4.

Table 4. 4 Improvement Rate, Absolute Weight, and Relative Weight Values of Customer Requirements

Customer Requirements	Improvement Rate	Absolute Weight	Relative Weight
CR1	1,25	9,38	11,85%
CR2	1,25	9,38	11,85%
CR3	1,25	9,38	11,85%
CR4	1,67	10,00	12,64%
CR5	1,67	6,00	7,58%
CR6	2,50	9,00	11,37%
CR7	1,67	4,00	5,06%
CR8	1,67	10,00	12,64%
CR9	2,50	12,00	15,17%

According to the results given in Table 4.4, the following comments can be made.

- The highest improvements are expected from CR6(innovative filter design) and CR9 (ease of directing in-cab air flow) since their improvement rate values are the highest.

- Since the absolute weight and relative weight values are directly proportional to each other, see equations (3.2) and (3.3), by looking at these two sections, it can be said that CR9 (Ease of directing in-cab air flow) was determined to be the most important customer requirement to be fulfilled in order to improve the customer satisfaction levels and company's competitive advantage in the market.
- Following the CR9, CR8 (Interior material selection layout in terms of in-cab temperature, ergonomics, and comfort) and CR4 (Effective operation of the vehicle air conditioner regardless of environmental factors) were determined to be the second most important customer requirements to be fulfilled in order to increase the overall comfort in the military vehicles of the subject company.

After the evaluation of CRs were completed, their corresponding TSs were needed to be determined, respectively. This process was also carried out by the inner departments of the subject company, i.e., product, quality, design, and research and development departments since it requires a technical and internal evaluation. There were 8 technical specifications determined in total. These TSs are given in Table 4.5.

Table 4. 5 Technical Specifications for the House of Quality Matrix

Technical Specifications (TSs)	Descriptions
TS1	Material selection
TS2	Air circulation
TS3	Humidity control
TS4	Energy consumption of A/C unit
TS5	Ease of maintenance
TS6	Noise control
TS7	Cabin volume
TS8	A/C unit performance capacity

As can be seen from Table 4.5, with respect to the 9 identified customer requirements, the internal teams of the subject company saw fit to determine 8 technical specifications in total. Detailed explanations of these TSs are given below.

TS1: The material selection comprises any component material, from the materials used in the dashboard construction to seat materials and inner wall plating, inside the cabin.

TS2: Air circulation deals with the in-cab air flow and like TS1 can be affected by various parameters, e.g., material selection, component and equipment layout inside the cabin, the number of operators in the vehicle, etc.

TS3: Humidity control was identified as another technical specification as it could be monitored and controlled by various digital and manual gauges used in the vehicle automation system, and of course, it could directly be affiliated with the in-cab temperature.

TS4: Since there were various parameters regarding the in-cab temperature of the vehicle identified as the customer requirements, the energy consumption of the air conditioning unit of the vehicle was determined as another technical specification.

TS5: Considering the periodical repair and maintenance activities not only for the air conditioning unit but also for the in-cab equipment and components of the vehicle, the ease of maintenance was identified as the fifth technical specification.

TS6: Since there are various electronic devices and systems established inside a military vehicle, the noise level created by those needs to be controlled. And, regarding this, noise control was determined as the sixth technical specification.

TS7: Cabin volume was identified as the seventh and one of the most crucial technical specifications since it directly affects the comfort parameter for military vehicles via air circulation, equipment/component layout, the number of personnel inside the cabin, etc.

TS8: Since in-cab temperature plays an important role in defining the technical specifications, the performance capacity of the air conditioning system in the vehicle was identified as the eighth and last technical specification.

After the technical specifications had been determined, their interrelationship was evaluated on the technical correlation matrix, located on the top section of the HOQ matrix. Figure 4.1

shows the constructed technical correlation matrix based on the strength of the relationship of TSs with each other.

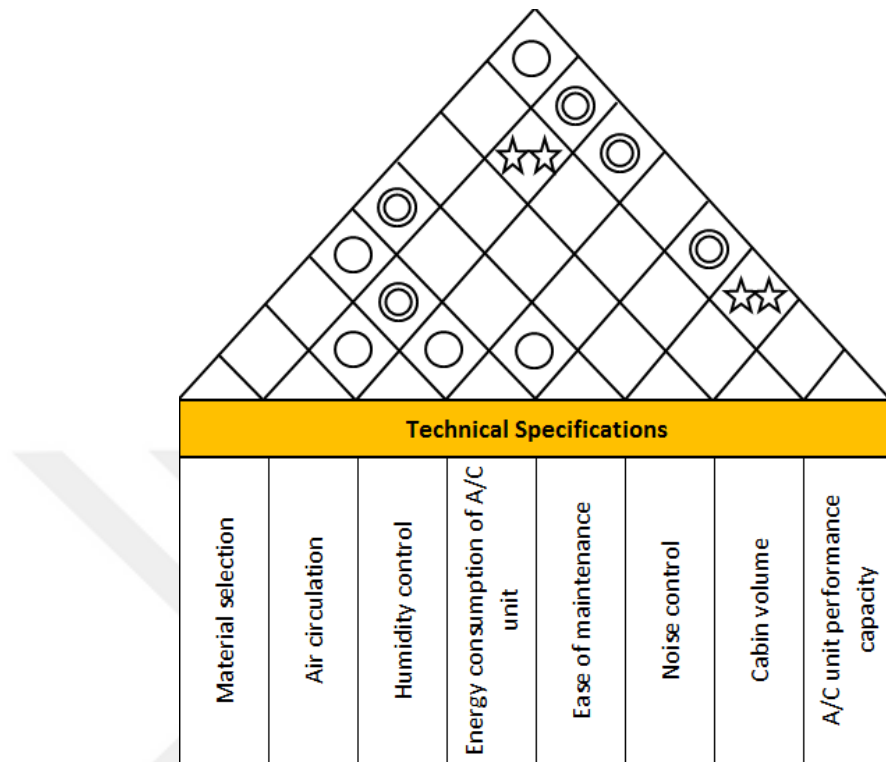


Figure 4. 1 Interrelationship of Technical Specifications on Technical Correlation Matrix

According to the data given in Figure 4.1, the following comments can be made.

- Air circulation (TS2) and cabin volume (TS7) have a negative but strong relationship with each other and the same can be said for noise control (TS6) and A/C unit performance capacity (TS8).
- Air circulation (TS2) and energy consumption of A/C unit (TS4) have a positive and strong relationship with each other just like material selection (TS1) and ease of maintenance (TS5) do.
- Material selection (TS1) has a strong but weak relationship with the energy consumption of the A/C unit (TS4) and the A/C unit performance capacity (TS8).

Since the TSs and their interrelationship had been identified and evaluated, the relationship between CRs and TSs could be investigated in the next step of the QFD application. The evaluation results of this process are given in Figure 4.2.

			Technical Specifications									
			Importance Level	Importance Percentage	Material selection	Air circulation	Humidity control	Energy consumption of A/C unit	Ease of maintenance	Noise control	Cabin volume	A/C unit performance capacity
Customer Requirements	Vehicle air conditioner cooling performance In-cab temperature from +50°C to +20°C in 10 minutes.	5	14,29	3	9	3	9	1	3	9	9	
	Vehicle air conditioner heating performance In-cab temperature from -30°C to +20°C in 15 minutes.	5	14,29	3	9	3	9	1	3	9	9	
	Cabin temperature to reach the desired state within the expected time	5	14,29	9	9	9	9	1	3	9	9	
	Effective operation of the vehicle air conditioner regardless of environmental factors	4	11,43	9	1	1	9	3	1	3	3	
	Fuel consumption performance of the vehicle 5 lts/hr max.	3	8,57	1	9	9	9	3	1	9	9	
	Innovative filter design	3	8,57	9	3	9	3	9	0	3	9	
	Availability of a digital control panel for air conditioning system	2	5,71	1	1	1	3	3	3	1	3	
	Interior material selection and layout in terms of warmth, ergonomics, and comfort	4	11,43	9	3	3	0	1	9	3	1	
	Ease of directing in-cab airflow	4	11,43	3	9	3	1	1	3	9	3	

Figure 4. 2 Relationship Between Customer Requirements and Technical Specifications

According to data gathered in Figure 4.2, the following comments about the relationship between CRs and TSs can be made.

- CR3 (cabin temperature to reach the desired state within the expected time) has strong relationships with most of the TSs, excluding TS5 (ease of maintenance) and TS6 (noise control).
- CR7 (availability of a digital control panel for air conditioning system) has either weak or average relationships with all of the TSs.
- There are no relationships at all between CR6 (innovative filter design) and TS6 (noise control) and between CR8 (interior material selection and layout in terms of warmth, ergonomics, and comfort) and TS4 (energy consumption of A/C unit)

After the evaluation CRs and TSs were completed, as the final step of the HOQ matrix approach, the absolute importance and relative score values of the TSs were calculated. As mentioned before, the evaluation of absolute and relative score parameters for the technical specifications is one of the most crucial steps of the HOQ matrix since it gives an idea about which technical specifications should be prioritized in order to increase the market share of

the company and the customer satisfaction to the maximum possible level. The calculations of the absolute and relative score values were conducted with respect to Equations (3.4) and (3.5), given in section 3. In Table 4.6, the results for the absolute and relative score values of the TSs are indicated.

Table 4. 6 Absolute Importance and Relative Score Values for Technical Specifications

Technical Specifications (TSs)	Absolute Importance	Relative Score
TS1	447,63	14,21%
TS2	486,13	15,44%
TS3	355,63	11,29%
TS4	448,13	14,23%
TS5	191,13	6,07%
TS6	238,38	7,57%
TS7	506,13	16,07%
TS8	476,13	15,12%

According to the data given in Table 4.6, the following comments can be made regarding the absolute importance and score values of technical specifications.

- TS7 (cabin volume) was defined to be the most important TS for the subject company and it was believed that if the design requirements for the cabin volume were fulfilled, it was possible to achieve a great level of customer satisfaction since most of the CRs would also be fulfilled.
- Following the TS7, TS2 (air circulation) and TS8 (A/C unit performance capacity) are the second and third most important TSs for the subject company, and fitting the design requirement of these two TSs could help the company fulfill most of the CRs and achieve a good level of customer satisfaction.
- TS5 (ease of maintenance) was defined to be the least important TS for the subject company and it was believed that although it would help the company achieve some

level of customer satisfaction, it still would not be enough to fulfill most of the CRs and stay competitive in the market.

As the QFD application stage was finalized, the obtained data would be used in the FMEA and TRIZ application stages, respectively. To briefly explain and summarize the results of the QFD application, some of the important data gathered from this stage is given below. It is important to state that the HOQ matrix of the QFD application conducted for the subject company is provided in the Appendices section of this study.

- Ease of directing in-cab air flow (CR9) was determined to be the customer requirement that requires improvement the most.
- The operational effectiveness of the air conditioner system (CR4), together with the interior material selection and layout (CR8) were determined to be other important customer requirements that possess room for improvement.
- Air circulation (TS2) and cabin volume (TS7) were evaluated as the most important technical specifications of all the design requirements. And it was stated by the subject company that these two parameters possess a technical contradiction among them. So, according to this evaluation, these two parameters would be used as improving and worsening features in the Contradiction Matrix of the TRIZ application stage.

Stage 2: Risk Analysis for the Technical Specifications

At the second stage of the study, an FMEA application was conducted specifically for the TSs that were determined in the QFD stage. This approach was conducted for several reasons. One is that it was believed to be beneficial to make a risk assessment on the TSs since they were the key parameters to customer satisfaction and the product/service development stage of the subject company. The other reason is that based on the literature review conducted for this study, there was no academic research or study identified that integrated the data gathered from FMEA analyses to the HOQ matrices and re-evaluated the hierarchical importance of the technical specifications based on the combination of RPN values with absolute importance and relative score parameters. So, this methodology is one of the parameters that help this study to fill the gap in the literature.

There were 8 technical specifications determined in the QFD stage. As in the nature of FMEA methodology, the severity, occurrence probability, and detectability parameters of those

technical specifications were evaluated, respectively. So, the technical specifications were treated as the potential failure modes and their respective RPN values were calculated, accordingly.

During a standard FMEA application, for each failure mode a potential failure effect, a potential cause, and current process controls are determined. But, during the interviews conducted with the subject company, for some of the technical specifications more than one parameter regarding the failure effects, causes of the effects, and current process controls were identified. Naturally, this resulted in more than one RPN value calculation for some of the technical specifications. Figure 4.3 represents a section of the FMEA method to better explain the indicated situation. The complete version of the FMEA methodology can be found in the Appendices section of this study.

Technical Specification	Potential Failure Mode	Potential Failure Effect	Severity (S)	Potential Causes	Occurrence (O)	Current Process Controls	Detection (D)	Risk Priority Number (RPN) (SxOxD)
<i>Parameters defined in the House of Quality Matrix</i>	<i>Description of what might go wrong</i>	<i>Description of the potential effects of the failure</i>	<i>How severe is the effect? (1: Low impact) (10: High impact)</i>	<i>Elements or conditions that cause the failure (How could the failure mode occur?)</i>	<i>Frequency of the cause occurrence (1: Not likely to occur) (10: Inevitable)</i>	<i>Existing controls to prevent the failure mode from occurring or detect it should it occur</i>	<i>Probability of the detection of the failure mode? (1: Very likely to be detected) (10: Not likely/too hard to be detected)</i>	<i>Multiply "Severity", "Occurrence", and "Detection" values (RPN ↑, Risk and Prioritization ↑)</i>
Material selection (1)	Fluctuation of cabin temperature outside of the limit values	Decreased durability of in-vehicle units	7	1) Cost reduction studies	8	Compliance tests for various environmental conditions	2	112
				2) Lack of technical knowledge	6			84
Material selection (2)	Deformation in vehicle components due to wrong material choice	Malfunctions in vehicle units	7	1) Cost reduction studies	8	Compliance tests for various environmental conditions	3	168
				2) Lack of technical knowledge	6			126
Air circulation	Irregularity in the health status of the personnel in the cabin	1) Reduction in cabin comfort parameter	8	1) Air conditioning system not working properly	7	Experience and observations of vehicle personnel	1	56
				2) Parameters that will prevent in-cab airflow	6			48
		2) Difficulty of vehicle personnel in performing their duties	7	3) The number of personnel in the vehicle exceeds the specified limit.	4			28

Figure 4. 3 FMEA for Technical Specifications (Partial)

As can be seen from Figure 4.3, since there were two potential failure modes and two potential causes determined for the material selection (TS1), this parameter had been evaluated under two categories, material selection (1) and material selection (2), resulting 4 RPN values in total for the material selection (TS1). The same can be said for the air circulation (TS2) since it possessed two different potential failure effects. Air circulation also had three potential causes. This indicates air circulation possesses three different RPN values in total.

Based on the specified FMEA application for 8 technical parameters, there were 19 RPN values determined. Although this result might have an indication for the risk assessment of the technical parameters, it needed to be simplified in order to attain one RPN value for each technical specification without compromising the data set. So, in that regard, each of the technical parameter's RPN values were treated as the new elements to produce a new data set in order to obtain one respective RPN value for each failure mode. To be more specific, the RPN values of each technical parameter were used as the minimum and maximum limits of triangular distributions. The minimum RPN value of a technical specification was assigned as the lowest limit of a triangular distribution, whereas the maximum RPN value of the same technical specification was assigned as the highest limit of the same distribution. So, the lowest and highest limits represented the lowest and highest values of risk assessment results of the TSs, respectively. Since, in practice, failure modes occur randomly in different frequencies on a daily/monthly/yearly basis, it was assumed that for each TS, failure modes occurred 100 times in total. This means that for each failure mode, between the lowest and highest limits of the triangular distributions for TSs, 100 random values with different RPN results were generated. After, the average values for each generated 100 RPN value were calculated. With that approach, one RPN value for each TS was obtained. Since there were 8 TSs determined in total, this process was repeated 8 times and conducted via MATLAB. Table 4.7 shows the calculated RPN values via this approach.

Table 4. 7 The Final RPN Values of Technical Specifications

Technical Specification (TS)	Probability of Distribution	Risk Priority Number (RPN)
Material selection (TS1)	Tria (84, 126, 168)	126.75
Air circulation (TS2)	Tria (28, 48, 56)	43.64
Humidity control (TS3)	Tria (63, 72, 72)	68.88
Energy consumption of A/C unit (TS4)	Tria (48, 128, 128)	102.45
Ease of maintenance (TS5)	Tria (70, 98, 98)	89.16
Noise control (TS6)	Tria (36, 144, 144)	107
Cabin volume (TS7)	Tria (144, 252, 252)	211.94
A/C unit performance capacity (TS8)	Tria (48, 72, 72)	62.86

As can be seen from Table 4.7, cabin volume (TS7) was determined as the technical specification with the highest RPN value. Following the cabin volume, material selection (TS1) and energy consumption of the A/C unit (TS4) were determined as the second and third technical specifications with the highest RPN values, respectively. Although seven out of eight technical specifications' RPN values exceeded the limit value of 40 RPN, TS1, TS4, and TS7 were the three parameters that exceeded the limit value of 100 RPN making them the three most risky failure modes, or most likely in this case, design requirements. According to these results, to have a better look at the new RPN values, Figure 4.4 shows the Pareto Distribution of the technical specifications.

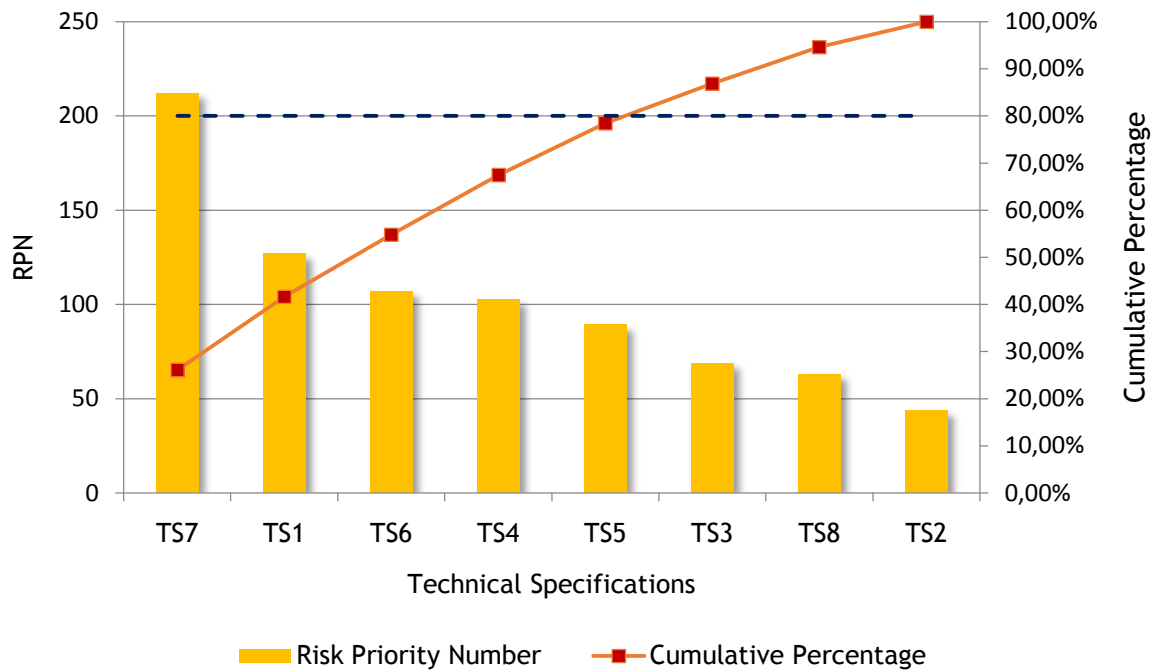


Figure 4. 4 Pareto Distribution of the Technical Specifications

According to the Pareto Distribution given in Figure 4.4, cabin volume (TS7), material selection (TS1), noise control (TS6), the energy consumption of A/C unit (TS4), and ease of maintenance (TS5) make the vital few of the technical specifications, whereas humidity control (TS3), A/C unit performance capacity (TS8), and air circulation (TS2) comprise the trivial many of the technical specifications. Based on this data, it can be said that in order to improve overall customer satisfaction and market share, and to satisfy customer requirements the potential failure modes and risk factors of the vital few group (TS7, TS1, TS6, TS4, TS5) of technical specifications should be prioritized.

In the final step of stage 2, the FMEA application for technical specifications, the RPN values gathered from the triangular distribution approach were integrated into the HOQ matrix. As mentioned at the beginning of this stage, this methodology was intentionally preferred in order to contribute to the literature by establishing a connection between the risk assessment of TSs and their potential technical contradictions. Briefly, The RPN results of the technical specifications were associated with the absolute importance and relative score parameters in the HOQ matrix. Figure 4.5 shows this connection on the bottom section of the matrix.

Absolute Importance	447,63	486,13	355,63	448,13	191,13	238,38	506,13	476,13
Relative Score(RS/Relative Importance)	14,21%	15,44%	11,29%	14,23%	6,07%	7,57%	16,07%	15,12%
Risk Priority Number (RPN)	126,75	43,64	68,88	102,45	89,16	107,00	211,94	62,86
RS-FMEA	18,02	6,74	7,78	14,58	5,41	8,10	34,06	9,50

Figure 4. 5 The RPN Integration to the House of Quality Matrix

As can be seen from Figure 4.5, the RPN values obtained from the triangular distribution approach were associated specifically with the relative score (relative importance) values of the technical specifications. This was done intentionally in order to identify new technical specifications that cause technical contradictions. Based on the data in Figure 4.5 and according to Equation (3.6), the highest three parameters in the result of the multiplication of RPN values with relative score values (RS-FMEA) were identified as material selection (TS1), the energy consumption of A/C unit (TS4), and cabin volume (TS7) with the values of 18.02, 14.58, and 34.06, respectively. According to the interviews conducted with the subject company it had been stated that these parameters created a number of potential technical contradiction scenarios that were to be evaluated in the next stage of the study, the TRIZ application.

Stage 3: Determination of Potential Solutions

In this stage, the technical contradictions determined in the QFD and FMEA applications were evaluated using the Contradiction Matrix and 40 Inventive Principles, respectively. In the QFD stage, air circulation (TS2) and cabin volume (TS7) were identified as the two technical specifications that possess technical contradictions. On the other hand, at the end of the FMEA stage, material selection (TS1), the energy consumption of the A/C unit (TS4), and cabin volume (TS7) were identified as the three key parameters that might possess several technical contradictions among them. So, there were 4 technical specifications chosen to identify the potential technical contradictions among them.

Firstly, based on the QFD results, the relationship between air circulation (TS2) and cabin volume (TS7) were investigated on the Contradiction Matrix. Both parameters' equivalent features on the matrix were identified and then the respective potential solutions proposed to solve the contradiction between them were chosen among the 40 Inventive Principles. Table 4.8 shows the details of this step.

Table 4. 8 Contradiction Matrix Evaluation of Air Circulation and Cabin Volume

Improving Specification	Equivalent Feature on the Matrix	Worsening Specification	Equivalent Feature on the Matrix	Inventive Principles	Suggested Solution
Cabin volume	Volume of stationary object	Air circulation	Quantity of substance / The matter	35, 3	3: Material change in the partial sections of the in-cab dashboard

As can be seen from Table 4.8, cabin volume (TS7) was determined to be the improving TS whereas air circulation (TS2) was the worsening technical specification. Their equivalent features on the Contradiction Matrix were identified as "volume of stationary object" and "quantity of substance/the matter", respectively. The intersecting cell of these two parameters possesses two possible solutions among the 40 Inventive Principles. These solutions are Principle 3 (Local quality) and Principle 35 (Transformation of properties), respectively. Based on the interviews conducted with the subject company, Principle 3 was seen as fit for a feasible resolution. According to Principle 3, it was suggested that if a design change was conducted based on the material overlay of the cabin dashboard it would eliminate the worsening of the air circulation since using different materials on the different sections of the dashboard could help decrease the overall thermal heating of the electronic systems inside the cabin.

As a second approach, to create another technical contradiction based on these two technical specifications, air circulation (TS2) was determined to be the improving specification whereas cabin volume (TS7) was determined as the worsening specification. Table 4.9 represents this situation and the potential solution principles described for this assumption.

Table 4. 9 Contradiction Matrix Evaluation for Cabin Volume and Air Circulation

Improving Specification	Equivalent Feature on the Matrix	Worsening Specification	Equivalent Feature on the Matrix	Inventive Principles	Suggested Solution
Air circulation	Duration of action of moving object	Cabin volume	Stability of the object's composition	13, 3, 35	13: Optimization for positioning of in-cab air vents

As can be seen from Table 4.9, air circulation (TS2) was identified as the improving specification whereas the cabin volume (TS7) was determined as the worsening specification. Their equivalent features on the Contradiction Matrix were identified as "duration of action of moving object" and "stability of the object's composition", respectively. As can be understood, the equivalent features of the technical specifications were also changed in this scenario. Based on these parameters, the potential inventive solutions identified on the Contradiction Matrix were Principle 13 (Do it in reverse), Principle 3 (Local quality), and Principle 35 (Transformation of properties). If the air circulation was to stay the same or improve, this could compromise the cabin volume. So, since the dashboard and various electronic systems inside the cabin were positioned on the front section of the vehicle, close to the steering wheel, the position of the A/C unit would be somewhere near the front section of the cabin, close to these electronic systems and devices. The electronic systems inside the dashboard generate a considerable amount of heat. Based on all these data and the interviews conducted with the subject company, Principle 13 was determined to be the best approach to solve this contradiction. The suggested solution was the optimization for the location redetermination of in-cab air vents in a way that could benefit the air circulation inside the cabin.

Based on the results of the FMEA-QFD integrated approach, the nature of relationships between the technical specifications material selection (TS1), the energy consumption of the A/C unit (TS4), and cabin volume (TS7) were investigated. According to the feedback gathered from the subject company, these three technical specifications possess possible

technical contradictions among them. So, they were investigated through the Contradiction Matrix. In Table 4.10, the contradiction between material selection (TS1) and energy consumption of the A/C unit (T4) was evaluated.

Table 4. 10 Contradiction Matrix Evaluation for Material Selection and Energy Consumption of A/C Unit

Improving Specification	Equivalent Feature on the Matrix	Worsening Specification	Equivalent Feature on the Matrix	Inventive Principles	Suggested Solution
Material selection	Quantity of substance/The matter	Energy consumption of A/C unit	Use of energy by stationary object	3, 35, 31	31: Porous material usage for in-cab equipment or material overlay

As can be seen from Table 4.10, the material quality/selection of the vehicle cabin wanted to be improved. This technical specification was identified as the "quantity of substance/the matter" on the Contradiction Matrix. On the other hand, it was stated by the subject company due to the usage of different materials inside the cabin energy consumption of the A/C unit (TS4) could increase. This was an unwanted situation, worsening specification, and it was identified as "use of energy by stationary object" on the Contradiction Matrix since the vehicle cabin and the A/C unit inside the cabin were treated as stationary objects in a physical space. By looking at the intersecting cell of these two features on the matrix there were three possible solutions indicated in total. These were Principle 3 (Local Quality), Principle 35 (Transformation of properties), and Principle 31 (Porous material). Based on the interviews conducted with the subject company Principle 31 was seen as the better approach among the three solutions. It was suggested that the usage of porous material for the overlay of equipment or materials inside the cabin should result in more stable air conditions in terms of temperature, humidity level, and air circulation inside the cabin. This could also provide more profitable, efficient, and stable energy consumption for the A/C unit (TS4).

The status of the features can be switched and new possible solutions can be generated in the Contradiction Matrix. To be more specific, contrary to the situation stated in Table 4.10, the

energy consumption of the A/C unit (TS4) was treated as the improving technical specification and the material selection (TS1) was determined to be the worsening technical specification, this time. Their equivalent features on the Contradiction Matrix were identified as the "use of energy by moving object" and "quantity of substance/the matter", respectively. As can be understood, the A/C unit was treated as a moving object this time since the energy consumption of both the vehicle and the A/C unit would be more when the vehicle is mobile. Table 4.11 sums up the described situation and shows the possible suggestions located on the Contradiction Matrix for this technical contradiction.

Table 4. 11 Contradiction Matrix Evaluation for Energy Consumption of A/C Unit and Material Selection

Improving Specification	Equivalent Feature on the Matrix	Worsening Specification	Equivalent Feature on the Matrix	Inventive Principles	Suggested Solution
Energy consumption of A/C unit	Use of energy by moving object	Material selection	Quantity of substance/The matter	34, 23, 16, 18	23: Automation system for A/C unit filter condition feedback and temperature monitoring and control

As can be seen from Table 4.11, when the condition of the specifications is switched the possible inventive solutions suggested on the Contradiction Matrix change as well. In this case, in order to improve the energy consumption of the A/C unit (TS4) it was identified as the "use of energy by moving object" on the Contradiction Matrix. On the other hand, although material selection (TS1) was determined to be the worsening specification its equivalent on the matrix stayed the same as "quantity of substance/the matter". For this scenario, there were 4 possible solutions identified in the matrix. They were Principle 34 (Rejecting and Regenerating Parts), Principle 23 (Feedback), Principle 16 (Partial or Excessive Action), and Principle 18 (Mechanical Vibration). Based on the interviews

conducted with the subject company, it was decided that making use of Principle 23 would be the best approach to solve this contradiction. As a result, two solutions were suggested. Since there were no systems integrated to monitor the filter condition, the vehicle personnel needed to check the filter condition and conduct the necessary maintenance activities accordingly in the current situation. But it was stated that if an automation system were to be integrated into the vehicle to monitor the filter condition of the A/C unit, this would determine the optimum time to conduct the maintenance activities for the filter resulting in more effective usage of energy for the A/C unit on the middle and long term and also there would be no need to compromise the material selection.

Another suggested solution for the situation stated in Table 4.11 was the implementation of an automation system, just like for the A/C unit filter, that could monitor and control the temperature variations in the cabin. Normally such a system already existed in the current product line of military vehicles of the subject company. But, based on Principle 23 (Feedback) it was stated that if a feedback system already existed, then its frequency or magnitude should be changed. So, based on the interviews conducted with the subject company a new temperature monitoring system with improved temperature tolerance values, integrated with the vehicle air conditioning system and providing profitability in energy consumption was suggested.

Stage 4: Determination of the Most Suitable Solution Among the Potential Solutions

Based on the data obtained in stage 3, there were 5 solutions identified and suggested to the subject company. These solutions were to be hierarchically ordered based on the subject company's time, equipment and human resources, and the budget allocated for the project development. As can be understood, the 5 suggested solutions on the TRIZ stage composed the 5 criteria to be evaluated in the decision-making process of AHP application in this stage. These 5 solutions were redetermined from "Solution 1" to "Solution 5", respectively for convenience purposes during the application. Below, all criteria and their respective equivalent solutions are given in detail.

- ***Solution 1:*** Material change in the partial sections of the in-cab dashboard in order to prevent the worsening of air circulation inside the cabin

- **Solution 2:** Porous material usage for in-cab equipment or material overlay in order to ensure profitability in the energy consumption of the A/C unit of the vehicle
- **Solution 3:** Automation system for A/C unit filter condition feedback in order to determine the optimum time for the maintenance activities for the A/C unit filter and ensure more effective energy usage for both middle and long terms
- **Solution 4:** A new automated temperature monitoring system with improved temperature tolerance values, integrated with the vehicle air conditioning system and providing profitability in energy consumption
- **Solution 5:** Optimization for positioning of in-cab air vents in order to improve the air circulation inside the cabin

The AHP application was conducted with a team of specialists among the R&D teams of the subject company, who were experienced with the methodology. The results showing the relative importance weights of the potential solutions evaluated through the AHP application are provided in Table 4.12 and Figure 4.6.

Table 4. 12 The AHP Application for the Potential Solutions

Potential Solutions	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Relative Importance Weights
Solution 1	1	3	0,20	3	0,3333	0,1229
Solution 2	0,3333	1	0,1429	2	0,2	0,0616
Solution 3	5	7	1	7	3	0,5096
Solution 4	0,3333	0,5	0,1429	1	0,2	0,0467
Solution 5	3	5	0,3333	5	1	0,2591

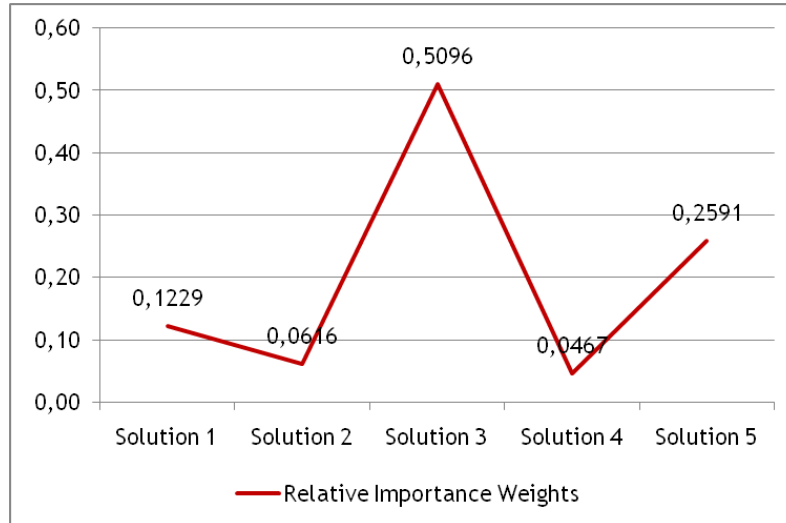


Figure 4. 6 Relative Importance Weight Distribution for the Potential Solutions

As can be seen from Table 4.12 and Figure 4.6, based on the AHP evaluation conducted with the subject company, Solution 3 was determined to be the most suitable solution for the company with a relative importance weight of 0,5096. Based on Equations (3.15) and (3.16), the CI and CR values were evaluated as 0,0486 and 0,0434, respectively. Since the CR value was determined to be lower than the limit value of 0,1 it can be said that the criteria evaluation was consistent. This means that the subject company's top priority in order to increase the comfort parameter in their military vehicle products will be the development and integration of an automated system that monitors the condition of the vehicle A/C unit filter to determine the optimum time for the maintenance activities of it. As stated before, this approach was not only believed to be beneficial for both the short and long-term energy consumption of the A/C unit, but also help personnel spend less time on maintenance activities for the A/C unit filter. Depending on the project's time and budget expenses considering the development of an A/C unit filter monitoring system, if the subject company intends to pursue and tackle more objectives in order to continue its operations for increasing the comfort parameter, then the next resolutions will be Solution 5 and Solution 1. These are the optimization for location-allocation of in-cab air vents for maximum air circulation inside the cabin and material selection for the cabin dashboard for prevention of worsening of in-cab air circulation, respectively.

5. CONCLUSION

In this study, based on the conducted literature review, the integration of QFD, FMEA, TRIZ, and AHP was used for the first time. This was done by working closely with a subject company that is based in the automotive and defense systems industry. The purpose of the study was to identify the key comfort parameters in military vehicles based on customer expectations and improve these parameters by using various methodologies and providing the most suitable and effective solutions possible.

Via the HOQ matrix, the customer requirements and their respective technical specifications were identified. There were 9 customer requirements and 8 technical specifications determined in total. The importance ratings of the customer requirements were evaluated, and later, the absolute importance and relative score values of the technical specifications were calculated. Based on these results, a technical contradiction was established between the air circulation and cabin volume, the two technical specifications.

In the FMEA stage, technical specifications were treated as the potential failure modes. During the conduction of this stage, there were 19 RPN results determined with respect to 8 technical specifications. So, more than one RPN value was evaluated for each technical specification. In order to assign one RPN value for each technical specification, for each failure mode the calculated RPN values were treated as the lowest and highest limits of a triangular distribution. Basically, the lowest and highest limits of a triangular distribution for a failure mode represented the lowest and highest RPN values of that respective technical specification. Later, it was assumed that there would be 100 failure modes that occurred with different RPN values between the lowest and highest RPN limits of each technical specification. Finally, the average values of these results were calculated resulting in the determination of one RPN value for each failure mode or technical specification.

The calculated RPN values were integrated with the HOQ matrix, and their association with the technical specifications was evaluated. With this approach, new technical contradictions were identified. Based on the literature review conducted for this study, since no other studies combined the data sets of QFD and FMEA in HOQ matrices like this, this was considered the other key element that enabled this study to establish a different approach than the others.

In the third stage of the study, all the obtained contradictions were put into the Contradiction Matrix of TRIZ and their respective inventive solutions were identified. There were 4 technical contradictions in total and by using the 40 Inventive Principles, a total number of 5 potential solution suggestions were generated.

In the final step of the study, together with the subject company, these generated solutions were evaluated by using the AHP methodology in order to determine their hierarchical order and the most suitable option among them, eventually. Based on the literature review conducted for this study, it was observed that no studies had used the joint application of QFD, FMEA, TRIZ, and AHP before. So, this aspect of the study was considered another parameter that distinguished it from other studies.

In the end, it was determined that the development of an automated A/C unit filter monitoring system with a relative importance weight of 0,5096 was the most suitable and profitable solution for the subject company to increase the comfort parameter for its military vehicles product line. As a closing statement of the conducted study, based on the subject companies' budget specifications and project timeline, it was suggested that the optimization for the location-allocation of in-cab air vents of military vehicles and material determination studies for the dashboard overlay with the second and third biggest relative importance weight results of 0,2591 and 0,1229, respectively, can also be investigated.

6. RECOMMENDATIONS

For future studies, different methodologies, applications, and techniques can be integrated into the developed approach of this study. In that matter, one of the suggested solutions to the subject company was the optimization application for the location-allocation of in-cab air vents of military vehicles. This suggestion can be investigated deeply and used in future studies to identify the best positioning for air vents and further improve the in-cab comfort parameter for military vehicle personnel.

Also, a cost reduction application combined with the TRIZ methodology can be benefited from in order to improve the material quality of the in-cab equipment and overlay. With that approach, new technical contradictions can be established and overall in-cab material selection and quality can be improved without compromising the budget limitations. As can be understood, this can also result in new creative solutions for increasing the overall in-cab comfort parameter for military vehicle personnel.

Besides, in future studies, other methods of multi-criteria decision-making can also be used in order to further benchmark the logic, applicability, and consistency of the methodology used in this study.

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APPENDICES

Appendix A. House of Quality Matrix

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Appendix B. FMEA Results

Technical Specification	Potential Failure Mode	Potential Failure Effect	Severity (S)	Potential Causes	Occurrence (O)	Current Process Controls	Detection (D)	Risk Priority Number (RPN) (SxOxD)	Recommended Action
Parameters defined in the House of Quality Matrix	Description of what might go wrong	Description of the potential effects of the failure	How severe is the effect? (1: Low impact) (10: High impact)	Elements or conditions that cause the failure (How could the failure mode occur?)	Frequency of the cause occurrence (1: Not likely to occur) (10: Inevitable)	Existing controls to prevent the failure mode from occurring or detect it should it occur	Probability of the detection of the failure mode? (1: Very likely to be detected) (10: Not likely/too hard to be detected)	Multiply "Severity", "Occurrence", and "Detection" values (RPN ↑, Risk and Prioritization ↑)	What are the actions to reduce the occurrence of the cause or to improve its detection ? Provide all actions for high RPNs and severity ratings of 9 and 10 .
Material selection (1)	Fluctuation of cabin temperature outside of the limit values	Decreased durability of in-vehicle units	7	1) Cost reduction studies	8	Compliance tests for various environmental conditions	2	112	Performing comparative tests of vehicle interior temperature values according to material types
				2) Lack of technical knowledge	6			84	
Material selection (2)	Deformation in vehicle components due to wrong material choice	Malfunctions in vehicle units	7	1) Cost reduction studies	8	Compliance tests for various environmental conditions	3	168	Performing comparative tests of vehicle interior temperature values according to material types
				2) Lack of technical knowledge	6			126	
Air circulation	Irregularity in the health status of the personnel in the cabin	1) Reduction in cabin comfort parameter	8	1) Air conditioning system not working properly	7	Experience and observations of vehicle personnel	1	56	After the optimum condition of the air outlets inside the cabin is determined by the simulation study, this situation is verified by performing live tests in the cabin.
				2) Parameters that will prevent in-cab airflow	6			48	
		2) Difficulty of vehicle personnel in performing their duties	7	3) The number of personnel in the vehicle exceeds the specified limit.	4			28	
Humidity control	Exceeding the limit values of humidity in the cabin	Deterioration in cabin materials and electronic systems due to deviation in humidity	9	1) Air conditioning system not working properly	7	1) Various measuring instruments inside the cabinet	1	63	Verification of the system, which can keep the humidity level within certain ranges, with endurance tests against various environmental conditions
				2) Using the vehicle outside of predetermined weather conditions	4	2) Experience and observations of vehicle personnel	2	72	
Energy consumption for A/C unit	Energy consumption to be higher than expected	Insufficient amount of fuel for the vehicle's range	8	1) Clogging of A/C unit filters	8	Experience and observations of vehicle personnel	2	128	Verification of the air conditioning system with resistance tests to various environmental conditions and periodic maintenance activities
				2) Electronic failure in the A/C unit	3			48	
Ease of maintenance	Maintenance activities taking longer than necessary	Limited use of the vehicle in the field	7	1) Lack of technical knowledge	7	Experience and observations of vehicle personnel	2	98	1) Support of authorized personnel to maintenance activities 2) Ensuring stock adequacy for spare parts/maintenance materials
				2) Lack of maintenance equipment	5			70	
Noise control	High noise level in the cabin	Personnel having hearing and communication problems	6	1) Lack of technical knowledge	6	1) Noise level measurement tests	1	36	Conducting and evaluating noise level measurement tests throughout the life cycle of the vehicle
				2) Cost reduction studies	8	2) Experience and observations of the staff	3	144	
Cabin volume	Cabin volume larger or smaller than expected	Failure to provide adequate weather conditions in the vehicle	9	1) Lack of knowledge in design activities	8	1) Verification of design activities with measuring instruments	2	144	1) Performing interim checks during design activities 2) Using insulating materials to minimize the air impermeability of the vehicle cabin
				2) Insufficient air impermeability of the vehicle	7	2) Using insulation materials for vehicle cabin air impermeability	4	252	
A/C unit performance capacity	Inability to perform in-cab air conditioning at the desired level or in the desired time	1) Reduction in cabin comfort parameter	9	1) Cost reduction studies	8	Experience and observations of vehicle personnel	1	72	Implementation of performance analyses and tests
		2) Difficulty of vehicle personnel in performing their duties	8	2) Lack of technical knowledge	6			48	

Appendix C. FMEA Integrated House of Quality Matrix

		Technical Specifications															
		Importance Level	Importance Percentage	Material selection	Air circulation	Humidity control	Energy consumption of A/C unit	Ease of maintenance	Noise control	Cabin volume	A/C unit performance capacity	Company Satisfaction Level	Planned Quality Level	Improvement Rate	Sales Advantage	Absolute Weight	Relative Weight
Customer Requirements	Vehicle air conditioner cooling performance In-cab temperature from +50°C to +20°C in 10 minutes.	5	14,29	3	9	3	9	1	3	9	9	4	5	1,25	1,50	9,38	11,85%
	Vehicle air conditioner heating performance In-cab temperature from -30°C to +20°C in 15 minutes.	5	14,29	3	9	3	9	1	3	9	9	4	5	1,25	1,50	9,38	11,85%
	Cabin temperature to reach the desired state within the expected time	5	14,29	9	9	9	9	1	3	9	9	4	5	1,25	1,50	9,38	11,85%
	Effective operation of the vehicle air conditioner regardless of environmental factors	4	11,43	9	1	1	9	3	1	3	3	3	5	1,67	1,50	10,00	12,64%
	Fuel consumption performance of the vehicle 5 lts/hr max.	3	8,57	1	9	9	9	3	1	9	9	3	5	1,67	1,20	6,00	7,58%
	Innovative filter design	3	8,57	9	3	9	3	9	0	3	9	2	5	2,50	1,20	9,00	11,37%
	Availability of a digital control panel for air conditioning system	2	5,71	1	1	1	3	3	3	1	3	3	5	1,67	1,20	4,00	5,06%
	Interior material selection and layout in terms of warmth, ergonomics, and comfort	4	11,43	9	3	3	0	1	9	3	1	3	5	1,67	1,50	10,00	12,64%
	Ease of directing in-cab airflow	4	11,43	3	9	3	1	1	3	9	3	2	5	2,50	1,20	12,00	15,17%
Absolute Importance				447,63	486,13	355,63	448,13	191,13	238,38	506,13	476,13						
Relative Score(RS/Relative Importance)				14,21%	15,44%	11,29%	14,23%	6,07%	7,57%	16,07%	15,12%						
Risk Priority Number (RPN)				126,75	43,64	68,88	102,45	89,16	107,00	211,94	62,86						
RS-FMEA				18,02	6,74	7,78	14,58	5,41	8,10	34,06	9,50						

Appendix D. Contradiction Matrix

		Worsening Feature																																								
		Improving Feature																																								
		Weight of moving object Weight of stationary object Length of moving object Length of stationary object Area of moving object Area of stationary object Volume of moving object Volume of stationary object Speed Force (Intensity) Stress or pressure Shape Stability of the object's composition Strength Duration of action of moving object Duration of action of stationary object Temperature Illumination intensity Use of energy by moving object Use of energy by stationary object Power Loss of Energy Loss of Substance Loss of Information Loss of Time Quantity of substance/the matter Reliability Measurement accuracy Manufacturing precision Object-affected harmful factors Object-generated harmful factors Ease of manufacture Ease of operation Ease of repair Adaptability or versatility Device complexity Difficulty of detecting and measuring Extent of automation Productivity																																								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39				
1	Weight of moving object	+		15, 8, 29, 34		10, 1, 29, 35		29, 2, 40, 28		5, 35, 14, 2		2, 8, 15, 38	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40	1, 35, 19, 39	28, 27, 18, 40	5, 34, 31, 35		6, 29, 4, 38	19, 1, 32, 34, 31	35, 12, 34, 31		12, 36, 18, 31	6, 2, 34, 19	5, 35, 3, 31	10, 24, 35	10, 35, 20, 28	3, 26, 18, 31	1, 3, 11, 27	28, 27, 35, 26	28, 35, 26, 18	22, 21, 18, 27	22, 35, 31, 39	27, 28, 1, 36	35, 3, 2, 24	2, 27, 28, 11	29, 5, 15, 8	26, 30, 36, 34	28, 29, 26, 32	26, 35, 18, 19	35, 3, 24, 37
2	Weight of stationary object		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2		8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14	26, 39, 1, 40	28, 2, 10, 27		2, 27, 19, 6	28, 19, 32, 22	19, 32, 35		18, 19, 28, 1	15, 19, 18, 22	5, 8, 13, 30	10, 15, 35	10, 20, 35, 26	19, 6, 18, 26	10, 28, 8, 3	18, 26, 28	10, 1, 35, 17	2, 19, 22, 37	35, 22, 1, 39	28, 1, 9	6, 13, 1, 32	2, 27, 28, 11	19, 15, 29	1, 10, 26, 39	25, 28, 17, 15	2, 26, 35	1, 28, 15, 35			
3	Length of moving object	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35		13, 4, 8	17, 10, 4	1, 8, 35	1, 8, 10, 29	1, 8, 15, 34	8, 35, 29, 34	19		10, 15, 19	32	8, 35, 24		1, 35	7, 2, 35, 39	4, 29, 23, 10	1, 24	15, 2, 29	29, 35	10, 14, 29, 40	28, 32, 4	10, 28, 29, 37	1, 15, 17, 24	1, 29, 17	15, 29, 35, 4	1, 28, 10	14, 15, 1, 16	1, 19, 26, 24	35, 1, 26, 16	17, 24, 26, 16	14, 4, 28, 29			
4	Length of stationary object		35, 28, 40, 29		+		17, 7, 10, 40		35, 8, 2, 14		28, 10	1, 14, 35	13, 14, 15, 7	39, 37, 35	15, 14, 28, 26		1, 10, 35	3, 35, 38, 18	3, 25		12, 8	6, 28	10, 35, 24, 35	24, 26	26, 4	29, 30, 6, 13	29, 9	26, 28, 32, 3	2, 32, 10	1, 18	15, 17, 27	2, 25	3	1, 35	1, 26	26		30, 14, 7, 26				
5	Area of moving object	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4	11, 2, 13, 39	3, 15, 40, 14	6, 3		2, 15, 16	15, 32, 19, 13	19, 32		19, 10, 32, 18	15, 17, 30, 26	10, 35, 2, 39	30, 26	26, 4	29, 30, 6, 13	29, 9	26, 28, 32, 3	2, 32	22, 33, 28, 1	17, 2, 18, 39	13, 1, 26, 24	15, 17, 13, 16	15, 13, 10, 1	15, 30	14, 1, 13	2, 36, 26, 18	14, 30, 28, 23	10, 26, 34, 2		
6	Area of stationary object		30, 2, 14, 18		26, 7, 9, 39		+				1, 18, 35, 36	10, 15, 36, 37		2, 38	40		2, 10, 19, 30	35, 39, 38			17, 32	17, 7, 40, 4	10, 14, 18, 39	30, 16	10, 35, 4, 18	2, 18, 40, 4	32, 35, 32, 3	26, 28, 18, 36	2, 29, 18, 36	27, 2, 39, 35	22, 1, 40	40, 16	16, 4	16	15, 16	1, 18, 36	2, 35, 30, 18	23	10, 15, 17, 7			
7	Volume of moving object	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17		+		29, 4, 38, 34	15, 35, 36, 37	6, 35, 21	1, 15, 29, 4	28, 10, 1, 39	9, 14, 15, 7	6, 35, 4		34, 39, 10, 18	2, 13, 10	35		35, 6, 13, 18	7, 15, 13, 16	36, 39, 34, 10	2, 22	2, 6, 34, 10	29, 30, 7	14, 1, 40, 11	25, 26, 28	22, 21, 27, 35	17, 2, 40, 1	29, 1, 40	15, 13, 30, 12	10	15, 29	26, 1	29, 26, 4	35, 34, 16, 24	10, 6, 2, 34			
8	Volume of stationary object		35, 10, 19, 14		35, 8, 2, 14		+				2, 18, 37	24, 35	7, 2, 35	34, 28, 9, 14, 17, 15			35, 34, 38	35, 6, 4			30, 6		10, 39, 35, 34	35, 16, 32, 18	35, 3	2, 35, 16	34, 39, 30, 18, 35, 4	30, 18, 35, 4	35				1		1, 31	2, 17, 26	35, 37, 10, 2					
9	Speed	2, 28, 13, 38		13, 14, 8		29, 30, 34		7, 29, 34		+	13, 28, 15, 19	6, 18, 38, 40	35, 15, 18, 34	28, 33, 1, 18	8, 3, 26, 14	3, 19, 35, 5		28, 30, 36, 2	10, 13, 19	8, 15, 35, 38		19, 35, 38, 2	14, 20, 19, 35	10, 13, 28, 38	13, 26	10, 19, 29, 38	11, 35, 27, 28	28, 32, 1, 24	10, 28, 32, 25	1, 28, 35, 23	2, 24, 35, 21	35, 13, 8, 1	32, 28, 13, 12	34, 2, 28, 27	15, 10, 26	10, 28, 4, 34	3, 34, 27, 16	10, 18				
10	Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12	+	18, 21, 11	10, 35, 40, 34	35, 10, 21	35, 10, 14, 27	19, 2		35, 10, 21	19, 17, 10	1, 16, 36, 37		19, 35, 18, 37	14, 15, 40, 5	8, 35, 10, 36		10, 37, 36	14, 29, 18, 36	3, 35, 13, 21	35, 10, 23, 24	28, 29, 37, 36	1, 35, 40, 18	15, 37, 36, 24	13, 3, 15, 37, 18, 1	15, 1, 3, 25	15, 17, 18, 20	26, 35, 10, 18	36, 37, 10, 19	2, 35	3, 28, 35, 37			
11	Stress or pressure	10, 36, 37, 40	13, 29, 35, 10	35, 1, 14, 16	35, 1, 14, 16	10, 15, 36, 37	6, 35, 36, 37	10, 15, 36, 37	6, 35, 36, 37	35, 24		+	35, 4, 15, 10	35, 33, 9, 18	30, 14, 27		35, 39, 19, 2		14, 24, 10, 37	2, 36, 14	2, 6, 25	37, 36, 4	10, 14, 36	37, 36, 4	10, 13, 19, 35	3, 35	22, 2, 37	2, 33, 27, 18	1, 35, 16	11	2	35	19, 1, 35	19, 1, 35	35, 37	35, 24	10, 14, 35, 37					
12	Shape	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 15, 34, 18	35, 10, 37, 40	34, 15, 10, 14	+	33, 1, 18, 4	30, 14, 10, 40	9, 25	22, 14, 19, 32	13, 15, 32	10, 6, 34, 14		4, 6, 2	14	35, 29, 3, 5	14, 10, 34, 17	36, 22	10, 40, 16	28, 32, 1	32, 30, 40	22, 1, 2, 35	35, 1, 35, 1	1, 32, 17, 28	32, 15, 26	2, 13, 1	1, 15, 29	16, 29, 1, 28	15, 13, 39	15, 1, 32	17, 26, 34, 10				
13	Stability of the object's composition	21, 35, 2, 39	26, 39, 1, 40	13, 15, 1, 28	37	2, 11, 13	39	28, 10, 19, 39	34, 28, 28, 18	33, 15, 21, 16	10, 35, 21, 16	2, 35, 40	22, 1, 18, 4	+	17, 9, 10, 30	13, 27, 35, 23	39, 3, 35, 23	35, 1, 32	32, 3, 27, 16	13, 19	27, 4, 29, 18	32, 35, 27, 31	14, 2, 39, 6	2, 14, 30, 40		35, 27	15, 32, 35		13	18	35, 24, 30, 18	35, 40, 27, 39	35, 19	32, 35, 35, 19	2, 35, 10, 16	35, 30, 34, 2	2, 35, 22, 26	35, 22, 39, 23	1, 8, 35	23, 35, 40, 3		
14	Strength	1, 8, 40, 15	40, 26, 27, 1	1, 15, 36	15, 14, 28, 26	3, 34, 40, 29	9, 40, 28	10, 15, 14, 7	9, 14, 17, 15	8, 13, 26, 14	10, 10, 3, 14	10, 30, 18, 40	13, 17, 35	+	27, 3, 26		30, 10, 40	35, 19	10	35		35, 28, 31, 40	29, 3, 28, 10	29, 10, 27	11, 3, 3, 27, 16	3, 27	18, 35, 37, 1	15, 35, 22, 2	11, 3, 10, 32	32, 40, 25, 2	27, 11, 3, 32	15, 3, 25, 28	2, 13, 27, 3	15, 40	15	29, 35, 10, 14						
15	Duration of action of moving object	19, 5, 34, 31		2, 19, 9		3, 17, 19		10, 2, 19, 30		3, 35, 5	19, 2, 16	19, 3, 27	14, 26, 28, 25	13, 3, 35	27, 3, 10	+	19, 35, 39	2, 19, 4, 35	28, 6, 35, 18		19, 10, 35, 38		28, 27, 3, 18	10	20, 10, 28, 18	3, 35, 10, 40	11, 2, 13	3	3, 27, 16, 40	22, 15, 21, 39	27, 1, 4	12, 27	29, 10, 13	1, 35, 13	10, 4, 29, 15	19, 29, 39, 35	6, 10	35, 17, 14, 19				
16	Duration of action by stationary object		6, 27, 19, 16		1, 40, 35				35, 34, 38					39, 3, 35, 23			+	19, 18, 36, 40				16		27, 16, 18, 38	10	28, 20,																