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Enhancement of City Liveability Model by Examining Sustainability, Resiliency and Smart City Dimensions

Şehirlerde Yaşanabilirlik Modelinin Sürdürülebilirlik, Dayanıklılık ve Akıllı Şehir Boyutları İncelenerek İyileştirilmesi

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Abstract

Liveability models of cities play an important role in many issues such as raising awareness in cities, determining management strategies, and determining and solving criteria that affect human life. However, current liveability models are inadequate in measuring liveability. For this purpose, the currently used EIU The Global Liveability Index model was evaluated and enriched by examining it from 3 aspects and turning it into a more comprehensive index in this article. Since sustainability, resilience and smart city index studies are intertwined with liveability, studies in these areas and their effects on liveability have been utilized. In addition to the equally weighted indicators under the 5 categories within the scope of this enriched model, missing indicators were added. Importance weighting has been done in terms of the impact of these indicators on liveability. This weighting study was carried out with the widely used Analytical Hierarchy Process (AHP) which is a systematic and consistent method. With the enriched index model, data of 6 cities were collected and a comparison study was carried out and applied. Melbourne has become the most liveable city among these cities. The revised liveability index is expected to provide a more comprehensive and reliable measure of the liveability of cities, considering a wide range of factors that can affect the life quality of residents. The enhanced index is expected to be useful for policymakers, urban planners, and researchers in assessing the liveability of cities and identifying areas for improvement. Ultimately, the goal of a liveability index is to provide a more reliable measure of the quality of life in cities, considering a wide range of factors that can affect residents' daily lives.

Keywords: Liveable City Index, Sustainability, Resiliency, Smart City, City Rankings, Liveability Index

Öz

Şehirlerin yaşanabilirlik modelleri, şehirlerde farkındalığın artırılması, yönetim stratejilerinin belirlenmesi, insan hayatını etkileyen kriterlerin belirlenip çözüm geliştirilmesi gibi birçok konuda önemli rol oynamaktadır. Ancak mevcut yaşanabilirlik modelleri yaşanabilirliğin ölçümünde yetersiz kalmaktadır. Makalemizde bu amaçla halihazırda kullanılan "EIU The Global Liveability Index" modeli 3 açıdan incelenerek zenginleştirilmiş ve daha kapsamlı bir endeks haline getirilmiştir. Sürdürülebilirlik, dayanıklılık ve akıllı şehir endeksi çalışmaları yaşanabilirlik ile iç içe olduğundan bu alanlardaki çalışmalardan ve yaşanabilirliğe etkilerinden faydalanılmıştır. Zenginleştirilen bu model kapsamında 5 kategori altında yer alan eşit ağırlıklı göstergelerin yanı sıra yaşanabilirliğin ölçülmesinde elzem olan ve sonradan eklediğimiz göstergeler de yer almaktadır. Bu göstergelerin yaşanabilirliğe etkisi açısından önem ağırlıklandırması yapılmıştır. Bu ağırlıklandırma çalışması yaygın olarak kullanılan sistematik ve tutarlı bir yöntem olan Analitik Hiyerarşi Süreci (AHP) ile gerçekleştirilmiştir. Zenginleştirilmiş endeks modeli kullanılarak 6 ilin verileri toplanmış ve karşılaştırma çalışması yapılmıştır. Melbourne bu şehirler arasında en yaşanabilir şehir olarak gözlenmiştir. Güncellenen yaşanabilirlik endeksinin, şehir sakinlerinin yaşam kalitesini etkileyebilecek çok çeşitli faktörleri göz önünde bulundurarak şehirlerin yaşanabilirliğine ilişkin daha kapsamlı ve güvenilir bir ölçüm sağlaması beklenmektedir. Yeni endeksin politika yapımcılar, şehir planlamacıları ve araştırmacılar için şehirlerin yaşanabilirliğini değerlendirme ve iyileştirme alanlarını belirleme konusunda faydalı olması amaçlanmıştır. Sonuç olarak güncellenen yaşanabilirlik endeksinin amacı, şehir sakinlerinin günlük yaşamlarını etkileyebilecek çok çeşitli faktörleri göz önünde bulundurarak şehirlerdeki yaşam kalitesinin ölçümünün daha güvenilir bir şekilde yapılmasını sağlamaktır.

Anahtar Kelimeler: Yaşanabilir Şehir Endeksi, Sürdürülebilirlik, Dayanıklılık, Akıllı Şehir, Şehir Sıralaması, Yaşanabilirlik Endeksi

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I. INTRODUCTION

In recent years, the concept of a liveable city has received significant attention as cities struggle with challenges such as climate change, resource scarcity and the need for technological advancement and strive to provide a high life quality to their residents. Achieving liveability requires a comprehensive understanding of the various factors that contribute to a city's overall sustainability, resilience, and smartness. For this reason, the integration of different indices such as the sustainability index, smart city index and city resilience index becomes very important in creating the multidimensional structure of liveability. It is crucial to examine the details of other models to understand the liveability model structure. Three models, presented comprehensively in the literature review section, were used to enrich EIU The Global Liveability as content, and indicators related to liveability were determined.

The sustainability index assesses a city's environmental, social, and economic performance, measuring its ability to use current needs without harming the living standards of future generations. It covers topics such as energy efficiency, waste management, biodiversity, and social inclusion. Sustainability indexes are created worldwide through studies of different dimensions. There have been studies in which countries measured their cities and areas on a national basis. For example, the Sustainable City Index for Malaysia study is a study that measures the sustainability status of Malaysia's major cities [1]. In addition to general sustainability indexes, there are also studies such as Environmental Sustainability Index, Index of Sustainable Economic Welfare and Living Planet Index [2]. These studies particularly focus on the sustainability of designated areas. In this study, the scope was kept wide, and sustainability was examined from a broad perspective, as in the Environmental and Social Sustainability Index study which focuses not only environmental aspects but health and social perspectives [3]. Arcadis, which is a popular and comprehensive sustainability index, was examined. Arcadis index consists of 3 basic headings, and these are people, planet, and profit. With this study, it is aimed to provide a sustainability measurement focused on sustainability of people, nature, and economy.

The smart city index, on the other hand, assesses a city's use of technology and digital infrastructure to improve services, improve governance and foster citizen participation. It considers factors such as digital connectivity, smart transportation systems, e-governance, and innovation ecosystems. In addition to focusing on quality of life, smart cities focus on public safety and security [4]. At the center of this concept is governance and ITC. Governance and ICT are particularly important branches of a mechanism that enables city authorities to communicate with citizens and shape society. The smart city concept is also

supported by institutions, organizations and organizations that work closely with city authorities and aim to provide solutions to the problems of cities. It is an inevitable fact that companies focus on this area. Some organizations create frameworks by doing their own work [5].

Finally, the resilient city index focuses on a city's ability to recover from shocks and stresses, including natural disasters, epidemics, and socioeconomic disruptions. It covers aspects such as disaster preparedness, emergency response systems, community engagement and adaptive infrastructure. Apart from the concept of sustainability, the concept of resilience has come to the fore with the increase in crises around the world. Particularly in Spain, where these crises are more visible, resilience studies are focused on this issue [6]. Since resilience also focuses on strategic issues, it has become one of the priority issues of states. There are also studies such as Strategic Resilience Indicators in this field and it has been an important source in determining the topics that will pose problems in the future [7].

While these existing indices provide valuable information on specific aspects of urban development, a more holistic approach is required to comprehensively assess liveability. By integrating the sustainability, smart city and flexible city indices, an improved liveability index can be developed that considers the interdependencies and synergies between these different dimensions. This new index provides a comprehensive framework for evaluating and comparing cities based on their ability to create sustainable, smart, and resilient environments that improve the quality of life of their residents.

The aim of this article is to enhance EIU The Global Liveability Index by synthesizing criteria and indicators from the existing sustainability, smart city, and resilient city indices as seen in Figure 1. A new framework will be proposed by analyzing the components of each index, identifying overlapping criteria, and exploring the potential complementarity of various factors. This framework will provide a comprehensive assessment of a city's liveability, considering its environmental sustainability, technological advances, and resilience to shocks and stresses.

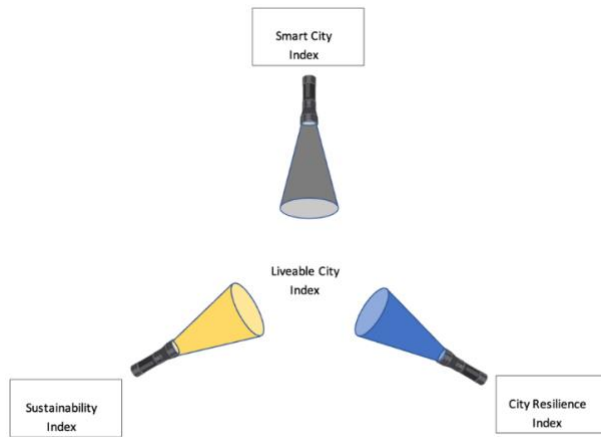


Figure 1. Liveable City Index Based on Sustainability, Resiliency and Smart City Index Dimensions

Moreover, this article aims to highlight the importance of including certain criteria from the resilience index, such as earthquake resistance, and the smart city index, such as response to pandemics, such as COVID-19, in the liveability index. Considering density, which is one of the liveability indicators, it has been observed that low density is safer for COVID-19 [8]. Likewise, the connection between liveable city and disaster management also has an impact on the quality of life [9]. By including these critical dimensions, the developed liveability index will more accurately present a city's ability to provide a high quality of life to its people under various conditions.

Through the enhancement of this liveability index, policymakers, urban planners and stakeholders will have a comprehensive tool to guide their decision-making, policy-making and urban development strategies. This index will contribute to the development of sustainable, smart, and resilient cities that prioritize the well-being and liveability of their citizens.

Liveability is also included in other concepts. Liveability and quality of life are at the forefront of smart city indexes. A significant number of indicators included in smart city indices have a positive impact on liveability [10]. For example, because of the study on green infrastructure, which is accepted as one of the smart city indicators in the USA, it has been observed that the sustainable construction of features such as building materials and water use have a positive effect on liveability [11]. There are also studies emphasizing that cities with low liveability rates can plan these problems for the future based on smart city applications [12].

The relationship between liveability and resilience is also seen in long-term studies. Creating a resilient city is of great importance for the formation of a livable city

on a long scale [13]. Sustainability and viability focus on similar areas in many respects. Social life is one of these areas. Social life, which expands from the family size to the size of cities and even countries, shows the connection between liveability and sustainability. For example, neighborhood relations have been evaluated as a subject that affects the quality of life for both concepts. This example can also be evaluated under the subject of social communication in the city dimension [14].

Overall, this article represents an important step towards developing a comprehensive liveability index that integrates the dimensions of sustainability, smart city, and resilient city. By synthesizing these indices and combining specific criteria for liveability, this research aims to contribute to efforts to build more liveable cities that are sustainable, smart, and resilient in the face of future challenges. The added value of this study is to both enrich an existing index study with a broad perspective and ensure that the equally weighted indicators in the existing index are weighted in order of importance by taking expert opinion. In this way, the liveability of cities will be measured with a more accurate and consistent scoring.

In this article, firstly, a comprehensive literature review was conducted under the title of literature on sustainable, liveable, resilient, and smart city index. Secondly, under the heading of methodology, indicators that were observed to improve the liveability-related index were determined and added to index. The liveability categories of stability, healthcare, culture and environment, education and infrastructure were examined, and aimed to improve the existing index by adding relevant indicators. The index indicators have been weighted by experts. Additionally, the Analytic Hierarchy Process (AHP) method was used to weigh the indicators, providing a systematic and consistent approach to assess the liveability of cities. Finally, under the result and discussion heading, six different cities were compared according to the current index and the results were interpreted. Enhancing the Global Liveability Index with current issues and a very comprehensive perspective such as smart city, sustainability and resiliency makes this study different from other indices.

2. LITERATURE REVIEW

When the literature was examined within the scope of the liveability study of cities, it was observed that there were common structures at many points with the concepts of sustainability, resiliency, and smart city. Based on these similarities, we focused on the parts included in these 3 index studies that may have an impact on liveability. For a comprehensive study, four city indexes including liveability, sustainability, resiliency, and smart city were examined in the

literature review, and sections related to liveability were identified. The methods used in these index studies were mentioned. Furthermore, the created index study was used for weighting on 6 cities with similar, different cultures and structures. Literature such as standards used in the world and accepted organizational outputs are also explained under this title.

In recent years, urbanization has been spreading rapidly, with more people claiming cities as their living spaces than ever before. As the world becomes more and more urbanized, the concept of "liveable city" has become important for country and city managers, city planners, architects, and researchers alike. The creation of features that increase the quality of life for city residents has brought along large-scale studies created in this context. The Green Agreement of the European Union (EU) and the Inflation Reduction Act (IRA) of the USA can be shown as works aimed at increasing the quality of life as well as creating economic and environmental value.

The concept of liveability encompasses a multidimensional framework that targets the quality of life and well-being of city residents. It aims to take steps for social structure in addition to physical infrastructure, considering social, economic, environmental, and cultural dimensions. Besides obvious issues such as housing or sustainable transportation systems; it is a holistic goal that aims to promote equitable, inclusive, and sustainable urban environments.

Enhancing a liveable city index is the main subject of this article. The index to be compared while doing this study is EIU The Global Liveability Index. The reason for choosing this index is that it is a comprehensive and regularly published study and was created by

experienced staff. The methodology was used by experienced teams for qualitative content and from existing external data for quantitative content. It was carried out through benchmarking studies [15].

The Global Liveability index consists of 30 indicators in 5 categories. These indicators are used to measure the liveability of cities and city rankings are made thanks to the surveys made. These five categories were determined as Stability, Healthcare, Culture & Environment, Education, and Infrastructure. Evaluated cities are named as acceptable, tolerable, uncomfortable, undesirable, or intolerable. Qualitative indicators are arranged because of internal evaluation. Quantitative indicators are arranged in line with data from external data sources. According to the calculations, a rating between 1-100 is created. 1 is intolerable and 100 is ideal. The liveability rating is given as points for all categories and indicators. The liveability score is calculated through category weights distributed equally into subcategories. In Table 1, The Global Liveability City Index category and indicators are listed [16]. The indicators shown below are weighted equally in the currently used index. This shows that the importance ranking between the indicators is not achieved. The system was developed by weighting the indicators by taking expert opinions in the categories determined in the methodology section.

The new indicators included in the enriched index are designed to be placed under the relevant 5 categories and shown under the methodology heading. In this study, a weighting study was carried out for the categories that included the added indicators. Other categories were accepted as equally weighted, and no updates were made.

Table 1. EIU The Global Liveability City Index

Category 1: Stability (weight: 25% of total)
Prevalence of petty crime
Prevalence of violent crime
Threat of terror
Threat of military conflict
Threat of civil unrest/conflict
Category 2: Healthcare (weight: 20% of total)
Availability of private healthcare
Quality of private healthcare
Availability of public healthcare
Quality of public healthcare
Availability of over-the-counter drugs
General healthcare indicators

Table 2. EIU The Global Liveability City Index (cont.)

Category 3: Culture and Environment (weight: 25% of total)
Humidity/temperature rating
Discomfort of climate to travelers
Level of corruption
Social or religious restrictions
Level of censorship
Sporting availability
Cultural availability
Food and drink
Consumer goods and services
Category 4: Education (weight: 10% of total)
Availability of private education
Quality of private education
Public education indicators
Category 5: Infrastructure (weight: 20% of total)
Quality of road network
Quality of public transport
Quality of international links
Availability of good quality housing
Quality of energy provision
Quality of water provision

Arcadis is a company that provides consultancy support on issues such as project, management, and design with the aim of improving the quality of life. Arcadis Sustainable Cities Index is one of its studies that has been published periodically since 2015. This index, used in the context of sustainability, was created in a citizen-centric structure. It was designed by experts in the field of indicators and methodology, using previous experience and data [17]. The method used in the Arcadis Sustainability Index report is based on average weighting. Indicators in the subcategory are mostly calculated equally by taking weighted averages. The expert team determined the weights and weighed them [18].

Boyd Cohen Smart City Index was designed by Boyd Cohen, primarily on the creation of a smart city framework for medium-sized cities. Cohen, whose smart city ranking studies started in 2012, created a comprehensive study with the methodology he created in 2014. It ranked the data collected from the specified cities using indicators. He applied the z-score to transform it into standard and meaningful data [19]. Using this study, the way has been paved for the evaluation of different cities within the scope of smart cities [20].

The Resilience Index is a framework created in 2014 as a joint effort by Arup and the Rockefeller Foundation [21]. There are 12 indicators in this framework created for the evaluation of cities. City data obtained according to this framework is analyzed. In this context, quantitative data were converted into numerical numbers and the World Council for City Data reporting on the International Organization for

Standardization (ISO): 37120 standard was used for performance measurement. Based on available data, hypothetical profiles from 1 to 10 were created. A Standard distribution has formed between very poor performance and great performance. After then, a study was conducted with 12 external experts and 10 Arup industry experts to validate the approach established [22].

This study presents a comprehensive liveability index enriched with the liveability aspects of sustainability, resilience, and smart city dimensions. Therefore, information about these dimensions is given in the following subsections.

2.1. Sustainability and Sustainable City Indicators

Sustainability has become a topic of increasing popularity as concerns about the future begin to increase. Problems affecting the balance of the world such as climate change, air pollution, rapid population growth and the need to build a better future encourage societies to take different measures. Establishing sustainable living spaces is one of the priority targets in this context. The rapid increase in the human population and the fact that a large part of this population lives in cities increases the importance of sustainability even more. The urban population, which was 55% in 2018, is estimated to be 65% in 2050 [23]. The increase in population and density in urban areas also brings various social, economic, and environmental effects. Some of the effects observed in recent years can be given as examples such as income inequality, poverty, lack of education, and inability to access resources [24]. Organizations such as the United Nations take some measures to minimize these effects

and to build a sustainable world. The goals established for Sustainable Development are one of them. It is aimed to create a sustainable and resilient world with 169 goals created under 17 headings, thanks to objectives such as hunger, peace, education quality and gender equality [25].

It is necessary to define the concepts of sustainability and sustainable development to better understand these structures. Although sustainability is such a broad and comprehensive concept that it cannot be expressed with a single explanation, different institutions/organizations have explained it with similar definitions. According to the definition of the World Bank, sustainability has been defined as the basis of this generation and it is a requirement to potentially transfer the quality of life to all future generations [26]. On the other hand, a definition made by the International Union for Conservation of Nature (IUCN)/ United Nations Environment Programme (UNEP)/ World Wide Fund (WWF) is as follows: "Sustainability is improving the quality of human life while living within the carrying capacity of supporting eco-systems" [27]. One of the common points of the definitions is to focus on what needs to be done to create a livable place for future generations. The relationship between the concept of liveability and sustainability will be examined in detail in the following titles.

Although sustainability and sustainable development are stated as similar concepts in some sources, different definitions are also made. Since sustainable development is a comprehensive process, it can be defined as the work done to ensure sustainability. Another definition of sustainable development is: "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [28]. United Nations Educational, Scientific and Cultural Organization (UNESCO) has defined sustainability as a long-term goal for all people, cities, and countries [29].

Index studies can be used to determine different characteristics of cities. In addition to liveability, resiliency and smart city indexes, sustainable cities index are the indexes to be focused on in this article. The sustainability index consists of 3 subheadings. The pillars of people (social), planet (environmental) and profit (economic) form the basis of sustainability. There is a comprehensive list of indicators under each heading [30]. With the announcement of the United Nations' Sustainable Development Goals call for action, an infrastructure was created that supports the national plans of governments for sustainable development. The evaluation of cities by index studies of institutions is also in line with these purposes. For instance, an index study was conducted for Mexican cities, considering the UN SDGs [31]. Likewise, in a study called "China Urban Sustainability Index", cities

in the range of 200,000 – 2,000,000 people were evaluated within the scope of the index [32]. As a comprehensive city index study, Arcadis the Sustainable Cities Index measured 100 different cities with people (social), planet (environment) and profit (economic), which form the basis of sustainability. The important outcomes of this index study include the long-term contribution of profit pillars to sustainability, the need for performance improvement in mid-level cities in all areas, and the importance of digitalization in the services provided by cities [30]. In this study, Arcadis's framework will be used as a sustainable city index. While creating the index, indicators were determined under 3 main headings. These indicators are also weighted with the determined methodology.

In the Sustainable Cities Index, a three-stage averaging process was used. Some indicators are composite, meaning they average over their component sub-indicators. The three sub-indices are calculated by taking the weighted averages of the component indicators, and the total score is calculated using the simple average of the three sub-indices [17].

2.2. Resiliency and Resilient City Indicators

The concept of resilient city, like the other concepts mentioned earlier, is a subject defined by different organizations with their own work. Organizations such as the United Nations, The Organization for Economic Co-operation and Development (OECD) and The Rockefeller Foundation have made definitions and created infrastructure and index studies for cities to have a resilient structure. It is important to establish an integrated management and a durable structure between countries. Many countries have created their own resilient plans. Countries that create resilient plans on many subjects such as economies, societies, institutions, environment, natural disaster attach importance to different titles according to their internal structures [33].

Resilience was used as an ecology term in the 1970s but has recently emerged as a broad definition. City Resilience Index study definition is as follows: "City resilience describes the capacity of cities to function, so that the people living and working in cities – particularly the poor and vulnerable – survive and thrive no matter what stresses or shocks they encounter" [34].

According to the definition of the United Nations, resilience focuses on the ability of a system or structure exposed to hazards to quickly and effectively resist, absorb, adapt, and recover from the effects of that hazard, while preserving its essential properties and functions [35]. Because resilience is considered as a process, plans and effects are created for long periods of time. As stated in the definition, resilience against natural disasters is an important criterion for cities. For city-sized systems, the purpose of natural disaster

resilience is the survival of these Urban Systems for a long time of periods [36].

City Resilience Index of The Rockefeller Foundation - Arup was chosen as the Resilient City index to enhance the liveability index in this article. This index is a comprehensive study that contributes to the comparison and development of cities. Although the even distribution of indicator weightings may seem problematic in terms of focusing on high priority issues, it is a valuable and educational study for city managers [37]. Qualitative and quantitative perspectives were used in the study. Under the 4 main pillars, 12 goals, 52 indicators and 156 sub-indicators were created. With these indicators, quantitative data are collected. It is also evaluated under the 7 qualities of a resilient system where the quantitative structure is determined for each indicator question. The 7 pillars used to evaluate cities in terms of their qualities are given below.

- Reflectivity
- Resourcefulness
- Robustness
- Redundancy
- Flexibility
- Inclusivity
- Integration

In Resilience Index, quantitative data were converted into numerical numbers and the World Council for City Data reporting on ISO: 37120 standard was used for performance measurement. Based on available data, hypothetical profiles from 1 to 10 were created. A Standard distribution has formed between very poor performance and great performance. After then, a study was conducted with 12 external experts and 10 Arup industry experts to validate the approach established [22].

2.3. Smart City and Smart City Indicators

Cities have been evaluated in many different contexts in recent years. Popular concepts such as 'Connected City', 'Calm City', 'Green City', 'Sustainable City', 'Brand City', 'Innovative City' and 'Digital City' are defined for cities. With these concepts, cities aim to attract investments, increase tourism income, and prevent unemployment by providing employment. Although all these concepts create a movement in the cities, none of these concepts fully express the city and its inhabitants. This is where the concept of the smart city comes to the fore. It includes inter-object communication, sustainability, innovation and digitality in cities.

Before explaining what, a smart city is, it would be helpful to explain what a smart city is not. Smart parking systems, smart streetlights, the expansion of the Wi-Fi network in the city and smart agriculture applications are city projects, but they do not represent

the smart city when applied alone. It is a limited and incomplete approach to see the definition of smart city as the creation of livable cities by combining information technologies with city management studies. Since the concept of Smart City is a new and changing concept, it is possible to talk about many definitions. Cities, institutions, organizations, and companies that make the definitions bring different definitions to the Smart City according to their own perspectives. Smart City definitions of some institutions and organizations are given below.

European Commission (EC) defines the concept as a place where traditional structures are made more efficient by using digital solutions to meet the demands of citizens and the business world [38].

Republic of Turkey Ministry of Environment, Urbanization and Climate Change's definition is "Smart City is defined as an approach that ensures that interoperable systems developed with cooperation between stakeholders meet expectations and problems with future foresight based on data and expertise" [39]. Purposes of smart cities are listed in national Smart City Strategy as:

- Construct the expectations and needs of cities as a triggering mechanism in all structures of the city,
- Advance the structure with three legs: physical, social, and digital,
- Comprehensively anticipate, identify, and resolve emerging difficulties,
- Create conditions suitable for development by ensuring communication of the structures in the city.

The International Telecommunication Union (ITU) uses the term smart sustainable city in its definitions. The main idea of the concept is a city that uses information and communication technologies (ICT) and many different tools to increase the quality of life, urban management and efficiency and competitiveness, while also meeting the needs of current and future generations without harming economic, social, environmental, and cultural values [40].

OECD's approach to the smart cities is that emphasizing that digitalization-enabled approaches should be created to create collaborative, multi-stakeholder and inclusive urban structures that increase the well-being of citizens [41]. For The British Standards Institution (BSI) smart city is important that the systems that design a sustainable, prosperous, and inclusive future for their citizens should be effectively integrated into the environments [42].

Smart city indices are evaluated in different scopes and formed according to the dynamics of institutions and countries. Indicators and titles created by the change of

cities and city management styles may change. Looking at the definitions of smart cities, it is seen that the concept of ICT has a common denominator. Digitization and data are also evaluated in this context.

Organizations such as the UN, Smart City Council, EU, ISO, and companies such as Frost & Sullivan experienced consultancy company in the field of smart city have created various functional areas. Frost & Sullivan created a measurement model for the Smart City on eight parameters. Cities are measured with these parameters listed as smart governance, smart energy, smart building, smart mobility, smart infrastructure, smart technology, smart healthcare, and smart citizen [43].

The cities of 28 countries that are members of the EU are examined within the scope of six functional areas created for smart city indicators. According to the EU, these are Smart Governance, Smart People, Smart Living, Smart Mobility, Smart Economy, and Smart Environment. In the document named "Mapping Smart Cities in the EU" published by the European Union in 2014, the smart city foundations and the functional areas where smart city maturity can be founded [44].

Giffinger developed one of the most prominent parameters of smart cities and Boyd Cohen improved the idea and created Smart Cities Wheel [45]. In this article, Boyd Cohen's smart city study was used to establish the connection with liveability. 6 smart city characteristics are described which are smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. To rank the cities, Giffinger described 74 indicators under the 6 characteristics [46]. European cities generally ranked high in the outcomes of this study. The sum of the pillar values of each city gives the evaluation result of that city. There are cities with some low pillar values but a high total smart city ranking. For instance, Luxembourg ranked first among mid-sized cities with populations ranging from 100,000 to 500,000. While the smart economy is Luxembourg's strongest feature, creativity and flexibility are below average. Ruse is the last city on the list, although some of the pillars. The city ranks 53rd out of 70 cities in the smart economy rankings. However, it ranks last because it received lower scores compared to other cities in other pillars [46]. Looking at these examples, cities need to consider the indicators included in each pillar to improve their rankings in the smart city index.

A detailed study has been done at the smart city pillar level and the categories are well defined. Smart Governance is defined as the management of all services and interactions that enable the communication of public, private, civil society, and European Union institutions so that the city can work effectively. Smart Economy includes online business and e-commerce, high productivity rate, ICT-oriented

production and services, and the creation of new business models. It also builds smart clusters and eco-systems. Smart Mobility encompasses ICT-based and integrated logistics and transportation systems. The Smart Environment pillar focuses on efficient energy sources, smart energy networks, measurement, control and monitoring, inspections and renewal of facilities, green buildings, and efficient use of green city needs. Smart People covers topics such as ICT-based work, access to education and training, adapting to human resources and capacity management, with the aim of creating an inclusive society that fosters creativity and supports innovation. Smart Living focuses on lifestyles, behaviors and consumption habits created with ICT supported solutions [42].

In Smart City Index, a set of indicators has been assigned to measure the six components of Dr. Boyd Cohen's Smart Cities Wheel. Each component consists of 3 indicators, a total of 19 sub-indicators. There are 62 indicators under these indicators. It has been simplified by selecting 400 indicators from different sources and reducing it to 62. 16 of these indicators target the new sustainable cities ISO standard (ISO 37120). The index created was evaluated for 120 cities, but the data of 11 cities could be collected. Data from each of the 11 cities was optimized using a mathematical formula called the z-score. Each of the 6 components was weighted to assign a maximum of 15 points. It was ensured that the city, which is the leader in each component, can be ranked in such a way that it can get a maximum of 90 points [47].

In the index studies described in the literature review, indicators that were seen to be linked to liveability and were predicted to contribute to liveability were determined. These indicators are 6 in total, 2 from the smart city index, 2 from the city resiliency index and 2 from the sustainability index. The positioning of these indicators in the liveability index, their explanations, and the category they fall into are explained in the methodology section.

After this section, the methodology where the method to be used for the index is explained in detail.

III. METHODOLOGY

In this section, existing index studies are evaluated in many contexts and the methods and processes necessary to further develop The Global Liveability Index study are mentioned. Some revisions were made to enrich The Global Liveability Index model detailed in the literature review. Thus, this current index to be used for the measurement of cities has been made understandable and easy to apply.

As mentioned in Table 1, it has been decided under which heading the relevant indicators included in the index consisting of 5 categories should be positioned. However, it has been observed that some indicators do

not fit into existing categories. In this context, the title of the 3rd category, designated as "Culture and Environment", is considered under "3.1 Culture" and "3.2 Environment". Hence, the "Culture and Environment" category, which has a weight of 25% in the total index, is divided equally and the "Culture" category is designed as 12.5% and the "Environment" category is designed as 12.5%.

There are 6 indicators recommended in the Global Liveability Index to prevent deficiencies arising from existing risks and negativities. Work-Life Balance, Effective mechanism for communities to engage with government, Green Space per Capita, Ease of Doing Business, Density, Supportive Financing Mechanism indicators are in the categories specified in the Table 2 below. Correct implementation of the weight of these indicators and their compatibility with other indicators are necessary for the accuracy of the index.

The process of weighting indicators within the Liveability Index is a crucial step that requires careful consideration. Several methodologies can be employed to assign appropriate weights to the diverse indicators from each dimension. When enhancing a new index for a livable city, it's important to employ robust survey methods to gather reliable and comprehensive data. Assessment of liveability index requires professionals and experts in relevant fields such as urban planning, architecture, sustainability, transportation, and social welfare. While creating existing indexes, the weighting of the indicators is done by experts. In the index study, which was enriched in the same way, a similar weighting was made by using the opinions of the people. The information shared by these experts can contribute to the determination of weights for different indicators in the index. To identify relevant experts, specific areas related to the liveability index were agreed. These are chosen from among urban planners, architecture, sustainability experts, transportation experts, experts in the fields of social welfare, environmental studies, and public health. Experts were determined according to their qualifications, experience, and knowledge in the relevant fields. Various expert groups are targeted to provide a comprehensive perspective.

A questionnaire was prepared focusing on different areas that are related to the dimensions of liveability. This survey contains a list of indicators or factors that contribute to liveability. A weight was assigned to each indicator and experts were asked to rate the importance of each indicator on a determined scale.

A rigorous and versatile methodological approach were used to design the liveability index that reflects the intertwined dimensions of sustainability, resilience, and smart city indicators. In this approach, the Analytical Hierarchy Process (AHP) decision making method was used. AHP method is used for

measurement of cities from different perspective. "Measuring liveability of cities is an important task as it provides useful information to the people who would like to choose the best place to live" [48].

The indicators that contribute to the liveability index by progressing through common points and that are included in other indexes are given in Table 2 and explained afterward. The added indicators are positioned under the most appropriate categories.

Table 3. Indicators Selected from Sustainability, Smart City, and Resilience Indexes included in Liveability Index

Indicator- Category			
C1. Stability	C3.1. Culture	C3.2. Environment	Index
Work-Life Balance			<i>Sustainability Index</i>
Ease of Doing Business			<i>Sustainability Index</i>
Supportive Financing Mechanism			<i>Resilience Index</i>
	Effective mechanism for communities to engage with government		<i>Resilience Index</i>
		Green Space per Capita	<i>Smart City Index</i>
		Density	<i>Smart City Index</i>

3.1. Identification of included indicators

Below, the specified indicators are explained and why they are included in the index is explained.

3.1.1. Work-Life balance

The "Work-Life Balance" indicator in the Arcadis Sustainability Index is closely related to the concept of liveability and can significantly influence the overall assessment of a city's liveability. Work-life balance refers to the equilibrium between one's professional and personal life, ensuring that work commitments do not overly encroach on personal time, well-being, and leisure activities. In this context, the best Work-Life balance 2019 index was prepared, considering workload, corporate support, and liveability parameters. Global crises such as covid have reshaped the work-life balance. Occupational branches whose infrastructure and business scope are suitable for this

have tried to overcome this crisis with methods such as remote working. It has become important for employers and employees to have an infrastructure in this regard. On the other hand, remote working conditions that are not properly planned result in increased working hours. All these factors are important for work-life balance [17].

3.1.2. *Ease of doing business*

Quality of life is an important factor in attracting and retaining talent or professionals, especially given working conditions. The "Ease of Doing Business" indicator in the Arcadis Sustainability Index relates to the business-friendly and regulatory environment of a city or country. It evaluates factors such as ease of starting and operating a business, obtaining permits, access to credit, protecting investors and enforcing contracts. There are important indirect links between "Ease of Doing Business" and "Liveability". The high number of procedures can cause unnecessary expenses for a large part of people's work. Good management of these processes can improve the quality of life [17].

3.1.3. *Supportive financing mechanisms*

The "Supportive Financing Mechanisms" indicator in the Resilience City Index refers to the availability and effectiveness of financial tools and mechanisms that support sustainable development and improve the quality of life in a city. Therefore, while there is no direct information that states the relativity of the "Supportive Financing Mechanisms" indicator with liveability, quality of life, and liveable city index, there is evidence to suggest that supportive financing mechanisms can affect economic growth, which is a crucial factor in determining the liveability of a city [29].

3.1.4. *Effective mechanisms for communities to engage with government*

The "Effective Mechanisms for Communities to Engage with Government" indicator in the Resilience City Index is closely related to the concept of liveability and has a significant impact on the overall assessment of a city's quality of life. Well-being is a dimension of liveability that is constantly concerned with community participation and social interaction. In this context,

participation and, accordingly, governance has an important place in improving people's quality of life [29].

3.1.5. *Green space per capita*

Access to green spaces, such as parks, gardens, and natural areas, has been consistently linked to improved physical and mental well-being. Green spaces offer opportunities for exercise, relaxation, and stress reduction, which contribute to residents' overall health and quality of life. Urban green spaces offer people more livable environmental conditions thanks to their refreshing and ecological benefits [49]. Organizations like the World Health Organization (WHO) and urban planning associations consistently highlight the positive impact of green spaces on residents' well-being [50].

3.1.6. *Density*

The "Density" indicator in the Arcadis Sustainability Index refers to the population density of a city, which is the number of people living per unit of land area. While there isn't a straightforward or universally agreed-upon relationship between density and liveability, there are complex and multifaceted dynamics that influence how density can impact a city's quality of life. One of the biggest problems in an earthquake is that it is difficult to reach places with high density and to take aid. At the same time, major problems can occur if infrastructures such as electricity, water and natural gas are disrupted in places where there is a dense population [50].

The proposed index is shown in Table 3 below. This table includes indicators that are compatible with liveability in other index studies and are included in the newly created index. The sections highlighted in bold under the categories are the newly added indicators. No changes were made as no indicators were added to other categories. The final version of the updated index is given in Table 9. Moreover, the importance weights of the main categories which already exist in the current index are not changed. The revision is only made for the categories including the added indicators. All the indicators within the related categories as seen in Table 3 are considered and AHP is applied to determine the local importance weights of them.

Table 4. The proposed Liveability Indicators with their descriptions

Category 1: Stability (Weight: 25% of total)	Definition
Prevalence of petty crime	Simple amount of crime (theft, extortion, etc.)
Prevalence of violent crime	The amount of violent crime (murder, stabbing, etc.)
Threat of terror	Cities with terrorist threat experience security and peace problems that reduce the quality of life.
Threat of military conflict	Military conflict is a major security issue
Threat of civil unrest/conflict	Civil conflict/unrest is an issue that negatively affects the quality of life.
Work-life Balance	Balance between the amount of time spent at work and time spent in private life
Ease of doing business	The importance of the regulatory and financial environment that facilitates the smooth running of business
Supportive financing mechanisms	Finance structure that allows businesses to adapt to changing circumstances and leverage contingencies against shocks.
Category 3.1: Culture (Weight: 12.5% of total)	Definition
Level of corruption	Abuse of entrusted management authority for private gain
Social or religious restrictions	Presence of masses who are subject to religious and social discrimination in society
Level of censorship	Social and cultural censorship
Sporting availability	Availability of accessible sports infrastructure in the city
Cultural availability	Presence of historical and cultural infrastructure (museum, theater, cultural play, dance, etc.) in the city
Food and drink	Access to healthy food, presence of access to cultural food types
Consumer goods and services	Level of access to consumer products and services
Effective mechanisms for communities to engage with government	Collective structure for communication and coordination between authorized institution and citizens.
Category 3.2: Environment (Weight: 12.5% of total)	Definition
Humidity/temperature rating	Climatic conditions of the city (humidity, temperature) affect liveability positively or negatively.
Discomfort of climate to travellers	The city's life challenges for travelers (tourists, short-term visitors) are considered
Density	Density of people in cities (km²/100,000 people)
Green space per capita	The ratio of green areas in the city to the sum of active and passive green areas (protected zones, military areas, forests, etc.)

3.2. AHP Methodology

The Analytic Hierarchy Process (AHP) is a decision-making methodology that helps prioritize alternatives based on a set of criteria. It is a structured approach that helps prioritize and make decisions based on a set of criteria and alternatives. The AHP method is widely used in various fields, including engineering, management, and social sciences. The AHP method is based on the principle that complex decisions can be broken down into smaller and more manageable parts. The method involves dividing a decision problem into a hierarchy of criteria and sub-criteria, and then comparing the importance of each criterion and sub-criteria relative to each other. The AHP method uses pairwise comparisons to determine the relative importance of each criterion and sub-criterion. Pairwise comparisons are then used to calculate the weights of each criterion and sub-criteria used to make the final decision. The AHP method is a flexible and adaptable methodology that can be used to solve a wide variety of decision-making problems. To use the methodology, it

is necessary to establish the general purpose and determine the weights of importance in the criteria [50].

The formulation proceeds in the following order. A matrix as shown in Table 3 is formed from the survey results obtained. This matrix is called the A matrix and is used as a pairwise comparison matrix. The main right eigenvector of matrix A is determined as 'w' [51].

Positive and reversed matrix equation 1 and equation 2 is shown:

$$e^T = (1, 1, \dots, 1) \quad (1)$$

$$w = \lim_{k \rightarrow \infty} \frac{A^k \cdot e}{e^T \cdot A^k \cdot e} \quad (2)$$

The pairwise comparison matrix with n objectives is an $n \times n$ matrix $A = \{a_{ij}\}$. In case of an incompatible matrix, the calculation must be repeated several times to solve the problem. To convert w to meaningful absolute values and normalized weight with the result, following equation 3, equation 4, equation 5, and equation 6 is used:

$$w = \lambda_{max} w, \quad \lambda_{max} \geq n \quad (3)$$

$$\lambda_{max} = \frac{\sum a_j w_j - n}{w_1} \quad (4)$$

$$A = \{a_{ij}\} \quad a_{ij} = \frac{1}{a_{ji}} \quad (5)$$

- A: Pair wise comparison
- w : Normalized weight vector
- λ_{max} : Maximum Eigen value of matrix
- A_{ij} : Numerical comparison between the values i and j
- In the next step, another formula $CR = CI/RI$ is used to validate the AHP results.
- CR: Consistency ratio
- CI: Consistency index

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

The purpose of using this formula is to determine that the results are measured consistently. Inconsistency ratio should be less than 0.10 for a healthy result [53].

3.3. Data collection

In this study, AHP, one of the multi-criteria decision making methods, was applied to measure global needs and problems and their impact on liveability. Due to its nature, AHP is an appropriate method in urban-scale regional planning in terms of both qualitative and quantitative indicator measurement. It is an important method to measure the liveability of cities. In addition, it can give advice to city managers to increase liveability [48].

The weighting was created through a pairwise comparison survey. All indicators are weighted by pairwise comparison with other indicators within their categories. The survey was conducted with experts who are highly aware of liveability in different areas. The experts who completed the survey are as follows, sustainability expert, smart city consultant, sociology professor, corporate consultant, economics professor, architect, and landscape architect. This study aimed to make a consistent weighting by taking the opinions of experts with different perspectives.

The experiences of seven experts were used to determine the importance weights of the indicators. The properties of the experts are as follows:

- A professor whose area of expertise is sustainable finance,
- An engineer with smart city and sustainability consultancy experience,
- An associate professor working on urban sociology,
- An architect specialized in his field,
- An experienced landscape architect,
- An institute director working on livable environments,
- An experienced consultant on city strategy

AHP Scale: 1- Equal Importance, 3- Moderate importance, 5- Strong importance, 7- Very strong importance, 9- Extreme importance (2,4,6,8 values in-between). Category weighting has remained stable as determined by The Global Liveability Index. Category 3 weighting is designed as a sub-category with equal weights as environment and culture.

3.4. City Ranking

As a result of the weightings created, 6 cities selected from different regions of the world are ranked among themselves in this index study. The selected cities were obtained from various index data, research results and reports. Among the indicators under each category, those with data from all cities participated in the evaluation. Indicators with no or missing data are not included in the weighting. When choosing cities, their location, cultural, economic, and environmental differences were taken into consideration. The purpose of this is to measure the liveability of different continents and cultures and to demonstrate that the index can be used on a global scale. Cities participating in the Index weighting are London, Montreal, Bogota, Kuala Lumpur, Melbourne, and Istanbul.

To apply normalization, the methods shown in equation 7 were used and the values of the cities on the indicator and category scale were transformed into logical values. Equation 8, 9, 10, and 11 are the definitions of normalization used. Minimum-maximum normalization is a technique used to transform the range of numerical values of a data set for a given range [52]. This range will generally be between 0-1, but it can also be created between different ranges. In this study, values between 1 and 10 were set to make city comparisons understandable.

$$X_{new} = (x_i - \min(x)) / ((\max(x) - \min(x))) \quad (7)$$

$$X_{new} = \text{The revised value of the dataset} \quad (8)$$

$$X = \text{Old value} \quad (9)$$

$$\text{Max}(X) = \text{Maximum dataset number} \quad (10)$$

$$\text{Min}(X) = \text{Minimum dataset number} \quad (11)$$

These indicators are Work-Life Balance, Ease of doing Business, Supportive Financing Mechanisms, Effective Mechanisms for Communities to Engage with Government, Green Space per Capita, and Density. Weighting was carried out by experts by including these indicators that were added later. The overall weighting of the index was determined by seven experts who gave weight to each indicator.

In Global Liveability Index, indicators are weighted equally. To improve results, experts' weights were applied to categories which have current indicators. In category Stability, Culture and Environment, current weighting was used. The weighting of indicators outside these three categories was kept as in the existing index, and no updates were made. Overall, for every expert pairwise comparisons have been applied to all indicators. Each expert weighs every indicator of determined category and come up with a result. As an example, the first expert stability category pairwise comparison steps are shown in in Table 4. Instead of the weighting made by all experts for each category, all steps of the first expert's weighting for the Stability category are shown. However, other expert and category data are shared in Table 7.

IV. RESULTS AND DISCUSSION

The aim of this article is to improve the liveability index by adding six new indicators to the old version.

Table 5. Pairwise Comparison Matrix for Stability Category (Expert 1)

Indicators	Indc.1	Indc.2	Indc.3	Indc.4	Indc.5	Indc.6	Indc.7	Indc.8
Indc.1	1	0.17	0.13	0.11	0.14	0.33	0.25	1
Indc.2	6	1	0.25	0.20	0.33	3.00	2.00	3.00
Indc.3	8	4	1	0.50	2	5	4	6
Indc.4	9	5	2	1	3	7	6	7
Indc.5	7	3	0.50	0.33	1	4	3	3
Indc.6	3	0.33	0.20	0.14	0.25	1	0.50	2
Indc.7	4	0.50	0.25	0.17	0.33	2	1	2
Indc.8	1	0.33	0.17	0.14	0.33	0.50	0.50	1

In Table 5, the normalized matrix was obtained by adding all the rows and dividing them by themselves.

Table 6. Normalized Pairwise Matrix for Stability Category (Expert 1)

Indicators	Indc.1	Indc.2	Indc.3	Indc.4	Indc.5	Indc.6	Indc.7	Indc.8
Indc.1	0.08	0.08	0.07	0.08	0.07	0.13	0.14	0.13
Indc.2	0.17	0.16	0.22	0.12	0.13	0.16	0.19	0.19
Indc.3	0.25	0.16	0.22	0.25	0.26	0.19	0.19	0.19
Indc.4	0.25	0.32	0.22	0.25	0.26	0.16	0.19	0.25
Indc.5	0.17	0.16	0.11	0.12	0.13	0.13	0.14	0.13
Indc.6	0.02	0.03	0.04	0.05	0.03	0.03	0.02	0.02
Indc.7	0.03	0.04	0.05	0.06	0.04	0.10	0.05	0.03
Indc.8	0.04	0.05	0.07	0.06	0.07	0.10	0.09	0.06

The weights are calculated by averaging all the elements of each row in the normalized matrix. All the elements were summed up and divided to indicator number which is 8 in Table 6.

Table 7. Weight of Indicators for Stability Category (Expert 1)

Indicators	Indc.1	Indc.2	Indc.3	Indc.4	Indc.5	Indc.6	Indc.7	Indc.8
Expert 1	0.10	0.17	0.21	0.24	0.14	0.03	0.05	0.07

All the experts' weightings were completed using the weighting data collected in Table 7.

Table 8. Expert Weighting for Each Indicator

Expert - Category (S=Stability, C=Culture, E=Environment)							
	Expert1	Expert2	Expert3	Expert4	Expert5	Expert6	Expert7
S1	0.1	0.02	0.03	0.06	0.09	0.08	0.05
S2	0.17	0.1	0.1	0.09	0.14	0.13	0.09
S3	0.21	0.23	0.19	0.22	0.24	0.24	0.25
S4	0.24	0.34	0.25	0.22	0.24	0.19	0.25
S5	0.14	0.15	0.25	0.22	0.14	0.21	0.15
S6	0.03	0.05	0.04	0.05	0.06	0.05	0.05
S7	0.05	0.07	0.07	0.05	0.05	0.05	0.09
S8	0.07	0.03	0.07	0.09	0.05	0.05	0.06
C1	0.25	0.31	0.31	0.24	0.28	0.27	0.31
C2	0.24	0.17	0.21	0.16	0.16	0.21	0.17
C3	0.1	0.18	0.15	0.19	0.17	0.17	0.18
C4	0.08	0.07	0.06	0.06	0.08	0.09	0.07
C5	0.08	0.07	0.1	0.05	0.08	0.05	0.07
C6	0.04	0.05	0.09	0.05	0.08	0.05	0.05
C7	0.04	0.1	0.05	0.09	0.08	0.05	0.1
C8	0.17	0.04	0.03	0.13	0.08	0.1	0.04
E1	0.37	0.1	0.14	0.11	0.18	0.19	0.19
E2	0.09	0.16	0.14	0.11	0.14	0.1	0.12
E3	0.38	0.28	0.26	0.3	0.36	0.37	0.42
E4	0.15	0.47	0.45	0.48	0.32	0.35	0.27

With this method, the outputs of all experts were calculated, and the weighting of the stability category was obtained in Table 8.

Table 9. Stability Category Overall Weighting

Indicators	Indc.1	Indc.2	Indc.3	Indc.4	Indc.5	Indc.6	Indc.7	Indc.8
Total Weight	0.06	0.12	0.23	0.25	0.18	0.05	0.06	0.06

The revised importance weights of the indicators are provided in Table 9. The related weights are local weights of the indicators within the main categories. The global weight of each indicator can be found via

the multiplication of its local weight by the main category's importance weight. The percentages are rounded.

Table 10. Revised liveability indicator benchmark

Category 1: Stability	Definition
Prevalence of petty crime	6.1%
Prevalence of violent crime	11.7%
Threat of terror	22.6%
Threat of military conflict	24.7%
Threat of civil unrest/conflict	18.0%
Work-life Balance	4.7%
Ease of doing business	6.1%
Supportive financing mechanisms	6%

Table 11. Revised liveability indicator benchmark (cont.)

Category 3.1: Culture	Definition
Level of corruption	28.5%
Social or religious restrictions	19.0%
Level of censorship	16.3%
Sporting availability	7.4%
Cultural availability	7.2%
Food and drink	5.9%
Consumer goods and services	7.3%
Effective mechanisms for communities to engage with government	8.5%
Category 3.2: Environment	Definition
Humidity/temperature rating	18%
Discomfort of climate to travellers	12%
Density	34%
Green space per capita	36%

To use the AHP method properly, the inconsistency ratio must also be evaluated to be able to have valid result. As calculated above, pairwise comparison matrix shown in Table 4 is used. Each of the columns are multiplied with associated indicator weights calculated in Table 6. The result of the inconsistency

index values is shown in Table 10. Then, row values are summed up and divided to indicator weights. Average of these result gives the λ_{max} which is calculated as 8.3266 as shown in equation 4. As the next step, equation 6 was used for CI which is 0.0466.

Table 12. Stability Category Inconsistency Calculation (Expert 1)

Indicators	Indc.1	Indc.2	Indc.3	Indc.4	Indc.5	Indc.6	Indc.7	Indc.8
Indc.1	0.10	0.09	0.07	0.08	0.07	0.12	0.15	0.14
Indc.2	0.20	0.17	0.21	0.12	0.14	0.15	0.20	0.21
Indc.3	0.30	0.17	0.21	0.24	0.28	0.18	0.20	0.21
Indc.4	0.30	0.34	0.21	0.24	0.28	0.15	0.20	0.28
Indc.5	0.20	0.17	0.11	0.12	0.14	0.12	0.15	0.14
Indc.6	0.03	0.03	0.04	0.05	0.04	0.03	0.02	0.02
Indc.7	0.03	0.04	0.05	0.06	0.05	0.09	0.05	0.04
Indc.8	0.05	0.06	0.07	0.06	0.07	0.09	0.10	0.07

By using $CR = CI/RI$ equation, CR is calculated as 0.0330. In Table 11, experts' CR scores were

calculated. Since all values are below 10% for consistency, no revisions were required.

Table 13. CR Score of Experts

CR(%)	Stability	Culture	Environment
Expert 1	3.3	2	6.5
Expert 2	3.6	2.8	1.1
Expert 3	3	4.3	0.4
Expert 4	0.6	2	5.6
Expert 5	1	0.4	4.3
Expert 6	1	1.3	0.4
Expert 7	1	0.8	2.6

In the stability category, work-life balance, ease of doing business, and supportive financing mechanisms were found to be as important as the prevalence of petty crime. Their weighting within the category is 5%, 6% and 6%, respectively. This is very close to the weight of prevalence of petty crime, which is 6%. Based on this data, work and doing business coverage has a

similar impact as minor crimes. Here, it shows that employment opportunities and work-related opportunities other than private life have an impact on liveability. In the environment category, density, and green space per capita were identified as very important for people's quality of life. Considering the environment category, density and green space

indicators are much more prominent than other environmental factors. The density of cities greatly affects the quality of life. It has been observed that the measurement of liveability in residential areas with high population density and low amount of green space has also changed. In the culture category, effective mechanisms for communities to engage with government were found to be as important as cultural and social availability. In the culture category, the indicator Effective mechanisms for communities to engage with government is above the importance weights of indicators such as food and drink, emphasizing that the harmony of city governments with citizens affects the quality of life. The development of a comprehensive liveability index that considers these factors can help policymakers, urban planners, and researchers identify problems for improvement and make informed decisions about how to improve the quality of life in cities. The Global Liveable Cities Index and other similar indices provide a useful starting point for developing a comprehensive liveability index that considers a wide range of factors.

Data analysis in this area was limited since the data of 6 cities was not accessible for the following indicators.

- "Threat of military conflict" and "Supportive financing mechanisms" indicators under the 1. Stability category.
- "Quality of private healthcare" and "Availability of over-the-counter drugs" indicators under the 2. Healthcare category.
- "Humidity/temperature rating" and "Discomfort of climate to travelers" indicators under the 3.1. Environment category
- "Sporting availability", "Cultural availability", "Food and drink" and, "Effective mechanisms for communities to engage with government" indicators under the 3.1. Culture category
- "Quality of international links" and "Quality of energy provision" indicators under the 5. Infrastructure category.

Tables 12-17 which contain the data of each city are shown below. Especially in developing countries, accessibility of city-scale data is limited. Therefore, in indicators where city data is not available, country data is taken as the source.

Table 14. Stability Category City Indicator Data

Category 1: Stability (weight: 25% of total)							
Indicator #	London (Europe-UK)	Montreal (N. America Canada)	Bogota (S. America-Colombia)	Kuala Lumpur (Asia-Malesia)	Melbourne (Australia)	Istanbul (Europe-Turkey)	Weight
In_1	6.40	10.00	1.00	3.52	1.09	1.54	6.1%
In_2	9.91	9.55	1.00	10.00	10.00	9.37	11.7%
In_3	5.50	7.03	1.00	10.00	8.47	2.53	22.6%
In_4	N/A	N/A	N/A	N/A	N/A	N/A	24.7%
In_5	6.85	7.75	1.00	9.64	10.00	2.62	18.0%
In_6	9.10	8.92	6.13	1.00	10.00	3.97	4.7%
In_7	10.00	7.75	1.00	9.37	9.10	6.22	6.1%
In_8	1.00	1.00	1.00	1.00	1.00	1.00	6%

Table 15. Healthcare Category City Indicator Data

Category 2: Healthcare (weight: 20% of total)							
Indicator #	London (Europe-UK)	Montreal (N. America Canada)	Bogota (S. America-Colombia)	Kuala Lumpur (Asia-Malesia)	Melbourne (Australia)	Istanbul (Europe-Turkey)	Weight
In_1	1.31	10.00	1.00	4.07	8.17	1.23	1/6
In_2	N/A	N/A	N/A	N/A	N/A	N/A	1/6
In_3	10.00	10.00	1.00	10.00	10.00	8.74	1/6
In_4	8.04	9.22	1.47	1.00	10.08	4.76	1/6
In_5	N/A	N/A	N/A	N/A	N/A	N/A	1/6
In_6	9.95	9.42	4.79	1.00	10.00	3.34	1/6

Table 16. Environment Category City Indicator Data

Category 3.1: Culture and Environment (weight: 12.5% of total)							
Indicator #	London (Europe-UK)	Montreal (N. America Canada)	Bogota (S. America-Colombia)	Kuala Lumpur (Asia-Malesia)	Melbourne (Australia)	Istanbul (Europe-Turkey)	Weight
In_1	N/A	N/A	N/A	N/A	N/A	N/A	18%
In_2	N/A	N/A	N/A	N/A	N/A	N/A	12%
In_3	2.82	4.34	4.63	1.00	10.00	2.82	34%
In_4	5.53	7.79	1.00	2.85	10.00	5.53	36%

Table 17. Culture Category City Indicator Data

Category 3.2: Culture and Environment (weight: 12.5% of total)							
Indicator #	London (Europe-UK)	Montreal (N. America Canada)	Bogota (S. America-Colombia)	Kuala Lumpur (Asia-Malesia)	Melbourne (Australia)	Istanbul (Europe-Turkey)	Weight
In_1	9.54	9.77	1.69	3.54	10.00	1.00	28.5%
In_2	6.00	10.00	9.00	1.00	9.00	2.00	19.0%
In_3	10.00	10.00	10.00	2.50	8.50	1.00	16.3%
In_4	N/A	N/A	N/A	N/A	N/A	N/A	7.4%
In_5	N/A	N/A	N/A	N/A	N/A	N/A	7.2%
In_6	N/A	N/A	N/A	N/A	N/A	N/A	5.9%
In_7	10.00	10.00	1.00	1.00	10.00	5.50	7.3%
In_8	N/A	N/A	N/A	N/A	N/A	N/A	8.5%

Table 18. Education Category City Indicator Data

Category 4: Education (weight: 10% of total)							
Indicator #	London (Europe-UK)	Montreal (N. America Canada)	Bogota (S. America-Colombia)	Kuala Lumpur (Asia-Malesia)	Melbourne (Australia)	Istanbul (Europe-Turkey)	Weight
In_1	10.00	1.23	2.85	1.00	6.54	10.00	1/3
In_2	6.19	1.35	1.69	10.09	1.00	6.19	1/3
In_3	9.64	8.92	1.00	2.44	10.00	9.64	1/3

Table 19. Infrastructure Category City Indicator Data

Category 5: Infrastructure (weight: 20% of total)							
Indicator #	London (Europe-UK)	Montreal (N. America Canada)	Bogota (S. America-Colombia)	Kuala Lumpur (Asia-Malesia)	Melbourne (Australia)	Istanbul (Europe-Turkey)	Weight
In_1	8.11	8.58	1.00	10.00	8.11	8.11	1/7
In_2	10.00	5.82	1.00	8.31	7.26	10.00	1/7
In_3	N/A	N/A	N/A	N/A	N/A	N/A	1/7
In_4	9.18	8.36	1.00	9.18	10.00	9.18	1/7
In_5	N/A	N/A	N/A	N/A	N/A	N/A	1/7
In_6	10.00	7.37	1.88	1.00	7.15	10.00	1/7
In_7	10.00	5.33	1.00	6.00	9.00	10.00	1/7

To apply normalization, the methods shown in equation 7 were used and the values of the cities on the indicator and category scale were transformed into logical values. Equation 8, 9, 10, and 11 are the definitions of normalization used. Minimum-maximum normalization is a technique used to transform the range of numerical values of a data set for a given range [54]. This range will generally be between 0-1, but it can also be created between different ranges. In this study, values between 1 and 10 were set to make city comparisons understandable.

$$X_{new} = \frac{(x_i - \min(x))}{(\max(x) - \min(x))} \quad (7)$$

$$X_{new} = \text{The revised value of the dataset} \quad (8)$$

$$X = \text{Old Value} \quad (9)$$

$$\text{Max}(X) = \text{Maximum dataset number} \quad (10)$$

$$\text{Min}(X) = \text{Minimum dataset number} \quad (11)$$

When comparing cities, normalization was arranged to rank them between values 1-10. In Figure 2, among the cities compared, Melbourne had the highest liveability index with a score of 8.93. It is followed by Montreal with 7.96, London with 7.87, Kuala Lumpur with 5.45, Istanbul with 4.19, and Bogota with 2.25. These rankings give a general idea about the liveability of these cities with the revised index.

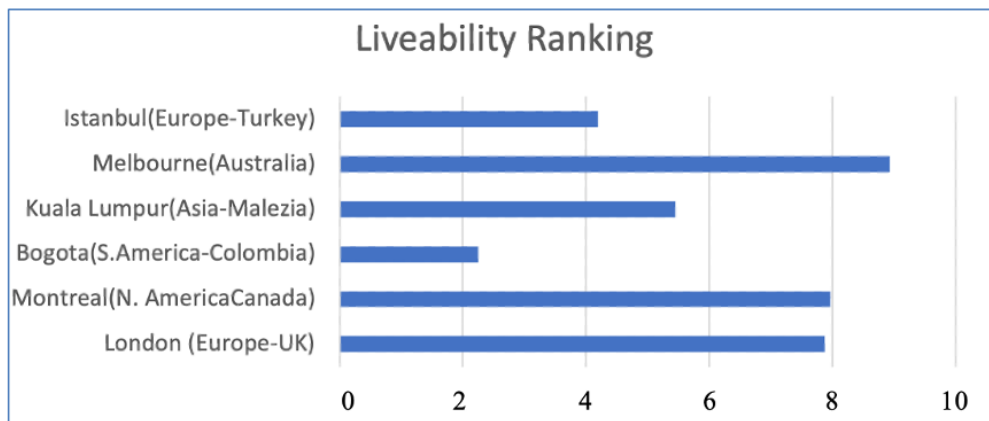


Figure 2. Revised Index Liveability Ranking of Cities

When the results of the existing index and the revised index are compared, a difference emerges. Cities are compared using the indicators and weight percentages of the existing index in Table 18 below.

Table 20. Current Index City Overall Ranking

Category Distribution							
Category	London	Montreal	Bogota	Kuala Lumpur	Melbourne	Istanbul	Weight
Stability	7.17	7.17	7.17	7.17	7.17	7.17	25%
Healthcare	7.33	9.66	2.06	4.02	9.56	4.52	20%
Culture and Environment	8.88	9.94	5.42	2.01	9.38	2.38	25%
Education	8.61	3.83	1.85	4.51	5.85	3.07	10%
Infrastructure	9.46	7.09	1.18	6.90	8.30	5.49	20%

In Figure 3, among the cities compared, Melbourne has a score of 7.12 which is same with London. Montreal, Kuala Lumpur, Istanbul, and Bogota received 6.77, 4.68, 4.40, and 3.30 points respectively. These rankings give a general idea about the liveability of these cities of current Index.

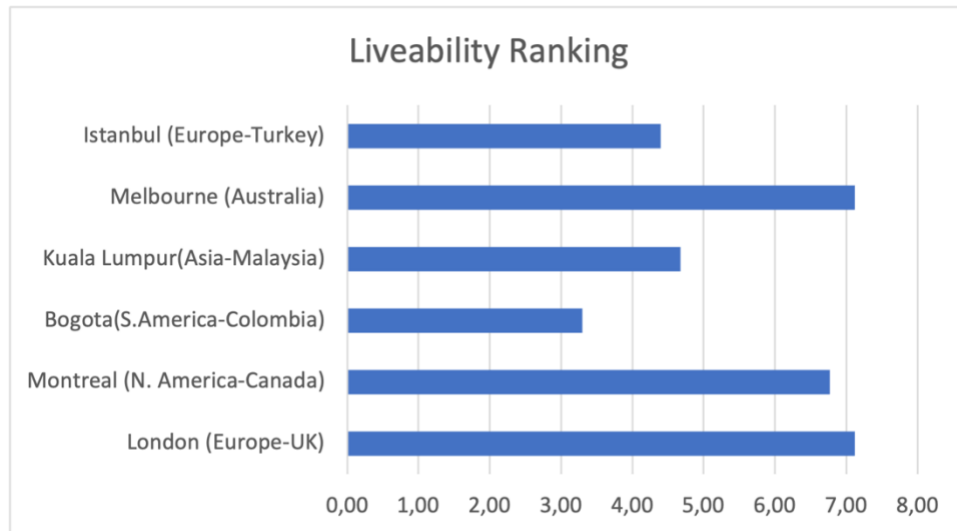


Figure 3. Current Index Liveability Ranking of Cities

V. CONCLUSION

The assessment of city liveability examined by sustainability, resiliency, and smart city dimensions is a complex and multidimensional task. This article aimed to enhance the Global Liveability Index that lacks factors such as work-life balance, ease of doing business, supportive financing mechanisms, density, green space per capita, and effective mechanisms for communities to engage with government. The results of this study show that these factors are crucial for the liveability of cities. It was observed because of the survey that the other indicators added to the current index are at least as important as the existing indicators.

The selected 6 cities were ranked with the updated liveability index model. The difference between this index and the old version is being more comprehensive. Especially in terms of environmental impact, density and green area ratio contribute to the ranking of environment category. Working integrated with the government has been shown to affect cultural liveability. Work life balance, ease of doing business and access to finance are also designed under the heading of Stability. When cities are evaluated on a category scale, Melbourne ranks first in the stability ranking with 9.49, while Bogota ranks last with an index score of 1.61. Crime, terrorism, and civil unrest indicators were seen as the main reasons for Bogota's low rankings. While Montreal had the highest score in the Healthcare category with 9.66, Bogota again ranked last. While it achieved the highest score in the Environment category, Kuala Lumpur ranked last with the lowest score of 1.94. Newly added indicators in this category, density, and green space per capita, affected the ranking. When evaluated in the culture category, Istanbul ranks last with a ranking of 1.87, while Melbourne ranks first. In the culture category, censorship, corruption, and restrictions were included in the evaluation. Food availability, sports and cultural activity data were not included in the evaluation

because they were not accessible. In the education category, London ranked first with a score of 8.61, while Bogota ranked last with a score of 1.85. Finally, in the infrastructure category, London was the city with the best infrastructure service with 9.46, while Bogota ranked last with 1.18.

When looking at the difference between the existing index and the revised index, a few points attract attention. In Figure 3, the current index result is shown. Although both indexes are evaluated out of 10 points, the scores vary greatly. For example, the difference between Istanbul and Melbourne was higher in the revised index calculation. In addition, when the revised index was used, Montreal was calculated to be a more liveable city than London, but the opposite was calculated in the existing index. In the existing index, London and Melbourne received the same score. Considering this difference, updating the index study affects both the rankings and the city performance scores.

In conclusion, the enhanced liveability index proposed in this article can provide a more reliable measure of the quality of life in cities, considering a wide range of factors that can affect residents' daily lives. The recommendations provided in this article can guide policymakers, urban planners, and researchers in developing strategies to improve the liveability of cities and promote sustainable development. Thanks to this index, the liveability of world cities can be ranked by using data from other cities. However, with this data, the index can be strengthened by using techniques other than the AHP such as ANP, DEMATEL methods and can be improved with fuzzy logic approach. The way for more comprehensive studies will be paved with the development of cities' data accessibility and open data portals. Finally, comparative studies can be applied with the existing approaches and the validation of the proposed index can be provided based on the field surveys.

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Çalışanın İş Sağlığı ve Güvenliği için Uygunluk Tespiti: Görüntü ve Ses İşleme ile Yorgunluk Tespiti ve Kişiye Özel Raporlama

Compliance Detection for Occupational Health and Safety of Employees: Fatigue Detection and Personalized Reporting with Image and Sound Processing

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Öz

Günümüzde teknolojinin ilerlemesi, iş sağlığı ve güvenliği alanında çalışanların güvenliğini artırmaya yönelik yeni sistemlerin ortaya çıkmasına olanak tanımıştır. Ancak, tüm bu güvenlik önlemleri alındığında bile, işçinin yorgunluğunun güvenlikte kritik bir rol oynadığı unutulmamalıdır. Yorgun bir işçi, ne kadar güvenlik protokolü olursa olsun, bu protokolleri uygulamakta zorlanabilir. Bu nedenle, özellikle dikkat ve özen gerektiren endüstriyel görevlerde, çalışanların yorgun olup olmadığını belirlemenin hayati öneme sahip olduğu kabul edilmektedir. Çalışmada, işçilerin uzun ve kısa vadede işlerini sağlıklı bir şekilde sürdürebilmeleri adına yorgunluk tespitine odaklanıldı. Bu bağlamda, gerçek zamanlı video görüntülerini kullanarak, görüntü işleme teknikleriyle yüz tespiti gerçekleştirildi ve yüzdeki belirli referans noktaları haritalandı. Göz ve ağız açıklığı ile başın eğiklik seviyesi, yorgunluk belirtileri olarak belirlendi ve bu parametreler eşik değerlere göre değerlendirildi. Ayrıca, işçinin dikkatini ve bilgisini ölçmek amacıyla yorgunluk tespit sırasında iş sağlığı ve güvenliğiyle ilgili sesli ve görsel sorular da soruldu. Böylelikle işçinin belirli iş aktiviteleri ve ekipmanlar için ne kadar hazır olduğu belirlenmeye çalışıldı. Ek olarak, önerilen sistemde kullanılan yüz tanıma ile bireysel yorgunluk raporları hazırlandı. Deneysel çalışmalar sonucunda, önerilen sistemin öznel veri setindeki performansı doğruluk %80, kesinlik %85, duyarlılık %73 ve F1 skoru %75 olarak hesaplanmıştır. YawDD veri seti üzerinde ise doğruluk %95.99, kesinliği %96.83, duyarlılığı %95.58 ve F1 skoru %95.59 olarak belirlenmiştir.

Anahtar Kelimeler: Görüntü işleme, İş sağlığı ve güvenliği, Konuşma işleme, Yorgunluk tespiti, Yüz tanıma

Abstract

Advancements in technology today have enabled the emergence of new systems aimed at increasing worker safety in the field of occupational health and safety. However, even with all these safety measures in place, it must not be forgotten that a worker's fatigue plays a critical role in safety. A tired worker may struggle to comply with safety protocols, regardless of how many are in place. Therefore, especially in industrial tasks that require attention and diligence, determining whether workers are fatigued is considered of vital importance. The study focused on detecting fatigue to ensure workers can sustain their work healthily in the long and short term. In this context, real-time video footage was utilized, and facial detection was performed using image processing techniques, mapping specific reference points on the face. Eye and mouth openness, along with the level of head tilt, were identified as signs of fatigue, and these parameters were evaluated against threshold values. Additionally, during fatigue detection, audio and visual questions related to occupational health and safety were asked to measure the worker's attention and knowledge. Thus, it was attempted to determine how prepared the worker was for certain work activities and equipment. Furthermore, individual fatigue reports were prepared using facial recognition in the proposed system. As a result of experimental studies, the performance of the proposed system on the subjective data set was calculated as accuracy 80%, precision 85%, recall 73% and F1 score 75%. On the YawDD dataset, accuracy was determined as 95.99%, precision as 96.83%, recall as 95.58% and F1 score as 95.59%.

Keywords: Image processing, Occupational health and safety, Speech processing, Fatigue Detection, Face Recognition

I. GİRİŞ

Günümüzde teknolojinin gelişmesiyle iş sağlığı ve güvenliği (İSG) alanında işçilerin çalışma alanlarındaki güvenliğini artırma amaçlı sistemler geliştirilmektedir. Endüstri alanında kullanılan sistemlerde büyük değişimler meydana gelmiştir. Bu değişimler sayesinde yeni, güçlü ve karmaşık sistemler geliştirilmiştir. Ancak bu sistemlerin kurulumu, kullanımı ve bakımı da bir o kadar zor ve tehlikeli bir hale gelmiştir. İşveren, işçiyi

tehlikelerden korumak için İSG kapsamında birçok önlem almaktadır. Bu önlemlerin birçoğu endüstriyel sistemlerin bulunduğu fiziki ortamlar içindir. Ek olarak kullanılacakları sistem ile ilgili kurulum, kullanım ve bakımı için eğitim verilmektedir. Ancak alınan bu önlemler işçinin yorgunluğunu tespit etmek için yeterli değildir. İşçinin endüstriyel bir sistemi kullanırken çok dikkatli olması gerekmektedir. Ufak bir hata işçinin yaralanmasına hatta ölmesine bile sebep olabilmektedir [1]-[2].

Bu güvenlik tedbirlerinin yanı sıra işçinin yorgunluğunun da güvenlik tedbirleri kadar önemli olduğu göz ardı edilmemelidir. İşçi için her ne kadar güvenlik önlemi alınsa da yorgunluk sebebiyle güvenlik protokollerini uygulanması oldukça zorlaşmaktadır. Şekil 1’de görülen, işçilerin mesai ve mola saatleri göz önüne alındığında yorgunlukla paralel yaşanan ölüm artışları özellikle ağır ve dikkat gerektiren endüstriyel aktivitelerde çalışan işçilerin, hayati risk içeren bu aktivitelere başlamadan önce yorgunluk tespitinin yapılmasının bir gereklilik haline geldiğini göstermiştir [3].



Şekil 1. Çalışanların kaza geçirdikleri saat dağılımı [3].

Geçmişten günümüze kadar İSG alanında görüntü işleme yöntemleri kullanılarak yorgunluk tespiti için birçok çalışma yapılmıştır. Shahzeb Ansari ve arkadaşlarının yaptığı çalışmada, berrak zihin veya zihinsel yorgunluktan etkilenirken sürücü durumlarının farklı sürüş modellerini tanımlama sürecine ve doğrudan ölçüm yaklaşımlarının geliştirilmesine katkıda bulunmuşlardır. Yapmış oldukları deneyleri, Unreal Engine 4 stüdyosu ile geliştirilmiş bir döngü içi sürücü simülöründe on beş sağlıklı denek üzerinde gerçekleştirmişlerdir. Deneyler de XSENS hareket yakalama sistemi kullanılıp, sürücünün baş duruşu hareketleri izlenerek sürücü zihinsel yorgunluğu ve uyusukluk seviyesi ölçülmüştür. Gözlemlenen düşük yük ve pasif mental yorgunluğun en önemli örüntüleri ise esneme, başın aşağı düşmesi ve kafa sallamak olarak bildirmişlerdir. Çalışmalarının sonucunda önerdikleri yöntemin, Karar Ağaçları (Decision Trees, DT), K-En Yakın Komşu algoritması (K-Nearest Neighbors, KNN), Destek Vektör Makinesi (Support Vector Machine, SVM), Topluluk Öğrenmesi (Ensemble Classifiers, EC) metodlarından daha iyi sonuçlar verdiğini belirtmişlerdir [4].

Zhe Cui ve arkadaşları, çalışmalarında gömülü sistemlerdeki bellek yetersizliği ve sınırlı bilgi işleme

gücüne sahip olması problemlerini ele alarak gerçek zamanlı yorgunluk tespiti işlemi yapmak için hafif bir sinir ağı modeli tasarlamışlardır. Bu sinir ağında sürücünün gözlerinin ve ağzının açılma ve kapanma durumlarını hızlı bir şekilde tanımlama yapabildiklerini belirtmişlerdir. Sürücünün yorgunluk durumunu kararlaştırmak için çok özellikli füzyon karar algoritmasını kullanmışlardır. Çalışmanın sonucunda önerilen modelin gerçek bir araç ortamında uyusukluk ve esneme davranışları için yüksek doğruluk oranında başarılı olduğunu belirtmişlerdir [5].

Faisal Dharma Adhinata ve arkadaşları, COVID-19 salgınında ekran başında geçirilen sürelerin uzaması ile verimliliğin azalması arasında bir bağ olduğunu ve kişilerin yorgunluk tespitinin önemli olduğunu belirtmişlerdir. Önerdikleri yorgunluk tespiti sistemin de yüz tespiti için gerekli olan yüz özelliklerini barındıran “UTA-RLDD” veri kümesini kullanmışlardır. Ek olarak Haar Cascades metoduyla veri kümesini bölümlere ayırmışlardır. Yüzdeki özellik çıkarımı için önceden eğitilmiş FaceNet algoritmasını kullanmışlardır. Elde edilen özellikler KNN ve çok sınıflı SVM metodları kullanılarak odaklanmış, odaklanmamış, yorgun olacak şekilde üç sınıfa ayrılmışlardır. Çalışmalarının sonucunda önerdikleri sistemin yüz algılama zayıflığının olduğunu ancak FaceNet ve KNN algoritmasının hibrit kullanımında yüksek doğruluk oranında başarılı olduğunu belirtmişlerdir [6].

Xing Li ve arkadaşlarının yaptığı çalışmada, var olan ağır işlem yükü içeren yorgunluk tespiti çalışmalarına alternatif olarak işlem yükü az olacak şekilde çalışan bir yöntem önermişlerdir. İnsan yorgunluğunun tespiti olarak esneme ve göz kırpmaya hareketleri temel alınmış ve yüz üzerinde ögeler (göz, burun, ağız vb.) Dlib kütüphanesi kullanılarak insan yüzü üzerindeki referans noktalarını kullandıklarını belirtmişlerdir. Göz ve ağız en boy oranını bu referans noktaları ile hesaplamış, belirledikleri bir eşik değerinin altında olup olmadığına bakarak göz ya da ağzın açık kapalılığını tespit ettiklerini belirtmişlerdir. Çalışmalarının sonucunda önerdikleri yöntemin yüksek tespit doğruluğu ve iyi bir gerçek zaman performansı olduğunu belirtmişlerdir [7].

Gulbadan Sikander ve Shahzad Anwar’ın yaptığı çalışmada, yorgunluğa bağlı olarak gerçekleşen trafik kazalarının, sürücülerin uyanık olduğu kazalara göre daha çok ölüm oranına sahip olduğu ve çevreye daha fazla zarar verdiği belirtilerek, sürücü yorgunluğu algılama alanındaki artan son gelişmelerin durumunun incelenmesi ve karşılaştırması sağlamışlardır. Sürücü yorgunluğunun algılanmasını, girdi özelliklerine göre beş kategoriye ayırmışlardır. Bunlar; öznel raporlama, biyolojik özellikler, fiziksel özellikler, sürüş sırasındaki araç özellikleri ve hibrit özelliklerdir. Gerçek zamanlı işleme için öznel raporlama ve biyolojik özelliklerin uygunluğunun sınırlı olduğunu,

bu sebeple sürücü yorgunluğu izlemede kullanımının kısıtlı olduğunu belirtmişlerdir. Bunun yanında güvenilir sistemler üretmek adına, daha iyi bir doğruluk sağlayacağı için fiziksel özellikler, günün saati, sürüş süresi, sürücü özellikleri gibi öğelerin kaynaştırılmasını önermişlerdir [8].

Qiang Ji ve arkadaşları, çalışmalarında yorgunluğun sebep olduğu kazaların ve can kayıplarının önemine değinerek, çeşitli duyuşal verilerden ve belirli ilgili bağlamsal bilgilerden gelen bilgileri entegre ederek insan yorgunluğunu modellemek ve gerçek zamanlı çıkarım yapmak için Bayes ağlarına dayanan olasılıksal bir çerçeve tanımlamıştır. Yorgunluğun zamanla gelişen bilişsel bir durum olduğundan hareketle, ilgili statik modelin, yorgunluğun dinamik yönünü yakalayamayacağını ifade etmişlerdir. Bu duruma çözüm olarak, insan yorgunluğunun zamansal yönünü de hesaba katmak amacıyla statik yorgunluk modeli, dinamik Bayes ağlarına dayalı olarak genişletmişlerdir. Böylelikle daha sağlam ve doğru bir yorgunluk modellemesine ve çıkarımına sahip olunmuştur. Çalışmalarının odağının, yüksek doğruluk veren bir yorgunluk modellemesi olmasından ziyade yorgunluğu ilkeli bir şekilde modelleyebilen teorik bir çerçeve olsa da, yorgunluk modeli yapısını iyileştirmek ve model parametreleştirmesini iyileştirmek için daha fazla araştırma çalışmasına ihtiyaç olduğunu ifade etmişlerdir [9].

Yuan Fang ve arkadaşları, geçirilen pandemi döneminde insanların çok uzun süre çalışmaya itildiğini ve bununla beraber iç aydınlatma ortamının insan sağlığı için önemli olduğunu belirterek, fiziksel iç ortam çevresel faktörlerinin, ilişkili renk sıcaklığının ve aydınlatmanın bilgisayarda yapılan iş yorgunluğu üzerindeki etkisini araştırmışlardır. İki farklı aydınlatma ayarı ve ilişkili renk sıcaklığı kullanılarak yapılan 10 dakikalık bir deneyde, yorgunluğu objektif olarak ölçmek için test sırasında elektroansefalogram, elektrokardiyograf ve göz hareketi gibi fizyolojik sinyaller izlenmiştir. Sekiz katılımcının öznel yorgunluğu, testi tamamladıktan sonra yapılan bir anket ile değerlendirilmiştir. Yapılan testteki hata oranı, çalışma performansı için temel faktör olarak alınmıştır. Subjektif ve objektif sonuçların analizi yoluyla, bilgisayar başında yapılan işin yorgunluğunun, aydınlatma ortamındaki değişikliklerden önemli ölçüde etkilendiği, aydınlatma ve ilişkili renk sıcaklığı ile yorgunluğun negatif olarak ilişkili olduğu ortaya konmuştur [10].

Sally Vegso ve arkadaşları, imalat işçileri arasındaki yaralanma riskinin, önceki hafta çalışılan saatlerle ilişkili olup olmadığını belirlemek için yaralanma olayını içeren vardiyadan önce çalışılan saatleri, yaralanma olmayan vardiyadan önce çalışılanlarla karşılaştırma yapmışlardır. Sezon ve iş tecrübesi gibi zamana bağlı değişkenleri minimize etmek için dört haftalık bir aralık seçilmiştir. Aynı zamanda yaralanan

çalışanların analize dâhil edilebilmesi için, yaralanma ve karşılaştırma haftasında aynı işte olması ve yaralanmadan 4 hafta önce tam olarak aynı gün çalışmış olması, kontrol haftasından itibaren 2 ay içerisinde iş değiştirmemiş olması gibi birtakım kurallar belirlenmiştir. Bu kurullarla birlikte, yapılan çalışmada yalnızca önceki hafta çalışılan saatlerin etkisi kişinin yorgunluğu üzerindeki etkisi gözlemlenmeye çalışılmıştır. Çalışanın yaralanma öncesi çalışma saatleri, kontrol haftasındaki saatleri önemli ölçüde aştığı görülmüştür. Vardiyadan önceki hafta altmış dört saatten fazla çalışan işçiler, kırk saat veya daha az çalışanlara kıyasla %88 daha fazla risk taşıyor olduğu tespit edilmiştir. Böylelikle, yaralanma riskinin bir önceki hafta çalışılan süre ile ilişkili olduğuna dair kanıt sağlanarak, fazla mesainin kontrolü işçi yaralanması riskini azaltabileceğini ifade etmişlerdir [11].

Bu tez çalışmasında, işçinin İSG kapsamında karşılaşılabilecekleri tehlikeleri en aza indirebilmek için endüstriyel alanda bir aktivite yapmadan önce yorgun olup olmadığını tespit edebilecek ve sonuca göre işçi ile ilgili öznel rapor oluşturabilecek bir sistem geliştirilmiştir. Sistem geliştirilirken kullanılan göz kapalılık, ağız açıklık ve baş sağ-sol eğiklik sayısının hesaplanabilmesi için gerekli olan yüz dönüm noktalarının elde edilebilmesini sağlayan Dlib kütüphanesinden yararlanılmıştır. Bunun yanında işçiye, çalışacağı alandaki yeterliliği ölçmek için sesli ve görsel İSG soruları yöneltilmiştir. Çalışanın yorgun olup olmadığını belirlemek için, ilgili kurumda bulunan İSG görevlisi tarafından maksimum göz kapalılık, ağız açıklık, baş sağ-sol eğiklik sayıları ve İSG sorularına verilmesi gereken minimum doğru cevap sayısı değerleri belirlenmelidir. Bu eşik değerlerine göre uygun sonuçlara sahip işçinin yorgun değil ise çalışma alanına girişine izin verilecektir. Raporlama sürecine tabi olan her işçi, face-recognition kütüphanesinin yüz tanıma sistemi ile tanınarak, daha önce sistem tarafından saptandığı belirtilen tüm özellikler bazında raporlanacaktır.

II. MATERYAL VE METOD

İSG kapsamında geliştirilen yorgunluk tespit sisteminin görselleştirilmesi Şekil 2'de gösterilmektedir. Bu sistemde, işçinin yapacağı aktivitenin hemen öncesinde, kendisinin yüzünü tam karşıdan net şekilde gören ve yeterli aydınlatmaya sahip olan bir alandaki kameraya bakmasıyla yorgunluk tespit işlemi başlamaktadır. İşçinin çalışma alanına girebilmesi için yorgunluk durumunun uygunluğunu belirleyecek olan bu düzende, göz açıklığı, esneme ve kafanın sağa sola eğim alması gibi uyku belirtisi içeren durumlarla beraber işçinin çalıştığı alana uygun olarak iş sağlığı ve güvenliği çerçevesindeki bilgisi görsel de içerebilen sesli sorular yardımıyla ölçülmektedir. Sorulacak olan sorular, ilgili kurumda bulunan İSG görevlisi tarafından belirlenmelidir. Önerilen süre olan bir dakikalık

süreçte, yorgunluk belirtisi eşik değerlerinin aşılması veya işçinin iş sağlığı ve güvenliği sorularına verdiği sesli yanıtların iş sağlığı ve güvenliği uzmanı tarafından belirtilen oranın üzerinde yanlış olması durumunda, işçinin yorgun olduğunu belirterek yapması gereken aktiviteye izin vermemektedir. Bunun yanı sıra işçiye özel raporlama yapılabilmesi için, sisteme önceden işçiye ait dijital fotoğraf yüklenerek yüz tanıma yapılmaktadır. Yüz tanıma işlemi "face-recognition" kütüphanesi kullanılarak gerçekleştirilmiştir. Kütüphanenin yüz tanıma konusundaki doğruluk değerinin, "Labeled Faces in the Wild" veri kümesi üzerinde %99.38 olduğu belirtilmiştir [12]. Bu yüz tanıma işlemi sayesinde de, yorgunluk tespiti için her seferinde işçi bilgilerinin sisteme girilmesine gerek kalmadan otomatik olarak raporlamaya başlayabilmektir.

İşçiye ait öznel raporlama içerisinde yedi adet özellik bulunmaktadır. Bunlar; işçi tanımlama bilgisi, uyuklama ve esneme sayısı ve baş eğikliği eşik değerini geçme sayısı, İSG testi cevabı, rapor başlangıç ve bitiş zamanıdır. Uyuklama sayısı bilgisi, göz kırpmaları haricinde gözlerin uyuklama bağlamında kaç kere kapandığı bilgisidir. Esneme sayısı, raporlama süreci boyunca kaç kere esnediğini ifade etmektedir. Baş eğikliği için verilen eşik değerini geçme sayısı ise raporlama süreci boyunca kaç kez başını sağa veya sola belirtilen eşik değerinden fazla eğdiğini belirtir. İşçi tanımlama bilgisi ve rapor başlangıç zamanı, yüz tanıma sonrası sorulan teyit sorusuna olumlu girdi vermesi ile raporun başladığı andaki zamandır. Rapor bitiş zamanı ise yorgunluk tespiti sürecinin bittiği andaki zaman bilgisidir.



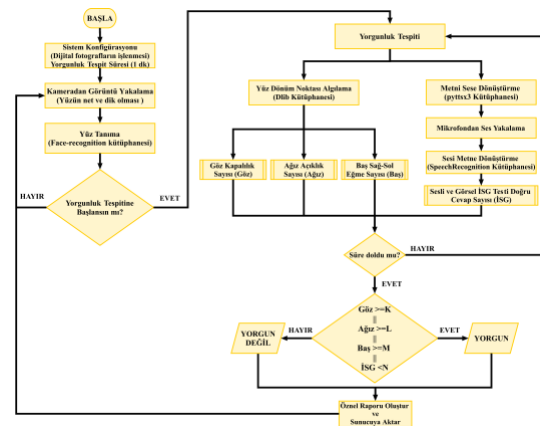
Şekil 2. Yorgunluk tespit sisteminin görselleştirilmesi.

Bu çalışma kapsamında göz açıklığı, esneme, sağa sola kafa hareketleri ve İSG testi incelenerek işçinin aktive öncesinde yorgun olup olmadığının tespiti yapılmaktadır. Şekil 3'te yorgunluk tespit sisteminin akış diyagramı gösterilmektedir. Akış diyagramında verilen K, L, M değerleri sırasıyla maksimum göz kapalılık, ağız açıklığı, baş sağ-sol eğme sayılarını, N

değeri ise minimum doğru İSG testi doğru cevap sayısını ifade etmektedir. Bu değişkenler güncellenebilir değerlerdir. İşveren veya İSG yetkilisi tarafından bu eşik değerler değiştirilebilir.

Önerdiğimiz sistemde işçinin yorgun olup olmadığının tespiti ve öznel raporun oluşturulabilmesi için aşağıdaki adımlar sırasıyla yapılmaktadır;

1. Yüz tanınması için yüzlere ait dijital fotoğraflar sunucudan alınarak işlenir.
2. Kamera karşısında yüzü net ve dik açıdan işçinin yüz tanınması gerçekleştirilir.
3. Yüzü tanınan işçiye yorgunluk tespitinin başlaması için soru sorulur. Hayır denilirse Adım 2'ye dönlür. Evet denilirse ekrandaki işçi ile yorgunluk tespitine başlanır.
4. İşçinin yorgunluk tespitinin yapılması için ayrılan süre için sayaç başlar. Önerdiğimiz sistem için sayaç bir dakika olarak belirlenmiştir.
5. İşçinin uykuya dalma (belirli bir süre gözünün kapalı olması), esneme ve başının sağa-sola eğiklik bilgileri tespit edilir. Bu sırada işçinin bilgili olması beklenen iş sağlığı ve güvenliği konularında, görsel de içerebilen sesli sorular yöneltilerek, sesli olarak kendilerinden cevap alınmaktadır.
6. Göz, ağız ve başın sağa-sola eğiklik için eşik değerler kontrol edilerek işçinin yorgun olup olmadığı bilgisi bildirilir. Bunun yanı sıra, sorulan soruya işçi tarafından verilen cevap değerlendirilerek, çalışma alanına girip giremeyeceği ile alakalı bir sonuç belirlenir.
7. İşçinin süre tamamlandığında kaydedilen bilgiler öznel rapor içerisinde yazılarak sunucudaki veri tabanına kaydedilir.
8. Adım 2'ye dönlür.



Şekil 3. Yorgunluk tespit sistemi akış diyagramı.

Önerdiğimiz sistemde bazı özel durumlarda sistemin davranışı değişmektedir. Bunlardan birincisi, kameradan alınan dijital görüntüde aynı anda tespit edilen yüz sayısı iki veya daha fazla ise, tek bir yüz kalıncaya kadar sistem bekleme durumunda çalışmaktadır. Sistem beklemede iken geçen süre, yorgunluk tespit süresi için kullanılan süreyi etkilemez. İkincisi, yorgunluk tespiti süreci başlayan işçi hariç

dijital görüntüde bir başkası ya da başkaları bulunuyorsa, sadece yorgunluk tespiti için seçilen işçi ekranda kalıncaya kadar sistem yine bekleme durumuna girmektedir. Üçüncüsü ise, bir işçi için raporlama süreci başladıktan sonra, raporlama süreci henüz tamamlanmadan önce işçinin yüzü dijital görüntüde görülemiyorsa, seçilen işçinin yüzü tekrar tanınana kadar sistem yine bekleme durumuna geçer. Raporlaması devam eden işçiye ait yüz tekrar tespit edildiğinde raporlama kaldığı noktadan devam eder.

2.1. Görüntü İşleme ile Yüz Tespit Tanıma

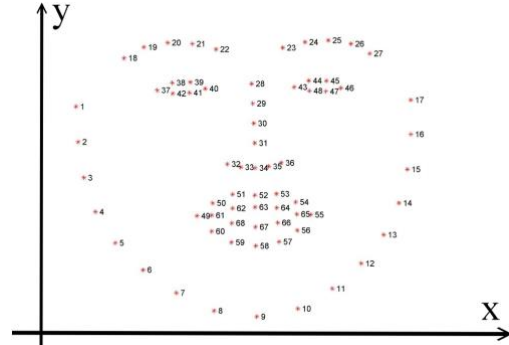
Çalışmada işçinin yüz tespiti için, Dlib'in sahip olduğu, Yönlendirilmiş Gradyanların Histogramları (Histogram of Oriented Gradients, HOG) ve Doğrusal Destek Vektör Makinesi (Linear Support Vector Machine, LSVM) tabanlı yüz tespiti fonksiyonu kullanılmıştır. Yüz tespiti için literatürde kullanılan Haar Cascade tespit algoritması değil de HOG tabanlı yüz tespitinin kullanılmasının sebebi, yanlış pozitif (false positive) oranının küçük olmasıyla beraber daha yüksek doğruluk elde edilebilmesi ve HOG tabanlı tespit, benzerlerinden üstün performans göstermesidir [13]-[14]. Yüz tespitinin akabinde, yüzdeki dönüm noktalarının tespiti için kullanılan daha önceden eğitilmiş yüz dönüm noktası detektörünün sahip olduğu model, regresyon ağaçları topluluğu (ensemble of regression trees) tabanlıdır ve bu sayede yüksek kaliteli tahminlerle mükemmel gerçek zamanlı performans başarabilmektedir [15]. Bu modelin eğitimi "ibug 300-W" veri kümesi üzerinde gerçekleştirilmiştir [16]. İlgili veri kümesi yüzlere ve bu yüzlerin 68 adet yüz dönüm noktalarına sahiptir. Belirtilen bu yapı sayesinde, yüzün dönüm noktalarının algılanma işlemi yapılarak insan yüzü 68 farklı referans nokta ile numaralandırılması sağlanmaktadır.

İşçilere ait verilerin öznel raporlanabilmesi için, Dlib kütüphanesinin sağladığı HOG özellik belirleyici ve Evrişimsel Sinir Ağları (Convolutional Neural Network, CNN) kullanılarak yüz tanıma işlemi gerçekleştirilmiştir [17].

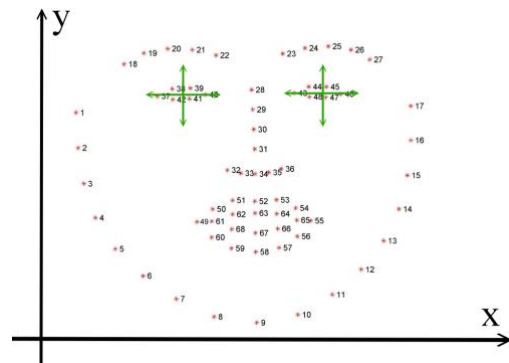
Şekil 4'te yüz üzerindeki referans noktalar gösterilmektedir. Bu noktalardan kullanmış olduğumuz 37-42 arası sol göz, 43-48 arası sağ göz, 49-68 arası ise ağız, 1-17 arası ise çene için ayrılmaktadır.

Şekil 5'te uyku durumu için kullanılan göz açıklık tespiti işleminde sağ göz için 37-42 arası sol göz için ise 43-48 arasındaki referans noktalarının kullanıldığı gösterilmektedir. Göz açıklığı (Eye Aspect Ratio, EAR) değeri, Eşitlik (1)'deki referans noktalara göre hesaplanmaktadır. Eşitlikler de bulunan p ifadesi, (x,y) düzleminde numaralandırılmış olan koordinatları belirtmek için kullanılmaktadır. Shrutu Mohanty ve arkadaşlarının yaptığı çalışmada, uykulu göz kırpması tespiti konusunda gerçek zamanlı veri üzerinde %82.02 ve "MRL Eye Dataset" veri kümesi üzerinde %93.25 doğruluk değerleri elde edilmiş olmasına dayanarak

EAR değeri 0.15 olarak belirlenen eşik değerini aşarsa gözün açık olduğu kabul edilmektedir [13]. Al-gawwam ve Benaissa'ya göre insanın göz kırpması süresi 100 milisaniye ile 400 milisaniye arasındadır. Bu süreler arasında EAR değeri 0.15'ten daha küçük ise bunun gözü kapalı değil sadece bir göz kırpması olduğu düşünülmektedir. İşçinin göz kırpması süresi 800-900 milisaniye süreyi aştığında uykulu veya istemsiz olarak gözlerini kırptığı kabul edilmektedir [18].



Şekil 4. Yüz üzerindeki 68 referans nokta.

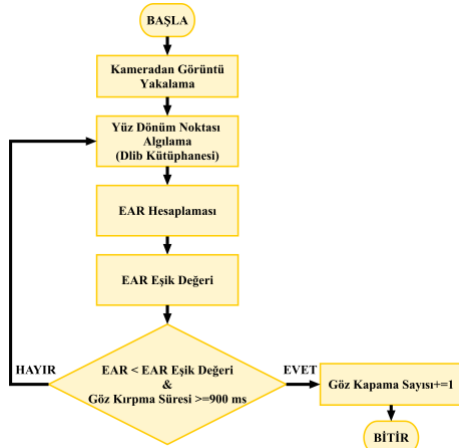


Şekil 5. Göz referans noktaları.

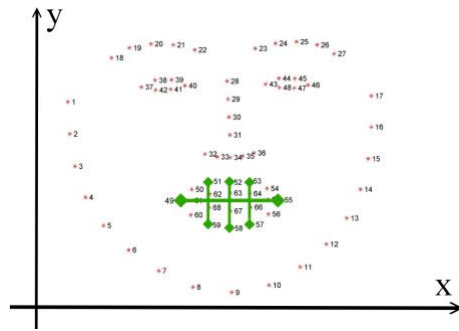
$$EAR = \frac{\|p_{38} - p_{42}\| + \|p_{39} - p_{41}\|}{2\|p_{37} - p_{40}\|} \quad (1)$$

Şekil 6'da Eşitlik (1)'de belirtilen EAR değerinin yanı sıra yorgunluk veya yorgunluğa bağlı istemsiz olarak göz kırpması ile bağdaştırılan göz kapalılık süresini de içeren, göz kapalılık sayısının tespitine ait akış diyagramı verilmiştir ve raporlanan işçiye ait nihai göz kapama sayısını bulma sürecini ifade etmektedir.

Şekil 7'de ağız açıklık tespiti için 49-68 arasındaki referans noktalarının kullanıldığı gösterilmektedir. Ağız açıklığı (Mouth Aspect Ratio, MAR) değeri Eşitlik (2)'deki referans noktalara göre hesaplanmaktadır. Shrutu Mohanty ve arkadaşlarının yaptığı çalışmada, esneme tespiti konusunda gerçek zamanlı veri üzerinde %85.44 ve "YawDD Dataset" veri kümesi üzerinde %96.71 doğruluk değerleri elde edilmiş olmasına dayanarak MAR değeri 0.83 olarak belirlenen eşik değerini aşarsa esneme durumunun oluştuğu kabul edilmektedir [13].



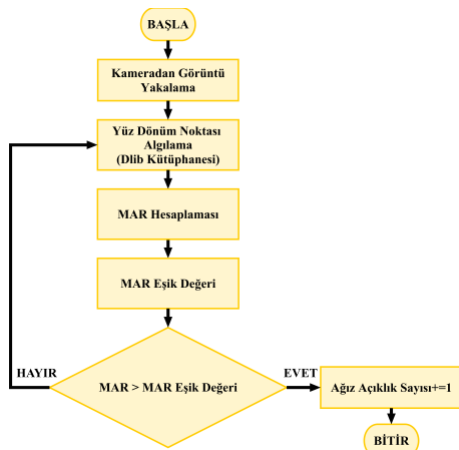
Şekil 6. Göz kapama sayısı tespiti akış diyagramı.



Şekil 7. Ağız referans noktaları.

$$MAR = \frac{\|p_{51} - p_{59}\| + \|p_{52} - p_{58}\| + \|p_{53} - p_{57}\|}{3\|p_{49} - p_{55}\|} \quad (2)$$

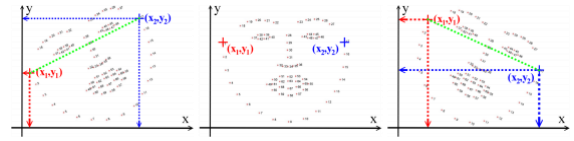
Şekil 8’de, Eşitlik (2)’de belirtilen MAR değerini içeren ağız açıklık sayısının tespitine ait akış diyagramı verilmiştir. Raporlanan işçiye ait nihai ağız açıklık sayısını bulma sürecini ifade etmektedir.



Şekil 8. Ağız açıklık sayısı tespiti akış diyagramı.

Şekil 9’da başın sağa sola eğikliğini tespiti için Şekil 4’te gösterilen 1. ve 17. referans noktalarının kullanıldığı gösterilmektedir. Baş eğikliği (Head Tilt Ratio, HTR) değeri Eşitlik (3)’teki formüle göre hesaplanmaktadır. Uyuklu kişiye ait baş hareketlerinin incelendiği çeşitli akademik çalışmalar ve deneysel

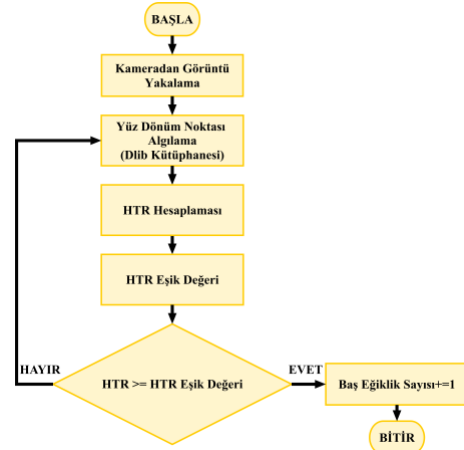
sonuçlar referans alınarak, HTR değeri 4’ten büyük ya da eşit ise işçinin uyuklu olduğundan ötürü başının sağa veya sola doğru eğildiği kabul edilmektedir [18]-[19]-[20].



Şekil 9. Baş eğimi için referans noktaları.

$$HTR = \frac{\|y_2 - y_1\|}{\|x_2 - x_1\|} \quad (3)$$

Şekil 10’da Eşitlik (3)’te belirtilen HTR değerini içeren baş eğiklik sayısının tespitine ait akış diyagramı verilmiştir. Raporlanan işçiye ait nihai baş eğiklik sayısını bulma sürecini ifade etmektedir.



Şekil 10. Baş eğiklik sayısı tespiti akış diyagramı.

2.2. Metin seslendirme ve sesi metne dönüştürme

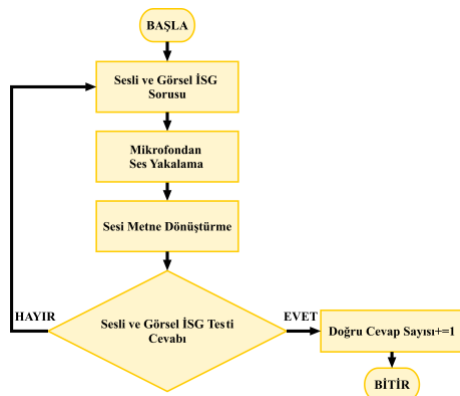
Sesten Metne Dönüşüm (Speech to Text, STT), konuşmanın bilgisayar tarafından algılanarak metne dönüştürülmesi işlemi ifade etmektedir. Sesten metne dönüşüm süreci, kişinin mikrofon tarafından yakalanan sesine ait analog sinyallerin dijital sinyallere dönüştürülmesi, frekans bantlarına ayrılarak spektrogramda analiz edilmesi ve akabinde ilgili sesin bir harf, hece veya kelime ile eşleşmesi süreçlerini içermektedir. Ek olarak konuşma şekli ve hızı, bölgesel aksan, cinsiyet gibi birçok farklılık modellenmesinde güçlüğü sebebiyet verebilmektedir [21]. Konuşma tanıma için Saklı Markov Modeli ve Derin Sinir Ağları kullanılabilir [22]-[23]. Bu şekilde sesin otomatik ve hızlı olarak yazıya dönüştürülebilmesi, metin üzerinden çeşitli işlemler yapılabilmesine imkân oluşturmaktadır. Sesin ifade ettiği bilgileri daha küçük boyutlarda saklayabilme, konuşmadaki kelime tekrar sayılarını bulabilme, işitme engelli bireylerle daha kolay iletişime geçilebilmesi gibi çeşitli faydalar sağlamaktadır.

speech_recognition kütüphanesi, çevrimiçi ve çevrimdışı ses tanıma yapılabilmesini sağlamaktadır. Kaydedilmiş ses dosyaları veya mikrofondan alınan ses girdisini metne dönüştürmek için kullanılmaktadır. Bu işlevi, bünyesinde barındırdığı birçok konuşma tanıma motoru/API desteği ile yerine getirmektedir. Çalışmada bunlardan biri olan Google Ses Tanıma kullanılarak ses girdisi alınmış ve metne dönüştürülmüştür. Kütüphane, mikrofondan ses girdisi alabilmek için “PyAudio” kütüphanesine ihtiyaç duymaktadır [24]. Bu sebepten ötürü bu kütüphaneden de faydalanılmıştır.

Metinden Sese Dönüşüm (Text to Speech, TTS) ise metnin sese dönüştürülmesi işlemidir. Bu dönüşüm, genel anlamda alınan metin girdisinin doğal dil işleme ve akabinde dijital sinyal işleme adımlarına tabi olması sonucu gerçekleşir [25]. Metnin ses olarak elde edilebilmesi ile disleksiye veya görme engeline sahip olan bireylerin daha rahat iletişime geçebilmesine, okuryazarlığı olmayan kişilerin bilgiye daha kolay erişebilmesine veya içerik üreticilerinin çok daha geniş bir kitleye hitap edebilmesine olanak sağlamaktadır.

pytsx3 kütüphanesi, metni konuşmaya dönüştürme işlemini yapmaktadır. Birçok dil seçeneği ile çalışabilmektedir ve kendisine alternatif olarak kullanılacak diğer kütüphanelerin aksine çevrimdışı çalışabilmektedir. İçerisinde Microsoft'un Metinden Konuşmaya motoru da dâhil olmak üzere çeşitli metinden konuşmaya motorlarını barındırmaktadır. Ses yüksekliği, dil ve konuşma hızı gibi birtakım özellikler ayarlanabilmektedir. Aynı zamanda verilen metnin, ses olarak kaydedilebilmesi de mümkündür [26].

Metinden sese ve sestten metne dönüşüm işlemlerinin kullanıldığı İSG testinin doğru cevap sayısının tespiti, Şekil 11'deki akış diyagramıyla belirlenmektedir. İSG testinde çalışana sorulacak olan sorular, ilgili kurumda bulunan İSG görevlisi tarafından belirlenmelidir.



Şekil 11. Sesli ve görsel İSG testi doğru cevap sayısının belirlenmesi akış diyagramı. Kompozit malzemeler geliştirilirken

III. BULGULAR

Uygulamanın geliştirildiği, çalıştırıldığı ve test işlemlerinin gerçekleştirildiği bilgisayar

konfigürasyonu olarak, Windows 10 Education işletim sistemine ve Intel Core i7 7700HQ 2.80GHz işlemci, 16 GB RAM, 128 GB SSD depolama, Nvidia GTX 1050 Ti 4GB ekran kartı donanımlarına sahiptir. Geliştirmede kullanılan Python sürümü 3.7.11'dir. Görüntü ve ses için, sisteme entegre mikrofon ve 720P 30 fps kamera kullanılmıştır.

Önerilen sistemin doğruluğunun, kesinliğinin, duyarlılığının ve F1 skorunun hesaplanabilmesi için 30 işçi (15 işçi yorgun, 15 işçi yorgun değil) üzerinden deneysel çalışma gerçekleştirilmiştir. Deneysel çalışma yapılırken kişinin yorgun bir kişi olup olmadığı bilgisi Watson et al. (2015) [27] çalışması referans alınarak belirlenmiştir. İlgili çalışma, 18-60 yaş aralığındaki bireylerin en az 7 saatlik bir uykuya ihtiyaç duyduğunu ifade etmektedir.

Gerçekleştirilen deneysel sonuçlardan Tablo 1'deki karışıklık matrisi (confusion matrix) elde edilmiştir. Buna göre; “True Pozitif”(TP) ve “True Negative”(TN) önerilen sistemin doğru olarak tahmin ettiği, “False Pozitif”(FP) ve “False Negative”(FN) ise önerilen sistemin yanlış olarak tahmin ettiği alanlardır.

Tablo 1. Sesli ve görsel İSG testi doğru cevap sayısının belirlenmesi akış diyagramı.

Karışıklık Matrisi	Gerçek Değer	
	Yorgun	Yorgun Değil
Tahmini Değer	Yorgun	TP:11 FP:2
	Yorgun Değil	FN:4 TN:13

Doğruluk değeri, önerdiğimiz sistemde, doğru tahmin ettiğimiz alanların toplam veri kümesine oranıyla hesaplanmaktadır. Öztürk vd. (2022) [28] çalışmasından referans alınan hesaplama işlemi Eşitlik (4)'te ifade edilmiş, önerdiğimiz sistemin doğruluğu %80 olarak hesaplanmıştır.

$$\text{Doğruluk} = \frac{TP + TN}{TP + FP + TN + FN} \quad (4)$$

Kesinlik değeri, pozitif olarak tahmin ettiğimiz değerlerin kaç tanesinin gerçekten pozitif olduğunu ifade etmektedir. Dewi et al. (2022) [29] çalışmasından referans alınan hesaplama işlemi Eşitlik (5)'de ifade edilmiş, önerdiğimiz sistemin kesinliği %85 olarak hesaplanmıştır.

$$\text{Kesinlik} = \frac{TP}{TP + FP} \quad (5)$$

Duyarlılık değeri, pozitif olarak tahmin etmemiz gereken kişilerin ne kadarını pozitif olarak tahmin ettiğimizi ifade etmektedir. Dewi et al. (2022) [29] çalışmasından referans alınan hesaplama işlemi Eşitlik (6)'da ifade edilmiş, önerdiğimiz sistemin duyarlılık %73 olarak hesaplanmıştır.

$$Duyarlılık = \frac{TP}{TP + FN} \quad (6)$$

F1 skoru değeri ise kesinlik ve duyarlılık değerlerinin harmonik ortalamasını ifade etmektedir. Dewi et al. (2022) [29] çalışmasından referans alınan hesaplama işlemi Eşitlik (7)'de ifade edilmiş, önerdiğimiz sistemin F1 skoru değeri %79 olarak hesaplanmıştır.

$$F_1 = 2 \frac{Kesinlik * Duyarlılık}{Kesinlik + Duyarlılık} \quad (7)$$

DeneySEL sonuçların elde edilmesi aşamasında, her bir işçi için gerçekleştirilen yorgunluk tespit sistemi aşamaları aşağıda detaylıca anlatılmaktadır.

İlk adımda, işçiye ait öznel raporlamamın başlayabilmesi için, sistemde kişiye ait karşıdan ve net görülebilen yüz görselinin (Örneğin “kadir.jpg”) bulunması gerekmektedir. Şekil 12’deki A görselinde görüldüğü gibi, yüz tanıma sistemi ile tespit edilen kişinin raporlanması işleminin başlatılabilmesi için teyit sorusu sorulmaktadır.

Şayet sorulan soruya, başka bir kişiyle devam edilmesi istenerek, “H” girdisi verilirse; Şekil 12’deki B görselinde görüldüğü gibi kişi tespiti tekrardan başlayıp, soru sorulduğunda tespit edilmiş olan kişi hariç yeni bir kişinin yüzünün ekranda görülmesi beklenir. Başlangıç kısmının sesli komut ile değil de klavyeden alınmasının sebebi sistemin ses haricinde klavye ile de çalışabileceğinin gösterilmesi için yapılmıştır.

Şayet sorulan soruya, tespit edilen kişi ile devam edilmesi istenilerek, “E” girdisi verilirse; Şekil 12’deki C görseli gibi yüzün dönüm noktalarının elde edilmesi işlemiyle beraber raporlama süreci başlamaktadır. Bu süreç, rapor için tanımlanan süre bittiğinde sonlanacaktır.

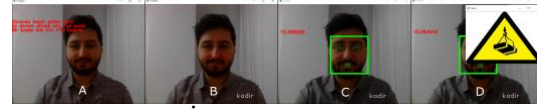
Raporlama sürecinin başlamasıyla birlikte işçiye, iş sağlığı ve güvenliği kapsamında kurumdaki İSG görevlisi tarafından belirlenen görsel ve/veya sesli olarak sorulan sorular Şekil 12’deki D görselinde gösterilmiştir. Soruya karşılık, işçiden mikrofon aracılığıyla alınan cevap bilgisinin kontrol edilmesi ve sonuçlandırılması Şekil 13’teki A görselinde gösterilmiştir.

Raporlama süreci boyunca, işçinin her an takibi yapılarak; Şekil 13’teki B görselindeki gibi göz yorgunluğu, Şekil 13’teki C görselindeki gibi esneme ve Şekil 13’teki D görselindeki gibi başın eğikliği tespit edilerek raporlanmaktadır.

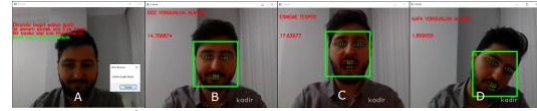
Bahsi edilen bu durum tespitleri yapılırken, şayet Şekil 14’teki A görselindeki gibi ekranda herhangi bir yüz tespit edilememesi, Şekil 14’teki B görselinde görülen ekranda birden fazla yüzün tespit edilmesi veya Şekil

14’teki C görselindeki ekranda tespit edilen yüze ait kayıt bulunamaması gibi durumlar sistem tarafından tespit edilir ve raporlama süreci duraklatılır. Raporlama işlemine tabi olan kişi, tekrardan ekranda görülürse raporlama sürecine devam edilir. Daha önce belirtildiği gibi süre tamamlandığında da işçiye ait rapor oluşturularak kaydedilir.

Son olarak ilgili kişi için sistem tarafından tespit edilenler bir metin belgesinde Şekil 14’teki D görselindeki gibi kayıt edilmektedir.



Şekil 12. A-İşçi teyit aşaması, B-Teyidin doğrulanması, C-Yüz tespiti, D- İSG soru sorulması



Şekil 13. A-İSG değerlendirilmesi, B-Göz yorgunluk alarmı, C-Esneme tespiti, D-Kafa yorgunluk alarmı



Şekil 14. A-İşçi tespit edilmeme durumu, B-Birden fazla yüz tespiti, C-Kayıtsız işçi tespiti, D-Öznel Raporlama

Tablo 2. Önerilen sistemin literatürdeki çalışmalarla yöntem bazında kıyaslanması.

Çalışma	Algoritma ¹	Hibrit ²	İSG Kullanımı
[30]	ZFace, Savitzky-Golay filter, Finite State Machine	Yok	Yok
[31]	Viola and Jones, Haar Cascades, Temperature Sensor LM-35, Pulse Oximeter	Var	Yok
[32]	Gripping Pressure, Heart Rate Variability, Commercial Cardiothoracic Belt	Yok	Yok
[33]	MSP-Net, PERCLOS, FOM	Yok	Yok
[34]	EEG, K-NN, SVM, LDA	Yok	Yok
Önerilen Sistem	HOG, Lineer SVM, CNN, EAR, MAR, HTR	Var	Var

¹Yorgunluk Tespit Algoritması

²Hibrit (Yüz Tanıma, İnteraktif İletişim, Öznel Raporlama)

Yapılan deneyler ile önerilen sistemin sahip olduğu özellikler, literatürdeki benzer çalışmalarla

kıyaslanarak Tablo 2’de gösterilmiştir. Kıyaslama kriterleri olarak; yorgunluk tespiti için kullanılan algoritmalar, yüz tanıma, interaktif iletişim, iş sağlığı ve güvenliği alanında kullanılıp kullanılmadığı ve öznel raporlama kullanılmıştır. Benzer sistemlerin birçoğunda yüz tanıma ve öznel raporlama varken interaktif iletişim ve İSG alanında kullanımı gözlemlenmemiştir. Bu da önerdiğimiz sistemin İSG kapsamında ilk ve öncül bir örnek olduğunu kanıtlar niteliktedir.

Önerilen sistemimizin ve literatürde yer alan farklı yöntemlerin doğruluk, kesinlik, duyarlılık ve F1 skoru metrikleri bakımından karşılaştırılması Tablo 3’te sunulmaktadır. Referans alınan çalışmalar genellikle yüksek doğruluk, kesinlik ve F1 skoru gibi metriklerde sistemimizden daha iyi sonuçlar elde etmişlerdir. Ancak, sistemimizin referans çalışmalara göre daha düşük performans sergilemesinin temel sebebi, gerçek dünya koşullarında sınırlı sayıda işçi üzerinde test edilmiş olmasıdır. Bu durum, standart veri setleri kullanılarak gerçekleştirilen referans çalışmalara kıyasla, ölçümlerin daha zorlu ve değişken koşullar altında yapılmasına yol açmaktadır. Gerçek dünya testleri, genellikle tahmin edilemeyen ve karmaşık faktörler içerir ki bu da sistemimizin performansını doğrudan etkileyebilir. Test grubunun genişletilmesi, sistemimizin çeşitli gerçek dünya durumlarına olan adaptasyonunu daha iyi anlamamızı ve bu koşullara göre optimizasyon yapmamızı sağlayabilir. Bu iyileştirmeler, sistemimizin performansını önemli ölçüde artırma potansiyeline sahiptir. Bunun yanı sıra, yorgunluk tespiti için literatürde genel olarak kullanılan YawDD veri seti üzerinde önerilen sistemimiz uygulandığında, aynı veri setini kullanan diğer çalışmalara oldukça yakın sonuçlar elde edildiği görülmüştür.

III. SONUÇLAR VE TARTIŞMA

İSG kapsamında işçiler için endüstriyel aktivitenin getirmiş olduğu hayati riskleri azaltmak veya tamamen ortadan kaldırmayı amaçlayan, işçinin dijital fotoğrafı üzerinden yüz tanıma, yorgunluk tespiti, işçinin iş sağlığı ve güvenliği ile alakalı bilgisinin ölçülmesi ve öznel raporlama yapılabilmesi için bir sistem tasarımı gerçekleştirilmiştir. Çalışma, yapılmış diğer çalışmalarda bulunan sadece göz ve ağız açıklığına bağlı olarak yorgunluk tespiti yapan sistemlerin üzerine, başın sağa-sola eğikliği, yüz tanımlaması, görsel içerebilen sesli sorularla işçinin bilgisinin ölçülmesi ve öznel raporlama özellikleri eklenmiştir. Sistem, işçinin kamera karşısına geçtiği andan öznel raporun sunucuya gönderilmesi anına kadar uçtan uca bir akış göz önüne alınarak geliştirilmiştir. İSG görevlisinin ilgili işçinin çalışma alanına münhasır hazırladığı sorular ile iş sağlığı ve güvenliğinin denetlenmesi çalışmaları alanında öncü kılmaktadır.

Tablo 3. Önerilen sistemin sonuçlarının literatürdeki çalışmalarla karşılaştırılması.

Çalışma	Veri Seti	Doğruluk (%)	Kesinlik (%)	Duyarlılık (%)	F1 Skor (%)
[4]	Özgün Veri	99.2	97.38	97.54	97.46
[5]	HFFD	98.30	98.2	-	-
[6]	UTA-RLDD	94.68	-	-	-
[13]	YawDD	96.71	-	-	-
[28]	Özgün Veri	98.00	98.00	-	-
[30]	ZJU	-	96.65	-	-
[31]	Özgün Veri	80.55	85.71	-	-
[32]	YawDD	95.99	94.80	95.58	95.19
[33]	EMD	98.00	-	-	-
	ZJU	96.89	98.02	-	-
	CEW	95.36	-	-	-
[34]	CEW ve YawDD	96.00	-	-	-
[35]	YawDD	99.42	97.7	99.50	96.70
Önerilen Sistem	Özgün Veri	80	85	73	71
Önerilen Sistem	YawDD	95.99	96.83	95.58	95.59

Gerçekleştirilen deneysel sonuçlara göre önerilen yorgunluk tespit sisteminin doğruluğu %80, kesinliği %85, duyarlılığı %79 ve F1 skoru %79 olarak hesaplanmıştır. Sistem mevcut haliyle belirli metriklerde referans çalışmalardan daha düşük performans gösterse de, gerçek ortamda test edilmesi ve pratik uygulamalara yönelik potansiyeli dikkate alındığında değerli bir katkıdır. Bunun yanı sıra, YawDD veri seti üzerinde önerilen sistemin doğruluğu %95.99, kesinliği %96.83, duyarlılığı %95.58 ve F1 skoru %95.59 olarak hesaplanmıştır. Buna göre; aynı veri setini kullanan diğer çalışmalara oldukça yakın sonuçlar elde edilmiştir. Ayrıca, sistemimizin İSG sesli ve görsel soru-cevap yeteneği ile sonuçların daha da iyileşeceği düşünüldüğünde, mevcut yöntemlere güçlü bir alternatif olabileceği kanıtlanmıştır. Bu yenilikçi özellik, kullanıcı etkileşimini artırarak sistemimizin etkinliğini ve kullanıcı memnuniyetini önemli ölçüde iyileştirebileceği düşünülmektedir.

Önerdiğimiz sisteme ek olarak, işçinin ses tonundan veya sistemde raporlanan diğer mevcut bilgiler üzerinden ekstra birtakım çıkarımlar (ses tonundan ve/veya göz açıklığından depresyon tespiti vb.) eklenebilir. Ayrıca endüstriyel aktivite hakkında işçinin yeterli bilgi sahibi olup olmadığı daha geniş bir kapsamda tespit edilebilir. Tüm bu bilgiler analiz edildiğinde işçinin endüstriyel aktivite için gerekli şartları sağlayıp sağlamadığı daha doğru şekilde kontrol edilebilir. Ek olarak işçilerin öznel raporları

kullanılarak yapay zekâ algoritmaları ile işverene işçinin yorgunluk durumuna göre çalışması gereken gün ve saatleri bildirebileceği bir öneri sistemi geliştirilebilir. Yorgunluk tespit sisteminde kullanılan kameranın çözünürlüğünün çok yüksek miktarda artırılmasıyla gözdeki yorgunluğa bağlı kızarıklık tespit edilebilir. Tespit edilen kızarıklığa bağlı yorgunluk seviyesi veya gözdeki hasar seviyesi ölçülerek, işçinin kendi işinde çalışması için uygunluğu ve yorgunluk seviyesi daha detaylı gözlemlenebilir. Yüz tespit ve tanıma algoritmalarının performans ve verimliliğinin artmasıyla birlikte, çalışmada tek bir kişi için işleyen raporlama sürecinin, aynı anda birçok kişi için yapılabileceği karmaşık bir sistem mimarisine geçilebilir. Yüz tespitinde ağız, burun ve çene dönüm noktalarının kullanımının yanı sıra, kaş için verilen dönüm bilgisinin kullanılmasıyla, işçinin raporlama sürecinde gözünü açık tutmak için kaşlarını kaldırması tespit edilerek önerilen sistemin çalışma doğruluğu da artırılabilir.

TEŞEKKÜR

Bu makale, 791052 numaralı yüksek lisans tezinden türetilmiş olup, iş sağlığı ve güvenliği alanında yenilikçi ve önemli bulgular sunmaktadır. Çalışmamızın test edilmesinde gönüllü olarak yer alıp, gerçek bir test ortamı oluşturan 30 işçi arkadaşımıza sonsuz teşekkürlerimizi sunarız. Onların katkıları, bulgularımızın doğruluğunu ve güvenilirliğini artırmada büyük bir önem taşımaktadır. Ayrıca, makalemizin hazırlanmasında değerli zamanlarını ayırarak bilimsel titizlikle değerlendirme yapan saygıdeğer hakemlerimize en derin teşekkürlerimizi iletmek isteriz. Kıymetli yorumları, yapıcı eleştirileri ve önerileri ile çalışmamızın kalitesini ve bilimsel katkısını artırmamıza yardımcı oldular. Çalışmamızın alanımıza sağladığı katkılarda, onların rehberlik ve desteklerinin payı büyüktür. Teşekkür ederiz.

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An Implementation-Based Study of the Detection of and Recovery from GPS Spoofing Attacks for Unmanned Aerial Vehicles

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Abstract

Unmanned Aerial Vehicles (UAV) are expected to be a critical component for logistics, agriculture, defense and enabling connectivity for post-5G communications. The utilization of drones in diverse sectors raises concerns about their vulnerability to potential attacks that disrupt or obstruct their operational mechanisms. In this work, we first demonstrate how navigation attacks can compromise a drone's system, using GPS jamming and spoofing attacks via HackRF One PortaPack Software Defined Radio (SDR) device. Next, we propose a mechanism called "Return-to-Start", which can protect a drone from loss by responding promptly to such widely spread navigational attacks. We evaluate the effectiveness of our solution through experiments on a Raspberry Pi-based drone we developed. Our experiments validate the robustness of Return-to-Start functionality in a variety of attack scenarios with different durations and GPS geolocations.

Keywords: Drone, UAV, GPS spoofing, GPS jamming, Software Defined Radio (SDR)

I. INTRODUCTION

Drones, also known as unmanned aerial vehicles (UAVs), will fly in urban airspaces in the coming decade(s). Their ability to capture footage or data from unique perspectives, as well as their increasing autonomy and precision, make them valuable tools in civilian applications such as agriculture, construction, delivery, surveillance, and search and rescue. UAVs are also employed in military operations; tactical drones, also known as medium-altitude long endurance drones (MALE) are used for reconnaissance and combat. Additionally, the ongoing research in post-5G vertical heterogeneous networks envision UAV base stations and relays to handle communication requirements and provide edge intelligence [1].

A critical component for using UAVs in such long range and long duration applications is being equipped with a sensor core comprising the Inertial Measurement Unit (IMU) and a Global Positioning System (GPS) system, which are integrated to calculate the moving drone's position, velocity, and altitude. The IMU and GPS are generally integrated to create a sensor fusion system, allowing the drone to benefit from both short-term reliable accuracy of the IMU and the absolute positioning information provided by GPS. This integrated approach enhances overall navigation accuracy and reliability, especially in scenarios where GPS signals may be temporarily lost or degraded.

As drones gain wide use in both civilian and military contexts, the threat of malicious activities directed towards these systems becomes increasingly terrifying. The impact of such attacks on under-prepared UAVs could result in theft, property damage, or injury/death of bystanders. Several attack vectors have even been proven successful in the field [2]. Among the critical attacks on UAVs is GPS spoofing. One of the most serious UAV security attacks was the capture of the US RQ-170 military UAV in 2011 [3]; another incident happened where a drone with radioactive material landing on the roof of the private residence of the Japanese prime minister [4]. For safety and privacy protection, some government regulators have encouraged drone manufacturers to build geo-fencing constraints into UAV navigation systems that would override the commands of the unsophisticated operator,

preventing UAVs from flying into protected airspaces. For example, drone producer DJI currently uses geofencing to prevent its drones from operating in the Washington D.C. area and nearby airports. Given how vulnerable GPS and other Global Navigation Satellite System (GNSS) are to jamming and spoofing attacks, an increasing focus has surfaced on designing UAV navigation and control systems that can operate in GNSS-denying environments. Unlike military UAVs' GPS signals, which are encrypted and cannot be modified [5], civil UAVs use civil signals that are unencrypted, unauthenticated, and predictable, allowing a user to produce or modify signals at will. As a result, tampering with them and using fake or false signals could alter and influence the movement of the civil UAV, steering it to an undesired target site [6].

This paper explores the extent of UAV vulnerability to signal blockage and fake GPS signals as a result of jamming and spoofing attacks. We have implemented a Raspberry Pi based drone, Tale, with a mechanism that allows it to fly and return to start position without relying on GPS when it is jammed. We have conducted field experiments on two test subjects, Tale and an a commercially available off-the-shelf drone, validating Tale's mechanism of recovery from GPS spoofing attacks, and we discussed the results. The main contributions of this work are summarized as follows:

- Developing GPS jamming and spoofing attacks to target UAV GPS receivers, showcasing the validity of the vulnerability,
- Developing a unique Raspberry Pi drone,
- Implementing the original Return-to-Start point function that can prevent and protect a drone from loss,
- Conducting field experiments to examine the effectiveness of the proposed approach in detecting and recovering from GPS jamming and spoofing attacks, and
- Promoting awareness among the public, the scientific community, and manufacturers that professional UAV systems should integrate a higher degree of security by proving the potential of such attacks and proposing a viable solution.

The rest of the paper is organized as follows: Section II presents background on drone classification, types, usage, communication method, the GPS mechanism, and GPS attacks. Section III summarizes related prior art. Section IV presents the hardware and software utilized and the solution approach. Section V describes the conducted experiments and discusses their results. Finally, Section VI concludes the paper and discusses possible future work.

II. BACKGROUND

We provide brief background on the systems enabling drone navigation, and we describe known navigational attack strategies.

2.1. Drone Navigation

UAVs need accurate navigation to operate autonomously or semi-autonomously and fly long distances. The Inertial Measurement Unit (IMU) in drones plays a crucial role in navigation, stability, and control. It typically consists of sensors like accelerometers and gyroscopes that measure the drone's acceleration and rotation rates. The IMU provides essential data to the flight controller, helping the drone maintain its orientation and stability in the air. By continuously monitoring changes in velocity and rotation, the IMU enables the drone to make real-time adjustments to its motors and control surfaces, ensuring precise and stable flight. Additionally, the IMU contributes to the drone's ability to navigate accurately, as it helps calculate changes in position over time, allowing for more reliable and autonomous flight operations. In many drone systems, the IMU and GPS are integrated to create a sensor fusion system, which allows the drone to benefit from both short-term reliable accuracy of the IMU and the absolute positioning information provided by GPS. This integrated approach enhances overall navigation accuracy and reliability, especially in scenarios where GPS signals may be temporarily lost or degraded.

The communication between a drone and its controller could take a place in different ways including a direct radio signal or via a Wi-Fi network. Most drones are equipped with a GPS module that enables them to know their location depending on a network of orbiting satellites. GPS location signal, when paired with data from an inertial measurement unit (IMU), gives accurate information that could be used for control purposes. A GPS-equipped UAV may offer both position and altitude information and essential vertical and horizontal coverage levels. In addition, it is always important to be aware of the UAV location, to prevent incidents in an area densely inhabited by other UAVs or manned vehicles. In fact, GPS in UAVs is vital whether the UAV is remote-controlled, autonomous, or semi-autonomous.

GPS is a United States-owned constellation of 31 satellites that orbit the Earth and make it possible for people with ground receivers to pinpoint their geographic location. It has at least 24 operational satellites that circle the globe once every 12 hours, guaranteeing that users would receive information from at least four satellites from any point on earth. With UAVs, GPS is often critical to safely flying the UAV as it is used as the primary sensor for the localization of

the drone [7]. In normal operation, GPS receivers deduce their position by calculating their distance from several satellites at once. Each satellite carries an atomic clock and broadcasts its location, the time, and a signature pattern of 1,023 plus and minus signs known as a pseudorandom noise code (or PRN code) [8].

GPS drone is also capable of navigation by *waypoints*, where a flight route may be planned by instructing the drone to go to specified GPS locations along with a predefined path using its autopilot mode. GPS also allows a drone to execute a position hold, which enables the drone to retain a stable location point and an altitude hold, which also enables the drone to maintain a set altitude while in flight mode, mapping, and reporting, which allows the drone to keep a record log for each flight.

Autonomous UAVs often depend on a GPS location signal, which, when paired with data from an inertial measurement unit (IMU), gives accurate information that could be used for control purposes. A GPS-equipped UAV may offer both position and altitude information and essential vertical and horizontal coverage levels. GPS navigation algorithms may provide continuous accuracy as long as adequate satellite signals are available during the UAV flight.

2.2. Drone GPS Attacks

2.2.1. GPS Jamming

GPS receivers in drones can be particularly vulnerable to external sources of interference. GPS jamming is one of the major attacks that severely impacts systems' availability. It is performed by transmitting random interfering signals with high strength such that the GPS signals and noise are indistinguishable. As the signal intensity of legitimate GPS signals is very low in nature, generating jamming signals at a higher intensity is relatively easy to achieve [9]. Jamming signals may be generated by simply re-broadcasting the GPS carrier signal, or by broadcasting it upon adding random noise.

Jammers operate against receivers, not transmitters. They can be used to block all wireless communication in a certain area. In open areas, signals from jammers can spread over much longer distances compared to that on land with obstructions. Upon losing the GPS signal, drones can no longer maintain the correct position; they may land or drift in the wind, potentially causing physical damage to people or buildings, or causing sensitive information to be seized by malicious actors.

2.2.2. GPS Spoofing

All cryptographic methods are vulnerable to attacks by specialized systems that can intercept a signal and retransmit it with greater power, thereby causing the receiver to switch from the legitimate signal to the

delayed replica [8]. GPS spoofing happens as radio signals conveying fake GPS location information are transmitted, to overpower the relatively weak GPS signals in two main ways. One approach is *meaconing*, where an attacker merely intercepts the legitimate GPS signals and rebroadcasts them on the victim's receiving frequency at a higher power than the original signal confusing the receiving navigation system. Another approach is using a radio transmitter to send what could be described as a *counterfeit (fake) GPS signal*, to manipulate a target receiver's position. The spoofing signals provide the drone with a false impression of its actual physical location, and as a result, the drone diverges from its original route and becomes susceptible to loss.

GPS spoofing poses a bigger threat than GPS jamming, since a spoofer could lead the target to produce an inaccurate PVT (Position, Velocity, Time) solution or even achieve total control over a drone's flight path by re-broadcasting or transmitting fake GPS signals.

III. RELATED WORK

In this section we present related prior work on causing and detection of GPS jamming and spoofing attacks on UAVs, and related work that studied UAV behavior postattack.

3.1. Previous Work on Creating Spoofing

Due to the decrease in hardware expenses and the availability of open-source software, unmanned aerial vehicles (UAVs) have gained accessibility over the last decade; this also contributed to their misuse. To assess the impact of attacks, several research efforts aimed to put spoofing attacks into good use, such as protecting the different GEO zones from malicious drones by means of neutralizing, taking down, or rerouting a drone [10], [11]. As an example, [12] presents a GPS spoofing based counter-UAV defense system that can remotely control a non-cooperating UAV to fly to a specified location for capture.

In recent years there has been a growing interest in the use of multiple drones, which coordinately move as a swarm, for covering a wide area in disaster management, traffic control, etc. applications. The study of spoofing a drone swarm using spatial spoofing has been proposed [13]. The idea in this work is, instead of tracking the movement of each drone and transmitting an individual spoofing signal per drone, estimating a fake position for each point where drones move. A technique for grounding violating drones and computing their launch location has been proposed in [14]. More recently, a Drone Position Manipulation (DPM) system that exploits the entire stack of sensing, state estimation, and navigation control have been proposed [15].

3.2. Previous Work on Detecting Spoofing

Ideally, in order to detect whether a drone has been hijacked, the acceleration and angular velocity reported by motion sensors can be compared with the position reported by GPS. However, since the position estimation via motion sensors may be inaccurate due to error accumulation over time, a method that estimates linear acceleration has been proposed [16]. The proposed method has been implemented on a Quadrotor drone, showing that the false-positive cases that happened with the straightforward comparison of the inertial navigation system with the GPS have been eliminated.

Another probabilistic algorithm to detect Global Navigation Satellite System (GNSS) spoofing attacks was proposed in [17]. The proposed integrity monitoring procedure was implemented using a small-sized antenna array and it utilizes Angle of Arrival (AoA) integrity-monitoring method. Other techniques utilizing the difference in the signal strengths of authentic GPS and spoofing signals, detecting the presence (or absence) of background noise, using radar ground stations that track UAV's perceived position information find outliers have also been proposed [18].

More recently, machine learning techniques have been used for detecting spoofing. [19] used several learning algorithms on signal features such as jitter, shimmer and modulation variants. [20] compared several tree-based machine learning models and [21] compared three ensemble models (Bagging, Stacking, and Boosting) in terms of accuracy of detecting GPS spoofing attacks.

3.3. Previous Work on Recovery from GPS Spoofing Attacks

Given the extent of how vulnerable the GPS and other GNSS are to signal jamming and spoofing attacks, and the potential damage to the environment, an increased focus on designing a UAV navigation and control system that can function in GNSS-denied environments has surfaced [22], [23].

In one previous work, the authors proposed to detect GPS spoofing based on the monocular camera and IMU sensor of a UAV, and then presented an image localization approach to support UAV's autonomous return using error reduction via computer vision [24]. The performance of the proposed mechanism was evaluated on a DJI Phantom 4 drone.

Another work for attack resilience was carried out in [25], where the authors proposed an information-sharing path planning algorithm for drone swarms, where drones collaboratively, step-by-step identify waypoints using geocaching and construct a path by sharing the information. The algorithm is implemented

over OMNeT++ and GNSSim, which allow building network simulations including GPS jamming and spoofing attacks.

Focusing on safety and security of UAVs, a resilient architecture for UAVs for dynamically managing the network even when subjected to an attack during a mission was proposed in [26]. The behavior of the proposed scheme is analyzed in two case studies, one involving a motor failure and the other involving a GPS spoofing attack. More recently, a mechanism utilizing smart contracts and Blockchain to render the drone network more resilient against attacks was proposed [27].

IV. SYSTEM DESIGN

In this section, we first describe the system setup used in creating the GPS attacks. Next, we explain the architecture and capabilities of our custom drone, "Tale".

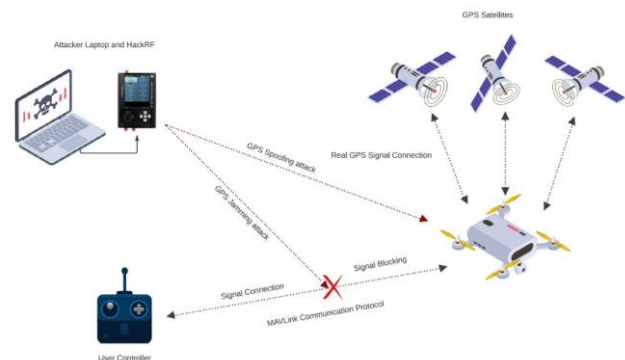


Figure 1. Overview of the drone GPS attack setup

4.1. Attack Design

As the drone relies on GPS for coordinate acquisition and control, it is possible to take over the drone with fake signals, guiding it towards a desired location. For this, the drone must lose connection to GPS signals and instead focus on a manipulated signal resembling the original GPS signal.

RF software-defined radios (SDR) can be configured to broadcast manipulated GPS signals. Our attack setup uses HackRF One, an open source SDR platform that covers the frequency spectrum of GPS transmissions. In our experiments, HackRF with the PortaPack companion has been used, to facilitate mobility. In addition, Mayhem firmware has been used with HackRF for investigating the signal flow and signal continuity on regular and irregular GPS signals. GUI-based attack implementation (using SigintOS) and command line-based attack implementation using GPSSDR-SIM [28] were performed; the former is used for viewing the trajectory and the latter is used for analyzing the signals. The setup for the GPS attacks is shown in Figure 1.

4.1.1. GPS Jamming Attack

This attack is aimed at blocking the GPS communication on the drone by drowning the GPS signals by the jamming signals, causing the operator to completely lose control over the drone, and potentially forcing the drone to land. An effective jamming attack is achieved by reducing the Signal-to-Noise-plus-Jamming Ratio (SNJR) of the target signal, to ensure that the target signal cannot be captured at the receiver. To achieve this, we increase the jamming signal strength to exceed the strength of the satellite signal on the drone. We assume that the signal strength of the GPS signals received by the drone in flight and the attacker on the ground (SDR device) are similar due to the proximity of jammers and receivers [31].

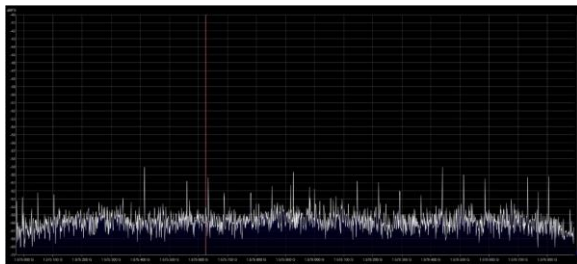


Figure 2. GPS jamming attack signal analysis. The peaks show the effect of noise generated by the attack

To generate the GPS jamming attack, we used the SigintOS to generate signals with 300 MHz bandwidth at 1.2-1.5 GHz frequency; the generated signals were transferred to HackRF over a USB connection. On the HackRF, signal was transmitted with an initial transmission power, and in a feedback loop the power of the signals were gradually increased until the receiver locked onto these new signals, causing the drone to begin its landing process. Figure 2 depicts the signal during the GPS jamming attack captured using SDRSharp software, where the peaks show the effect of noise generated by the attack. A flowchart of the attack generation and the drone behavior during the GPS jamming attack is illustrated in Figure 3.

Another critical condition in the success of a jamming attack is timing, *i.e.*, when and for how long is the exposure to jamming signal observed. There are different jamming types in the literature; two of them have been considered in this work, namely *constant jamming* and *periodic pulse jamming* attacks. With *constant jamming*, the jammer broadcasts a powerful signal continuously, to completely block the target device's packet reception. With *random jamming*, a jammer generates signals for random periods and turns to sleep for the rest of the time. *Periodic pulse jamming* is a variant of *random jamming*, with jamming and sleeping cycles alternating periodically. While the continuous approach is more effective, it consumes more energy compared to jamming in intervals; we

have observed the impact of both approaches on the drones.

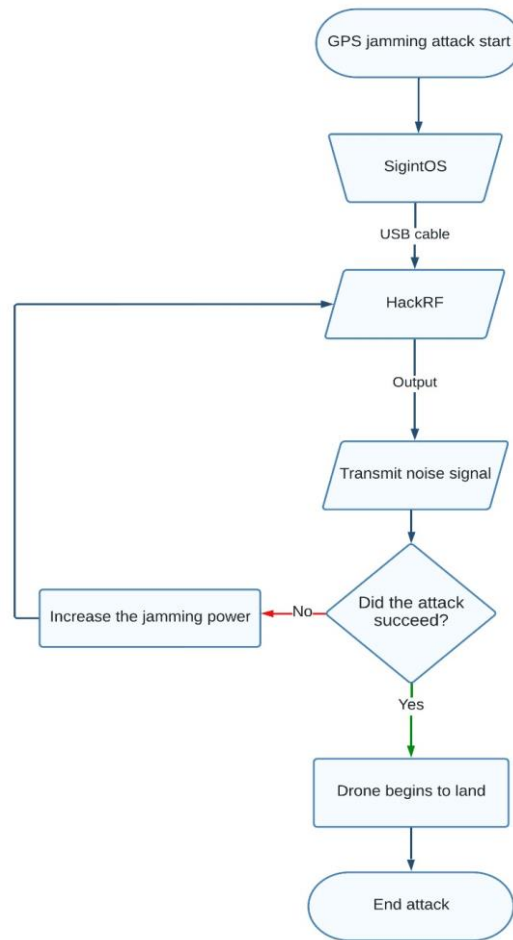


Figure 3. Flow chart depicting the steps of the jamming attack

4.1.2 GPS Spoofing Attack

For this attack, we provide the drone the GPS coordinates of a no-fly zone, *i.e.*, *geofence zone*, to force the drone to land immediately. A no-fly zone is an area of airspace where drones are allowed to fly only with special permits. While the targeted drone is flying, fake GPS signals are transmitted to indicate that the drone has entered a no-fly zone.

In our experiments, the GPS-SDR-SIM software is used by the HackRF device to create a GPS baseband signal stream that could be converted to RF using the SDR platform. The generated GPS broadcast ephemeris indicates the GPS satellite constellation with fake coordinates; this signal can be utilized to define a stationary point or a trajectory.

Different drones may be built and programmed differently; for example, an attack using an authorization zone might land a drone but not another, or some drones may have unlocked some geofence zones. Hence, the experiments are repeated using the coordinates of different geofence zones and permitted

flying areas till the spoofing attack is successful. A detailed flowchart of the attack generation and the drone behavior during the GPS spoofing attack is illustrated in Figure 4.

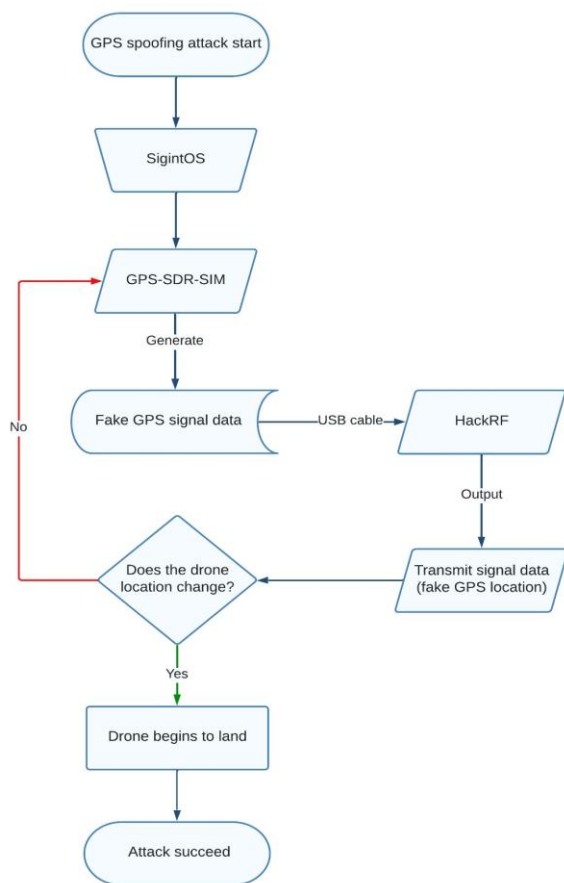


Figure 4. Flow chart depicting the spoofing attack

4.2. The Design of “Tale”

Tale is developed on a drone frame using different electronic cards and components containing Raspberry Pi 4, flight control board, Raspberry Pi 4G/LTE Cellular Modem Kit, and radio telemetry toolkit. The drone core builds on Raspberry Pi 4. From among the open-source autopilot projects (e.g., ArduPilot, Paparazzi UAV, Dronecode, LibrePilot, PX4), PX4 autopilot [29] was chosen since it offers a versatile collection of tools for drone developers and provides easy integration with the other components in Tale system such as the Ground Control Station (GCS) (i.e., Mission Planner) and the communications protocol. Micro Aerial Vehicle Link (MAVLink) [30] protocol is used for establishing and retaining connection with the Mission Planner. In terms of Flight Control circuit board, Pixhawk PX4 Flight Controller Autopilot PIX 2.4.8 was used on Tale; it serves as a hub for other peripherals such as the GPS module, Radio Telemetry, Raspberry Pi 4G LTE Cellular Modem Kit, and

different sensors. A summary of the hardware components of Tale are listed in Table 1 and Figure 5 demonstrates the main hardware components on the physical drone. Tale’s software components are summarized in Table 2.

Table 1. Tale Hardware Components Specifications

Hardware	Specification
Raspberry Pi	Ver. 4, 4GB
Flight Control Board	Pixhawk PX4 2.4.8
GPS module	u-blox NEO-M8N, FW SPG 3.01
Radio Telemetry	CUAV P9 Radio Telemetry
Raspberry Pi 4G-LTE Cellular Modem Kit	Sixfab Raspberry Pi 3G/4G & LTE Base HAT

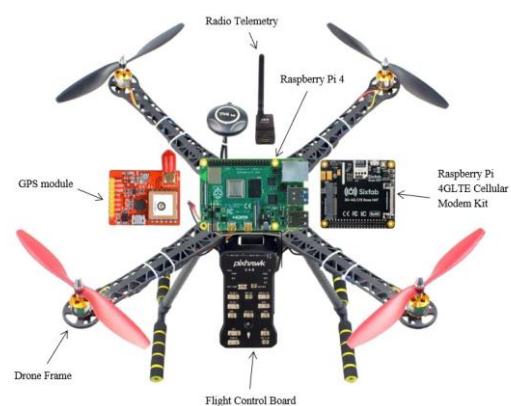


Figure 5. Tale system hardware overview

Table 2. Tale Software Components Specifications

Component	Specification
Raspberry Pi OS	Debian v11, Kernel v5.15
Mission Planner	Ground Control Station v1.3.77
PX4-Autopilot	Flight control solution v1.12.3

For communications, Tale comprises a GPS module as well as a cellular connection. The Sixfab 3G/4G/LTE Base HAT enables the Raspberry Pi to connect to the cellular data network. The CUAV P9 data link communication module is used for radio telemetry; it is compatible with the Pixhawk flight control board and supports long range. The module can operate at a variety of frequencies for 3G and LTE. For GPS, the u-blox NEO-M8N GPS module is used. In addition to yielding high positioning accuracy in urban and rural areas with varying signal strengths, the module also supports GPS signal attack detection. Tale also incorporates a set of sensors, such as LiDAR, gyroscope, accelerometer, and piezoresistive accelerometers. Figure 6 depicts the system architecture of Tale.

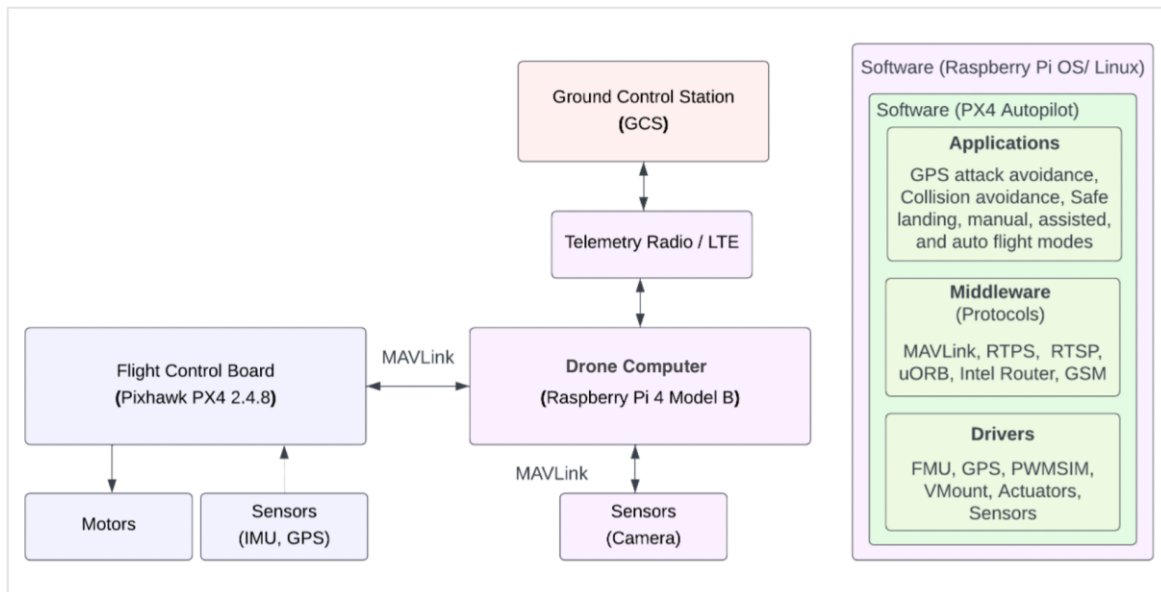


Figure 6. Tale system architecture

4.2.1. Detecting GPS Attacks

On Tale, the detection of GPS spoofing attacks relies on phase delay measurements. The detection thresholds for spoofing are defined. If the phase delay difference between the received GPS signals and the original signal are below the defined threshold, spoofing detection event is raised. The probability of spoofing detection becomes greater when combined with selecting accurate thresholds that are inclusive of potential phase delays. Figure 7 shows the signal during the GPS spoofing attack phase, which was performed using SDRSharp software, where the peak indicates the start of the attack.

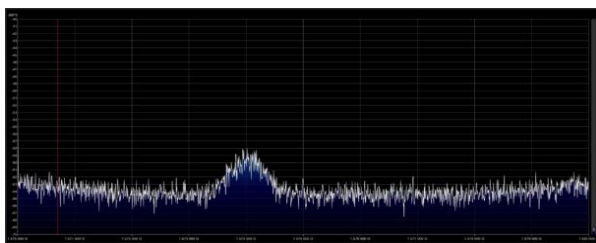


Figure 7. GPS spoofing attack signal analysis on Tale

The effectiveness and reliability of this method have been quantified in terms of the ratio of false alarms and the probability of counterfeit signal detection. False alarm or inaccurate detection may happen in the case of the GPS module receiving physical damage, in the presence of a GPS transmitter and receiver satellite dish nearby, or if the phase delay differences between received legitimate satellite signals are below the specified threshold. Through several experiments, Tale exhibited 99% spoofing detection accuracy when the carrier to noise ratio was at least 43 dBHz. The flowchart of the developed detection method is in Figure 8.

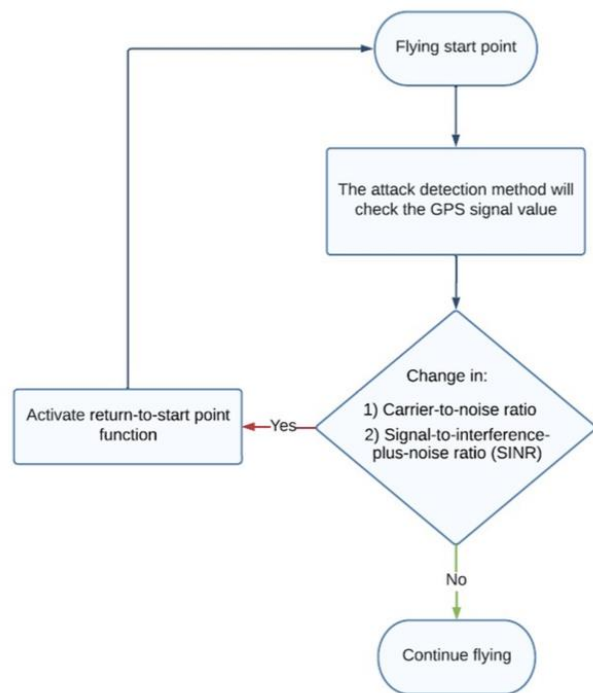


Figure 8. Tale GPS attack detection method flowchart

4.2.2. Return-to-Start Function

As Tale starts flying, it continuously synchronizes the GPS coordinates in real-time and records the distance and direction information acquired via the GPS. Tale records the direction changes at 45° and 90° angles according to the device orientation and motion. Towards this, Tale benefits from the integration of and the communication between the PX4 autopilot and the ground station Mission Planner. Tale sensors including the GPS work all together to provide the needed data and with the use of the flight control board (PIXHAWK PX4), the latitude, longitude, altitude, the angles

between the waypoints, and the distance between the waypoints are calculated. Tale stores the computed data and communicates it to the Mission Planner. Figure 9 shows a screenshot from Mission Planner, displaying some of the computed data that Tale utilizes in its Return-to-Start function.

Tale’s recovery solution depends only on the previously saved data to make its way back to the start point. As soon as a GPS jamming or GPS spoofing attack is detected, Tale disables the GPS function and navigates using the (inverse) directions and distances recorded during the flight. For example, if it flew with 10 m/min south(-z) for 10 minutes, it would fly back with 10 m/min for 10 minutes in the north direction (z) right after disabling the GPS. Using this unique autopilot code, Tale is able to safely reach its starting point independently from any control signals.

The Return-to-Start function depends on the Alternate Angles Theorem, which states that when two parallel lines are cut by a transversal, then the resulting alternate interior angles or alternate exterior angles are congruent. Tale records its flight route using its compass, since relying on the GPS coordinates would be erroneous in case of jamming or spoofing attacks.

V. EXPERIMENTS

We have designed a setup for evaluating the behavior of our custom developed drone, Tale, under GPS jamming and GPS spoofing attacks. To assess the observed behavior, we have performed the same set of experiments on a COTS (commercial off-the-shelf) drone as well, which allowed us to observe and discuss the behavior of both drones under attack. Figure 11(a) shows the drones’ planned route for the experiments, in terms of a series of four waypoints described in GPS coordinates.

GPS jamming was performed by signaling the L1 frequency at 1.575.420.000 Hz and L2 frequency at 1.227.600.000 Hz. In the GPS jamming attack experiments, four different attack strategies are applied, with the signals being generated according to the intervals listed in Table 3. The first three types aim to observe the behavior of the devices under test when jamming attacks are launched at different times and for different durations. Some drone types try to re-connect

to controller upon regaining GPS connectivity; our experiments were repeated with varying attack and pause times, and we present the three scenarios that present different behaviors. The fourth jamming type transmits the jamming signal for the duration of the attack.

In the spoofing experiments, the coordinates of different geo-zones were specified to the target. We have experimented with fake GPS coordinates representing “permitted zones” (*i.e.*, areas where flying a drone is allowed according to local regulations), “restricted zones” (*i.e.*, areas where drone flights are restricted or subject to specific conditions such as altitude, time of day, or obtaining special permissions from aviation authorities) and specifically “altitude zones” (*i.e.*, areas with restricted flight altitude), and “authorization zones (*i.e.*, areas where drone flights must be explicitly authorized by aviation authorities). In these experiments, the target drones were attacked for 2 minutes, with 15 seconds of attack and 15 seconds of pause duration. During the attack, the victim notices a sudden change in the reported GPS location.

Table 3. GPS Jamming Attack Time Intervals

Jamming Type	Attack Time	Pause Time	Total Observation Duration
Pulsed jamming #1	3 sec.	2 sec.	3 min.
Pulsed jamming #2	5 sec.	5 sec.	3 min.
Pulsed jamming #3	10 sec.	10 sec.	3 min.
Continuous jamming	3 min.	-	3 min.

5.1. GPS Navigation Attacks on Commercial Drone

The first drone used in the experiments is a commercial over the counter UAV. This device was chosen due to being relatively inexpensive and supporting a functionality that enabled it to fly back to the point where it last received a moderately strong GPS signal. The drone relies on the controller to direct its movement. In addition, the drone also relies on data from onboard sensors such as GPS and barometer readings to maintain a steady flight; in these experiments, it was configured to be controlled only via GPS.

	Bu	Delay				Lat	Long	Alt	Frame	Beme	Ust	Asax	Grad %	Angle	Mesa	AZ
1	WAYPOINT	0	0	0	0	39,8373307	32,8097865	100	Relative	X	🏠	🏠	713...	90,0	100,0	38
2	WAYPOINT	0	0	0	0	39,8394028	32,8107601	100	Relative	X	🏠	🏠	0,0	0,0	244,9	20
3	WAYPOINT	0	0	0	0	39,8401277	32,8101057	0	Relative	X	🏠	🏠	-10...	-45,6	140,1	325
4	WAYPOINT	0	0	0	0	39,8398764	32,8088397	100	Relative	X	🏠	🏠	89,6	41,9	149,9	256

Figure 9. Mission Planner data received from Tale drone

5.1.1. GPS Jamming Experiments

In the first experiment (*i.e.*, pulsed jamming #3), a periodic GPS jamming attack was initiated, with jamming signal transmission for 3 seconds and pausing for 2 seconds, repeating for a total duration of 3 minutes. During the 3-second interval where the jamming signal was transmitted, the connection between the drone and the GPS controller was blocked, and the drone remained to hover stable since it lost its communication. During the 2-second intervals where the attack was stopped, it was observed that the drone continuously sought to reconnect with the controller, intermittently succeeding and failing. Within this attack-paused interval when the drone reconnected to its controller, the user was able to move the drone, but it instantly stopped again with the next attack interval.

A similar pattern was observed in the second experiment (*i.e.*, pulsed jamming #3), where it was observed that the drone stopped its flight movement and remained to hover stably for 5 seconds, then regaining connection with the controller when the attack was paused where the flight movement could resume until it was re-attacked. It was observed that the drone was able to successfully reconnect to the controller approximately 2.5 seconds after the attack was paused; thus, while the connectivity was intermittent in experiment #1, it always succeeded in experiment #2.

In the third experiment (pulsed jamming #3), the behavior changed as the jamming attack duration was longer (10 seconds). This time the drone landed in the area it was in within the 10-second attack interval, then re-connecting to its controller in the pause interval and taking off to continue flying again, until the next attack period.

Finally, in the fourth experiment, after the jamming attack that started and continued without stopping, the drone landed in the area it was in, and did not fly again as it completely lost its communication signal.

5.1.2. GPS Spoofing Experiments

Upon losing GPS connection, this drone is able to resume flight once it reconnects to GPS; hence, GPS spoofing attack has been repeated in three different

experiments to assess behavior with different attack durations.

In the first experiment, the GPS spoofing attack was launched by transmitting fake GPS coordinates for a *Permitted* flying area for 15 seconds, and as a result, the drone could not be controlled by its user for the duration of the attack. After the 15-second interval, it was observed that the drone control resumed normally.

In the second experiment, the GPS coordinates for an *Authorization Zone* were transmitted. As a response, a warning was prompted to the user to control the drone to leave the area within 30 seconds. For the duration of 15 seconds of attack time, communication could not be established between the user and the drone, but as soon as the attack stopped, for the following 15 seconds the communication was re-established, and the drone was allowed to leave the area.

In the third experiment, a *Restricted Zone* fake GPS coordinates were transmitted during the attack. As a result, a 15 seconds of signal communication was lost again, and when the attack ended the communication was re-established with the drone, and control was restored.

Several repetitions of these experiments demonstrated that this drone always landed upon experiencing a spoofing attack. A capture retrieved from its user application (Figure 10(a)) shows the real location of the drone, before any attack occurred, demonstrating the change of drone location due to the GPS spoofing attack in the second phase of the experiment, more precisely, it shows how the fake GPS signals manipulate a target receiver's position during the attack time (Figure 10(b)).

As we mentioned, the selected commercial drone was in fact potentially capable of moving to the *last known good* location. Our experiments showed that this feature relies on GPS coordinates to complete. This renders the drone vulnerable to being damaged or captured, shall it lose its GPS connectivity upon a malicious attack that transmits wrong coordinates for 10 seconds or more.

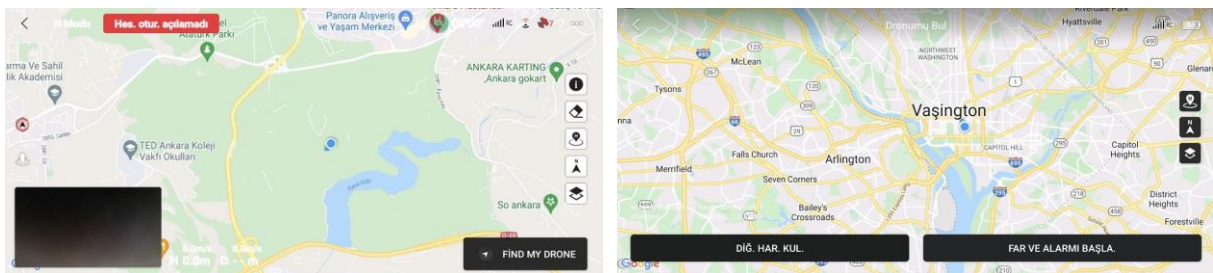


Figure 10. The actual and spoofed locations with the commercial drone

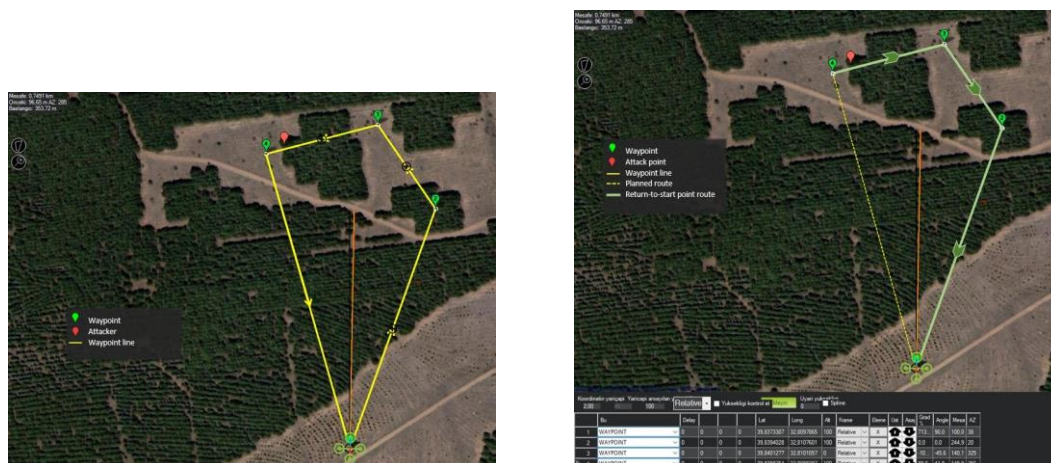


Figure 11. The planned drone flight route using Mission Planner, and the route that was followed with Return-to-Start functionality

5.2. GPS Navigation Attacks on Tale

In the following, we explain how Tale performed under both attack scenarios; and in particular, we validate the performance of Return-to-Start functionality.

5.2.1. GPS Jamming Experiments

The same four set of jamming experiments (as listed in Table 3) have been repeated on Tale.

For the first experiment, the plan was to repeat the same scenario of initiating a GPS jamming attack every 3 seconds and stopping for 2 seconds, repeatedly for a total of 3 minutes. However, the drone signal was almost immediately cut when it received the attack. Even after the attack stopped, Tale could not regain its communication signal with its user. The drone returned to the flying position from where it started, confirming the successful execution of the Return-to-Start function.

Similarly, in both the second experiment (jamming for 5 seconds and pausing for 5 seconds, for a total of 3 minutes) and the third experiment (jamming for 5 seconds and pausing for 5 seconds, for a total of 3 minutes), Tale could not regain connection to its user and successfully returned to the flying start position using the Return-to-Start function.

In the fourth experiment, after the continuous jamming attack was launched, Tale once again lost its

communication signal with its user and flew right back to the starting position. Figure 11(b) shows how Tale reacted to the GPS jamming attack using the Return-to-Start function.

5.2.2. GPS Spoofing Experiments

In these experiments, fake GPS signals corresponding to different GEO zones such as Restricted Zones, Altitude Zones, and Authorization Zones were transmitted in the launched attack.

First, the GPS spoofing attack was started by transmitting fake GPS coordinates for a *Permitted* flying area. Tale drone lost the GPS signal in its first seconds and consequently, stopped all connections with the user controller. Tale returned to its start location according to the Return-to-Start function, following the inverse path from the moment it received the attack.

In the next experiment, the fake GPS attack location was established to be an *Authorization Zone*. The communication signal was abruptly cut, and the drone returned to the initial position as in the first experiment.

Finally, *Restricted Zone* GPS coordinates were transmitted in the fake GPS attack. As was observed in the previous experiments, the signal was disconnected without warning and the drone returned to the point it started flying from.

5.3. Observations

We summarize our observations on the responses of the two drones to GPS navigational attacks and highlight the benefits of Tale's Return-to-Start function.

The same implementations of GPS jamming and GPS spoofing attacks were repeated on both devices. Overall, the drones were affected from the attacks in different ways. When the GPS jamming attack was performed in periodic pulses in the first three experiments on the COTS drone, the drone was temporarily able to restore communication with its controller and resume flight towards the last known good location, until it was attacked again. With the continuous attack, as the drone did not have GPS connectivity, it landed where it was attacked. On the other hand, Tale was affected similarly from both continuous jamming and periodic pulse based jamming attacks. Differing from the COTS drone, the communication between the controller and the drone would not be restored when the attack stopped. In both cases, Tale blocked the connection as soon as it detected an attack, and it continued its flight using the Return-to-Start function. Hence, the number of the received attacks did not make a difference for Tale.

When a GPS spoofing attack occurs and the fake GPS signals reach a drone, the GPS location appears as if the drone is in a Restricted Zone, an Altitude Zone, or an Authorization Zone. The geolocation fields in the COTS drone software prevent it from flying in those GEO zones, mostly giving a short warning, or forcing it to land at its current location. However, since those GEO zones are not specified in the software of the Tale drone, it perceives the GPS spoofing attack as an abnormal signal change, leading the Tale drone to return to the point of departure by turning off the GPS module and only depending on its Return-to-Start function to navigate. This feature offers the drone a way to recover from jamming or spoofing attacks.

It was observed that the Tale drone reacted identically to the attacks with different GEO zones. At the same time, it was made clear that at the time of an attack, Tale would lose its control signal with its user and would cease to connect again, until completing its way back to

the starting position only relying on the built-in Return-to-Start function.

No matter what type of navigational attack Tale received, when responding to one, it returned to the point of departure without using signal communication, solely depending on its Return-to-Start functionality. Tale drone was able to detect and recover from the GPS signal attacks, ultimately evading being captured. Table 4 summarizes the differences between the two experiments and how each drone reacted to the GPS navigational attacks.

VI. CONCLUSION

Unmanned Aerial Vehicles (UAVs) or drones find an increasing number of use cases in communications, surveillance, delivery, agriculture and airborne fog computing systems. The continuous functionality and mobility of drones are critical in each of these scenarios; unfortunately, GPS navigational attacks on such drones are rather easy to achieve.

In this work, we implemented GPS navigation attacks on a commercially available drone and a custom drone named Tale that was developed to counter the effect of navigational attacks with its recovery mechanism. Tale solution design ensures that the drone recovers from GPS jamming and spoofing attacks, alleviating vulnerability against property theft and privacy violation. Two distinct types of signal attacks have been designed, and related experiments have been conducted, demonstrated, and analyzed on these two drones. The attack framework was mainly created and performed to assess the drones' reaction and how they behave in critical conditions such as signal blockage. To bring things together, and upon analyzing the facts, a comparison between the two drones against GPS attacks was conducted and presented.

This paper aims to contribute to the growing body of research addressing the critical issue of drone security by experimentally analyzing the detection of and recovery from spoofing attacks. As drones become increasingly integral to our daily lives, safeguarding their operation from adversarial interventions becomes imperative, underscoring the urgency and relevance of our investigation in the face of emerging security threats.

Table 4. Summary of Comparison Between the Two Drones That Were Tested

Comparison Points	COTS Drone	Tale Drone
GPS spoofing attack	Forced to land	Evaded landing
GPS jamming attack	Forced to land	Evaded landing
Landing	Yes	No
Attack detection	Yes	Yes
Recovery possibility	Low	High
Return-To-Start function	-	Activated in response to attacks
GPS related vulnerability	Depends on GPS connection; vulnerable to GPS attacks.	-
GPS communication in flight mode	Yes	Yes
GPS communication when returning to start point or last good coordinates	Yes	No
Possibility of returning to start	Low	High

There are two limitations of this study that provides an opportunity for future work: First, currently Tale cuts off its communication signal upon inferring an attack, and no signal can reach the drone until it goes back to the starting point, even if the threat has passed. Second, if the battery is not enough for the returning distance, the drone will have to force land or fall since it exhausts its battery on the return path. Future improvements can include estimating the distance that can be traveled with the remaining battery and warning the user to land at a waypoint on the return path before reaching the start location if the battery is insufficient to fly the drone back to the start location.

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Elektrikli Araçlarda Batarya Kutusu İmali İçin Termal Özellikleri İyileştirilmiş Hibrit Polimer Kompozitlerin Geliştirilmesi ve Mekanik Özelliklerinin İncelenmesi

Development of Hybrid Polymer Composites with Improved Thermal Properties and Investigation of Their Mechanical Properties for Battery Module Case Manufacturing in Electric Vehicles

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Öz

Elektrikli araçlar, ulaşımın sürdürülebilirliği için oldukça önemlidir ve içten yanmalı motorlu araçlar gibi fosil yakıtlar kullanılmadıklarından çevreye zararlı gaz salınımında bulunmamaktadırlar. Elektrikli araçların bu özelliğinden faydalanmak için kullanıcılarını teşvik etmek amacıyla çeşitli çalışmalar yapılmaktadır. Bu çalışmada, elektrikli araçlardaki batarya kutusu üretimi için termal iletkenliği ve darbe direnci iyileştirilmiş polimer esaslı hibrit kompozit bir malzeme geliştirilmesi amaçlanmıştır. Yaygın kullanımı ve üretim kolaylığı nedeniyle matris olarak Poliamid 6 (PA6) kullanılmış, termal iletkenliğini artırmak için ise hegzagonal bor nitür (hBN) ve grafen nanopulcuk (GnP) kullanılmıştır. Bu malzemelere ek olarak, zeminden kaynaklanabilecek potansiyel darbe hasarı durumunda dayanıklılığı artırmak için bir stiren-etilen-bütadien-stiren (SEBS) elastomer takviyesi eklenmiştir. Kompozitler ekstrüzyon ve enjeksiyon kalıplama ile üretildikten sonra, numunelerin mekanik testleri; üç nokta eğme ve Izod darbe dayanımı testleriyle yapılmıştır. Kütlece %30 hBN kullanılması durumunda eğilme dayanımı ve modülünde sırasıyla %22 ve %101.1'lik bir iyileşme sağlanmıştır. Kütlece %2.5 GnP kullanılması durumunda eğilme dayanımı ve modülü değerlerinde sırasıyla %14.1 ve %55.6'lık bir iyileşme sağlanmıştır. Kütlece %5 SEBS kullanıldığında darbe dayanımını değerinin %58.5 arttığı tespit edilmiştir. Ayrıca termal karakterizasyon için diferansiyel taramalı kalorimetre analizleri ve termal iletkenlik ölçümleri yapılmıştır. Kütlece %30 hBN eklendiğinde termal iletkenliğin %194.3 arttığını görülmüştür. Daha sonra, malzemelerde hasar mekanizmalarını incelemek için kırılma yüzeyleri taramalı elektron mikroskopuyla (SEM) incelenmiştir. Son olarak, Halpin Tsai (HT) yaklaşımı kullanılarak kompozitlerin mikromekanik modelleri kurulmuştur. Bu modellerin doğruluğunu tespit etmek için ise deneysel verilerle karşılaştırma yapılmıştır.

Anahtar Kelimeler: Elektrikli araçlar, Batarya kutusu, Hegzagonal bor nitür, Grafen nanopulcuk, Hasar mekanizmaları

Abstract

In the realm of transportation sustainability, electric vehicles play a crucial role. The aim of this article was to create a hybrid composite material using polymers that would have enhanced heat conductivity and impact resistance. This material would be used to manufacture battery casings for electric cars. Polyamide 6 (PA6) was selected as the matrix material owing to its convenient manufacturing process and extensive application. Additionally, hexagonal boron nitride (hBN) and graphene nanoplatelets (GnP) were incorporated to enhance the thermal conductivity of the matrix. Furthermore, to enhance the structural integrity against potential ground impact damage, a styrene-ethylene-butylene-styrene (SEBS) elastomer reinforcement was used alongside the aforementioned elements. Following the extrusion and injection molding processes, the composites underwent mechanical testing using three-point bending and Izod impact tests. When 30 wt.% hBN was added, there was a 22% improvement in flexural strength and a 101.1% improvement in flexural modulus. Similarly, when 2.5 wt.% GnP was added, there was a 14.1% improvement in flexural strength and a 55.6% improvement in flexural modulus. Then, thermal analyses were performed through Differential Scanning Calorimetry (DSC) and thermal conductivity measurements. Furthermore, it was observed that the addition of 30 wt.% hBN resulted in a significant increase of 194.3% in thermal conductivity. Subsequently, the fracture surfaces were subjected to scanning electron microscopy (SEM) in order to investigate the underlying causes of material damage subsequent to failure. The Halpin-Tsai (HT) micro-mechanical model was used to estimate the modulus of the composites.

Keywords: Electric cars, Battery case, Hexagonal boron nitride, Graphene nanoplatelets, Failure mechanisms

I. GİRİŞ

İklim değişikliği günümüzün en önemli problemlerinden biridir ve fosil yakıtların kullanılması sonucunda ortaya çıkan karbondioksit emisyonu bu problemin ana nedenlerinden biridir. 1970'ten bu yana CO₂ emisyonları yaklaşık %90 artış gösterirken, ulaşım sektörü bu emisyonunun %25'inden sorumlu olarak karşımıza çıkmaktadır [1,2]. Karbondioksit emisyonunu azaltmak için otomotiv endüstrisinde köklü değişiklikler yapılmaktadır. İçten yanmalı motorlardan elektrik motorlarına geçiş, bu değişikliklerin en önemlilerinden biri olarak kabul edilmektedir. İçten yanmalı motorlu araçlara kıyasla, elektrikli araçlar düşük karbon salınımına neden olurlar ve aynı zamanda yakıt verimleri yüksek olup daha az karmaşık yapıya sahiptirler. Öte yandan, elektrikli araçlar içten yanmalı motorlu araçlara kıyasla daha pahalıdır. Birçok ülke yönetimi, elektrikli araçların kullanımını teşvik etmek için elektrikli araçlara yönelik vergileri düşürme ve elektrikli araçlar için ayrılmış otopark alanları oluşturma gibi avantajlar sağlamaktadır. Ayrıca, Avrupa Birliği 2035'ten itibaren benzinli ve dizel araçların satışının yasaklanmasına karar vermiştir [3]. Bu karar, elektrikli araçlara geçişi hızlandırmayı ve karbon emisyonu kaynaklı iklim değişikliği ile mücadeleyi hızlandırmayı amaçlamaktadır. Bu karar paralelinde elektrikli araçların kullanımının artışı ve araç maliyetlerinin düşüşü beklenmektedir. Tüm bu durumlar göz önüne alındığında, elektrikli araçların öneminin gün geçtikçe daha da artacağı öngörülmektedir.

Otomotiv sektöründeki köklü değişiklikler ve sektörle ilgili alınan kararlar ile birlikte otomotiv firmalarının da yatırımları elektrikli araçlara doğru yönelmektedir. Tesla, Lucid Motor ve TOGG gibi doğrudan elektrikli araçlara yoğunlaşan firmaların yanında Ford, BMW ve Volkswagen gibi firmalar da elektrikli araçlara önemli yatırımlar yapmaktadır. Yatırım odağının bu yöne kaymasıyla beraber elektrikli araçlar için en kritik konulardan biri olan batarya teknolojisiyle ilgili çalışmalar da hızla ilerlemektedir. TOGG, Gemlik'te açtığı araç üretim tesislerinin yanı sıra bir batarya geliştirme ve üretim kampüsü de açarak bu alanda önemli adımlar atmıştır [4]. Batarya teknolojisindeki şarj süresi, sürüş menzili gibi kısıtlar ve müşterinin elektrikli araçlarda düşük maliyet beklentileri otomobil üreticilerini farklı türde elektrikli araçlar üretmeye itmektedir. Bu sebeple araç üretiminde şarj süresi, sürüş menzili, yakıt fiyatları ve çevresel kaygılar gibi değişkenler de dikkate alınmaktadır. Bu değişkenler, elektrik enerjisinin depolanma yöntemiyle doğrudan ilişkilidir. Elektrikli araçlar, içten yanmalı motorlu araçlardaki yakıt tankının rolünü üstlenen yüksek voltajlı bataryalar kullanır. Bu bataryalar, elektrik motoru için elektriğin depolanmasından direkt olarak sorumludur. Elektrikli araçlarda, yüksek enerji yoğunluğunu sağlayabilme ve uzun kullanım ömürleri nedeniyle, lityum iyon piller (LİP) batarya sistemlerinde sıklıkla kullanılmaktadır. Lityum iyon

pillerin şarj edilebilir olması ile beraber temiz enerjinin kullanımında da kritik bir rolü vardır [5]. Özellikle elektrikli araçların kullanımının yaygınlaşması için pillerin yüksek verimlilikte çalışmaları beklenmektedir. Bu bağlamda pil verimliliği ile pil çalışma sıcaklığı arasında önemli bir ilişki vardır. Piller normal şartlarda 15 ile 40°C arasında çalışmaktadır ($\pm 5^\circ\text{C}$) ve bu aralık dışında kullanıldıklarında, pil ömrü ve performansı önemli ölçüde düşer [6]. Ayrıca, Joule etkisi nedeniyle içerisinden akım geçen malzemelerde ısınma gözlenir ve dolayısıyla pillerin çalışması esnasında sıcaklık artışı gözlenmektedir. Pil çevresindeki sıcaklık, çalışma esnasında güvenli çalışma eşik değerlerinden ($T > 90^\circ\text{C}$) daha yüksekse, araçta bir kaza riski meydana gelmektedir [6]. Bu riskle başa çıkmak için, araçlar pil sıcaklığını belirli bir aralıkta tutmak için bir pil yönetim sistemi (BMS) ile donatılmıştır. Bu teknoloji, aşırı ısınmış pilin sıcaklığını düşürmek için hava ile soğutma benzeri bir yaklaşımı kullanır. Ancak, hava ile soğutma termal iletkenliğin düşük olduğu malzemelerde teknik beklentileri karşılamayabilir. Bu durumda, soğutma için alternatif bir yöntem ise kanallar aracılığıyla soğutucu akışkan dolaşımı yapmaktır. Bu yaklaşım daha iyi bir soğutma performansı sağlar ancak yüksek maliyeti de beraberinde getirir. Pil sisteminde soğutma bir bütün olarak düşünüldüğünde; pillerin, batarya kutusunun ve tüm elektronik bileşenlerin termal iletkenlik katsayısı ısı transferi açısından oldukça önemlidir.

Piller, araçta batarya kutusu adı verilen bir bölmede bulunur. Batarya kutusu, batarya sisteminde hem termal özellikler hem de mekanik özellikler açısından oldukça önemlidir. Endüstride batarya kutusu malzemesi olarak alüminyum sıklıkla kullanılmaktadır. Alüminyum hem yüksek termal iletkenliğe sahip olması hem de ucuzluğu nedeniyle tasarım açısından isterleri önemli ölçüde karşılamaktadır [7]. Diğer bir ister ise batarya kutusunun hafifliğidir. Elektrikli araçlar, içten yanmalı motora sahip araçlara göre yaklaşık 300 kg daha ağır gelmektedir. Bu farkın kaynağı, araçlarda kullanılan batarya sistemidir [8]. Bu durumda alüminyuma alternatif olarak polimer kompozit malzemelerin kullanılması, termal ve mekanik özellikleri sağlamanın yanı sıra ağırlık azaltımı konusunda da faydalı sonuçlar doğuracaktır. Batarya termal yönetim sistemi için, soğutma hem taşınım hem de iletimle gerçekleştiği için batarya kutusunun termal iletkenliği önemli bir parametredir. Literatürde farklı bileşenler kullanılarak termal iletkenliği iyileştirmeye yönelik birçok çalışma yapılmıştır. Bu çalışmalarda genellikle termal iletkenliği artıran takviyelere odaklanılmıştır. Seramik esaslı olarak; bor nitrür (BN) [9] ve silika [10], karbon esaslı olarak; grafit [11] ve grafen oksit [12] termal iletken takviye malzemesi olarak yaygın olarak kullanılmaktadır. Temel2019 senesinde yaptığı bir çalışmada, parafine %7 oranında Grafen nanopulcuk (Graphene nanoplatelet/GnP) ekleyerek, sıvı ve katı

fazdaki termal iletkenlikteki değişimi incelemiştir. Elde ettiği sonuçlara göre, sıvı ve katı fazda termal iletkenliğin sırasıyla %130 ve %230 iyileştiğini tespit etmiştir [13]. Yüksek termal iletkenlik sunan dolgulardan biri de grafen benzeri atomik yapısı nedeniyle genellikle beyaz grafen olarak da adlandırılan hegzagonal bor nitrür (hBN)'dür. hBN katmanlı yapısı nedeniyle polimer matrisinde termal iletim ağları oluşturur ve ısı transferi sırasında termal direncin azalmasına neden olur [14]. hBN'nin oda sıcaklığında yaklaşık 550 W/mK düzlem içi termal iletkenlik değerine sahip olduğu tespit edilmiştir [15]. Bu özelliğinden dolayı hBN, termal iletkenliğin iyileştirilmesi ile ilgili çalışmalarda kullanılan önemli bir takviye malzemesidir. hBN'nin farklı kompozitlerdeki termal performansını inceleyen çeşitli çalışmalar bulunmaktadır. Gong ve arkadaşları tarafından yürütülen bir çalışmada, karboksil uçlu polibütadien (CTPB) ve hBN ile takviye edilen epoksinin termal iletkenliği incelenmiştir. Bu çalışma kapsamında, hBN'nin yüzey aktivasyonu için silan kullanılmış ve işleme tabi tutulmayan grup da kontrol grubu olarak incelenmiştir. hBN miktarlarının %10 ile %40 arasında değiştiği durumlar için termal iletkenlik ölçümleri yapılmıştır. Yüzey aktivasyonu yapılmayan kütlece %40 hBN takviyesi için termal iletkenliğin yaklaşık %200 arttığı, silan aktivasyonu yapılan kütlece %40 hBN takviyesi için ise termal iletkenliğin yaklaşık %300 arttığı gözlemlenmiştir [16].

Termal yönetim dışında, araç güvenliği de otomotiv endüstrisinde büyük öneme sahiptir. Otomobil kazalarından sonra, batarya sistemi hasar görebilmektedir. Kazalara bağlı hasar riskini azaltmak için, pillerin batarya kutusuna montajı kritik bir ve montaj genellikle iki farklı teknikte yapılır. İlk tekniğe göre, piller aracın ortasına T şeklinde monte edilir ve dış etkenlerden korunur. Ancak, bu düzenleme, araç içindeki alanın azalması nedeniyle yolcu konforunun azalmasına neden olabilmektedir. İkinci teknikte ise montaj katmanlar halinde yapılır. Bu yöntemle, yolcu için kalan iç mekân, T tasarımına kıyasla daha geniştir. Ancak, bu yöntemde, aracın zeminle olan mesafesi azalmaktadır. Azalan mesafe ile zeminden gelebilecek darbelerin hasara neden olması söz konusudur. Bu nedenle, batarya kutusunda kullanılan malzemenin olası hasar durumlarına karşı darbe dayanımı son derece önemlidir. Literatürde darbe dayanımını iyileştirmek üzerine yapılan çalışmalar bulunmaktadır. Gong ve arkadaşları, hBN miktarı arttıkça, hBN partiküllerinin matris malzemesine göre yüksek rijitliği nedeniyle kompozitin elastisite modülünü arttırdığını, ancak çekme, eğilme ve darbe dayanımının takviyesiz matris malzemesine göre kademeli olarak azalttığını gözlemlemiştir. Kütlece %40 hBN kullanıldığında, takviyesiz matrise göre çekme dayanımının %32, eğilme dayanımının %47 ve darbe direncinin %61 azaldığı görülmüştür [16]. Darbe dayanımındaki düşüşü telafi etmek için ise enerjiyi sönümleme konusunda etkili olan elastomerler yaygın olarak

kullanılmaktadır. Stiren Etilen Bütilen Stiren (SEBS), yüksek darbe dayanımı nedeniyle en sık kullanılan elastomerik malzemelerden biridir. Okan ve arkadaşları tarafından yapılan çalışmada, matris olarak kullanılan polipropilenin yanında kütlece %5 oranında SEBS kullanılması durumunda elde edilen termoplastik hibrit kompozitin darbe sönümleme performansının iyileştiği gözlemlenmiştir [17]. Öte yandan, SEBS tek başına kullanıldığında matrisle arayüzey bağlanma kuvvetinin kısıtlı oluşu nedeniyle, SEBS'in diğer malzemelerle arayüzey aktivasyonunu iyileştirmek için maleik anhidrit aşılantı polietilen (MAPE) kullanılmaktadır. Gao ve arkadaşları, kütlece %5 maleik anhidrit ile modifiye edilmiş SEBS'in termoplastik poliüretan karışımına eklenmesiyle darbe dayanımının %100 arttığını gözlemlemiştir [18]. Bir diğer takviye malzemesi olarak kullanılan GnP, yüksek mukavemeti ve rijitliği sayesinde polimerik malzemelerle beraber kullanıldığında matriste bir omurga görevi görür ve bu sayede mekanik özellikleri olumlu etkiler [19]. Okan ve arkadaşları tarafından yapılan bir çalışmada, homojen bir şekilde matrisle karıştırılmış GnP'nin eğilme dayanımı ve modülünü iyileştirdiği tespit edilmiştir [17].

Otomotiv sektöründe kullanılan polimerler incelendiğinde, poliamidler, mühendislik polimerleri arasında önemli bir grubu oluşturur. Poliamid ailesi içerisinde Poliamid 6 (PA6), beyaz eşya ve otomotiv gibi sektörlerde üretim kolaylığı, avantajlı mekanik özellikleri ve yüksek kimyasal direnci sayesinde sıklıkla kullanılmaktadır [20].

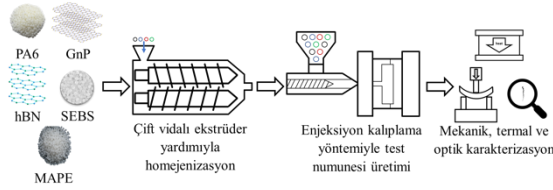
Yukarıda da önemli örnekleri verildiği üzere, hBN ve GnP'nin ayrı ayrı takviyesinin polimer kompozitlerin ısı ve mekanik karakteristiklerini nasıl etkilediğini inceleyen çalışmalar sıklıkla görülmüştür. Ayrıca, polimer matrislerine elastomerlerin eklenmesi sonucunda darbe direncinin değişimine yönelik çalışmalar da görülmüştür. Ancak, yazarlar, hBN, GnP ve SEBS takviyelerinin yüzey aktivasyon ajanlarıyla birlikte poliamid 6 matrisinde eş zamanlı kullanıldığı kompozitlerle ilgili çalışmalara rastlamamıştır. Ayrıca bu şekildeki hibrit kompozitlerde çoklu takviyelerin eş zamanlı kullanılmasıyla birlikte ortaya çıkabilecek sinerjik etkileri sistematik olarak inceleyen bir araştırma da bulunmamaktadır. Bu nedenle, bu çalışma, kompozitlerin imalatı ve sonrasında deneysel karakterizasyonlarının gerçekleştirilmesiyle elde edilecek sonuçlarla birlikte bu alandaki boşluğu doldurmayı amaçlamaktadır.

Bu çalışmada, üretilecek kompozit bileşimlerin belirlenmesinin ardından, PA6 matrisi, hBN, GnP, SEBS ve MAPE ile birlikte çift vidalı ekstrüder kullanılarak karıştırılmış ve kompozitler granül şeklinde imal edilmiştir. Daha sonra, bu granüllerden plastik enjeksiyon yöntemi kullanılarak test numuneleri üretilmiştir. Numunelerin imalatından sonra, üç nokta eğme testi, Izod darbe dayanımı testi, DSC analizleri,

termal iletkenlik ölçümleri ve mikroskopik gözlemler de dahil olmak üzere deneysel karakterizasyonlar gerçekleştirilmiştir. Sonrasında kompozitlerin mekanik özellikleri mikromekanik modeller kullanılarak belirlenmiş ve elde edilen sonuçlar deneysel verilerle karşılaştırılmıştır.

II. MATERYAL VE METOD

Bu çalışmanın genel ve basitleştirilmiş akış şeması Şekil 1’de verilmiştir. Bu çalışmada kullanılan PA6, Eurotec firmasından NB40 NL FY50 koduyla temin edilmiştir. PA6 malzemesi 1.16 g/cm³ yoğunluğa sahip olup, UL94 standardına göre yanıcılık açısından V2 olarak sınıflandırılmaktadır.



Şekil 1. Kompozit imalat ve karakterizasyon akış şeması

h-BN, Nanografi®’den NG04CO0301 ürün koduyla temin edilmiştir. Yoğunluğu 2.3 g/cm³, saflık derecesi %99.7’dir. GnP ise Nanografi® firmasından NG01GNP0109 koduyla tedarik edilmiştir. GnP’nin yoğunluğu 2.2 g/cm³, saflık değeri %99.9’dur. Yüksek grafen oranlarının beraberinde getirdiği aglomerasyon oluşturma ihtimalini azaltmak için COOH ile yüzey aktivasyonu gerçekleştirilmiş GnP’ler kullanılmıştır. SEBS G401.A82.N koduyla Elastron TR firmasından temin edilmiştir. SEBS, 0.89 g/cm³ yoğunluğa sahiptir. Bu çalışmada, SEBS ile PA6 arasındaki arayüzey etkileşimini arttırmak için yüzey aktivasyon ajanı olarak maleik anhidrit enjekte edilmiş polietilen (MAPE) kullanılmıştır. MAPE, ATABOND-1550 koduyla TMB Polimer firmasından temin edilmiştir. Çalışmanın deneysel kısmında, kompozit imalinde kullanılan takviyelerin, kompozitlerin mekanik ve termal özelliklerine etkisinin incelenmesi hedeflenmiştir. Bu sebeple 5 farklı kompozisyon belirlenmiştir. İlk olarak, takviyelerin yer almadığı %100 PA6 matris, referans grup olarak belirlenmiştir. Sonraki kompozisyonların hepsinde PA6 matris olarak kullanılmış olup, kütlece yüzde miktarı denge olacak şekilde ayarlanmıştır. PSM kompozisyonunda ise kütlece %5 oranında SEBS ve MAPE eklenerek SEBS’in etkisinin gözlemlenmesi hedeflenmiştir. Diğer bütün kompozisyonlarda SEBS ve MAPE aynı oranda kullanılmıştır. PHS30 kompozisyonunda ek olarak kütlece %30 oranında hBN kullanılmıştır. Bu kompozisyonla hBN’nin etkilerinin tesbiti hedeflenmiştir. Bir diğer kompozisyon olan PHS35 ile hBN’nin kütlece oranı %30’dan %35’e çıkartılmıştır. Bu kompozisyon ile hBN miktarının artışının deneysel sonuçlara etkisinin tespiti hedeflenmiştir. Son kompozisyonda ise içeriğinde kütlece %30 hBN kullanılan kompozisyona ek olarak kütlece %2.5 oranında GnP takviyesi yapılmıştır. Bu kompozisyonla

da GnP’nin kompozite etkisinin incelenmesi hedeflenmiştir. Kompozit kompozisyonları belirlendikten sonra imalat aşamasına geçilmiştir. Hazırlanan kompozitlerin isimleri ve içerikleri Tablo 1’de verilmiştir.

Tablo 1. Kompozisyon tablosu [21]

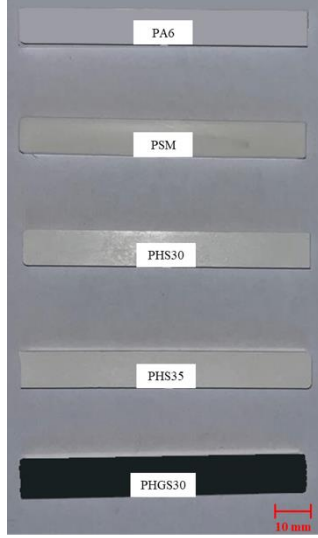
Kompozisyon Adı	PA6 (%k.)	hBN (%k.)	GnP (%k.)	SEBS (%k.)	MAPE (phr)
PA6	100	-	-	-	-
PSM		-	-	5	5
PHS30	Denge	30	-	5	5
PHS35		35	-	5	5
PHGS30		30	2.5	5	5

Kompozitlerin imalat süreci iki aşamada gerçekleştirilmiştir. İlk aşamada malzemelerin homojen bir şekilde karıştırılması amacıyla Leistritz ZSE 27 MAXX marka çift vidalı ekstrüder kullanılıp her kompozit için bileşik oluşturulmuştur. Kullanılan çift vidalı ekstrüderin vida çapı 28.3 mm, kovan çapı 28.5 mm ve vida uzunluğu 1358.4 mm’dir. Elde edilen bileşikler kullanılarak ikinci aşamada Bole BL90EKH/C220 marka cihaz kullanılarak plastik enjeksiyon yöntemiyle üretim gerçekleştirilmiştir. Kullanılan plastik enjeksiyon cihazının vida çapı 28.4, vida uzunluk/çap oranı 20’dir. Çift vidalı ekstrüderde homojen bir şekilde karıştırılan kompozisyonlar granül şeklinde enjeksiyon cihazına beslenmiştir. Yapılması planlanan testlerin standartlarına göre numuneler üretilmiştir.

Üretim aşamaları tamamlandıktan sonra deneysel karakterizasyonlar gerçekleştirilmiştir. Numunelere yoğunluk ölçümü, diferansiyel taramalı kalorimetre (DSC) analizi, termal iletkenlik ölçümü, üç nokta eğme testi ve Izod darbe dayanımı testi yapılmıştır. Yapılan tüm testler oda sıcaklığında gerçekleştirilmiştir. Malzemelerin yoğunlukları ISO 1181-1 standardına uygun olarak ölçülmüştür. Ölçüm için MatsuHaku GP-300E model cihaz kullanılmıştır.

Malzemelerin ısıl davranışını incelemek için DSC analizi yapılmıştır. Referans bir numune kullanılarak yapılan incelemede, DSC cihazında iki numune varken sıcaklık artırılarak veya azaltılarak numuneler arasındaki sıcaklık farkı kontrol edilir. Cihazdan ısıl enerjinin sıcaklıkla nasıl değiştiğini gösteren bir ısı akısı-sıcaklık eğrisi elde edilmiştir. Bu eğriyi kullanarak camı geçiş sıcaklığını bulabilmek için, oda sıcaklığında itibaren eğrinin eğiminin ilk defa gözle görülür şekilde değişim gösterdiği noktanın başlangıç ve bitiş noktalarını bağlayacak şekilde bir “onset” çizgisi çekildikten sonra bu çizginin orta noktasının eğri üzerinde tekabül ettiği noktaya karşılık gelen

sıcaklık değeri camsı geçiş sıcaklığı olarak belirlenmiştir. Termal iletkenlik ölçümleri için disk şeklindeki numuneler kullanılmıştır. Numunelerin çapı 25.4 mm ve kalınlığı 1 mm'dir. Isıl iletkenlik testi TA-Discovery Xenon Flash DXF 200 model test cihazı kullanılarak yapılmıştır. Her bileşim için termal iletkenlik testini gerçekleştirmek üzere üç set numune kullanılmıştır.



Şekil 2. Üç nokta eğme testi numuneleri

Üç nokta eğme testi ISO 178 standardına uygun olarak hazırlanan (boy 80 mm, en 10 mm ve kalınlık 4 mm) Şekil 2'deki numunelerle 50 mm/dak hızla yapılmıştır. Test sonucunda malzemenin eğilme dayanımı, kopma birim şekil değişimi ve eğilme modülü değerleri tespit edilmiştir. Üç nokta eğme testi için Hegewald & Peschke model test cihazı kullanılmıştır. Her kompozisyon için üçer set numune kullanılarak üç nokta eğme testi gerçekleştirilmiştir.

Izod darbe dayanımı testi ISO 180 standardına uygun numuneler ile gerçekleştirilmiştir. Izod darbe testi numunenin çentikli veya çentiksiz olmasına göre farklılık gösterir. Bu çalışmada çentiksiz Izod darbe dayanımı testi yapılmıştır. Test esnasında darbe çekici kullanılmaktadır. Çekiç numuneye çarpacak şekilde serbest bırakılır ve numunenin kırılması sağlanır. Çekiçteki kaybedilen enerji miktarına bakılarak malzemenin darbe esnasında sönmüleyebildiği enerji tespit edilir. Izod darbe dayanımı testi için Instron Ceast 9050 model test cihazı kullanılmıştır. Her kompozisyon için üçer set numune kullanılarak darbe dayanımı testi gerçekleştirilmiştir. Mekanik karakterizasyon tamamlandıktan sonra, kırılan numunelerin kırılma yüzeyleri Tescan Vega 3 taramalı elektron mikroskobu (SEM) kullanılarak incelenmiştir.

III. SONUÇLAR VE TARTIŞMA

Bu bölümde, çalışma esnasında gerçekleştirilen yoğunluk testi, DSC ve termal iletkenlik ölçümleri, üç nokta eğme testi, Izod darbe dayanımı testi ve

mikroskopik gözlemlerle ilgili sonuçlar ve bu sonuçlarla ilgili yorumlar yer almaktadır.

Yoğunluk testi, PA6, PSM, PHS30, PHS35 ve PHGS30 olmak üzere beş adet kompozisyonunda yapılmıştır. Elde edilen sonuçlar Tablo 2'de verilmiştir. PA6 kodlu kompozisyonun teorik yoğunluğu 1.17 g/cm³ olarak ölçülmüştür. Kütlece %5 SEBS eklenen PSM kodlu kompozisyonunda, SEBS yoğunluğun düşmesine sebep olmuştur. Kütlece %30 ve 35 hBN kullanılan PHS30 ve PHS35 kodlu kompozisyonlarda yoğunlukta artış tespit edilmiştir. Kütlece %2.5 GnP kullanılan PHGS30 kodlu kompozisyonunda ise oran az olduğu için yoğunlukta değişim görülmemiştir. Yoğunluklarda gözlemlenen değişiklikler eklenen takviyelerin yoğunlukları ve kütle oranlarıyla genel olarak orantılıdır. Kompozisyonlara ait yoğunluk değerleri teorik olarak hesaplandığında PA6, PSM, PHS30, PHS35 ve PHGS30 için sırasıyla 1.17, 1.15, 1.49, 1.55 ve 1.52 olarak hesaplanmıştır. Elde edilen sonuçlar, teorik sonuçlarla artış ve azalış bakımından paralellik göstermektedir.

Tablo 2. Kompozitlerin camsı geçiş sıcaklıkları

Kompozisyon Adı	Yoğunluk (g/cm ³)
PA6	1.17
PSM	1.12
PHS30	1.25
PHS35	1.27
PHGS30	1.27

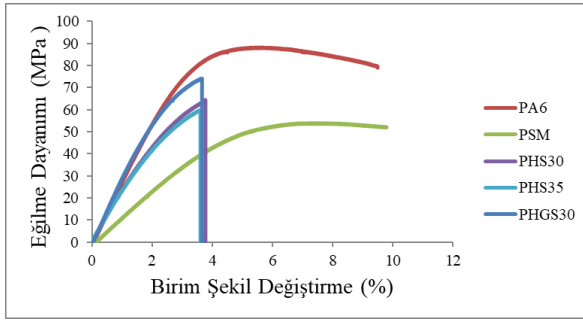
DSC analizi tüm kompozisyonlarda gerçekleştirilmiştir ve DSC eğrileri makaleye ait ek bilgideki Şekil 1,2,3,4 ve 5'te verilmiştir. Elde edilen sonuçlardan bu malzemelerin camsı geçiş sıcaklıkları (T_g) elde edilmiştir. Camsı geçiş, polimerlerde, malzemenin ısınma sonucunda rijit halden kauçuğumsu hale geçtiği durumu ifade eder ve yarı kristal malzemenin amorf fazı içinde meydana gelir. Artan polimer zincir hareketliliği, malzeme özelliklerinde değişikliklere neden olur. Örneğin, sıcaklık değişimine bağlı olarak malzemenin rijitliği azalabilmekte ve termal genişleme katsayısı ve ısı kapasitesi artabilmektedir. Isı kapasitesindeki artış camsı geçiş sıcaklığının tespit edilmesini sağlar. Bu çalışmada DSC ölçümlerinden elde edilen camsı geçiş sıcaklığı değerleri Tablo 3'te verilmiştir.

Tablo 3. Kompozitlerin camsı geçiş sıcaklıkları

Kompozisyon Adı	Camsı Geçiş Sıcaklığı (°C)
PA6	75.45
PSM	73.37
PHS30	90.55
PHS35	92.03
PHGS30	93.27

DSC sonuçlarına göre, hBN ve GnP takviyesiyle birlikte kompozitlerin camı geçiş sıcaklıklarında artış gözlemlenmiştir. Bu durumun kök nedeni olarak, matriste daha fazla sayıda partikül bulunmasıyla birlikte PA6 zincirlerinin hareketi engellenerek, rijit durumdan kauçuğumsu duruma geçiş gecikir ve böylece T_g 'de bir yükselme gözlemlenir. T_g 'nin yükselme eğilimi, GnP takviyesiyle de devam etmiştir. Bu durum GnP'lerin polimerle yaptığı yüksek arayüzey alanı ile ilintilidir. Çünkü, nanopulcukların kullanılmasıyla beraber artan yüzey alanı kauçuğumsu hale geçişte polimer zincirlerinin hareketini kısıtlar ve bu kısıtın aşılabilmesi için zincirlerin daha yüksek enerjiye sahip olması gerekir. Bu yüksek enerji de sıcaklık artışı (artan T_g) ile birlikte sağlanır [21,22]. SEBS ise PA6'nın T_g 'sini düşürmüştür. Bu durumda SEBS'in düşük T_g 'si ve zincirlerinin yüksek mobilitesi ile ilişkilidir.

Mekanik özelliklerin belirlenmesi için üç nokta eğme testi tüm kompozisyonlar üzerinde gerçekleştirilmiştir. Test sonucunda elde edilen eğilme dayanımı ve birim şekil değiştirme eğrileri Şekil 3'te verilmiştir.



Şekil 3. Kompozisyonlara ait eğilme dayanımı-birim şekil değiştirme eğrisi

Bu eğriler oluşturulurken her kompozisyon için ortalama değere en yakın olan test sonucu kullanılmıştır. Bu testle malzemelerin eğilme dayanımı, eğilme modülü ve eğilmedeki birim şekil değişimi değerleri de elde edilmiştir ve elde edilen değerler Tablo 4'te verilmiştir.

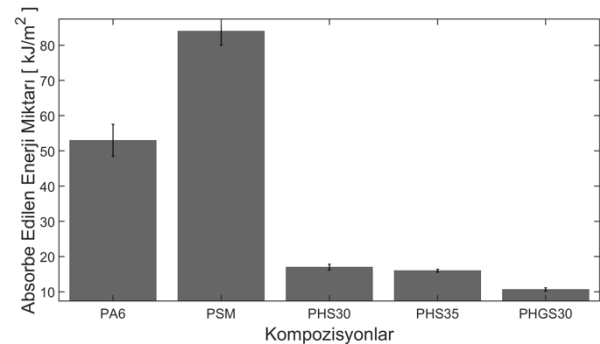
Tablo 4. Üç nokta eğme testi sonuçları

Kompozisyon Adı	Eğilme Dayanımı (MPa)	Eğilme Modülü (MPa)	Eğilmedeki Birim Şekil Değişimi (%)
PA6	88.00±0.3	2749.00 ±35	20.94±0.04
PSM	53.13±1.70	1210.99 ±50.00	24.98±0.12
PHS30	64.83±0.73	2435.41 ±68.96	7.72±0.05
PHS35	59.95±0.17	2418.35 ±56.60	7.37±0.16
PHGS30	74.00±0.60	3789.00 ±60.00	5.53±1.01

SEBS malzemesinin düşük mukavemet ve rijitlik değerlerinin bir sonucu olarak ya da diğer bir deyişle SEBS'in kauçuğumsu tabiatı neticesinde kompozitin eğilme dayanımında %39.6'lık, eğilme modülü değerinde %55.9'luk bir düşüş ve eğilmedeki birim şekilde değiştirme değerinde %19'luk bir artış görülmüştür [17]. Bu düşüşü ikame etmek için, kütlece %30 hBN kullanılması durumunda ise PSM kompozisyonuna göre kompozitin eğilme dayanımı değerinde %22'lik bir artış, eğilme modülünde de %101.1'lik bir artış görülmüş ve öte yandan eğilmedeki birim şekil değiştirme değerinde ise %69'luk bir düşüş görülmüştür.

Teorik olarak, polimerik malzemeler sert inorganik partiküller ile takviye edildiğinde, bu sert malzemeler matris içinde bir omurga görevi görür. İmalat esnasında kullanılan arayüzey takviye ajanlarının da etkisiyle matris ve GnP'ler arasında oluşması muhtemel fiziksel çapraz bağlar aracılığıyla polimerin moleküler zincir hareketi kısıtlanır ve böylece kompozit malzemelerin rijitliği (elastisite modülü) artış gösterir [27]. İnce pulcuk benzeri inorganik partiküller (yani GnP'ler) ile takviye söz konusu olduğunda, GnP'ler yüksek mukavemetleri neticesinde deforme olmadan kalırken matris göreceli deformasyona uğrayacaktır. Sonuç olarak, yüke dik arayüz çekme kuvvetini sürdürürken, yüke paralel arayüz kesme kuvvetini sürdürecektir. Nano takviyelerin yüksek yüzey alanı sayesinde, iç yapıda birim alan başına düşen kuvvet yani gerilme düşecek ve bu sayede kompozit malzeme kopmadan daha yüksek bir mukavemet gösterecektir [28, 29].

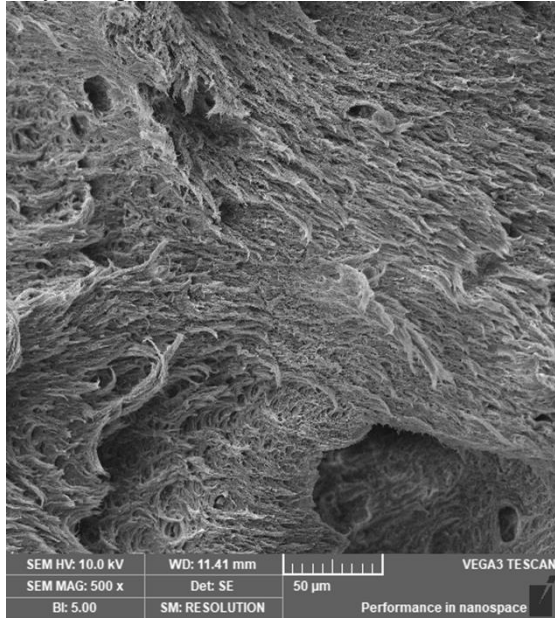
Eğilme dayanımının incelenmesinden sonra, giriş bölümünde de belirtildiği üzere kompozitlerin batarya modülü muhafazasında kullanılması durumunda, muhafazanın aracın alt kısmından, yol tarafından, alabileceği darbelere karşı dayanımını gözlemlemek için Izod darbe dayanımı testi, tüm kompozisyonlara uygulanmıştır ve elde edilen değerler Şekil 4'te verilmiştir.



Şekil 4. Izod darbe dayanımı testinden elde edilen sonuçlar

Kütlece %5 SEBS kullanılması kompozitin darbe dayanımında %58.5'lik bir artışı beraberinde getirmiştir. SEBS elastomerik bir malzeme olduğu için darbe sönmüleme tabiatına sahiptir ve bu durumda

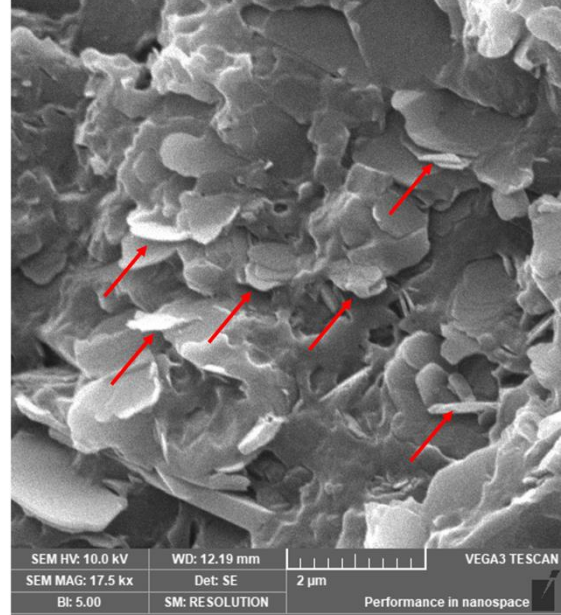
kompozitin absorbe ettiği enerji miktarını olumlu yönde etkilemiştir [16]. Kütlece %30 hBN kullanılması durumunda kompozitin darbe dayanımında %79.8'lik, kütlece %35 hBN kullanıldığı durumda ise %80.9'luk bir azalma görülmüştür. hBN seramik olarak sınıflandırılan bir takviye malzemesidir ve seramikler iç yapılarındaki süreksizlikler nedeniyle gevrek özellik gösterirler [25]. Artan hBN miktarıyla da birlikte kompozitlerin kopma uzamaları önemli ölçüde düşmüş, diğer bir deyişle kompozitler daha gevrek bir karakteristik göstererek darbe sönümleme özelliklerinde düşüş yaşanmıştır. Son olarak, kütlece %2.5 GnP takviyesinin darbe dayanımı üzerine etkilerine eğilecek olursak, GnP takviyesi kompozitin darbe dayanımında ortalama %37.2'lik bir azalmaya sebep olmuştur. Yukarıda deney sonuçlarının yorumlanmasında ortaya konulan hipotezleri desteklemek için SEM ile kırılma yüzeyleri incelemesinde bulunulmuştur. PSM grubu kompozitlerde kopma uzamasının arttığı görülmüştür ve kırılma yüzeyleri de bunu destekler niteliktedir. Şekil 5'te, PSM kompozit grubunun kırılma yüzeyi, düzensiz uzamış bölgelerin yer aldığı pürüzlü bir dokuya sahiptir.



Şekil 5. PSM numunesinin kırılma yüzeyi

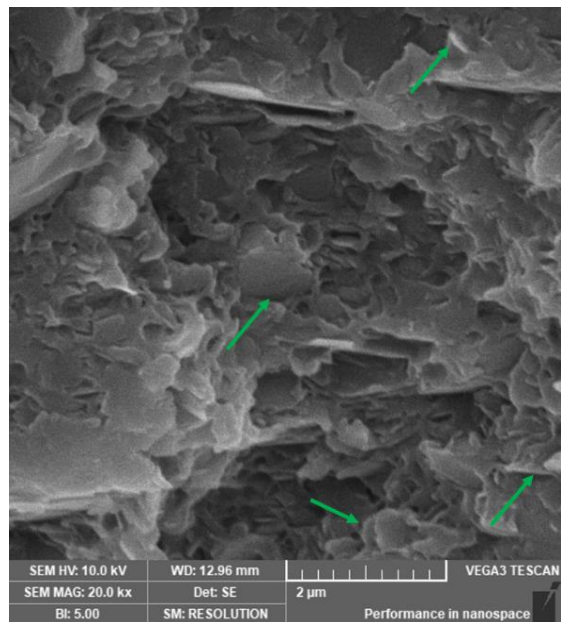
Pürüzlü yüzeyler sünek bir kırılma modunun göstergesidir ve kopma uzamasının arttığına işaret eder. Bununla paralel olarak, kırılma mekaniğinde pürüzlü yüzeyler, artan bir yüzey alanına da işaret eder ve daha fazla yüzey oluşturmak daha fazla yüzey enerjisi gerektirir. Bu enerji, birincil çatlağın yayılması için gerekli olan ve sonunda kırılmaya neden olan birim şekil değişimi enerjisi ile karşılanır. Sonuç olarak, numunenin kırılması ertelenir ve bu da kırılma anındaki gerilmenin artmasına neden olur. Ek olarak, Şekil 5'teki uzun segmentler, daha spesifik olarak uzun kırılma paternleri veya fibriller, lokalize plastik deformasyonunun bir sonucu olarak matris içinde meydana gelen sünek hasarın göstergesidir [31]. Şekil

6'da ise PHS35 numunesine ait bir kırılma yüzeyinin SEM görüntüsü verilmiştir. Bu şekilde kırmızı oklarla ince plaka şeklindeki hBN'ler küçük bir alanda kümelenmiştir. Bu kümelenmeler, gerilme konsantrasyonuna neden olurlar ve bu bölgelerde hBN kümelerinin etrafında mikro çatlaklar oluşabilir. Yük altında, mikro çatlaklar yayılabilir ve bu durum kompozitlerin mukavemetini düşüren erken hasarla sonuçlanabilir.



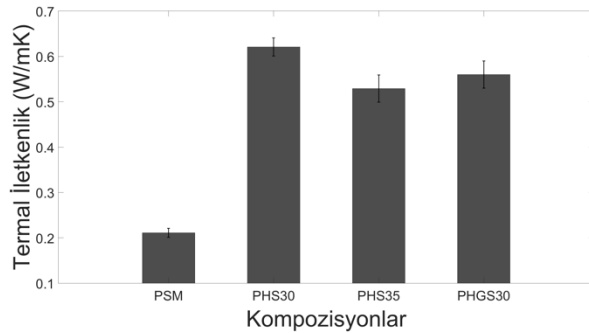
Şekil 6. PHS35 numunesinin kırılma yüzeyi

PHS30 grubu için de gerçekleştirilen benzer büyütme oranlarına sahip SEM görüntüsü Şekil 7'de verilmiştir. Bu görüntüde hBN'ler yeşil oklarla gösterilmiştir, öte yandan bu resimde PHS35 grubunda gözlemlenen küçük bir alana sıkışan birçok hBN'nin varlığına rastlanılmamıştır. Bu durum PHS30 grubunda yoğun bir aglomerasyon olmadığını göstermektedir.



Şekil 7. PHS30 numunesinin kırılma yüzeyi

Mekanik karakterizasyonlardan sonra, hBN ve GnP'lerin termal iletkenlik üzerindeki etkisini belirlemek için termal iletkenlik ölçümleri yapılmıştır ve elde edilen sonuçlar Şekil 8'de verilmiştir. Sonuçlar, %30 hBN eklendiğinde termal iletkenliğin PSM kompozisyonuna göre %194.3 arttığını göstermektedir. Isı akısıyla aynı hızda olan termal kanalların oluşumu, termal iletkenliğin iyileştirilmesinin temel unsurudur. BN plakalarının polimer matris içerisinde rastgele dağıldığı durumda, BN'ler yüksek çap-kalınlık oranına sahip oldukları için termal yol oluşturarak birbirleriyle temasa geçerler. Dikey olarak hizalanan BN plakalarında ise termal temaslar oldukça azalır ve bu durum termal iletkenliği olumsuz etkiler. hBN'nin kütle konsantrasyonu %30'dan %35'e çıktığında termal iletkenlik %15.3 azalmıştır.



Şekil 7. Kompozisyonlara ait termal iletkenlik testi sonuçları

Kalınlık boyunca kümelenmiş BN plakalarının varlığının, ısı iletkenliğinde bir azalmaya yol açtığı varsayılmaktadır. Nanopulcuklardan (1 µm çapında) oluşan ince bir filmin termal iletkenliği, daha büyük parçacıklardan (15 µm çapında) oluşturulan bir filmle karşılaştırıldığında %60.8 daha düşüktür [32]. Bileşimdeki GnP'lerin varlığı, termal iletkenlikte yaklaşık %9.82'lik bir azalmaya yol açmıştır. Bu çalışmada kullanılan GnP'lerin küçük çapları (1.5 µm) göz önüne alındığında, fonon dispersiyonunun neden olduğu temas direnci ve termal iletkenlikte beklenen artışın görülmemesi olasıdır.

Tüm bu deneysel incelemelerden sonra, kompozitlerin mekanik özellikleri mikro mekanik modellerden istifade edilerek hesaplanmıştır. Bu bağlamda, nanopartikül takviyeli kompozit malzemelerin elastik özelliklerinin tahmini için katkı maddesinin geometrisine, oryantasyonuna ve matrisin elastik özelliklerine dayalı çeşitli modeller vardır. Bu modellerden birisi de Halpin-Tsai (HT) modelidir. GnP takviyesi için modifiye edilmiş HT modeli 1, 2, 3, 4, 5 ve 6 numaralı denklemleriyle verilmiştir [33-35].

$$E_C = \frac{3}{8}E_L + \frac{5}{8}E_T \quad (1)$$

$$E_L = E_m \left(\frac{1+\xi\eta_L V_f}{1-\eta_L V_f} \right) \quad (2)$$

$$E_T = E_m \left(\frac{1+2\eta_T V_f}{1-\eta_T V_f} \right) \quad (3)$$

$$\eta_L = \frac{E_f/E_m - 1}{E_f/E_m + \xi} \quad (4)$$

$$\eta_T = \frac{E_f/E_m - 1}{E_f/E_m + 2} \quad (5)$$

$$\xi = \frac{2D_f}{3t_f} \quad (6)$$

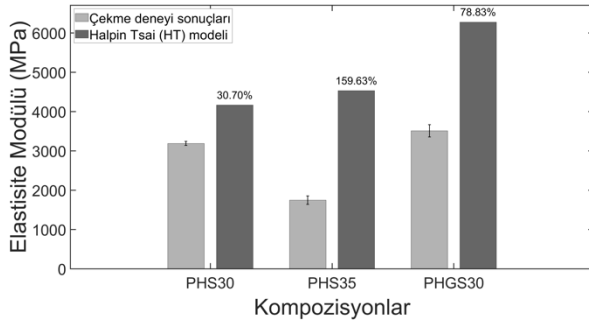
E_c , E_m ve E_f sırasıyla kompozit, matris ve takviye malzemenin elastisite modülüdür. V_f ve ξ ise sırasıyla hacim oranı ve takviye malzemesinin şekil faktörüdür. Yukarıda verilen denklemler ve kompozit kompozisyonları göz önünde bulundurularak, kompozitlere ait elastisite modülü değerleri bulunmuştur. Elastisite modülü hesaplaması yapılırken PSM kompozisyonu için karışımlar kuralından faydalanılmıştır [36]. Geri kalan kompozisyonlar için pulcuk (platelet) şeklindeki takviyeler için geliştirilmiş HT modeli kullanılmıştır. Geliştirilmiş HT modeli için takviyelerin 2 boyutlu ve 3 boyutlu rastgele yönelimini açıklayan iki farklı yaklaşım bulunmaktadır. Daha iyi bir yakınsama sağladığı için 1 numaralı denklemden, 2 boyutlu rastgele yönelimi açıklayan HT modeli kullanılmıştır [35]. Bu denklemden bulunan E_L ve E_T sırasıyla boyuna ve enine elastisite modülünü temsil eder. Bu değerleri hesaplamak için 2 ve 3 numaralı denklemlerden faydalanılmıştır. Pulcuk şeklindeki takviyeler için ξ fonksiyonu 6 numaralı denklemden hesaplanmaktadır [33]. ξ değeri hesaplanırken kullanılan D_f ve t_f sırasıyla takviye malzemenin çap ve kalınlığıdır [37]. PHS30 ve PHS35 kompozisyonuna ait elastisite modülü hesaplanırken, E_m için karışımlar kuralından PSM için elde edilen veriler kullanılmıştır. hBN'ye ait D_{hBN} ve t_{hBN} değerleri Tablo 5'teki gibi alınmıştır.

Tablo 3. Kompozitlerin camı geçiş sıcaklıkları

Kompozisyon Adı	D_f (nm) (Çap)	t_f (nm) (Kalınlık)
hBN	790	98.75
GnP	1500	3

PHS30 ve PHS35 için hBN miktarları hacimsel oranları değiştirilerek elastisite modülü değerleri hesaplanmıştır. PHGS30 kompozisyonunda E_m olarak HT modelinden PHS30 için elde edilen veriler kullanılmıştır. GnP'ye ait D_{GnP} ve t_{GnP} değerleri Tablo 5'teki gibi alınmıştır. Şekil 9'da HT modeline ait nümerik sonuçlar verilmiş ve nümerik sonuçlar ISO 527 standardına göre gerçekleştirilen çekme deneylerinden elde edilen deneysel modül değerleriyle karşılaştırılmıştır. Çekme testleri, numunelerin 50 mm/dak hızla çekilmesiyle gerçekleştirilmiştir. Çekme testi için Hegewald & Peschke model test cihazı

kullanılmıştır. Her kompozisyon için üçer set numune kullanılarak çekme testleri gerçekleştirilmiştir.



Şekil 9. Deneysel sonuçlar ile ve HT modeline ait sonuçların karşılaştırılması

Elde edilen sonuçlarda HT modeli kullanılarak elde edilen elastisite modülü değerlerinin, deneysel olarak elde edilen değerlerden daha yüksek olduğu görülmüştür. Bu farkın, HT modelinin, takviyelerin mükemmel şekilde yönlendirilmiş ve eşit şekilde dağıldığı varsayımından kaynaklandığı düşünülmektedir [33]. PHS35 kodlu kompozisyonda ise diğer kompozisyonlara göre önemli bir fark oluşmuştur. Şekil 6'da verilen kümelenmelere bağlı olarak deneysel sonuçlardaki düşüş bu durumu açıklar niteliktedir.

Son olarak da HT modeli, matris takviye arayüzey kalitesini dikkate almamaktadır. Her ne kadar bu çalışmada arayüzey iyileştirici ajanlar kullanılsada oluşması ihtimal dahilinde olan arayüzey problemleri de deneysel sonuçlarla farklılıklara yol açabilmektedir.

IV. SONUÇ

Otomotiv endüstrisinde elektrifikasyonla birlikte köklü bir değişim meydana gelmektedir. Bu değişime destek olacak sonuçların yer aldığı bu çalışma, elektrikli araçların batarya kutularını termoplastik kompozit bir malzeme kullanarak üretip, ağırlığı azaltmayı amaçlamıştır. Çalışmada, kompozitlerin matrisi olarak PA6 kullanılmış, termal iletkenliği artırmak için hBN kullanılmış, termal iletkenliğini ve mekanik özelliklerini iyileştirmek için GnP kullanılmış ve darbe direncini artırmak için SEBS kullanılmıştır. Malzemelerin homojen bir şekilde karıştırılması için çift vidalı ekstrüder kullanılarak ekstrüzyon işlemi gerçekleştirilmiştir. Üç nokta eğme ve Izod darbe dayanımı testlerinde kullanılmak üzere numune üretimlerinde plastik enjeksiyon yöntemi kullanılmıştır. Elde edilen kompozitlerin yoğunluğu, piyasada sıklıkla batarya kutusu olarak kullanılan alüminyumun yoğunluğuna göre yaklaşık %50 daha düşüktür. Bu sebeple geliştirilen kompozitler hafifletme uygulamalarında kullanılmak üzere önemli bir potansiyel taşımaktadır. Çalışma kapsamında gerçekleştirilen üç nokta eğme testlerine göre, kütlece %30 hBN kullanıldığında eğilme dayanımı ve eğilme modülü sırasıyla %22 ve %101.1 artmaktadır. hBN miktarı kütlece %35'e çıkartıldığında kütlece %30

kullanıldığı duruma göre eğilme dayanımı ve eğilme modülü sırasıyla %7.5 ve %0.7 azalmıştır. Yapılan Izod darbe dayanımı testinde PHGS30 kompozisyonunda darbe dayanımı değerinin düştüğü görülmüştür. %30 hBN eklendiğinde termal iletkenliğin %194.3 arttığı görülmüştür. Sonrasında, Halpin-Tsai mikromekanik modelinden elde edilen veriler, deneysel sonuçlarla karşılaştırılmış ve takviyelerin mükemmel şekilde hizalanıp, eşit olarak dağıldığı durumu modelleyen HT yaklaşımında elastisite modülü değerinin deneysel değerlere göre daha yüksek çıktığı görülmüştür. Bu sonuçlar, kompozitlerin daha ileri imalat yöntemleriyle, örneğin ultrasonik karıştırıcı ekstrüder, imalatıyla daha da iyileştirilebilir potansiyeline sahiptir. Geliştirilen kompozitlerden elde edilen sonuçlar gelecekte yapılacak çalışmalar için oldukça değerlidir ve otomotiv endüstrisinde batarya kutusu imalatında kullanılmak üzere umut vaat etmektedir.

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Solving an Order Batching and Sequencing Problem with Reinforcement Learning

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Abstract

The purpose of this research is to determine whether a DRL solution would be a suitable solution for the OBSP problem and to compare it with traditional methods. For this purpose, models trained utilizing the PPO algorithm were tested in a complex and realistic warehouse environment, and an attempt was made to measure whether a strategy was developed to decrease the number of orders being late. A heuristic method was also applied and the results were compared on the same environment and data. The results showed that DRL approach that combines heuristics with the PPO algorithm outperforms the heuristics in minimizing the tardy order percentage in all tested scenarios.

Keywords: Reinforcement Learning, Order Batching and Sequencing, Proximal Policy Optimization, Warehouse Optimization

I. INTRODUCTION

Warehousing entails the act of storing physical goods or inventory within a warehouse or stock facility prior to their sale or distribution. It enables companies to meet the increasingly demanding customer requirements for fast and effective order processing, a necessity heightened in the digital age. Optimization of warehouse operations is an issue that needs to be addressed in e-commerce, and has gained more importance with the increasing e-commerce volume. Solutions in this area are necessary to enhance efficiency, reduce costs, improve order accuracy, maximize space utilization, streamline workflow, and increase overall productivity, thereby meeting customer demands effectively and maintaining competitive advantage.

Mainly two types of stock systems can be mentioned in today's warehouses, which are Person-to-Goods (PtG) and Goods-to-Person (GtP) systems. In PtG systems, order pickers follow designated paths, which can lead to inefficiencies when dealing with small orders due to extensive walking among the shelves and the central depot. GtP systems leverage automated solutions to bring items to pickers stationed at specific areas. GtP offers fast order picking and significantly decreases the reliance on human labor, but they come with a considerably higher initial investment compared to PtG systems.

Items must be collected from the warehouse stock systems before orders are prepared. The two types of picking methods are single-select and multi-select. In single-select method, just one order is picked in a tour, whereas in multi-select method multiple orders are selected. Single-select results in shorter lead times but carries the potential drawback of inefficient traveled distances, while batching orders leads to longer lead times but boosts the picker's productivity.

Optimizing stock systems, on the other hand, is crucial for improving the overall performance of a warehouse. It enhances efficiency, accuracy, and productivity while reducing costs and errors. The optimization of a specific warehousing system which combines PtG and GtP stock systems to improve efficiency is studied in the literature. Because of the limited capacity of warehouse resources and tight delivery schedules, an order picking plan is

required to reduce the quantity of late orders. For instance, a Deep Reinforcement Learning (DRL) based approach is proposed in [1] for the optimization of order picking process to cope with the tardiness in delivery in a specific warehouse environment. Heuristics, which are often employed in optimization problems where the search space is vast and exploring every possible solution is not feasible have also been applied by many researchers with a purpose of minimizing tardy orders or decreasing total processing time of the orders [2][3]. [4] proposes a strategy to optimize warehouse layout, aiming to minimize transport time and reduce injury risks by employing association rule analysis with the apriori and FP-growth algorithms.

This research aims to create a method that determines an order picking strategy to use, with the goal of minimizing order delays in an environment where resources are limited. To be more specific, it should be decided whether orders will be picked individually, or in batches, and if they will be picked in batches, which orders will be in the same batch. The problem is called Order Batching and Sequencing Problem (OBSP) in existing literature, and proposed solutions are mostly conventional methods such as heuristics.

In [1], a deep reinforcement learning (DRL) methodology that applies a Proximal Policy Optimization (PPO) algorithm for minimizing the number of tardy orders on their specified warehousing concept is proposed. The solution is improved by including a more dynamic warehouse environment, and optimizing the RL solution in [5].

The purpose of the study is to investigate whether DRL will be a good solution to OBSP of a warehouse system that has been already utilized in e-commerce. The main criteria is minimizing the number of tardy orders, which has become an issue of increasing importance because of time-limited delivery expectation and order uncertainties in today's e-commerce. This research is also built upon the same environment given in [1] since it fulfills the requirements for the topic and reflects the general. The generalizability of the DRL solution is investigated by testing the methods used in the previous literature with different order arrival data. In addition, how the performance of the solution could be improved with different parameters was tested.

This paper is structured as follows: Relevant literature in problem domain has been overviewed in Section 2. How the problem is formulated to apply for both RL solution and heuristic solutions are presented in related subsections of Section 3. In Section 4, the experimental findings are deliberated. Conclusion and some possible future improvements are given in Section 5.

II. RELATED WORK

Traditional warehousing systems need to adapt to the requirements such as small orders, wide variety, strict delivery timelines, and fluctuating workload. Order picking in a batching, zoning and sorting environment is the most researched topic in this context, however it still needs further research to address the characteristics of e-commerce [6].

In logistics, there exists many machine learning solutions for various problems. For instance, [7] proposes a novel approach using multiple machine learning models to address Pallet Loading Problem, which involves maximizing the number of boxes loaded onto a pallet and a major issue in shipments.

Interest on Reinforcement learning (RL) applications especially in logistics increased a lot in the last few years. Q-learning, both tabular form and Deep Q-Network (DQN) is the most favored RL method researched, followed by policy gradient and actor-critic methods. Among all the RL agents used, multilayer perceptrons and regression are the most popular ones. Heuristics such as genetic algorithms, greedy algorithms and dynamic programming are used as benchmarking methods in many studies [8].

RL is advantageous over heuristics because it learns parameters to determine actions based on the current state whereas in heuristics predefined rules are utilized, it may learn from historical data and integrate forecasting and optimization whereas heuristics only uses forecasting on prediction and it can rely on simulation environments. The limitations of RL are the challenge in handling complex multi-agent systems and coming up with generalized solutions, the cost and complexity of the solutions, and partially observable states [8].

In following sections, some heuristics and RL solutions in the literature are reviewed.

2.1. Heuristic Approaches for OBSP

Metaheuristic algorithms utilizing Iterated Local Search, Attribute-Based Hill Climbing, and a basic tabu search principle have been employed in [9] to reduce the overall tardiness for a specific collection of customer orders. The results of the proposed methods are evaluated against the typical constructive heuristics such as the Earliest Due Date rule on various categories of problems. It has been demonstrated that the results are highly improved and the proposed solutions can be used for a more efficient order picking system. Later, Variable Neighbourhood Descent and Variable Neighbourhood Search have been implemented within [10] on the same problem with the same objective, the findings indicated that the suggested approaches may improve the order picking effectiveness.

A heuristic solution grounded on the Variable Neighbourhood Search method to achieve a minimum tardiness in the context of the OBSP has also been proposed in [2], and it has been shown that the proposed algorithm is better than the state of the art in aspect of quality and speed.

The modified seed algorithm proposed in [3] aims to reduce the overall picking, sorting and packing duration in an OBSP with limited buffers. The initial seed algorithm attempts to consolidate orders with nearby stock locations into the same batch to minimize picking time. However, it fails to achieve coordinated production of the order picking process and sorting-packing process with limited buffers. Therefore, the modified algorithm takes into account the relationship between the current batch and the previous batch in terms of processing time.

Heuristics have also been utilized in many related problems in operations research domain. For instance, the order picking problem is handled in [11]. A method involving multiple Genetic Algorithms (GAs) is introduced for optimizing batch picking, taking into account travel costs and order due times. The results showed that batch picking achieves better results than single order picking in general, and the proposed model has a solution quality better than all benchmark models in all datasets.

The joint order batching and picker routing problem in warehouses that is seldom studied together and not studied at all for warehouses consisting of multiple blocks is investigated in [12]. They formularized the issue revolving around an exponential quantity of connectivity constraints and presented several inequalities based on the conventional layout of warehouses. They showed the applicability of the proposed method by presenting results for problems with up to 5000 orders.

2.2. Reinforcement Learning Applications for OBSP

Reinforcement Learning (RL) is a subset of machine learning focused on teaching agents to make sequences of decisions in dynamic environments to maximize cumulative rewards. Unlike supervised learning, where models are trained on labelled data, or unsupervised learning, which seeks to identify patterns in unlabeled data, RL relies on trial-and-error interactions to discover optimal strategies. Deep Reinforcement Learning (DRL) integrates RL with deep learning techniques to solve problems in complex environments.

There exist a few studies with RL on the specific problem of OBSP. In [1], it is questioned how can a DRL solution contribute to minimizing the quantity of late orders within a particular warehousing concept. The problem is formulated as a Semi-Markov Decision Process and solved with a Proximal Policy Optimizaiton (PPO) algorithm. To benchmark the algorithm, several heuristic solutions are also

developed. A simulation model built in a 3D simulation program to assess the effectiveness of the algorithms and an order dataset belong to an e-commerce company are used. It is concluded that DRL is a preferred method because it generalized across various warehouse setups well, eliminating the need to train a new agent. The importance of the study is that there was no literature about solving order batching problems with DRL at its time. A paper based on [1] has been published later [13].

An RL algorithm for a different kind of batching problem is studied in [14]. The problem was minimizing the difference between the target weight and the real weight of a product batch. The difference which is called as giveaway can cause customers get an extra amount or lose some of the product they ordered. There are regulations called e-weighting regulations applied by European Union Directive to prevent customers getting a less amount. They converted the environment to a model that changes in episodes to implement RL. The complexity of the algorithm increased in several iterations to close to a real production setup, and the results was passing the e-weighting regulations after the third iteration.

Cals, Zhang, Dijkman, and van Dorst (2021) later published a paper based on Cals (2019). They applied PPO in conjunction with a heuristic rule to adress OBSP. The agent used heuristics for sequencing decisions and DRL for batching decisions, and the resulting performance was compared to several heuristic approaches. Results showed that the agent utilizing DRL for order batching surpasses the heuristics accross most warehouse settings examined, and the results are more robust and generalizable.

[5] and [15] worked on the same problem and addressed the problem in a more realistic way by involving larger instances of hourly orders. They also included a second objective of reducing order picking costs in addition to the first objective of reducing tardy order percentage. All these improvements added more complexity to the problem, so he improved the solution by using a method utilizing Bayesian optimization for shaping rewards. Additionally, they involved approximating DRL policies using decision trees, which can then be used to deduce logic and generate understandable decision rules, thus enhancing the explainability of the learned policies.

III. METHODOLOGY

3.1. Problem Description

The scope of this research is finding a solution to schedule and fulfill orders for a warehouse system. This research is built upon the same warehousing system mentioned in [1] due to the difficulty of accessing real data. Also, the concept applies for modern warehouses and suitable to study the research topic. The warehousing system is developed by an anonymous

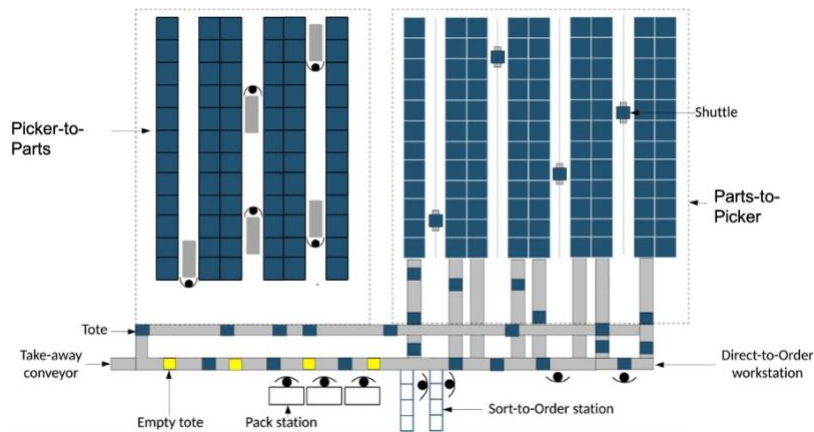


Figure 1. PtG and GtP order retrieval system incorporating a pack zone, StO and DtO zones [1]

logistics company to provide solutions to the problems in e-commerce market such as tight delivery schedules, orders with small number of items, large assortment, fluctuations in workload, labour scarcity and growing e-commerce market.

The proposed system combines PtG and GtP to take advantage of both, and also applies a unique batching method by using single-select and multi-select simultaneously. When using this warehousing setup, two choices must be rendered:

1. When should single-select or multi-select be chosen
2. If multi-select is chosen which orders ought to be combined together in the same batch

The first issue is an order batching problem, whereas the second one is a sequencing problem. Therefore, the problem is an Order Batching and Sequencing Problem (OBSP). The issue is complex because there are many inputs that will affect the decisions. The decisions are influenced by the attributes of the orders, various processing stages, limitations in capacity, and uncertainties associated with the orders.

There exist two kind of stock systems, PtG and GtP, and three kind of operating areas in the proposed warehouse system which is shown in Figure 1. Items are stored on shelves or palettes in PtG systems, and picker stops at the locations where certain items are stored and picks the quantity needed. The GtP system operates as an Automated Stock/Retrieval System (AS/RS), retrieving items from shelves and transporting to a area at which a picker is stationed. The picker then retrieves the requested items from the tote. In the PtG approach, where single-select is implemented, the picker gathers the items into a carton box, preparing them for shipping without stopping at areas. When multi-select, totes are used in the PtG system. Two kinds of totes exist which are product totes and batch totes. Product totes contains items of same SKU and are stored in the GtP whereas batch totes are

created in the PtG system while multi-select. Batch totes are subsequently moved to either the GtP system or a packing area.

Totes have the option to be conveyed to three distinct areas: direct-to-order (DtO) zones, sort-to-order (StO) zones, and packing zones. At a DtO zone, totes of products arrive sequentially, and the required items for each order are picked and deposited into a carton box. Alternatively, batches can be formed by gathering items one by one into a batch tote instead of a carton box. These batch totes are stored in GtP system, later dispatched to either a StO or packing zone. At a StO zone, orders are sorted, buffered and packed. First, a picker extracts products from a batch tote and positions them in a put wall, where shelves are designated to a unique order one at a time. After the put wall is occupied and the needed products are gathered for every individual order, they are sent to the buffering area. Then, the operator asks for a put wall, places it into the packing area, packages each order in a carton box and sends it to shipping. Product totes can also be used instead of batch totes, but it may cause long queues since many of them will be required. When all items does not exist in PtG system, A hybrid approach involving both product totes and batch totes is also feasible for completing the missing items from GtP system. At a pack zone, only batch totes arrive and sorting is not required since each item within the batch corresponds to a single order. Here, the processed orders consist of one type of product.

An order consisting of only one item and one SKU is referred to as a single-item order (SIO). An order that contains multiple items and multiple SKUs is called multiple item order (MIO). Order type is an important factor on order picking process.

This research concentrates on aforementioned stock units and areas. Other aspects of the warehouse system are disregarded to prevent further complexity in the problem. Additionally, certain assumptions are made, such as consistently having adequate capacity to buffer

orders and always being able to transport totes between processes via conveyors. Although the proposed warehouse system is designed for much higher amount of orders, research is limited by 360 to 500 orders per hour. The algorithm takes inputs including a warehouse configuration with pickers, shuttles, and areas, as well as order arrival events. It sequentially allocates orders to the elements of the warehouse, ensuring that the limitation on capacity is respected and the number of late orders is minimized.

3.2. Solution Methods

A DRL solution is applied on the aforementioned OBSP. Also a heuristic solution is applied to use as a benchmark. The details of the applied methods are given in the following sections.

3.2.1. Deep reinforcement learning basics

RL is a type of machine learning where an agent learns to make a sequence of decisions (actions) within an environment to maximize a cumulative reward signal. Upon taking an action, the environment responds with a reward and possibly a new state. The aim of the agent is to acquire an optimal policy which makes its long-term reward as large as possible. The conceptualized model of RL can be viewed in Figure 2.

DRL is a subfield of machine learning that merges principles from RL with deep learning techniques, to enable agents - the learner or decision maker that interacts with the environment - to learn how to make decisions.

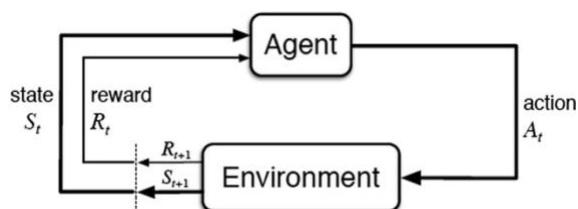


Figure 2. A conceptual model for reinforcement learning [17]

DRL has shown remarkable achievements in numerous fields such as robotics, gaming, autonomous driving, finance, and healthcare. It poses significant challenges, including sample inefficiency, instability during training, and the need for extensive computational resources. However, recent advances in algorithms (e.g., deep Q-networks, policy gradient methods), hardware (e.g., GPUs, TPUs), and environments (e.g., simulation platforms like OpenAI Gym) have accelerated progress in DRL research and applications.

Considering that the OBSP involves making consecutive decisions in presence of uncertain demand and postponed rewards (order batching might decrease the capacity for other orders usage, possibly causing

delays), Deep Reinforcement Learning (DRL) may be an appropriate method for a solution.

3.2.2. Simulation model

Simulation environments are necessary develop, test, and refine RL agents in a safe, efficient, and cost-effective manner. The simulation environment for the DRL agent for our specific OBSP has been developed using OpenAI Gym [16]. There exist seven entities which are shuttle, picker, order/batch, product tote, batch tote, carton box and queues in the simulation model. Entities can carry data by means of its attributes. Whenever an entity moves between the parts of the warehouse, an event is triggered. There exist four main events which are arriving, picking, order consolidation and shipping.

The simulation model's environment interacts with the DRL agent to facilitate learning. It is structured as a semi-Markov decision process (SMDP), comprising transition times, a finite state space, a set of actions, and a reward function. The DRL agent tries to solve instances within each episode, that is comprised of a sequence of states, actions, and rewards, terminating when all orders are fulfilled or when an excessive number of late orders accumulated.

State space is represented with three main components: the number of orders that are not processed yet, available capacity and extra information such as the count of late orders, the count of fulfilled orders, and the present simulation time. Action space is formulated so that there are two actions - single-select and multi-select - for each order category plus the “do nothing” action when there is no available capacity, there are 11 actions totally. Taking an action in case of no order or choosing an order when there is no capacity is considered to be an infeasible action. In such instances, the state remains unchanged, and orders remain unprocessed. If wait action is chosen when there are orders and capacities, it is also an infeasible action and not performed. The action and state formulas are taken from [5].

The reward function similar to the reward function in [1] is shown in Equation 1, a reward proportional to the finished order percentage by the conclusion of the episode, with penalties imposed for late orders and infeasible actions. w is the sum of the count of late orders and count of non-processed orders. N is the total count of orders. Then, $1 - w/N$ is the ratio of the processed orders before their cut-off time, and the reward exponentially depends on this value. An environment is simulated for the agent to know how the state changes as a result of its actions. The engagement between the agent and the simulation model is shown in Figure 3. After action a is performed, the simulation model simulates the action till state s changes to s' . At the time that orders arrive or available capacity increase or decrease, the state changes. When orders are ready for shipping, tardiness information is received.

$$r(s, a, s') = \begin{cases} -0.5 & \text{if infeasible action} \\ -1.5 & \text{if late order} \\ (1-w/N)^2 & \text{if episode finishes} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Transition time τ is minimal when capacities are available, but it increases significantly when the wait action is selected. The agent needs to learn the actions for each O_{cijk} , and the capacities needed for each of the actions. This is encouraged by giving a penalty for infeasible actions.

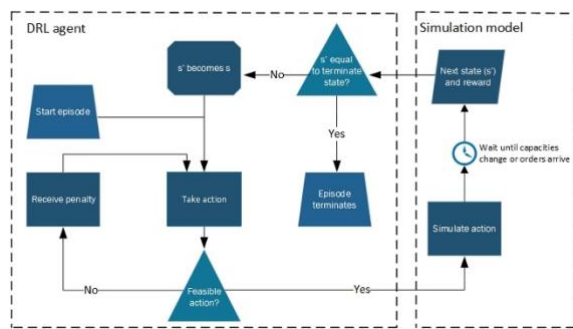


Figure 3. Interaction of the DRL agent with the simulation model [1]

3.2.3. Proximal policy optimization

Proximal Policy Optimization (PPO) introduced by [18] is a cutting-edge RL method designed to optimize policies for decision-making tasks in environments with complex and continuous action spaces. PPO is a member of the policy gradient methods family that directly learn the optimal policy through gradient ascent on the objective function. PPO finds applications in various industries including gaming, robotics, finance, healthcare, and autonomous systems and it has been proved that PPO achieves good stability, sample efficiency and robustness in various environments [19][20].

PPO algorithm is chosen to be applied to OBSP. One of the reasons is that it is an extension of Trust Region Policy Optimization (TRPO) and Actor Critic with Experience Replay (ACER) algorithms which are both extensions of DQN -the first developed DRL algorithm- with the recent improvements. Another reason is reducing computational expenses. Since PPO only updates policies instead of individual states as in DQN, training time is significantly reduced. The third reason is the success of PPO algorithm in coming by a more general strategy so that it can be applied to another warehouse settings later on.

Self-dependence of training data on the policy creates instabilities in the process of training in RL. Besides, parameter tuning is sensitive in a considerable amount. PPO solves these problems of RL.

PPO is an online learning algorithm as opposed to DQN, which means it learns directly from encountered experiences rather than storing and replaying. This method employs a policy gradient approach, necessitating the computation of an estimator for the policy gradient and its utilization within a stochastic gradient ascent algorithm. Gradient estimators has a common form in Equation 2. In neural network implementations, gradient estimator can be obtained by differentiating objective function in Equation 3. The policy π_θ takes states as input and proposes actions as log probabilities. \hat{A}_t is the advantage function which is the comparative value of chosen action for current state. It is the difference between cumulated and discounted sum of rewards G_t and the baseline estimate.

$$\mathcal{G} = \hat{E}_t[\nabla_\theta \log \pi_\theta(a_t \vee s_t) \hat{A}_t] \quad (2)$$

$$L^{PG}(\theta) = \hat{E}_t[\log \pi_\theta(a_t \vee s_t) \hat{A}_t] \quad (3)$$

G_t is formulated in Equation 4. γ indicates the discount factor which is a value in $[0,1]$, so the importance of future rewards are less than the close ones. \hat{A}_t is calculated after all rewards in the episode is collected. Baseline estimate is the value function in state s_t , which is produced by the neural network and has some variance. \hat{A}_t indicates the comparative value of the chosen action over the expectation of the state.

$$G_t = R_t + \gamma R_{t+1} + \dots = \sum_{k=0}^{\infty} \gamma^k R_{t+k} \quad (4)$$

Due to the parameter updates of the neural network extending beyond the range of collected data, advantage function predicts the wrong estimate. This problem is solved in TRPO formulated which is also the basis for PPO. A limit on the policy update magnitude is applied as in Equation 5.

$$\max_{\theta} \hat{E}_t \left[\frac{\pi_\theta(a_t \vee s_t)}{\pi_{\theta_{old}}(a_t \vee s_t)} \hat{A}_t \right], \text{ subject to } KL_{\pi_{\theta_{old}}}(\pi_\theta) \leq \delta \quad (5)$$

However, this additional overhead of KL constraint in optimization process can cause problems in training. This is solved by the clipping operation in the objective function of PPO as formulated in Equation 6. $\frac{\pi_\theta(a_t \vee s_t)}{\pi_{\theta_{old}}(a_t \vee s_t)}$ is denoted by $r_t(\theta)$. Expectation over the minimum of two terms is calculated. First term is the default objective, and the second term is obtained by applying a clipping operation on the first term where ϵ is between 0 and 0.2.

```

Algorithm 1 PPO for DeepRele
PPO Initialization
Simulation model initialization create interaction between agent and model
for episode = 1 to T-steps do
    Load dataset set and initialize problem instance
    sample action  $a_t$  using current policy  $\pi_\theta$ 
    if Action == Feasible then
        Let environment simulate action  $a_t$  and receive reward  $r_t$  and the next state  $s_{t+1}$ 
    else
        Receive penalty  $r_t$  for infeasible action
         $s_{t+1} = s_t$ 
    end
    end
    Compute advantage estimates  $\hat{A}_t, \dots, \hat{A}_T$ 
    Optimize  $L_t$ , via minibatch gradient descent
     $\pi_\theta = \theta_{old}$ 
    if end of episode then
        break
    end

```

Figure 4. PPO Algorithm for the proposed warehouse system [1]

$$L^{CLIP}(\theta) = \hat{E}_t[\min(r_t(\theta)\hat{A}_t, clip(r_t(\theta), 1 - \epsilon, 1 + \epsilon)\hat{A}_t)] \tag{6}$$

The PPO objective function is created by adding extra terms to $L^{CLIP}(\theta)$ as in Equation 7. $L_1^{VF}(\theta)$ updates the baseline network. $S[\pi_\theta](s_t)$ encourages exploration. c_1 and c_2 weights are hyperparameters to be adjusted.

$$L_t^{CLIP+VF+S}(\theta) = \hat{E}_t[L_t^{CLIP}(\theta) - c_1L_1^{VF}(\theta) + c_2S[\pi_\theta](s_t)] \tag{7}$$

PPO training algorithm for the proposed warehouse system is shown in Figure 4.

3.2.4. Heuristic algorithm

Least Slack Time (LST) rule which is a heuristic method that assigns a priority to the orders with least slack times is applied as a benchmark. Slack time is defined as the difference between the amount of time until the due date of the order and the total processing time. When slack time turns negative, single-select is applied. Our algorithm for LST batching and sequencing rule is as follows:

1. Orders are ordered by ascending cut-off times
2. Orders are grouped into batches or single orders according to greedy rule
3. Slack time of each order/batch is calculated
4. If there are batches that have a negative slack time, those are dismantled into single orders
5. Order/batches are ordered by ascending slack time
6. First order/batch in the list is selected to be processed

3.3. Experiments

Order arrival events dataset shared by [21] is utilized in this research. It is a public dataset that includes

purchase data from April 2020 to November 2020 from a major online retailer of home appliances and electronics. The dataset includes the information of order arrival times and products in each order, which are interested for OBSP. The other required information for our algorithm, such as the stock location of items and the composition of orders are generated in the scope of this work. The dataset is chosen because it is e-commerce purchase history data which is suitable for the proposed warehouse system. The dataset includes 1.4M orders and 2.6M items in total. It is observed that order arrivals are concentrated on morning hours, see Figure 5 for order arrival distribution.

Some preprocessing steps are done to simplify the problem, such as removing the outliers which are orders consisting of 10 or more items and orders containing more than one from the same SKU. Only hours between 06:00 and 12:00 is taken into consideration since these are the busiest hours. The cut-off times are generated since they do not exist in the original dataset, however cut-off times will be applied to decide the tardiness of the order. Two cut-off time settings with every hour or 15 minutes between 07:00 and 13:00 are examined. Items that are purchased before 12:00 will be delivered same day, so orders before 12:00 are processed same day and have cut-off times before 13:00. A pareto analysis has been done, and the most frequently ordered items are placed in PtG stock whereas the others are placed in GtP.

Scenarios are created from the order arrivals dataset processed according to these assumptions. Each scenario is analysed for different order throughput and resource settings and with settings in Table 1 between 06:00 and 12:00. Orders before 06:00 are not considered. All orders that are not processed between

release and next cut-off moment are considered to be tardy.

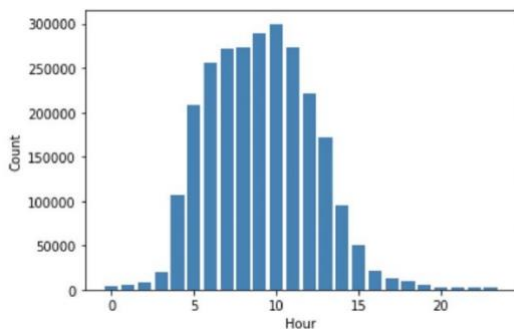


Figure 5. The distribution of order arrivals aggregated over a span of 30 days

Order arrivals have been released to the simulation environment at the start of the hour or once in every 15 minutes depending on the scenario. Then, it is decided which orders will be picked and whether it will be a batch or a single order. The decision is a result of the learned policy of the agent in DRL experiments, and depends on a rule in heuristic experiments. After the items for the order/batch is picked, it follows the designated path in our specific warehouse environment. The orders are accepted to become tardy when their shipping time exceed the cut-off time specified for each scenario.

Table 1. Different scenarios applied for order arrivals dataset

Scenario	A	B
Length of run	1 hour	1 hour
SKU distribution	PtG - 70% GtP - 30%	PtG - 70% GtP - 30%
Order releasing times	Every hour	Every 15 minutes
Cut-off times	Every hour	Every 15 minutes

Same experiment setup has been applied for both heuristics and DRL algorithm to be able to compare them. Two different order throughput setting has been applied for each scenario, which are 360 and 500 orders per hour. Resources are 9 pickers, 15 shuttles, 1 DtO zone, 1 StO zone and 1 packing zone for all experiments. The number of warehouse resources and order throughput values have been determined by running heuristic experiments several times beforehand, and trying to achieve a low percentage of tardy orders. Four experiment have been done with LST, symbolized with lst360_3600, lst360_900, lst500_3600 and lst500_900. The first number in the model name symbolizes the order throughput and the second number symbolizes the order arrival interval in terms of seconds.

For the DRL algorithm experimentation, a training step is also required. Train and test datasets are obtained by splitting the original dataset randomly, and getting 70% for training, and the remaining 30% for testing. PPO algorithm is utilized for training, the model is trained for 1000000 steps. The step size, the number of steps per update is 1024. The discount factor is 0.9999. MlpPolicy is used as policy model. The clipping parameter is 0.2. Learning rate is 0.0003. The other parameters are all default values. Four models are trained: a360_3600, a360_900, a500_3600 and a500_900. The first number in the model name symbolizes the order throughput and the second number symbolizes the order arrival interval in terms of seconds.

The results are examined and compared in terms of tardy order percentage. Also, robustness and action strategy of the DRL solution are investigated.

All experiments are conducted on the same virtual machine on Microsoft Azure. The virtual machine is Standard D16as v5 size (16 vcpus, 64 GiB memory) and has a Linux (ubuntu 20.04) operating system. For training and testing the PPO model, stable-baselines3 package [22] and PyTorch [23] is used, and Tensorboard is used for monitoring the behaviour of the agent.

IV. RESULTS AND DISCUSSION

4.1. Tardy Order Percentages

To adjust the reward formula, different weights for penalties are tested for 1 hour order arrival interval and for 360 and 500 order throughputs. The effect of different reward formulas in terms of tardy order percentages can be viewed in Table 2. First we had applied smaller penalties, and after some trial and error, we decided on larger penalties. The weights for small penalties are -0.005 for infeasible action and -0.0075 for tardy order which are the weights used in [1], whereas for large penalties they are -0.5 and -1.5 respectively. Larger penalties resulted in more difference for higher order throughputs.

The reward formula is a fundamental component in RL that directly impacts how the agent learns and behaves. Its design requires careful consideration to ensure that it effectively guides the agent towards the intended goals while avoiding pitfalls and promoting efficient learning. The choice between large and small penalties in RL depends on the specific requirements and constraints of the task. By providing a strong deterrent against suboptimal actions, large penalties can help the agent converge to a better policy more quickly, as it more decisively learns which actions to avoid. However, they can cause instability. Small penalties, on the other hand, allow the agent to explore the environment more freely, understanding a broader range of actions and their outcomes without being overly discouraged by mistakes. However, they lead to

a slower convergence. On our specific problem, smaller weights might not have been sufficient to strongly discourage tardy orders.

Table 2. Tardy Order Percentage for Different Reward Formulas with Standard Deviation Given in Paranthesis

Trained Model	Penalty Weights	Mean (%)
a360_3600	(-0.005, -0.0075)	1.91(1.79)
a360_3600	(-0.5, -1.5)	1.6 (1.74)
a500_3600	(-0.005, -0.0075)	12.15 (10.15)
a500_3600	(-0.5, -1.5)	8.51 (2.24)

After deciding on the reward formula, 4 different models are trained with the PPO algorithm for 360 and 500 order throughputs, and 1 hour and 15 minutes order arrival intervals. The models are tested for 20 episodes. LST rule has been applied on the same settings for same number of episodes and the results are compared for each setting. Table 3 shows the resulting average tardy order percentages and standard deviations.

Table 3. Comparison of Tardy Order Percentages of LST and PPO Algorithms

Experiment	Mean (%)	Standard Deviation(%)
lst360_3600	3.73	2.68
a360_3600	1.91	1.79
lst360_900	0.0	0.0
a360_900	0.0	0.0
lst500_3600	24.83	3.17
a500_3600	8.51	2.24
lst500_900	23.2	12.01
a500_900	8.3	9.1

It is observed that the agent trained with DRL achieves around a one third lower tardy order percentage for all settings when compared with the benchmark of applied heuristic. The higher order throughput values result in higher tardy order percentages as expected. The mean values are slightly lower when an arrival interval of 15 minutes applied, however the standard deviation is higher in that case. We observed that the amount of decrease in tardiness when DRL applied is significant especially when the amount of orders to be processed is higher.

The overall performance of the DRL agent in terms of tardy order percentages is higher than the heuristics,

which is compatible with the previous studies [1][5]. It shows that RL can be an effective solution for achieving a lower tardy order percentage in logistics due to its ability to learn optimal strategies through interactions with the environment. It may be a promising method for the tight delivery schedules and order uncertainties frequently encountered in today’s logistics solutions.

4.2. Action Strategy

The actions taken by the agents on each episode for different order throughput values and order arrival interval of 1 hour are logged during training and visualized in Tensorboard as shown in Figure 6. The last chart shows do nothing action which is selected when there are no capacity or available orders. Action1, action3, action5, action7 and action10 represent single-select actions whereas the others represent multi-select actions. First 4 actions are for picking single item orders, whereas the others are for multiple item orders. Action1, action2, action5 and action6 is for picking items that are stored in PtG stock. Action3, action4, action7 and action8 is for picking items that are stored in GtP stock. Action9 and action10 is for picking items from both PtG and GtP stocks.

The count of average performed actions per episode is higher in case of a high order throughput almost for all actions. It makes sense because more actions will be required to pick more orders. The results are only different for action1 and action5. Action1 and action5 was for picking items by order from PtG stock area.

Our agent may take a multi-select decision instead of single-select for a high order throughput value for PtG stocks only because total picking time for PtG decreases more than GtP when orders are batched. To explain it with an example; suppose that they will be 3 items in the batch. Then, total picking time will be roughly $3 \times 30 + 100 = 190$ to pick them from PtG, and roughly $3 \times 15 = 45$ for picking them from GtP. When not batched, the time will be $(30 + 100) \times 3 = 390$ for PtG stock and will not change for GtP. There is a constant value symbolizing the time for picker to arrive to the location of the item in PtG stock, which explains the decision of the agent.

The distribution of numbers of actions diversifies mostly in action2, action6 and action8. Action2 increases for the low order throughput value, whereas it decreases for the high order throughput value. For action6 and action8, the situation is the vice versa. All of them are multi-select actions. The difference between the categories these actions address is that action 2 is for single item orders, whereas action 6 and 8 is for multiple item orders. We can make an inference that our agent improves a strategy to select multi-select actions more for single item orders and less for multiple



Figure 6. The mean number of actions executed per episode for different order throughputs during training for 1 hour arrival interval

item orders when total number of orders is high. It may be because of that batching single item orders requires less time to process orders at areas. For the case of smaller arrival intervals, the same strategy development is not observed.

Generally, the number of do-nothing actions is smaller for a low order throughput value. It may be because of resource deficiency met when high number of orders started to be processed in our warehouse environment.

Developing an action strategy is essential for an RL agent’s success. It provides the framework within which the agent learns and makes decisions, ensuring that the agent can efficiently and effectively navigate its environment to achieve the desired goals. By monitoring the actions taken by our RL agent during training, it is observed that it develops an action strategy to achieve a lower number of tardy orders in a capacity constraint environment.

4.3. Robustness Analysis

The agents trained on 360 and 500 order throughputs are also tested on 500 and 360 orders respectively for different order arrival intervals, to observe how will

they behave when there is a lower or higher order throughput is experienced than they are trained on.

Resulting tardy order percentages can be viewed on Table 4. It is observed that the agent trained on 500 hourly orders processes all orders in time when it met 360 hourly orders. The other agent which is trained on 360 hourly orders, does not perform as well as the one trained on 500 orders as expected. However, it can still achieve better than the heuristic approach.

Table 4. Tardy Order Percentage for Models Tested on Different Order Throughput Values Than They Trained

Trained Model	Test Order Throughput	Mean (%)
a360_3600	500	18.97 (2.73)
a360_900	500	0.57 (1.55)
a500_3600	360	0.0 (0.0)
a500_900	360	0.0 (0.0)

The behaviour of the RL agent in case of order uncertainty and variability is important since it is a case that frequently occurs in today's warehouses, especially in e-commerce. It is shown that the the proposed RL solution may cope with the order peeks, and exhibit an acceptable performance.

V. CONCLUSION

In this research, the performance of a DRL solution on an OBSP problem with an objective of minimizing the tardy order percentage is investigated. The results are compared to a heuristic solution which is applied on the same warehouse environment and order arrival dataset. The following conclusions are obtained:

1. DRL with an LST applied for sequencing gives better results than LST batching and sequencing on our specific problem for all of the applied scenarios.
2. The proposed solution is robust to changes in order throughput.
3. It is observed that our agent develops an action strategy that will decrease the time for an order to be prepared.

The DRL model may be improved by including different techniques for optimizing reward function, further investigating different model parameters. There exists studies with the methods based on PPO and proved to have a better sample efficiency [24][25]. Following up recent improvements in RL algorithms and including in our solution may improve the results. For a better simulation of a real life problem, higher order throughputs may be experimented and a more detailed warehouse simulation may be used. Other performance metrics such as maximization of the utilization of resources may be measured to investigate the versatility of the solution.

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Pano Klimalarında Farklı Soğutucu Akışkan Kullanımının Analizi

Analysis of Different Refrigerant Usage in Cabinet Air Conditioners

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Öz

Çalışma sürecinde, küresel beklenti ve taleplerin sürekli değişerek güncellendiği iklimlendirme sistemlerindeki soğutucu akışkan kullanımı çevresel ve termal faktörlerle irdelenerek değerlendirme sonuçları ortaya konulmuştur. Çalışmada kıyas elde edebilmek amacıyla pazardaki en büyük paya sahip soğutucu akışkanlardan R134a ve R404A'nın yanında; bu soğutucu akışkanlar ile aynı aileden, ozonu aşındırma potansiyeli (ODP) ve küresel ısınma potansiyeli bakımından (GWP) çevre etkileri en az olarak görünenlerden R32 soğutucu akışkanı ile beraber günümüzde kazandığı ivme ile gelecekte kullanımından söz ettirmesi beklenen halojen içermeyen doğal soğutucu akışkanlar grubunda nitelendirilen ve olumlu çevresel etkileri ile öne çıkan R290 soğutucu akışkanları ele alınmış, her bir soğutucu akışkan için benzer soğutma kapasitesi sağlayacak şekilde pano kliması özelinde analitik termal tasarımlar yapılmış ve tüm parametreler genel bir kıyasa tabi tutulmuştur. Farklı çevresel ve termofiziksel etkiler barındıran akışkanların değerlendirilmesi ile aradaki farkların açıkça ortaya konulabilmesi hedeflenmiştir. Çalışmada detaylı sistem tasarımları matematiksel ve pratik kuramlar ile gerçekleştirilmiş, diğer muadiller ile çevre, enerji, sürdürülebilirlik, işletim, verimlilik, güvenlik, konularında analizler yapılarak kapsamlı bir çerçeve oluşturulması amaçlanmıştır. Sistemlerin termal performans değerlendirmesinde ölçüt olarak alınan ve matematiksel olarak sunulan; ısı eşanjörü verimliliği, kompresör hacimsel verimi ve sıkıştırma oranları, sistemlerin genel enerji tüketimleri, enerji ve ekserji verimlilik analizlerinin her birinde R290 ve R32 soğutucu akışkanlarının diğer iki soğutucu akışkana karşı avantajı ortaya konulmuştur. R290 ve R32 soğutucu akışkanlarının sahip olduğu bu termal performans avantajlarının yanına, CO₂ eşdeğeri şarj miktarı analizi ile değerlendirilen çevresel etkiler bakımından da avantajları eklenerek tüm analizlerde başta halojen içermeyen doğal soğutucu akışkan grubu üyesi R290 olmak üzere R290 ve R32 soğutucu akışkanlarının önde olduğu tespit edilerek sunulmuştur. Bu çalışmanın ele aldığı ürün gamından yola çıkıp daha yüksek oranlarda kullanım ile çevresel faktörler ve iklim değişikliği konularına dikkat çekmesi hedeflenmektedir.

Anahtar Kelimeler: Enerji, HVAC, Pano Kliması, Soğutucu Akışkan, Verimlilik

Abstract

The study aimed to evaluate the use of refrigerant in HVAC systems, where global expectations and demands are constantly updated, with environmental and thermal factors. In order to obtain a comparison in the study, in addition to R134a and R404A, which are the refrigerants with the largest share in the market; R32 refrigerant, which is from the same family as these refrigerants and appears to have the least environmental impact in terms of ozone depletion potential (ODP) and global warming potential (GWP), and R290 refrigerants, which are in the group of natural halogen-free refrigerants, are discussed. Analytical designs of cabinet air conditioners were made to provide similar cooling capacity for each refrigerant and all parameters were compared. It is aimed to clearly reveal the differences by evaluating refrigerants with different environmental and thermophysical effects. In the study; it is aimed to create a comprehensive framework by analyzing the issues of environment, energy, sustainability, operation, efficiency and safety among refrigerants. In thermal performance evaluation of systems; The advantages of R290 and R32 refrigerants over the other two refrigerants were revealed in each of the heat exchanger efficiency, compressor volumetric efficiency and compression ratios, general energy consumption of the systems, energy and exergy efficiency analyses. In addition to these thermal performance advantages of R290 and R32 refrigerants, their advantages in terms of environmental effects have been added with the CO₂ equivalent charge amount analysis. Thus, in all analyses, R290 and R32 refrigerants, especially R290, a member of the halogen-free natural refrigerant group, were found to be at the forefront and presented. Based on the product discussed in this study, it is aimed to draw attention to environmental factors and climate change issues with higher usage rates.

Key Words: Energy, HVAC, Cabinet Air Conditioner, Refrigerant, Efficiency

I.GİRİŞ

Soğutma, iklimlendirme sistemlerinin hizmet ettiği bireysel sahalarda konfor ön plana çıkarken; endüstriyel sahalarda güvenlik, süreklilik, stabilite ve ekonomik faktörler ön plana çıkmaktadır.

Endüstriyel tip pano kliması uygulamalarında kontrol, kumanda ve haberleşme panolarında elektriksel komponentlerin yaydığı ısı yükü bertaraf edilerek pano içindeki bileşenlerin ısı ve nem dengesi dış ortam koşullarından bağımsız olarak sağlanmakta olup sistemlerin bakım, arıza, komponent değişimi, duruşlardan kaynaklı kayıplarının önüne geçilmiş olur.

Küresel bakışta her geçen gün artan haberleşme, uzaktan erişim, bireyler arasında mesafeden bağımsız kurulan sosyal ağlar, gündelik işlerin her geçen gün teknoloji dünyasına adapte oluşu beraberinde daha efektif haberleşme ve veri çözümleri oluşturmuş, bu kapsamda her geçen gün sistem panolarının yaydığı ısı miktarı artma eğilimi göstermiştir.

Bir soğutma çevriminin ısı transfer mekanizması soğutucu akışkanlar vasıtasıyla yürütülür. Isı alış verişini faz değişimi esnasında ortam sıcaklığını referans alarak gerçekleştirirler. Buhar sıkıştırma çevrimleri ile çalışan soğutma makinalarında bu husus geçerlidir. [1]

Endüstriyel kompakt tip pano klimaları, mekanik sıkıştırılmalı buhar çevrimi prensibiyle çalışan klasik soğutma makinaları ile aynı sistem elemanları ve çalışma döngüsüne sahiptir. Bu sistemleri diğer sistemlerden ayıran en önemli özellik iç ve dış ünite ayrımı olmaksızın tek gövdede kullanım şansı sunabilmeleridir. Endüstriyel sahada genellikle 250 watt – 10000 Watt soğutma kapasitesi arasında ürünler bulunmaktadır.

Çalışmanın soğutucu akışkan penceresi irdelendiğinde; HVAC endüstrisi 1900'lerin başlarında ortaya çıktığından bu yana muazzam şekilde büyüdü ve birçok değişiklik geçirdi. Sadece donanım ve teknoloji gelişmelele kalmadı, aynı zamanda bu sistemlerde kullanılan soğutucu maddeler de çok gelişti. [2]

General Motors araştırma laboratuvarlarında Charles Kettering'in yönetiminde çalışan Thomas Midgley, 1928'de kloroflorokarbonlar (CFC'ler) olarak bilinen soğutucu akışkanları icat etmekle tanınmaktadır. CFC'ler ve onların yakın akrabaları olan hidrokloroflorofarbonlar (HCFC'ler), o zamanlar yaygın olarak kullanılan soğutucu akışkanların yanıcı ve toksik olmayan en güvenli alternatifleriydi [2].

CFC-11, CFC-12 ve HCFC-22 gibi CFC'ler ve HCFC'ler, o zamana kadar kullanılan Kükürt Dioksit (SO_2), Metil Klorür (CH_3CO) ve Amonyak (NH_3) gibi yaygın şekilde kullanılan yanıcı ve toksik soğutucu akışkanların yerini neredeyse tamamen aldı [2].

1974'te Frank Rowland ve Mario Molina, CFC'lerin ve HCFC'lerin yüksek kararlılıkları ve uzun ömürleri

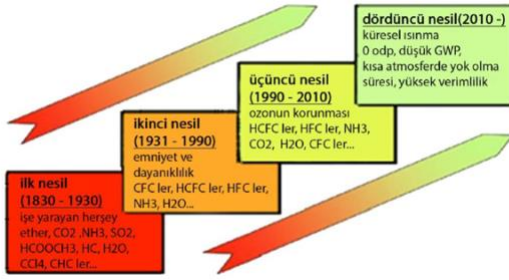
sayesinde atmosferin üst katmanlarına, özellikle stratosfere erişebileceklerini, orada UV ışınlarına maruz kalacakları için ayrışacaklarını ve klor atomları açığa çıkartacaklarını öne sürdüler. Ayrıca serbest klor atomlarının nihayetinde ozon moleküllerini (O_3) parçaladığı ve bundan dolayı da stratosferdeki ozon miktarını azalttığı bir kimyasal reaksiyon meydana geleceğini de öne sürdüler [2]. Bu çalışmalar süreklilik kazanarak soğutucu akışkan dönüşümünün hidroflorokarbonlar (HFC) ve hidrokarbonlar (HC) şeklinde ilerleyerek devam etmesinin yolunu açmıştır.

Bu soğutucu akışkan dönüşümü küresel bazda da sürekli olarak güncelliğini sağlamış otoritelerin ortak tavırlarının göstergesi olmuştur. Bu bağlamda en fazla etki sağlayan protokol ve düzenlemeler;

- 1- Rowland ve Molina'nın buluşuna takiben Birleşmiş Milletler Çevre Programı (UNEP), 1987 senesi sürerken "Ozon Tabakasını Olumsuz Etkiler Bırakabilecek Maddelere İlişkin Montreal Protokolü" imzalandı. Bu anlaşma, o güne dek Birleşmiş Milletler'in sponsorluğunu yaptığı en başarılı uluslararası anlaşma olarak kabul edildi [2].
- 2- Kigali değişikliği, hidroflorokarbonların (HFC) üretimini ve kullanım süreçlerini kontrol altına alıp iklim değişikliğine karşı verilen mücadelede büyük bir unsur olarak öne çıkmıştır. HFC endüstriyel proseslerinin kontrolü, CFC'ler ve HCFC'ler ile beraber ozon tabakasına olumsuz etkiler barındıran bileşenlerin azaltımı vasıtasıyla Montreal Protokolü ile elde edilen olumlu iklim unsurlarına katkı sunmuştur [3].
- 3- Avrupa Birliği üzerinden 2006 senesinde yayına sunulan EC 842 / 2006 ve 1 Ocak 2015 itibariyle işleme koyulan (EC) 517/2014 Florlu Gazlar Yönetmeliği (F-Gaz), hidroflorokarbon (HFC) tipinde sera gazlarını kapsayan soğutma sistemlerinden sorumlu işletmeci, operatör ve saha servis yetkilileri için belli zorunluluklar barındırmaktadır [4].

Calm yapmış olduğu çalışmada, tüm bu dönüşümleri dikkate alarak soğutucu akışkanların nesillerini belirtmiştir [5].

Şekil 1’de soğutucu akışkan nesilleri ve bu nesillere ait örnek soğutucu akışkanlar verilmektedir.

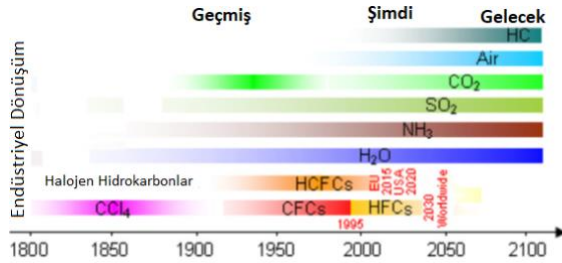


Şekil 1. Geçmişten Bugüne Soğutucu Akışkanlar [5]

Çalışmada konu alınacak soğutucu akışkanlardan R134a, R404A ve R32 HFC ailesine dahil iken, R290 ise HC ailesine dahildir. Bu sayede piyasa kullanımı yüksek olan farklı ailelerden soğutucu akışkanlar arasında bir kıyas kurulması hedeflenmektedir.

Şekil 1’ de çalışmada detaylandırılan akışkanlardan R290’ın dahil olduğu HC ailesinin bazı üyelerinin kimyasal bileşimi nedeniyle birinci nesile, çevresel özellikleri nedeniyle de dördüncü nesile yakın olduğu görülmektedir. Bu bağlamda Abas N. ve ark., [25] çalışmalarında bu konuyu inceleyerek soğutucu akışkan ailelerini detaylandırmışlardır.

Şekil 2’de detaylı soğutucu akışkan dönüşümünün zaman çizelgesi verilmektedir.



Şekil 2. Detaylı Soğutucu Akışkan Dönüşümü [25]

Şekil 2’de görüldüğü üzere Hidrokarbon (HC) soğutucu akışkanlar HVAC uygulamalarının ortaya çıktığı ilk yıllarda da kullanım alanı bulmuşken 2000’li yıllardan başlayarak 2100 lü yıllara kadar gelecek kullanımı bakımından da potansiyel olarak değerlendirilmektedir.

İlk yıllarda kullanım alanı bulan türleri genellikle halojenlerken, son dönemde ve gelecekte kullanımının artması beklenen türleri ise halojen içermeyen çevre dostu soğutucu akışkanlardır. Bu nedenle ele alınan R290 akışkanının arttırılan ve arttırılacak kullanımı gözetilerek çalışma da ele alınmıştır.

Emanı, M. S. ve ark. [26] yaptıkları çalışmada halojen içermeyen soğutucu akışkanları geleceğin soğutucu akışkanları olarak tanımlamışlardır. Halojen içermeyen, doğal R290 soğutucu akışkanı bu bağlamda değerlendirilebilir.

Literatür anlamında her ne kadar soğutucu akışkanların birçok farklı soğutma sistemi üzerinde değerlendirilmesi üzerinde durulsa da, hem pano klimalarının birim soğutma kapasitesinin düşük olması hem de sektörel olarak kullanımının son dönemdeki teknolojik gelişmelere bağlı olarak artışı nedeniyle kendi sahasını yeni oluşturması ile ilgili bir literatür çalışması bulunmamaktadır. Bu çalışmanın bu noktada literatüre özgün değer kazandırması hedeflenmektedir.

Çalışmanın soğutucu akışkan bölümünün özgün değeri değerlendirildiğinde ise, diğer çalışmalardan farklı olarak hem çevresel hem termal faktörler birbiri ile kıyaslamalı olarak verilerek çalışma sonunda elde edilen tüm faktörler bakımından fikir birliğine varılması hedeflenmiştir. Bu duruma ek olarak muadil çalışmalarda kıyaslamalar iki farklı soğutucu akışkan grubu üzerinden gitmektedir. Bu çalışmada, popüler soğutucu akışkan ailelerinin başında gelen ve azaltım takviminde değerlendirilen HFC ailesinden hem en çok kullanılanları hem de çevresel etkileri en az olanlardan bir üyesi ele alınmış, her üç soğutucu akışkanda halojen içermeyen doğal soğutucu akışkanlar kategorisindeki R290 ile kıyaslanarak birebir kıyas yerine çoklu kıyas elde edilmiştir. Bunun dışında temel olarak literatürde direkt bu dört soğutucu akışkanın birbiri ile kıyaslaması konusunda bir çalışma bulunmamaktadır.

1.1. Literatür Araştırması

Tezin çıkış noktasında bulunan soğutucu akışkanlar ve soğutma sistemlerinin termal dizaynı kapsamında birçok çalışma yapılmış ve küresel bakışın tepkisi daima güncel tutulmuştur. Bu bağlamda incelenen çalışmalar şu şekilde analiz edilebilir.

Alarco Carrier [2], ilk çıkış noktalarından bu yana soğutucu akışkanların güncel pazar dönüşümünü incelenmiştir. Bu bağlamda öncelikle 1900’lü yıllarda ortaya çıkan HVAC endüstrisinin ilk etaplarında kullanılan yanıcı ve toksik soğutucu akışkanlar açığlanmış ardından bunların yerini kloroflorokarbonlar’ın (CFC) alış sürecinin aktarılmıştır [2].

Onat A. ve ark. [13], çalışmalarında dönem şartlarında sık kullanılan soğutucu akışkanların çevresel etkilerini araştırmış ve bu soğutucu akışkanlara alternatif soğutucu akışkanlar üzerinde incelemeler gerçekleştirmişlerdir.

Calm J. ve ark. [5], soğutucu akışkan değişim süreçlerini bir şablona oturtarak soğutucu akışkanları dört nesil altında incelemiş, 2010’lu yılların başından itibaren soğutucu akışkanlarda çevre parametrelerinin başı çektiğine değinmiştir.

Abas N. ve ark., [25], yaptıkları çalışmada soğutucu akışkan ailelerinin detaylı ayrımı üzerinde durmuşlardır. Çalışmada detaylandırılan akışkanlardan R290’ın dahil olduğu HC ailesinin bazı üyelerinin kimyasal bileşimi nedeniyle birinci nesile, çevresel özellikleri nedeniyle de dördüncü nesile yakın olduğu görülmektedir. Bu

konudaki karışıklıkları gidermek adına oluşturdukları soğutucu akışkan tarih çizelgesinde HVAC uygulamalarının en başında kullanılan Hidrokarbonların (HC) halojen içerikli olduğu, R290 gibi halojen içermeyen, doğal, yeni nesil soğutucu akışkanların ise bugünden başlayarak gelecek kullanımına ayna tutarak konunun netlik kazanması üzerinde durmuşlardır. [25]

Erten S. ve ark. [29], sabit soğutma kapasitesine sahip HFC R404A yanında R290(propan) soğutucu akışkanı kullanılan iki adet buhar sıkıştırma mekanik soğutma çevrimi sistemini enerji verimliliği bakımından kıyaslamışlardır. Testlerde 25 °C sıcaklık değeri sabit tutulurken bağıl nem de %60 seviyelerinde dengede bırakılarak kıyaslama gerçekleştirilmiştir [29].

COP değeri 2,5 olarak belirlenen R290 soğutucu akışkanı ile çalışan sistemin, COP'si 2,2 olarak tespit edilen R404A soğutucu akışkanlı sisteme göre avantajı sunulmuştur. Çalışma sonucunda doğaya olumsuz etkisi en düşük düzeylerde olan R290 soğutucu akışkanının R404A'ya göre yaklaşık %13-14 daha verimli olduğunu ortaya koyulmuştur. [29]

Zheng H. ve ark. [31], Çalışmalarında R134a kullanılan bir soğuk muhafaza sisteminde R290 kullanımını farklı parametreler bakımından değerlendirerek R134a'nın 1400 gramlık optimum şarj aralığını R290'ın 600 gramda yakaladığını ortaya koyup R290'ın daha az şarj miktarı ile minimum çevresel salınım avantajını ortaya koymuştur. Ayrıca soğutma performansı bakımından sistemleri değerlendirdiğinde R290 sisteminin ortalama soğutma etkisinin, optimum şarj miktarıyla R134a'ninkinden yaklaşık %52 daha yüksek olduğunu belirterek R290 özelinde pozitif çevresel etkilerin, termal etkiler ile doğru orantısını ortaya koyulmuştur [31].

Okudan M. O. [32], Sektörel kullanımı R134a ve R404A ile benzer biçimde yüksek ve aynı kimyasal aileye dahil olan R410A soğutucu akışkanını içeren soğutma sistemlerine, çevresel etkiler bakımından daha olumlu sonuçlara sahip muadil soğutucu akışkanlar önerilebilir üzerinde çalışmalar yapmıştır.

Bu bağlamda GWP değeri düşük ve kullanım alternatifi olarak sunulabilecek muhtemel soğutucu akışkanlardan R454B,R452B ve R32'nin termal performans verilerini irdelemiştir. Çalışma özelinde soğutma kapasiteleri değerlendirildiğinde R-32 soğutucu akışkanın yer aldığı sistemin diğer muadillerine göre soğutma kapasitesinde %6,67 artış sağlandığını tespit etmiştir. Aynı zamanda çalışma kapsamında R32 soğutucu akışkanın gaz şarjı ve GWP etkisi bakımından da avantajları sunulmaktadır. [32]

Zeng M. ve ark. [33], Çalışmalarında (R134a/R290, 55/45), karışımının R404A soğutucu akışkanının yerine kullanılmasını önermek adına bir dizi analiz gerçekleştirmişlerdir. Analizler sonucunda aynı koşullar altında karışımın COP'si R404A'ninkinden daha yüksektir; buna paralel olarak soğutma kapasitesi

R404A'ninkinden daha iyidir. Karışımın hacimsel soğutma kapasitesi ve sıkıştırma oranı açısından R404A'ya benzer bir tepki gösterdiğini tespit etmişlerdir [33].

Termal performansı çevresel performans bakımından da değerlendirdiklerinde karışımın GWP'sinin R404A'ninkinden %81,83 daha düşük olduğunu ortaya koymuşlardır [33].

Sanchez D. ve ark. [34], deneysel çalışmalarında R134a yerine kullanılabilir 0 GWP oranına sahip çevreci bir soğutucu akışkan tespit etmeyi hedeflemişlerdir. Bu hedefe yönelik baz aldıkları soğutucu akışkanları 0 ve -10°C evaporasyon sıcaklıklarında değerlendirmişlerdir. Çalışmalar sonucunda R290'ın (propan), soğutma kapasitesi ve COP açısından en iyi sonuçları elde ederek sırasıyla %40,5–%67,4 ve %22,4–%2,8 arasında bir artış sağladığını ortaya koymuşlardır [34].

Şişman S. ve ark. [22], çalışmalarında R404A'nın yaygın kullanımına dikkat çekmiş ve bu noktadan yola çıkarak bu yaygın kullanıma düşük GWP oranlı soğutucu akışkanlar ile bir muadil bulmayı hedeflemiştir. Yapılan çalışmalar sonucunda R32 soğutucu akışkanının kritik sıcaklık bakımından R404A'ya ve EER değeri bakımından incelenen tüm soğutucu akışkanlara kurduğu üstünlük tespit edilmiştir. Çalışma sürecinde yapılan tespitler ışığında R404A soğutucu akışkanlı sistemlerde incelenen soğutucu akışkan seçeneklerine geçiş ile GWP değerinin düşürülmesinin avantajları sunulmuştur. [22]

Erdoğan M. ve ark. [10], ısı eşanjörleri termal dizaynı konusunu incelemiş, bu bağlamda genel transfer katsayısını elde etmek amacıyla kabul görmüş güncel korelasyon ve bağıntılar vasıtasıyla iç yüzey ve dış yüzey taşınım katsayısı hesaplarını gerçekleştirerek genel transfer katsayısını elde etmiş ve sistem kapasitesine ulaşmanın yöntemi üzerinde çalışmışlardır.

Aynı çalışma özelinde genel soğutma kapasitesini belirlemede gerekli olan bir diğer ana unsur olan ortalama logaritmik sıcaklık farkı da incelenip analiz edilmiştir [10].

Özşen M. ve ark. [12], kanatlı borulu yoğuşurucu eşanjörünün, kabul gören farklı bağıntılar üzerinden matematiksel modellerini ortaya koymuş, ardından tasarlanan sistemi testlere tabi tutarak gerçek şartlar ile matematiksel modeller arasındaki kaymayı ortaya koyarak EUROVENT standardına göre kabul edilebilir kayma miktarını tanımlamıştır.

Çalışma özelinde kullanılan korelasyonlar ile reel sonuçlar arasındaki farkın önemli ölçülerde değişim gösterebileceği açıkça belirtilmiştir [12].

Emanı, M. S. ve ark. [26] yaptıkları çalışmada halojen içermeyen soğutucu akışkanları geleceğin soğutucu akışkanları olarak tanımlamışlardır. Halojen içermeyen, doğal R290 soğutucu akışkanı da bu bağlamda değerlendirilebilir [26].

Tablo 1’de bu alanda incelenen çalışmaların genel perspektifi sunulmaktadır.

Tablo 1. Literatür Araştırması Özeti

Çalışma	Çalışılan Soğutucu Akışkanlar	Çalışma İçeriği
Onat A. ve ark. [13]	Genel Soğutucu Akışkan Nesilleri	Çevresel Etkiler / Olumlu Çevresel Etkilere Dair Alternatif
Calm J. ve ark. [5]	Genel Soğutucu Akışkan Nesilleri	Soğutucu Akışkan Nesilleri
Abas N. ve ark., [25].	Genel Soğutucu Akışkan Nesilleri	Soğutucu Akışkan Nesilleri Detaylandırma
Demirci E. ve ark. [28]	Genel Soğutucu Akışkan Nesilleri	Doğal Soğutucu Akışkan Kullanımındaki Gelişme Süreçleri
Ertan S. ve ark. [29].	R404A / R290	Soğutucu Akışkan Performans Kıyaslaması
Colbourne D. ve ark. [30]	Genel Soğutucu Akışkan Nesilleri	Soğutucu Akışkan Kimyasal Yapı Değerlendirmesi
Zheng H. ve ark. [31]	R290 / R134a	Soğutucu Akışkan Performans Kıyaslaması
Okudan M. O. [32]	R290, R600, R717, R744	Soğutucu Akışkan Performans Kıyaslaması
Zeng M. ve ark. [33]	R290 / R134a / R1270 / R404A	Soğutucu Akışkan Performans Kıyaslaması
Sanchez D. ve ark. [34]	R290 / R134a / R1234yf / R1234ze / R600a / R152	Soğutucu Akışkan Performans Kıyaslaması
Şişman S. ve ark. [22]	R404A / R32 / 1234yf	Soğutucu Akışkan Performans Kıyaslaması
Erdinç M. ve ark. [10]	CO ₂	Isı Eşanjörü Termal Dizaynı
Özgen M. ve ark. [12]	R404A	Matematiksel ve Reel Şartlar Arası Kayma Miktarı Sınırlandırması
Cingiz Z. ve ark. [18]	R22 / R417A / R438A / R422A / R422D	Ekserji Analizi
Hu X. ve ark. [20]	R404A	Soğutucu Akışkan Şarj Miktarı Değerlendirmesi
Emam, M. S. ve ark. [26]	Genel Soğutucu Akışkan Nesilleri	Yeni Nesil Soğutucu Akışkan Sınıflandırması

1.2. Pano Kliması Yapısı ve Çalışma Prensipleri

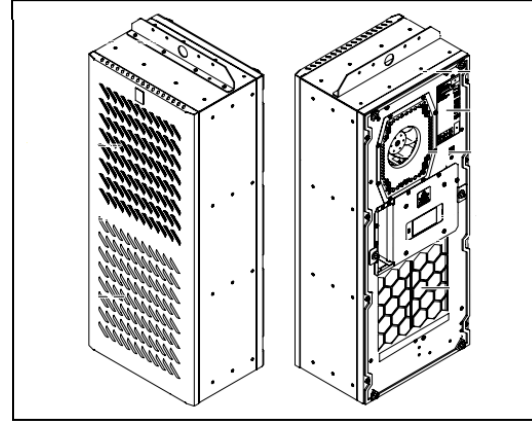
Endüstriyel kompakt tip pano klimaları, mekanik sıkıştırılmalı buhar çevrimi prensibiyle çalışan klasik soğutma makinaları ile aynı sistem elemanları ve çalışma döngüsüne sahiptir. Bu sistemleri diğer sistemlerden ayıran en önemli özellik iç ve dış ünite ayrımı olmaksızın tek gövdede kullanım şansı sunabilmeleridir.

Pano kliması iç yapısında kompresör, evaporatör, kondansör ve kısılma valfi gibi ana elemanların yanında sistem ihtiyacı doğrultusunda filtreler, yağ ve likit tutucular gibi ek donanımlar bulunabilir.

Kompresör tarafından sıkıştırılarak sıcaklığı artırılan kızgın buhar fazındaki soğutucu akışkan kondenserdeki ısı transfer etkisi ile doyma sıcaklığına getirilerek yoğunlaştırılır.

Genleşme cihazından geçerek basıncı düşürülen soğutucu akışkan buhar+likit fazında çalışma şartlarına göre belirlenen kuruluk derecesinde evaporatöre girer. Evaporatörde tekrardan doyma noktasını yakalayarak buharlaşan soğutucu akışkan aşırı ısıtılarak kompresöre iletilir ve döngü devam eder.

Şekil 3’te pano klimasında bulunabilecek komponentler ve cihaz içi dizayn verilmektedir.



Şekil 3. Örnek Pano Klima Yapısı [35]

II. MATERYAL VE METOD

Bu bölümde, ilk bölüm içerisinde nedenleri irdelenerek seçilen R134a / R404A / R290 / R32 soğutucu akışkanları için aynı veya yakın soğutma kapasitelerine sahip kompakt tip pano kliması termodinamik dizaynı gerçekleştirilmiş, sonuçlar analizlere tabi tutularak performans verilerinin kıyaslanması için zemin hazırlanmıştır.

2.1. Isı Eşanjörü Dizaynı

Çalışma özelinde tüm akışkanlar için ısı eşanjörü termal modelleri, endüstriyel pano kliması kullanım alanları dikkate alınarak eşanjör içi akış için ARI HT [21] ve eşanjör dışı akış için DIN 3168 standardı uyarınca kurulacaktır [6].

Çalışmada analizleri gerçekleştirilen dört soğutucu akışkan için de (R134a / R290 / R32 / R404A) özdeş evaporatör ve kondansör ısı eşanjörleri tasarlanmıştır.

Bu sayede değerlendirmeler esnasında ısı eşanjörü konstrüktif dizaynı performans etkileri sabit tutularak, termal performans direkt olarak soğutucu akışkan türü ile ilişkilendirilip sistemin daha şeffaf olarak değerlendirilmesi amaçlanmıştır.

Referans olarak evaporatör eşanjörünün R134a soğutucu akışkanı için termal tasarım adımları aşağıda detaylı olarak açıklanmış bunun yanında termal model FRTCoils® yazılımı ile de değerlendirilerek bulunan ısı kapasite farkının kabul edilebilir sınırlar çerçevesinde olduğundan diğer eşanjör modelleri de yazılım ile doğrulanmıştır [7].

Termal modeldeki tüm soğutucu akışkanların termodinamik özellikleri, soğutma çevrim noktalarının basınç entalpi diyagramları üzerinde işaretlenmesi ile tespit edilen faz ve sıcaklık değerleri ışığında CoolPack® yazılımından alınmıştır [8].

Aynı şekilde eşanjör üzerinden geçirilen havanın termodinamik özellikleri de CoolPack® yazılımından alınmıştır [8].

Eşitlik (1)'de kanatlı bir boru üzerindeki ısı transfer miktarı en temel haliyle;

$$Q = U \cdot A \cdot \Delta\theta_{LM} \quad (1)$$

/Q: Toplam Soğutma Kapasitesi (W); U: Genel Isı Transfer Katsayısı (W/m²·K); A: Isı Transfer Yüzey Alanı (m²); $\Delta\theta_{LM}$: Logaritmik Sıcaklık Farkı (K) /

biçiminde ifade edilir [9].

Burada U.A değeri kirlenme olmadığı varsayılarak Eşitlik (2)'deki gibi hesaplanır [9], [10].

$$\frac{1}{UA} = \frac{1}{h_i A_i} + \frac{\ln d_o/d_i}{2\pi k L} + \frac{1}{\eta_o h_o A_o} \quad (2)$$

/ h_i : İç Yüzey Taşınım Katsayısı (W/m²·K); A_i : Isı Transfer İç Yüzey Alanı (m²); $d_o = D$: Dış Çap (m); d_i : İç Çap (m); k : Isı İletim Katsayısı (W/m.K); L : Uzunluk (m); h_o : Dış Yüzey Taşınım Katsayısı (W/m²·K); η_o : Dış Yüzey Etkinliği; A_o : Isı Transfer Dış Yüzey Alanı (m²) /

Dış yüzey etkinliği Eşitlik (3)'teki gibi hesaplanır [9].

$$\eta_o = 1 - \frac{A_f}{A} (1 - \eta_f) \quad (3)$$

/ A_f : Tüm Kanat Yüzey Alanı (m²); η_f : Kanat Verimi /

İki fazlı akışın olduğu evaporatörde Kenning ve Cooper denklemleri ile akışkan tarafı ısı taşınım katsayısı elde edilir [10].

Bunun için öncelikli olarak Eşitlik (4)'ten Nusselt sayısı hesaplanır.

$$Nu_i = (1 + 1,8 \cdot X^{-0,87}) \cdot 0,023 \cdot Re_i^{0,8} \cdot Pr_i^{0,4} \quad (4)$$

/ Nu_i : İç Yüzey Nusselt Sayısı; Re_i : Doymuş Sıvı Reynolds Sayısı; Pr_i : Doymuş Sıvı Prandl Sayısı /

Eşitlik (4)'teki X Lockhart Martinelli parametresidir ve kuruluk derecesine göre Eşitlik (5)'teki gibi ifade edilir [10].

$$X = \left(\frac{(1-x)}{x} \right)^{0,9} \left(\frac{\rho_v}{\rho_l} \right)^{0,5} \left(\frac{\mu_l}{\mu_v} \right)^{0,1} \quad (5)$$

/ X : Lockhart Martinelli Parametresi; x : Kuruluk Derecesi; ρ_v : Doymuş Buhar Yoğunluğu (kg/m³); ρ_l : Doymuş Sıvı Yoğunluğu (kg/m³); μ_l : Doymuş Sıvı Dinamik Vizkozite (kg/m.s); μ_v : Doymuş Buhar Dinamik Vizkozite (kg/m.s) /

Nusselt sayısının tespitinin ardından ilgili şartlardaki Reynolds sayısı Eşitlik (6)'daki gibi hesaplanır [10].

$$Re_l = \frac{G_m(1-x)d_i}{\mu_l} \quad (6)$$

/ G_m : Kütle Akışı (kg/s.m²) /

Öncelikle Eşitlik (7)'den hedeflenen soğutma kapasitesi için, çalışma noktalarında belirlenen entalpi farkından soğutucu akışkan debisi tayin edilir ve termal dizayn ilerletilir

$$Q = m(h_{out} - h_{in}) \quad (7)$$

/ m : Kütleli Debi (kg/h); h_{out} : Çıkış Entalpisi (kJ/kg); h_{in} : Giriş Entalpisi (kJ/kg) /

Eşitlik (6)'daki Reynolds sayısının tespiti için gereken kütle akışı Eşitlik (8)'deki gibi hesaplanır [10].

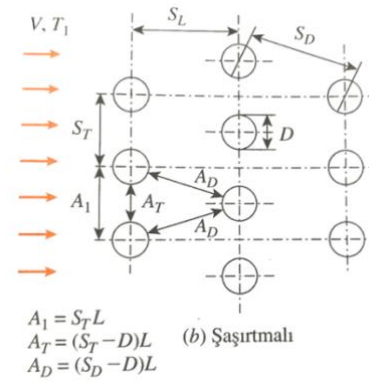
$$G_m = \frac{m}{\pi \cdot d_i^2 / 4} \quad (8)$$

Hesaplanan Nu_i sayısı ile iç yüzey taşınım katsayısı Eşitlik (9)'daki gibi tespit edilir [10].

$$h_i = \frac{Nu_i k}{d_i} \quad (9)$$

İç yüzey taşınım katsayısı hesaplandıktan sonra, boru dışı taşınım katsayısı ve kanat parametresi de ayrı ayrı hesaplanarak eşanjörün dış yüzey ısı transfer katsayısı elde edilir. Dış yüzey taşınım katsayısının belirlenmesinde hava akışı, boru içindeki soğutucu akışkan akışına karşı 90 derecede ilerlediği için boru demetleri üzerinden çapraz akış korelasyonları uygulanır.

Şekil 4'te şaşırtmalı boru demetinde dış ısı taşınım katsayısı hesabında ihtiyaç duyulacak parametreler kesit görünümünde verilmektedir.



Şekil 4. Şaşırtmalı Boru Demetinde Diziliş Parametreleri [11]

Borular arası belirlenen alanların ardından maksimum hava hızı hesaplanarak Eşitlik (10)'daki gibi hesaplanarak ısı eşanjörü yüzeyindeki hava akımının ulaşabileceği limit değeri tayin edilir [11].

$$V_{max} = \frac{S_T}{S_T - D} v \quad (10)$$

/ V_{max} : Maksimum Hız (m/s) /

Psikrometrik diyagram üzerinden istenen kapasitede, işaretlenen çalışma noktalarına göre eşanjöre giren 35°C sıcaklıktaki hava 24,2°C'ye kadar

soğutulmaktadır. Bu nedenle havanın termodinamik özellikleri bu değerlerin ortalaması olan 29,6°C sıcaklığı için alınacaktır.

Hava tarafı için Reynold sayısı Eşitlik (11)'deki hesaplanır [10].

$$Re_D = \frac{\rho \cdot V_{max} \cdot D}{\mu} = \frac{V_{max} \cdot D}{\nu} \quad (11)$$

/ Re_d : Hava Tarafı Reynolds Sayısı; ρ : Yoğunluk (kg/m^3); μ : Dinamik Vizkozite ($kg/m.s$); ν : Kinematik Vizkozite (m^2/s) /

Dış taşınım hesabında tek faz kabulü ile tek faz termodinamik bağıntıları kullanılabilir. Boru demetleri üzerinden çapraz akışta $N_L > 16$ ve $0,7 < Pr < 500$ için Nusselt sayısı bağıntıları Eşitlik (12)'deki gibidir; [11]

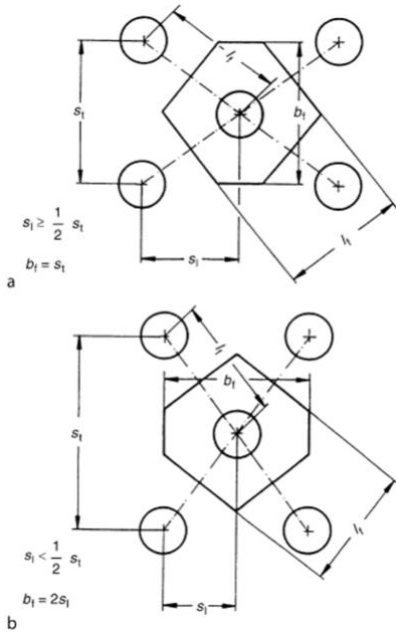
$$Nu_D = 0,35 \cdot \left(\frac{S_r}{S_L} \right)^{0,2} \cdot Re_D^{0,6} \cdot Pr^{0,6} \cdot \left(\frac{Pr}{Pr_s} \right)^{0,25} \quad (12)$$

/ Nu_d : Hava Tarafı Nusselt Sayısı; Pr : Prandl Sayısı; Pr_s : Akışkanın Çıkış Sıcaklığında Hesaplanacak Prandl Sayısı /

Eşitlik (13)'te, hesaplanan Nusselt sayısı vasıtasıyla dış yüzey taşınım katsayısına geçiş sağlanır [10].

$$Nu_d = \frac{h_o \cdot D}{k} \quad (13)$$

Hesaplanan dış yüzey taşınım katsayısına kanat geometrisi etkisinin de, fin verimi parametresinin hesaplanarak katılması ile optimum dış yüzey taşınım katsayısına erişim sağlanmış olur. Şekil 5'te dış taşınım katsayısı hesabında kanatçık tarafı için gerekli olan parametreler kesit görünüm üzerinde verilmektedir. [9]



Şekil 5. Kanatların Şaşırtmalı Boru Demetinde Dizilişi [9]

$$\eta_f = \frac{\tanh X^1}{X^1} \quad (14)$$

Eşitlik (14)'te verilen denklemdeki X^1 bir sabittir ve Eşitlik (15)'teki gibi hesaplanır [9].

$$X^1 = \varphi \frac{d_o}{2} \sqrt{\frac{2a_m}{\lambda_f \delta}} \quad (15)$$

Eşitlik (15)'te verilen φ bir sabittir ve Eşitlik (16)'daki gibi hesaplanır [9].

/ a_m : Boru ve Kanatçık Arası Ort. Isı Transfer Katsayı Oranı ($W/m^2 \cdot K$); λ_f : Fin Yüzeyinin Isı İletim Katsayısı ($W/m K$); δ : Kanat Kalınlığı (m) /

$$\varphi = (\varphi^t - 1)(1 + 0,35 \cdot \ln \varphi^t) \quad (16)$$

Eşitlik (16)'da verilen φ^t bir sabittir ve Eşitlik (17)'deki gibi hesaplanır [9].

$$\varphi^t = 1,28 \frac{b_f}{a_o} \sqrt{\left(\frac{l_f}{b_f} - 0,2 \right)} \quad (17)$$

Eşitlik (17)'deki l_f ve b_f parametreleri Şekil 5'te belirtilen boru - kanat arasındaki geometrik mesafelerdir [9].

Eşitlik (18)'den boru ve kanatçık arası ortalama ısı transfer katsayısı oranı hesaplanmasıyla beraber genel ısı transfer katsayısı tespitine geçilir [9].

$$a_m = \frac{Nu_d \cdot \lambda_{air}}{d_o} \quad (18)$$

/ λ_{air} : Havanın Isı İletim Katsayısı ($W/m K$) /

Genel fin veriminin de hesaplanması ile bulunan tüm değerler Eşitlik (2)'de yerine koyularak genel ısı transfer katsayısı elde edilir.

$$U = 45,454 \text{ W/m}^2 \text{ K}$$

Logaritmik ortalama sıcaklık farkı paralel akış veya ters akış düzenlemesi için Eşitlik (19)'da verildiği gibi yazılabilir [10].

$$\Delta \theta_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)} \quad (19)$$

/ ΔT_1 : Eşanjöre Akışkan ve Hava Giriş Çıkış Sıcaklık Farkı 1 (K); ΔT_2 : Eşanjöre Akışkan ve Hava Giriş Çıkış Sıcaklık Farkı 2 (K) /

Logaritmik ortalama sıcaklık farkı, tasarlanan ısı eşanjörünün çalışma noktasındaki soğutucu akışkan giriş - çıkış ve hava giriş sıcaklıklarına göre FRTCoils® çıktısından almır [7].

R134a (7,2 – 18,3 °C)

Hava (35 – 24,2 °C)

$$\Delta \theta_{LM} = 20,66 \text{ K}$$

Hesaplanan tüm değerler Eşitlik (1)'deki genel denklemde yerine yazılarak evaporatör ısı eşanjörünün soğutma kapasitesi elde edilir.

$$Q = 45,454 \frac{W}{m^2 K} \cdot 1,3m^2 \cdot 20,66 K$$

$$Q = 1220 W$$

Özşen M. ve ark. [12], Avrupa' da iklimlendirme sistemlerinin ısı performans analizi ve değerlendirmesi noktasında büyük kesimlerce kabul görmüş Eurovent kuruluşunun sertifikasyon sağlanması için teorik ve pratik olarak eldesi gerçekleştirilen değerlerin % 5 sapmasına, eğer test tekil bir şekilde yapılıyor ise üst limit olarak %8 sapmasına izin vermekte olduğunu bildirmişlerdir. Bu doğrultuda farklı bağıntılar kullanarak yaptıkları ısı kapasite hesapları ve test sonuçları ile aradaki farkı sırası ile %16,41 - %18,47 - % 5,14 - %19,66 - %15,90 şeklinde hesaplamışlardır. [12]

Çalışmada hesaplanan farkların ortalamasının yaklaşık %15 olduğu görülmektedir. Bu bağlamda çalışmada analitik çözümü yapılan R134a evaporatör eşanjörünün hesaplanan 1,22 kW'lık kapasitesi FRTCoils® ile hesaplandığında 1,36 kW olarak tespit edilmiş bu da aradaki farkın yaklaşık %10 olduğu böylece hem deneysel veri ile örtüştüğü hem de sınırlamayı %2'lik bir miktarda aştığı için uygulanabilir olduğuna karar verilmiştir.

Bu noktadan yola çıkarak belirlenen tasarım adımları çalışmaya konu olan her dört soğutucu akışkanın evaporatör ve kondenser ısı eşanjörüne FRTCoils® üzerinden uygulanmış, sonuçlar Tablo 2 ve Tablo 3'te özetlenerek sunulmuştur [7].

Tablo 2. Evaporatör Isı Eşanjörleri Tasarım Özeti Tablosu

ÖZELLİK	R32 EVAPORATÖR	R290 EVAPORATÖR	R134 EVAPORATÖR	R404A EVAPORATÖR
KALIP	25x22	25x23	25x24	25x25
BORU (inc)	5/16	5/16	5/16	5/16
ÖLÇÜLER	317*66*102	317*66*102	317*66*102	317*66*102
TOPLAM KAPASİTE (kW)	1,56	1,53	1,36	1,45
ISI TRANSFER ALANI	1,3	1,3	1,3	1,3
LOG. SICAKLIK FARKI (K)	21,09	20,85	20,66	20,86
DEVRE / SIRA / BORU	1*3*4	1*3*4	1*3*4	1*3*4
HAVA TARAFI				
HAVA (°C) / BN (%) GİRİŞ	35 / 40	35 / 40	35 / 40	35 / 40
HAVA (°C) / BN ÇIKIŞ (%)	23,4 / 63,6	23,5 / 63,8	24,2 / 64,2	23,8 / 64
HACİMSEL DEBİ (m³/h)	267	267	267	267
BASINÇ KAYBI (Pa)	35,7	35,6	33,9	35,1
AKIŞKAN TARAFI				
EVAPORASYON / SH	7,2 / 11,1	7,2 / 11,1	7,2 / 11,1	7,2 / 11,1
KONDENZASYON / SC	54,4 / 8,3	54,4 / 8,3	54,4 / 8,3	54,4 / 8,3
KÜTLESEL DEBİ	23	20	33	47
GİRİŞ / ÇIKIŞ ENTALPİ (kJ/kg)	289 / 530	325 / 603	266 / 413	269 / 379
BASINÇ KAYBI (kPa / K)	6,7 / 0,2	12,4 / 0,7	25,7 / 1,9	24,4 / 1,1

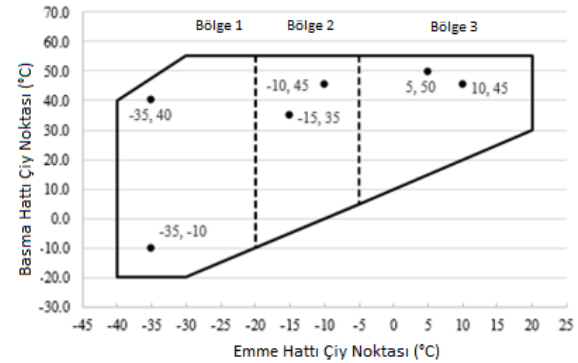
Tablo 3. Kondanser Isı Eşanjörleri Tasarım Özeti Tablosu

ÖZELLİK	R32 KONDANSER	R290 KONDANSER	R134 KONDANSER	R404A KONDANSER
KALIP	25x22	25x23	25x24	25x25
BORU (inc)	5/16	5/16	5/16	5/16
ÖLÇÜLER	317*88*152	317*88*152	317*88*152	317*88*152
TOPLAM KAPASİTE (kW)	2	1,96	1,94	1,95
ISI TRANSFER ALANI	2,8	2,8	2,8	2,8
LOG. SICAKLIK FARKI (K)	12,54	12,51	12,42	12,7
DEVRE / SIRA / BORU	1*4*6	1*4*6	1*4*6	1*4*6
HAVA TARAFI				
HAVA (°C) / BN (%) GİRİŞ	35 / 55	35 / 55	35 / 55	35 / 55
HAVA (°C) / BN ÇIKIŞ (%)	47,8 / 28	47,5 / 28,4	47,4 / 28,6	47,4 / 28,5
HACİMSEL DEBİ (m³/h)	487	487	487	487
BASINÇ KAYBI (Pa)	49,4	49,4	49,4	49,3
AKIŞKAN TARAFI				
EVAPORASYON / SH	7,2 / 11,1	7,2 / 11,1	7,2 / 11,1	7,2 / 11,1
KONDENZASYON / SC	54,4 / 8,3	54,4 / 8,3	54,4 / 8,3	54,4 / 8,3
KÜTLESEL DEBİ	25	21	35	50
GİRİŞ / ÇIKIŞ ENTALPİ (kJ/kg)	529 / 288	653 / 324	439 / 265	399 / 267
BASINÇ KAYBI (kPa / K)	6,6 / 0,1	7,9 / 0,2	14,4 / 0,4	14,9 / 0,3

2.2. Kompresör Seçimi

AHRI 540-2020 standardına göre, subkritik buhar sıkıştırmalı soğutma çevrim çalışma aralıkları görsel olarak çalışma diyagramlarına yansıtılmıştır. Kompresör seçimlerinde, çalışma noktalarının ilgili diyagram sınırları içerisinde kalmasına dikkat edilmelidir. [14]

Şekil 6'da AHRI 540-2020 standardına göre tanımlanan kompresör çalışma diyagramı ve sınırları verilmektedir.



Şekil 6. AHRI 540-2020'ye Göre Subkritik Çevrimde Kompresör Çalışma Diyagramları [14]

Kompresörün Hacimsel Verimi;

Geometrik yer değiştirme ve emiş hacminin bir fonksiyonudur. Eşitlik (20)'deki oran ile elde edilir. Ayrıca kompresörün sahip olduğu geometrik yer değiştirmesi, kompresörün sıkıştırma hacmiyle devir sayısının çarpımına elde edilmektedir [15].

$$\eta_{volumetric} = \frac{\text{Emiş Hacmi}}{\text{Geometrik Yerdeğiştirme}} = \% \quad (20)$$

Kompresörün İzentropik Verimi;

Kompresör verimliliğinin değerlendirilmesi noktasında, hacimsel verimin yanında izentropik verim de incelenen bir diğer parametredir [15]. İzentropik verim her ne kadar ideal buhar sıkıştırmalı soğutma çevriminde sıkıştırmanın sabit entropide olduğu kabulü

ile hesaplanabilse de, gerçek çevrimde; sistem elemanlarında sürtünme, ısı transferi gibi nedenler ile oluşan tersinmezlikler vasıtasıyla sıkıştırmanın izentropik olması mümkün olmayacağından çalışmada sürecinde kompresör verimliliği hacimsel verim perspektifinden incelenmektedir.

Kompresörün Sıkıştırma Oranı;

Sıkıştırma oranı ise sistemin tasarımı, içerdiği soğutucu akışkanın çalışma noktalarındaki evaporasyon ve kondenzasyon basınçlarına göre şekillenir. Son dönemde gelişen motor teknolojileri vasıtasıyla yüksek sıkıştırma oranlarında dahi düşük enerji tüketimi sağlanabilmektedir. Bileşenlerin seçim noktalarında bu parametrelerin her biri hesaplanarak ortak bir perspektiften kıyası sağlanacaktır.

Soğutma sistemlerinde kompresörler, sadece buhar fazındaki soğutucu akışkanı sıkıştırabilecek biçimde üretilmiştir. Sıkıştırma işlemi sürecinde kompresörlere dönüş hattı sürekli kontrol edilir.

Sıvının ilerlemesinin önüne geçilmek için bir dizi önlemler alınır. Pistonlu soğutma kompresörleri klima ve soğutma uygulamalarında yüzdesel olarak en yaygın kullanım sahası edinmiş mekanik sıkıştırma elemanlarıdır [27].

Çalışmada tasarlanan soğutma sistemlerinin üç adeti için pistonlu hermetik tip kompresör kullanılırken (R134a / R290 / R404A), R32 soğutucu akışkanı için düşük kapasitelerde hermetik tip pistonlu kompresörün bulunmaması nedeniyle bu soğutucu akışkan için rotary tip kompresör seçilerek tasarım gerçekleştirilecektir.

2.3. Bakır Boru Tesisat Dizayını

Emiş boru hattı hat dizaynında en fazla üzerinde durulması gereken tesisat olarak değerlendirilebilir. Boru çapı optimum değerinden büyük tutulur ise tesisatta barındırılan yağın hatlar boyunca akışının sağlanamamasına, mali açıdan bakıldığında ise gereksiz yere artan yatırım kalemlerine neden olduğu gibi, diğer taraftan bakır boru çapı gereğinden küçük tayin edilir ise yüksek basınç kaybına ve yüksek akış hızlarına, dolayısıyla aşırı sesli çalışan bir tesisat kurgusuna neden olacaktır. [1]

Sıvı hattı çaplarının belirlenmesinde en önemli nokta akışkanın hat boyunca ilerlerken aşırı basınç kayıplarına uğrayarak kaynamasını yani buharlaşmasını önlemektir [16].

Sıvı fazdaki akışkanda kaynama olması genişleme valfinin verimli çalışmasını, evaporatöre giden sıvı akışkanın kontrollü şekilde yapılmasını aksatmaktadır. Bunları engellemek için boru çapı seçimi yapılırken, toplam basınç düşümünün 2 psi değerini geçmemesine dikkat etmek gerekir. Borularda sıvı darbesi, ses, titreşim oluşmaması için akışkan maksimum hızı 1,5 m/s olacak şekilde boyutlandırma yapılmalıdır. [16]

Basma hatları hesaplanırken, emiş hatlarındaki özelliklere dikkat edilmelidir. Basınç kayıpları çok kritik olmasa da, akışkan basınç kayıpları kompresör çıkış basıncının artmasına sebep olabilir. Bu basınç artışı kompresör enerji tüketimini artırır, volumetrik verimi düşürerek soğutma kapasitesinin düşüşüne neden olur. Yatay hatlarda en az 2,5 m/s, düşey hatlarda en az 5 m/s akışkan hızı sağlanması gerekirken, 20 m/s akışkan hızı geçilmemelidir. [16]

Tüm soğutucu akışkanlar için boru çaplarının belirlenmesinde Tablo 4'te R134a emme hattı için verilen örnekteki gibi birbirine yakın en optimum iki çap arasında değerlendirme yapılarak daha uygun olan kalın font ile işaretlenmiştir.

Sistemdeki hat belirlendikten sonra basınç entalpi eğrisi üzerinden faz ve yoğunluk tespiti yapıp, elde edilen hacimsel debinin belirlenen boru kesitindeki akış hızının sınırlandırılmalar dahilinde kalmasına dikkat edilerek hat boyutlandırması gerçekleştirilir.

Tablo 4. R134a Emme Hat Boyutlandırması

R134a					
EMME			EMME		
Hat Basıncı	3,729	bar	Hat Basıncı	3,763	bar
Entalpi	413,2	kJ/kg	Entalpi	413,2	kJ/kg
Kompresör Emme Hat Çapı	8,1	mm	Kompresör Emme Hat Çapı	8,1	mm
$V=v \cdot A$			$V=v \cdot A$		
$m=V \cdot \rho$			$m=V \cdot \rho$		
V	1,929	m ³ /h	V	1,91	m ³ /h
A	2,82743E-05	m ²	A	5,02655E-05	m ²
v**	68224,41894	m/h	v**	37998,24266	m/h
v	18,95122748	m/s	v	10,55306741	m/s
ρ (kg/m ³)	17,22		ρ (kg/m ³)	17,39	
m	33,21738	kg/h	m	33,2149	kg/h
Boru Dış Çapı	8	mm 5/16"	Boru Dış Çapı	10	mm 3/8"
Boru İç Çapı	6	mm	Boru İç Çapı	8	mm
Φ	0,006	m	Φ	0,008	m
d	0,003	m	d	0,004	m
A	2,82743E-05	m ²	A	5,02655E-05	m ²
A	2,82743E-05	m ²	A	5,02655E-05	m ²

Tüm soğutucu akışkanlara göre belirlenen sistemlerin boru çaplarından sonra özel basınç kayıpları da dikkate alınıp genel basınç kayıp hesapları yapılarak tesisat tasarımı hız ve basınç kaybı ilişkisi ile doğrulanır. Tablo 5'te tüm sistemler için hesaplanan basınç kayıpları bar ve doyma sıcaklığı kaybı üzerinden verilmektedir

Tablo 5. Genel Basınç Kayıpları

	R134a			R290		
	Basma	Emme	Likit	Basma	Emme	Likit
Basınç Kaybı (bar)	0,125	0,009	0,023	0,013	0,005	0,01
Doyma Sıcaklığı Kaybı (K)	0,3	0,1	0,1	0	0	0
	R404A			R32		
	Basma	Emme	Likit	Basma	Emme	Likit
Basınç Kaybı (bar)	0,131	0,008	0,025	0,062	0,012	0,016
Doyma Sıcaklığı Kaybı (K)	0,2	0	0	0,1	0	0

2.4 Sistemlerin Ekserji Çözümlemesi

Sistemlerde kompresör seçiminin ardından yapılabilecek enerji analizini destekleyerek daha berrak hale getirmek amacıyla sistemlerin ekserji analizleri de gerçekleştirilip değerlendirme çerçevesine katılmıştır.

Yeni bir enerji kaynağı tespit edildiğinde, merak edilen ve tüm süreci şekillendirecek işlemlerden ilki enerji miktarının tayin edilmesidir. Yalnızca bu bilgiyi edinmiş olmak, bu enerji kaynağını işleyecek güç santrali yapmaya karar vermek için tek dayanak noktası olmamalıdır. Bunun yanında ek dayanak noktası oluşturarak asıl tespit edilmesi gereken, enerji unsurunun iş yapabilme potansiyelidir.

Bunun da en büyük göstergesi tespit edilen enerjinin ne kadarının kullanılabilir işe dönüştürülebileceğidir [17].

Bu bakımdan, termodinamikte bu süreci anlatabilecek bir literatürün tayin edilmesi değerlidir. Bu unsur ekserji yani kullanılabilirlik olarak tanımlanmıştır [17].

Belirli bir hal içerisinde olan sistemin enerji iş potansiyeli, sistemden elde edilebilecek en yüksek orandaki yararlı iştir. Sistem ile en fazla işi gerçekleştirebilmek için, hal değişimi neticesinde sistemin ölü hale gelmesi gerekmektedir. Var olan sistemin ölü halde geçmesi çevreyle termodinamik açıdan dengede olması anlamına gelir. Sistemin ölü haldeki özellikleri sıfır indeksi ile gösterilir. [17]

Enerji muhafazası termodinamiğin ilk kanununda irdelenmiştir. Ancak sadece bu kanun vasıtasıyla reel sistem performansının tayin edilmesi hedefleniyor ise yeterli olmayacaktır. Sistemin muhakkak ekserji unsuru açısından da değerlendirilmesi gerekmektedir. Birim kütle için ekserji, Eşitlik (21)'deki gibi hesaplanmaktadır [18];

$$\psi = h - h_0 - T_0(s - s_0) \quad (21)$$

/ ψ : Birim Kütle Ekserjisi; s : Entropi ($kJ/kg.K$); s_0 : Ortam Entropisi ($kJ/kg.K$) /

Eşitlik (21)'e her bir soğutucu akışkana göre özel olarak belirlenerek ekserji çözümlenmesine karakter katacak soğutucu akışkan kütleli debisi de eklenir ise sistemin ekserji davranışı, Eşitlik (22)'deki hali almaktadır [18].

$$Ex = m[(h - h_0) - T_0(s - s_0)] \quad (22)$$

Bu eşitlikte çevre hali koşulları olarak belirli sıcaklık, tüm sistemlerin tasarımlarının referans olarak alındığı DIN 3168 normu çevre sıcaklığı olan $T_0=35^\circ C$ olarak, P_0 ise 1 atm şeklinde belirlenmiştir [19].

Termodinamiğin ikinci kanunu analizi vasıtasıyla, irdelenen sistemlerin kondenser eşanjörü, evaporatör eşanjörü, kompresör ve genişleme valfindeki ekserji yıkım oranları Eşitlik (23), Eşitlik (24), Eşitlik (25) ve Eşitlik (26)'daki gibi hesaplanabilir [18].

$$Ex_{yıkım\ kond.} = Ex_2 - Ex_3 - Q_{kond} \left(1 - \frac{T_0}{T_{kond}}\right) \quad (23)$$

/ Q_{kond} : Kondenser Isı Çıkışı (kW); T_0 : Ortam Sıcaklığı ($^\circ C$); T_{kond} : Kondenzasyon Sıcaklığı ($^\circ C$) /

$$Ex_{yıkım\ evaporatör} = Ex_4 - Ex_1 + Q_{evap} \left(1 - \frac{T_0}{T_{evap}}\right) \quad (24)$$

/ Q_{evap} : Evaporatör Isı Girişi (kW); T_{evap} : Evaporasyon Sıcaklığı ($^\circ C$) /

$$Ex_{yıkım\ komp} = Ex_1 - Ex_2 + W_{komp\ elekt} \quad (25)$$

$$Ex_{yıkım\ GV} = Ex_3 - Ex_4 \quad (26)$$

/ $Ex_{yıkım}$: Ekserji Yıkımı /

Toplam yıkım Eşitlik (27)'de tanımlanır. ; [18]

$$Ex_{Toplam} = Ex_{yıkım\ kondanser} + Ex_{yıkım\ evaporatör} + Ex_{yıkım\ komp} + Ex_{yıkım\ GV} \quad (27)$$

Sistemin genel ekserji verimi Eşitlik (28)'de sunulduğu gibidir [18].

$$\eta_{Ex} = \frac{Ex_4 - Ex_1}{W_{komp}} \quad (28)$$

/ η_{Ex} : Ekserji Verimi; W_{komp} : Kompresör Enerji Girişi (kW) /

III. BULGULAR VE TARTIŞMA

3.1.CO₂ Eşdeğeri Şarj Miktarı ve Çevre Etkisinin Analizi

Tablo 6'da soğutucu akışkanların birim şarj miktarına referans olarak verilen CO₂ cinsinden şarj miktarı vasıtasıyla detaylı bir değerlendirme yapmak mümkündür;

Tablo 6. İncelenen Soğutucu Akışkanların Referans CO₂ Eşdeğeri [4]

Soğutucu Akışkan	GWP	Referans Şarj Miktarı (kg)	Ton CO ₂
R-134a	1430	1	1,43
R-404A	3922	1	3,922
R-290	3	1	0,003
R-32	675	1	0,675

Hu, X. ve ark., [20] bir sistemdeki soğutucu akışkan miktarını optimize etmek adına yapmış oldukları deneysel çalışmalar sürecinde, soğutucu akışkanın ilgili fazdaki birim hacminin kilogramı üzerinden soğutucu akışkanın termodinamik özellikleri ile bir yakınsama yapılması metodu geliştirmişlerdir. Bu metottan yola çıkarak başlangıç şarj miktarı ve dolayısıyla CO₂ eşleniği daha net hesaplanabilir. Bu çalışmaya göre [20] soğutucu akışkan kütlelerine, hat hacmi ve soğutucu akışkanın özgül hacmi arasında bir korelasyon kurularak öngörü getirilebilir.

$$m = \frac{V}{v} \quad (29)$$

Çalışmada sistemlerin tamamı ARI HT standardına göre [21] tasarlandığından soğutucu akışkanların basınç entalpi diyagramları üzerinden evaporasyon sıcaklığındaki doyma basıncına karşılık gelen değerlerde özgül hacimleri CoolPack® [8] yazılımından alındığında;

$$R134a = 0,05422 \text{ m}^3/\text{kg}$$

$$R404A = 0,02606 \text{ m}^3/\text{kg}$$

$$R290 = 0,07848 \text{ m}^3/\text{kg}$$

$$R32 = 0,03606 \text{ m}^3/\text{kg}$$

Bu noktada yukarıdaki eşitlik değerlendirildiğinde birim hacimde en az soğutucu akışkan kütlesine ihtiyaç gerektiren akışkan sıralamasının $R290 > R134a > R32 > R404A$ olduğu görülmektedir.

Tablo 2’de ısı eşanjörü tasarım bölümünde istenen soğutma kapasitesini elde edebilmek amacıyla gereken kütleli debi sıralamasında verilen, benzer soğutma kapasiteleri için R404A’nın soğutucu akışkan debisi 47 kg/h iken, R290’ın soğutucu akışkan debisinin 20 kg/h olması da bu yargıyı desteklemektedir. Görüldüğü üzere aynı kapasite için daha az R290 sirkülasyonu yeterlidir.

Bu noktadan CO_2 eşdeğeri şarj miktarına geçmek için, 1 birim R290 gazının özgül hacmi için 1,47 birim R134a; 3,03 birim R404A; 2,2 birim de R32 soğutucu akışkan gerektiğinden kıyaslama yapabilmek adına 1 kg R290 baz alınarak soğutucu akışkanların GWP oranları ile CO_2 eşdeğeri şarj miktarına bir yaklaşım yapmak mümkündür.

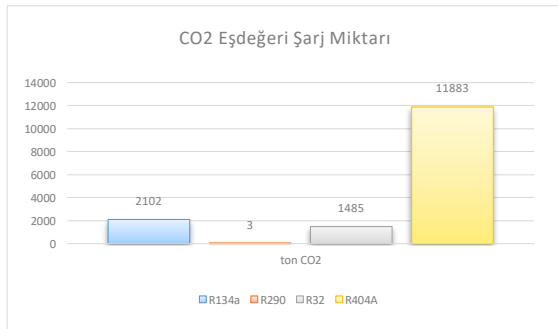
$$R134a = 1430(GWP) \cdot 1,47 \text{ kg} = 2102 \text{ ton } CO_2$$

$$R290 = 3(GWP) \cdot 1 \text{ kg} = 3 \text{ ton } CO_2$$

$$R404A = 3922(GWP) \cdot 3,03 \text{ kg} = 11883 \text{ ton } CO_2$$

$$R32 = 675(GWP) \cdot 2,2 \text{ kg} = 1485 \text{ ton } CO_2$$

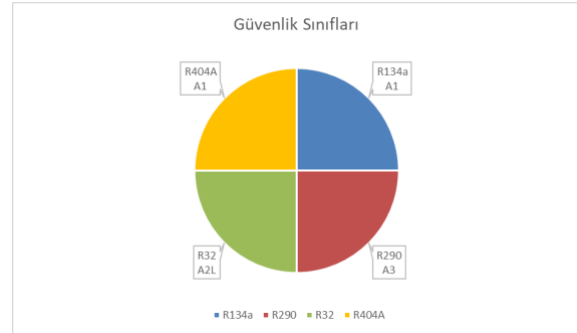
Şekil 7’de her dört soğutucu akışkan içinde öngörülen şarj miktarlarından yola çıkılarak hesaplanan CO_2 eşdeğeri şarj miktarı verilmektedir.



Şekil 7. Sistemlerin CO_2 Eşdeğeri Şarj Miktarları

3.2. Soğutucu Akışkanların Güvenlik Gereksinimleri Analizi

Şekil 8’de çalışmada analiz edilen dört soğutucu akışkanın güvenlik sınıfları verilmektedir [22, 23].

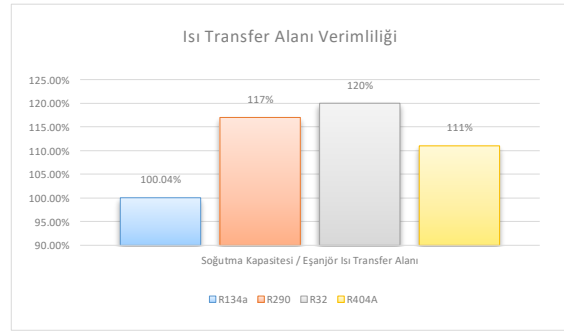


Şekil 8. Kullanılan Soğutucu Akışkanların Güvenlik Sınıfları

A1 sınıfındaki R134a ve R404A için alev yayılımı yok-düşük zehir oranı özellikleri geçerli iken; A2L sınıfındaki R32 için düşük zehir – düşük tutuşabilirlik oranı; A3 sınıfındaki R290 için ise düşük zehir – yüksek tutuşabilirlik oranı söz konusudur. Bu noktada gelecek nesil doğal soğutucu akışkan R290 ve R32 ile çalışırken iş sağlığı ve güvenliği prosedürlerinin önemini vurgulamak gereklidir [22, 23].

3.3. Isı Eşanjörü Verimlilik Analizi

Şekil 9’da tasarlanan ısı eşanjörlerinin birim alanından elde edilen soğutma kapasitesi birbirleri ile kıyaslanarak verilmektedir.

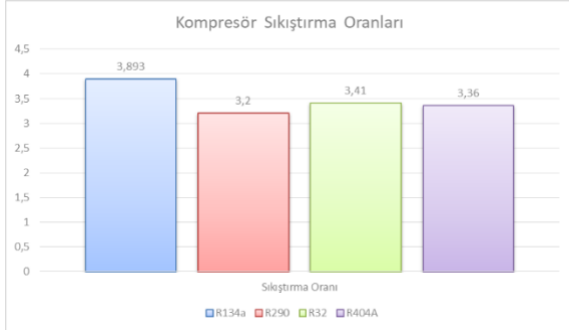


Şekil 9. Isı Eşanjörleri Transfer Alanı Verimlilikleri

Her dört soğutucu akışkan için de sabit ısı eşanjörü ve dolayısıyla sabit ısı transfer yüzeyi dizaynı bu değerlendirmenin yapılmasına olanak sağlamıştır. R290 ve R32 soğutucu akışkanlarının şarj miktarları diğer muadillerine göre düşük olsa da transfer alanı verimliliğinde üst noktada yer almaktadır. Bu da ileriki aşamalarda bu noktada bir maliyet optimizasyonunun yapılabileceğini göstermektedir.

3.4. Kompresör Sıkıştırma Oranı Analizi

Şekil 10'da her dört soğutucu akışkanı içeren sistemlerin evaporasyon ve kondenzasyon noktalarındaki basınçlarını oranlayarak elde edilen sıkıştırma oranları verilmektedir.

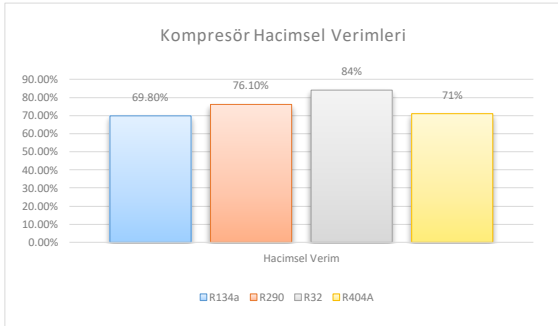


Şekil 10. Sistemlerin Kompresör Sıkıştırma Oranları

Şekil 10'de görüldüğü üzere R290 soğutucu akışkanı kullanılan sistemdeki düşük sıkıştırma oranı hem kompresör ömrünü uzatacak hem de ileriki bölümlerde değerlendirilecek sistemin enerji tüketimi parametresine olumlu bir etki sunacaktır.

3.5. Kompresör Hacimsel Verim Analizi

Şekil 11'de her dört soğutucu akışkanı içeren sistemler için hesaplanan, kompresör ömrü ve performansı çatısı altında değerlendirilen kompresör hacimsel verimleri verilmektedir.

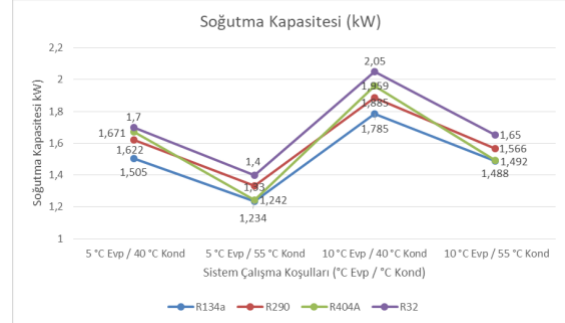


Şekil 11. Sistemlerin Kompresör Hacimsel Verimleri

Bu değerlendirmeden görüldüğü üzere R32 ve R290 soğutucu akışkanı birim kompresör hacmine göre en fazla soğutma kapasitesini sağlamaktadır. Bu durum hem maliyet analizi hem de sistemlerin sürdürülebilirlik – bakım, işletim giderleri açısından avantaj sunan bir özellik olarak karşımıza çıkmaktadır.

3.6. Kompresör Soğutma Kapasite Analizi

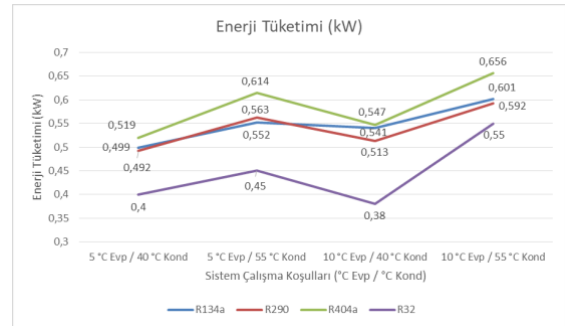
Her dört soğutucu akışkan için de seçilen kompresörler ile birlikte verilen üretici performans eğrileri üzerinden çalışma şartları analiz edilip; Şekil 12'de kompresörlerin ilgili çalışma şartlarındaki genel soğutma kapasiteleri verilmektedir.



Şekil 12. Seçilen Kompresörlerin Genel Soğutma Kapasiteleri

3.7. Kompresör Enerji Tüketim Analizi

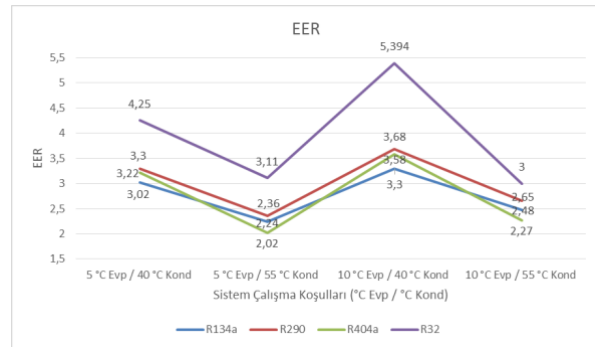
Şekil 13'te ilgili çalışma şartlarında kompresörlerin genel enerji tüketimleri verilmektedir.



Şekil 13. Seçilen Kompresörlerin Genel Enerji Tüketimleri

3.8. Kompresör Enerji Verimlilik Oranı Analizi (EER)

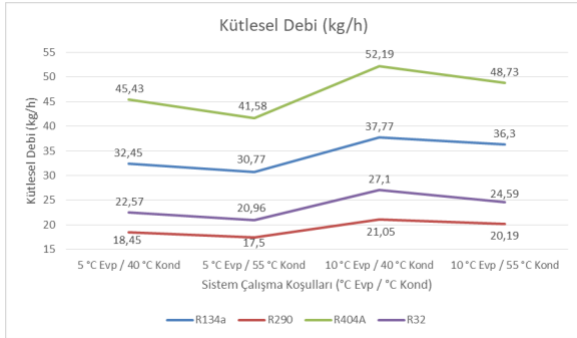
Şekil 14'te ilgili çalışma şartlarında kompresörlerin enerji verimlilik oranları (EER) verilmektedir.



Şekil 14. Kompresörlerin EER Oranları

3.9. Soğutucu Akışkan Kütlesel Debi Analizi

Şekil 15'te kompresörlerin ilgili çalışma şartlarında sağlayacağı soğutucu akışkan kütlesel debileri verilmektedir.

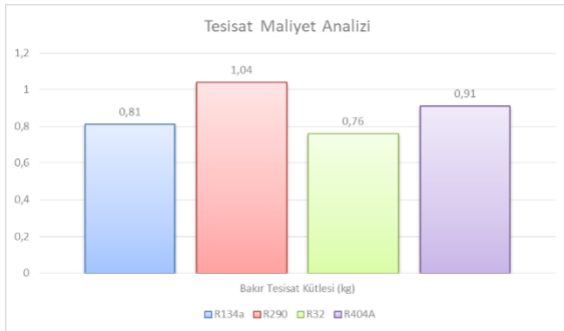


Şekil 15. Seçilen Kompresörlerin Kütlesel Debileri

3.10. Bakır Boru Tesisatı Maliyet Analizi

Şekil 16'da önceki bölümlerde hatlardaki hız sınırları ve sürtünme kayıpları dikkate alınarak çapları belirlenen bakır boru tesisatları arasındaki maliyet kıyaslaması verilmektedir.

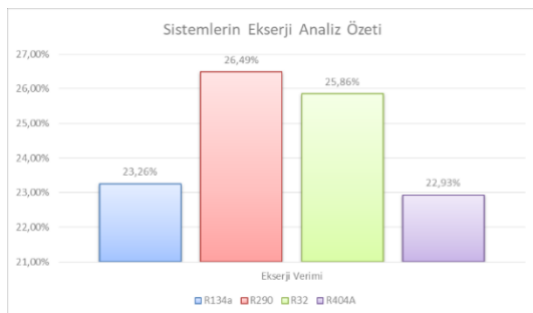
Belirlenen boru iç ve dış çapları dikkate alınarak tesisatın içerdiği bakır hacmi hesaplanmış ardından bakırın katı haldeki özkütlesi ile [24] ile çarpılarak tesisattaki bakır kütlesine bir yaklaşım yapılarak maliyet analizi oluşturmak hedeflenmiştir.



Şekil 16. Tesisat Maliyet Analizleri

3.11. Kullanılabilir Enerji (Ekserji) Analizi

Şekil 17'de elde edilen enerjinin kullanılabilirlik boyutunu değerlendirmek amacı ile irdelenen sistem içi ekserji analizleri verilmektedir.



Şekil 17. Sistemlerin Ekserji Verimleri

IV. SONUÇ

Sistemlerin çevresel etkileri değerlendirildiğinde, soğutucu akışkanlar arasındaki GWP (Küresel Isınma Potansiyeli) bakımından üstünlük R404A > R134a > R32 > R290 şeklindeken, atmosfer ömrü konusunda da R404A > R134a > R290 > R32 sıralaması incelenen soğutucu akışkanların çevre sınırlarını ve bu noktadaki doğru orantıyı net bir şekilde ortaya koymakta, global unsurların soğutucu akışkan azaltım takvimini oluştururken aldıkları dayanağı göz önüne sermektedir.

Çalışmada çevre etkileri analizini somut verilere dayandırmak için F gaz yönetmeliği vasıtasıyla iklimlendirme dünyasına kazandırılan ton CO₂ cinsinden şarj miktarı her bir soğutucu akışkan için hesaplanmış, bu hesaplama sürecinde gelecek nesil halojen içermeyen doğal soğutucu akışkan R290 ve HFC ailesinin çevre dostu üyelerinden R32 soğutucu akışkanların birim kütlesinin içerdiği yüksek enerji miktarı ile diğer soğutucu akışkanlara göre gerektirdiği düşük kütlesel debi vasıtasıyla düşük soğutucu akışkan şarj miktarına dikkat çekilmiş ve sonuç olarak R404A > R134a > R32 > R290 sıralaması elde edilmiştir. Bu noktada çalışmada incelenen soğutucu akışkanlardan çevreye en zararlı olanların R404A ve R134a oldukları görünürken en az çevre etkisine sahip soğutucu akışkanın ise R290 olduğu ortaya konulmuştur.

Çevre etkileri analizinin ardından sistemlerin termal performans analizleri; birim soğutma kapasitesi başına enerji tüketimi ve eldesi, enerji verimlilik analizleri, ekserji analizleri, ilk yatırım unsurlarına olan etkiler, iş girişi olan sistem bileşenlerinin (kompresör) performansı gibi maddeler altında incelendiğinde;

Tasarlanan ortak evaporatör ve kondenser ısı eşanjörleri ile bu majör sistem bileşenlerinin sabit tutulması amaçlanmış, tüm performans analizleri soğutucu akışkanlar üzerinden iletilemiştir.

Isı eşanjörlerinin sabit tutulması ile birim ısı transfer alanından alınan soğutma kapasitesi bakımından ilişki R32 > R290 > R404A > R134a biçimindedir.

Bu da gelecek nesil doğal soğutucu akışkan R290 ve çevre dostu HFC 32 kullanımının daha büyük ölçeklerde düşünüldüğünde kullanılacak eşanjör boyutunu küçülterek sistem ekonomisine olumlu etki yapacağı görülmektedir.

Sistemlerin birbirine yakın soğutma kapasitelerinde enerji tüketim oranları arasında R404A > R134a > R290 > R32 sıralaması tespit edilirken buna bağlı olarak enerji verimlilik oranları arasında ise R32 > R290 > R404A > R134a sıralaması ortaya çıkmaktadır. Bu da enerji tüketimi, sürdürülebilirlik, enerji verimliliği gibi termal performans değerlendirme ölçütlerinde de; çevre performanslarında olduğu gibi gelecek nesil halojen içermeyen doğal soğutucu akışkan R290 ve çevre dostu HFC R32'nin avantajını ortaya koymaktadır.

Sistemlerin enerji verimlilikleri noktasındaki analiz kompresör performansı üzerinden detaylandırıldığında kompresörlerin hacimsel verimlilikleri arasındaki ilişkinin $R32 > R290 > R404A > R134a$ iken, sıkıştırma oranları arasındaki ilişkinin $R134a > R32 > R404A > R290$ şeklinde olması ile kompresör ömrünün ve daha önceden incelendiği üzere enerji tüketiminin çevre dostu akışkanlarda diğer soğutucu akışkanlara göre daha avantajlı olduğu ve bu sayede enerji verimliliği ve ilk yatırım maliyeti boyutlarının da genel enerji değerlendirmesine bir referans sağladığı ortaya konulabilir.

Ekserji analizi sonucunda elde edilen ekserji verimleri arasındaki $R290 > R32 > R134a > R404A$ sıralamasıyla çalışmada irdelenen tüm performans ve çevre analizlerinde gelecek nesil halojen içermeyen doğal soğutucu akışkan R290 ve HFC R32'nin diğer popüler HFC soğutucu akışkanlara üstünlük kurduğu, bu iki akışkan arasında ise tüm analizler kapsamından performans ve çevre optimizasyonu yapıldığında R290 soğutucu akışkanının öne çıktığı ortaya konulmuştur.

Bu bağlamda çalışma sonucunda ülkemizdeki soğutucu akışkan dönüşüm entegrasyonlarının ivmesinin bu değerlendirmelere dikkat edilerek hız kazanmasının gerekliliği tüm parametreler bakımından ortaya konulmuştur.

TEŞEKKÜR

Sunulan araştırma makalesi, Marmara Üniversitesi Fen Bilimleri Enstitüsü Makine Mühendisliği Bölümünde irdelenen “Pano Klimalarında Farklı Soğutucu Akışkanların Kullanımının Araştırılması” adlı yüksek lisans tezini baz alarak ortaya konulmuştur.

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Projected Changes in High Temperatures in Coastal Tourism Destinations: A Case Study of the Turquoise Coast

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Abstract

The effects of climate change may manifest themselves in different ways, but when it comes to coastal tourism, extreme temperatures, which are the unavoidable consequences of climate change, come to the fore. The study examined the changes that extreme temperatures can make on major coastal tourism destinations by using such indices as hot summer days, tropical nights, combined hot days and tropical nights, and days with dangerous apparent temperature (> 40.6 °C). Under the RCP4.5 and RCP8.5 scenarios, increases in these indices are expected for Antalya, Aydın, Balıkesir, İzmir, and Muğla on the Turquoise Coast in the near (2021-2050) and distant (2071-2100) future. The projections based on both scenarios indicate that there might be a rise in the number of hot summer days, tropical nights, and days exceeding the critical human thermal comfort conditions on the Turquoise Coast. Expected increases may reach the highest values under the pessimistic scenario at the end of the century. The increase in these indices caused by rising temperatures may adversely affect the tourism sector due to changes in tourism demands, destinations, and seasonal shifts.

Keywords: Climate change, Summer tourism, Temperature extremes, Turquoise Coast

I. INTRODUCTION

Today, we have started to feel the direct or indirect effects of climate change in every sector, and this situation primarily threatens the life and health of living and also impacts the built environment, for example, tourism infrastructure [1,2]. It is possible to determine the level of this threat by evaluating changes not only in average temperatures or precipitation but also in extreme events. Changes in the frequency, severity, impact area, and duration of extreme climate events resulting from climate change form the basis of physical and economic losses in many sectors [3]. Could the risks arising from changes in extreme climatic events pose a future comfort level threat for people trying to rest during their summer holidays? The answer to this question is quite significant in terms of sectoral adaptation of tourism to climate change. Understanding changes in climate parameters such as pressure, temperature, humidity, wind, and precipitation [4] constitutes the main aspect of climate change studies [5]. Climate change has adverse effects on natural, social, and economic sectors, including water resources, agriculture, ecosystems, forestry, health, insurance, and industry. The effects of climate change on the tourism sector have been investigated in recent years. The changes brought about by these effects can adversely affect tourism, a vital economic sector. To be more explicit, extreme climate events associated with temperature and precipitation may affect human health and comfort, and therefore the tourism sector since tourists prefer to travel to destinations where they will benefit from a feeling of well-being and comfort [6-13].

Poor thermal comfort conditions can affect the quality of human life. Coastal tourism is the largest market segment of global tourism and is highly dependent on the thermal climate of a tourism destination. Therefore, the effects of climate change on the thermal comfort level of beach tourists are worth examining because comfort level is a key factor for tourists to choose a destination. Although climate change occurs at the global level, every economic industry can feel its impacts in different ways in various regions [14]. The effects of climate change on coasts are inevitable and are already damaging some areas whose economies depend heavily on coastal tourism [15]. The increase in temperature may become a significant threat to Mediterranean tourism and the economies of Mediterranean countries fueled by tourism revenues [16-19]. Over the past few decades, summer seasons with extremely hot temperatures have been increasing in various parts of the world [20-23]. This ongoing trend will affect the comfort level of people and, more importantly, lead to an increase in heat-related deaths [24-29].

Some indices have been developed to obtain general information about the climatic attractiveness of popular summer tourism destinations in terms of human comfort. The Tourism Climate Index (TCI), the first to examine human comfort levels in tourism-related activities, was designed in 1985 [30]. However, some researchers stated that TCI was based on subjective opinion and modified it. Beach Climate Index (BCI), developed in 2000, was one of them [31]. BCI was developed by modifying TCI by conducting surveys with more than 1600 beach users. However, it was developed only for beach use and cannot be used for other daytime activities. Also, conducting surveys only on northern European beaches makes them unsuitable for tourists vacationing in other regions because preferences change as well as tourist profiles. Climate Index for Tourism (CIT) was also designed by surveying tourists [32]. However, since all the participants examined in the study were university students, the narrow age distribution of the research sample group caused the index to lack cross-cultural information [32]. The Modified Climate Index for Tourism (MCIT) [33] uses hourly data rather than averages and assesses the suitability of a day's weather for tourist activities. Another index called Holiday Climate Index (HCI) was developed [34]. HCI does not rely on subjective opinions, as it uses the available literature on tourists' climate preferences from a series of surveys compiled over the previous decade to determine rating scales and weights for sub-indices. The development of these indices based on tourist preferences is one of their limitations because the preferences vary according to socio-demographic characteristics such as age, gender, the type of tourism environment and activity, and the climatic characteristics of the country from which the tourists come. For this reason, it is debated whether the use of

questionnaires is reliable [35-37]. Since this study aimed to examine the changes brought by extreme temperatures in comfort level, other parameters such as precipitation and wind were ignored, and three biometeorological indices, hot summer days, tropical nights, and apparent temperature, were used. Hot summer days become much more stressful if nighttime temperatures do not provide cooling relief, and tropical nights make it harder for the body to cool down and recover from hot summer days. The combination of hot days and tropical nights is particularly dangerous for human comfort and health. On the other hand, high risk from heat stress is not related to temperature alone but is a function of the combined consequences of temperature and humidity [38,39]. Since high humidity tends to reduce the efficiency of the human body's cooling system by preventing sweat from evaporating, humidity levels can make extreme heat much more dangerous and unbearable [39]. The study examined apparent temperature, including the effect of humidity, along with hot summer days and tropical nights, to comprehensively interpret the behavior of heat stress in response to climate change. Such a combination may lead to serious health problems and be fatal, apart from adversely affecting the level of comfort. For this reason, knowing that such conditions will occur in a particular location can be helpful in planning for adapting to a changing climate and protecting vulnerable groups from heat. Moreover, despite a growing consensus on the future severity of extreme heat stress, geographic patterns and the magnitude of projected changes are poorly understood at the regional and local levels. Therefore, our study aims to shed light on the literature in terms of being a study at the regional level.

Extremely hot summer days are often accompanied by hot or tropical nights [40]. Tropical nights significantly impact sleep comfort and prevent people from recovering from heat during the day [41]. Densely populated areas along the eastern Mediterranean coast will be significantly affected by tropical nights [42]. The rise in hot summer days and tropical nights will lead to water and energy consumption and vector-borne infectious diseases that can cause significant economic losses in the tourism sector [41]. Recently, the apparent temperature, which reflects the combined effect of air temperature and relative humidity, thus providing a better physical sense of the current climatic conditions, has also attracted the attention of researchers [43]. Apparent temperature, based on a model of thermal balance of the human body [44], has been used in several studies of temperature-related discomfort, morbidity, and mortality [45-50]. Examining the changes in these indices can help us detect changing thresholds of human comfort level caused by extreme temperatures and take necessary precautions by measuring the response of human sensation to environmental conditions. These indices reflect changes in different aspects of climate, effectively

support scientific studies in detecting extreme climatic changes and facilitate comparison between extreme weather events in different regions [29,51,52].

The temperatures are already high in the provinces on the Turquoise Coast. This situation prompted us to investigate further the relationship between the number of hot summer days, tropical nights, and the number of days with dangerous apparent temperature, and the values which are above a certain threshold because proper measurement of human exposure to extreme temperatures is a necessary basis for studying the impacts of extreme temperatures on human comfort. It can also help determine the steps to be taken regarding the tourism sector. In this context, using climate change projections, the study aims to examine the changes brought by future extreme temperatures in the Turquoise Coast, which attracts millions of visitors as a coastal tourism destination in Türkiye and to draw

attention to the effects of extreme temperatures on summer coastal tourism in terms of human comfort.

II. MATERIALS AND METHOD

2.1. Domain

Since the areas where tourist movements are most intense are the sea and lake shores, coastal tourism is economically very important for Türkiye, which is a land surrounded by water on three sides and having various climatic characteristics. South and southwest of Türkiye are coastal tourism paradises with their uniquely beautiful beaches, sand, and sun opportunities, which have a long holiday period, and the climate that makes them suitable for coastal tourism [53]. Thanks to the warm weather and suitable climatic conditions in the summer months, they become popular sea-sand-sun oriented regions. The provinces studied in the study are located in the south-southwest and west of Türkiye (Figure 1).



Figure 1. Map of the study region

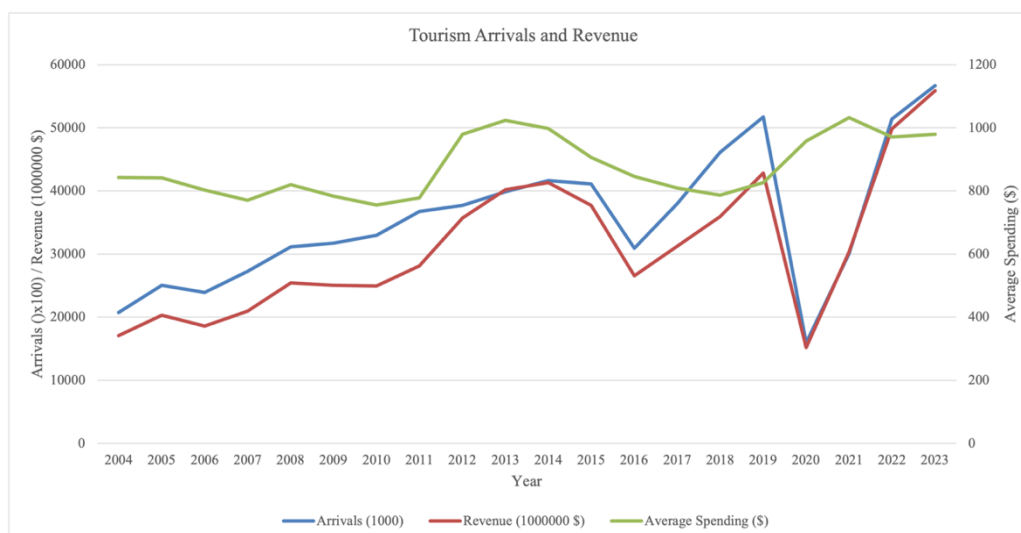
The tourism industry increases the population of a destination and causes seasonal population movements throughout the year. In most Mediterranean countries, population and population densities increase several times during the summer months [54]. Therefore, the population of the provinces that are the subject of the research increases several times during the tourism season. The approximate populations of the provinces examined as of 2021 are given in Table 1. The summer populations of these five metropolises, each with a resident population exceeding 1 million, are experiencing further growth due to the influx of tourists. Tourism arrival, revenue and average spending information across Türkiye between 2004 and 2023 is also provided in Figure 2. Excluding the period of pandemics, it is evident that there is a positive trend in Türkiye's tourism revenue.

2.2. Materials

The tourism sector in Türkiye is mainly focused on sun-sea-sand tourism, with large facilities established in coastal areas. The sector is heavily dependent on “the Turquoise Coast,” also known as “the Turkish Riviera,” located along the Aegean and Mediterranean coasts in the southwestern part of Türkiye. The coastline is Türkiye's most popular tourist destination, and it is aptly named the Turquoise Coast with its turquoise-toned waters. It is famous for destinations such as İzmir, Balıkesir, Aydın, Muğla, and Antalya, and attracts more than 20 million tourists every year [55]. In addition, the region includes various hiking trails in the coastal and inland areas, along with the famous Lycian Way. It also offers a range of optional activities such as scuba diving, paragliding, and mountain biking.

Table 1. Populations and number of tourist arrivals of 5 provinces (thousand) [55]

Province	Antalya	Aydın	Balıkesir	İzmir	Muğla
Population	2,620	1,134	1,251	4,426	1,021
Tourist arrivals (2010-2019)	139,366	12,128	5,277	26,876	19,462

**Figure 2.** Tourism arrivals, revenue and average spending in Türkiye (2004-2023)

2.3. Methods

The study examined whether the advantage provided by the Mediterranean climate on the Aegean and Mediterranean coasts would turn into a disadvantage in the future. Three different indices were utilized: hot summer days, tropical nights, and apparent temperature (heat index). In calculating these indices, high resolution (10-km horizontal resolution) maximum temperature, minimum temperature, and relative humidity data were obtained using the regional climate model RegCM4.4, driven by the MPI-ESM-MR global climate model of the Max Planck Meteorological Institute in Germany.

The aforementioned indices calculated using these climate variables were compared to the past period of 1971-2000 under two different scenarios, RCP4.5 and RCP8.5, for the two future periods (2021-2050 and 2071-2100). The regional climate model RegCM4.4 was used to obtain the data. RegCM4.4 is a regional climate model widely used in climate-related studies [12,19,56-64]. It is a user-friendly model [65]. RegCM4.4 [65,66] dynamically downscaled the low-resolution outputs of the MPI-ESM-MR [67], under the RCP4.5 (optimistic) and RCP8.5 (pessimistic) scenarios [68] and provided high-resolution climate data (10 km horizontal resolution). Here, the acronym RCP stands for “Representative Concentration Pathway”. In order to comprehend the potential future changes in climate, it is imperative to project the appropriate course of global climate action. Therefore,

RCPs are designed to provide realistic future possibilities of human-induced forcing, covering a spectrum ranging from a scenario characterized by proactive reduction (RCP2.6), to two moderate scenarios (RCP4.5 and RCP6.0), and a progressively increasing emissions scenario (RCP8.5). Basically, RCP scenarios are classified based on their cumulative radiative forcing by the end of the century. RCP4.5 is a pathway that aims to stabilize the amount of radiative forcing at 4.5 W/m² after the year 2100 without exceeding this level. On the other hand, RCP8.5 corresponds to an increase in radiative forcing of 8.5 W/m² by the year 2100. When the two scenarios are compared in terms of atmospheric carbon dioxide concentration levels, the RCP4.5 scenario predicts that the CO₂ level will be approximately 487 ppm in the middle of the century and about 538 ppm by the end of the century. In contrast, the RCP8.5 scenario projects a significant increase to approximately 541 ppm by 2050 and a dramatic rise to about 936 ppm by 2100. The climate change community commonly classifies the RCP4.5 scenario as an optimistic scenario and the RCP8.5 scenario as a pessimistic scenario. Therefore, the study focused on two fundamental cases, one optimistic and one pessimistic. In brief, the study examined how increases in temperature extremes alter comfort levels for Türkiye’s Aegean and Mediterranean coastal destinations under two different scenarios for the next three decades and the end of the last century.

2.3.1. Indices

2.3.1.1. Hot summer days

Hot summer days (HSD) is defined as the average number of days with a maximum temperature equal to or above 35 °C [28,69]. However, 37 °C threshold was used for Turquoise Coast in this study. As can be seen from some studies on hot summer days in the Mediterranean, this is the most appropriate threshold, as the studied area is already warm, and temperatures equal to or a little higher than 35 °C are quite common and are perceived as normal [9,12,20]. Hence, the selection of this threshold value is not arbitrary.

2.3.1.2. Tropical nights

Tropical nights (TN) index is defined as the average number of days with a minimum temperature above 20 °C [42,70]. However, as mentioned earlier, since the Turquoise Coast is already warm and these night-time temperatures (20 °C) are common during the summer months, 25 °C threshold was employed for TN based on the studies in the literature [71-73].

2.3.1.3. Combined hot days and tropical nights

The study also examines the frequency of days that experience both hot summer days and tropical nights simultaneously. The combined hot days and tropical nights (CHT) index is defined as the average number of days where the maximum temperature reaches 37 °C or more and the minimum temperature remains at 25 °C or higher throughout the day [8].

2.3.1.4. Apparent temperature

Apparent temperature (AT) is described as the temperature which considers the effect of both temperature and relative humidity, and it is usually referred to as heat index. Thermal comfort is a way to explore the impacts of climate change on comfort and health by quantifying the human sensation of environmental conditions. AT is also a measure of thermal comfort based on how the average person “feels” based on environmental conditions such as temperature and humidity [74]. AT was originally developed to measure thermal comfort [44] and has since been widely used in studies of the relationship between human comfort and health and extreme temperatures [8,47,48,75-78].

In the study, AT was used alongside other indices to represent the effect of exposure to typical temperatures commonly experienced in warmer months. Future changes in relative humidity may increase or stabilize the effects of extreme temperatures on human comfort

or health [8]. To account for this effect, AT was calculated from the 3-hour resolution data and considered the daily maximum values of the apparent temperature. This calculation presents a combined measure of temperature and humidity stress [44]. A threshold value of 40.6 °C was used for AT in the study [8] because AT reaching levels of 40.6 °C signifies that heat-related “danger” may arise [8,79]. Therefore, in this study, apparent temperature above 40.6 °C was defined as dangerous. AT was used in this study because it was developed as a comfort index that accurately represents the human response to a wide temperature range [44]. The following formula to calculate AT was used [44]:

$$AT = c_1 + c_2T + c_3T^2 + RH(c_4 + c_5T + c_6T^2) + RH^2(c_7 + c_8T + c_9T^2) \quad (1)$$

where T is temperature, RH is relative humidity c stands for coefficients. The coefficients are defined as follows [8]:

$$c_1 = -8.7847, c_2 = 1.6114, c_3 = -0.012308, c_4 = 2.3385, c_5 = -0.14612, c_6 = 2.2117 \cdot 10^{-3}, c_7 = -0.016425, c_8 = 7.2546 \cdot 10^{-4}, c_9 = -3.582 \cdot 10^{-6}$$

III. RESULTS

The study analyzed the changes in the number of hot summer days and tropical nights and days above the dangerous apparent temperature to address the signs of climate change on the Turquoise Coast. The sum of hot summer days and tropical nights were also evaluated together as a single index value.

3.1. Changes in the number of hot summer days

In the RCP4.5 scenario (Figure 3), an increase in the number of HSD in the near future and the distant future compared to the 1971-2000 reference period was detected. On the Turquoise Coast, there will be an increase in the number of HSD by 10-20 days in the near future, 2021-2050, and an increase up to 30 days in the distant future, namely 2070-2099 period. In the RCP8.5 scenario, the figure resembles the RCP4.5 scenario for the near future (2021-2050), and an increase of 10-20 days in the number of HSD in the near future is expected. However, in the distant future (2070-2099), an increase of 50-60 days is expected in the number of HSD on the Turquoise Coast compared to the 1971-2000 reference period (Figure 3).

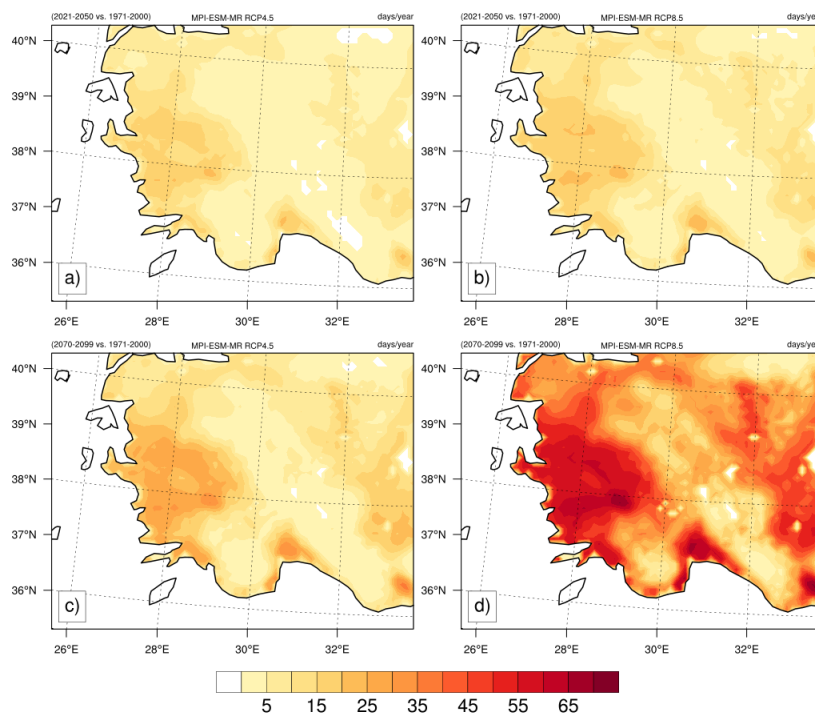


Figure 3. Changes in the number of HSD, a) RCP4.5 for 2021-2050; b) RCP8.5 for 2021-2050; c) RCP4.5 for 2070-2099; d) RCP8.5 for 2070-2099

When analyzed on a provincial basis, an increase in HSD is foreseen in all provinces for each scenario and period (Table 2). The lowest increase is expected in Antalya and the highest in Aydın. On the Turquoise Coast, an annual average increase of 4-15 days is expected in the near future for the RCP4.5 scenario, and an annual average increase of 8-26 days is anticipated in the distant future in the same scenario.

For the RCP8.5 scenario, an average annual increase of 5-18 days is expected in the near future. For the RCP8.5 scenario, the most increase is expected in the distant future. The least increase is foreseen in Antalya (27 days) and the highest in Aydın (up to 56 days). In general, the highest annual average increase is projected in Aydın, followed by İzmir, Muğla, Balıkesir, and Antalya, respectively.

Table 2. Annual changes in the number of HSD on a provincial basis

Provinces	RCP4.5		RCP8.5	
	2021-2050	2070-2099	2021-2050	2070-2099
Antalya	4.29	8.52	5.60	26.94
Aydın	15.11	25.20	17.56	56.01
Balıkesir	6.62	11.14	9.47	35.36
İzmir	12.05	19.95	14.52	47.94
Muğla	8.40	15.48	10.25	39.18

3.2. Changes in the number of tropical nights

As seen, the number of TN in both maps increases more in the seaside in the RCP4.5 and RCP8.5 scenarios (Figure 4) in the near (2021-2050) and distant (2070-2099) future periods. This is to be expected, as seas

have a high heat capacity and daily minimum temperatures at night are higher than on land. Due to the increase in the number of TN, the highest increase is expected in coastal areas.

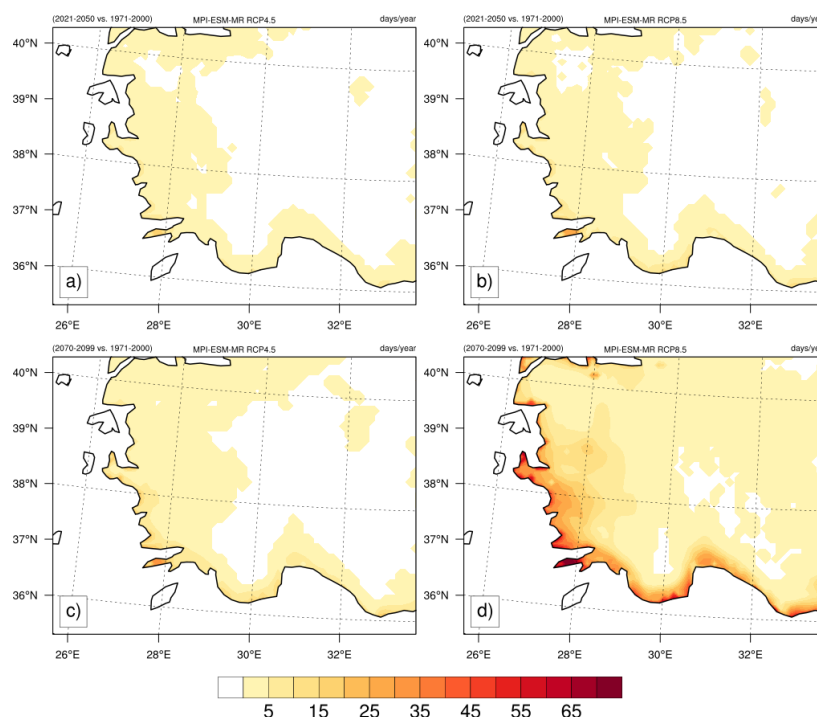


Figure 4. Changes in the number of TN, a) RCP4.5 for 2021-2050; b) RCP8.5 for 2021-2050; c) RCP4.5 for 2070-2099; d) RCP8.5 for 2070-2099

When analyzed on a provincial basis, it is seen that an increase in TN is predicted for all provinces for each scenario and period (Table 3). The lowest increase is foreseen in Balıkesir and the highest increase in Muğla. An annual average increase of up to 3 days is foreseen for the RCP4.5 scenario in the near future, and an annual average increase of 3-7 days is foreseen in the distant future in the same scenario.

For the RCP8.5 scenario, an annual average increase of up to 5 days is expected in the near future. For the RCP8.5 scenario, an increase of 6-25 days is predicted in the distant future. The lowest increase is foreseen in Balıkesir (6 days), and the highest increase is foreseen in Muğla (up to 25 days). In general, the highest annual average increase is expected in Muğla, followed by İzmir, Aydın, Antalya, and Balıkesir, respectively.

Table 3. Annual changes in the number of TN on a provincial basis

Provinces	RCP4.5		RCP8.5	
	2021-2050	2070-2099	2021-2050	2070-2099
Antalya	1.21	3.78	2.83	15.38
Aydın	1.37	3.51	2.00	19.94
Balıkesir	0.24	0.75	0.45	6.11
İzmir	2.31	5.29	3.34	23.22
Muğla	3.08	6.88	4.90	25.30

3.3. Changes in the number of hot summer days and tropical nights

The spatial change in the number of CHT for both RCP4.5 and RCP8.5 scenarios compared to the reference period can be seen in Figure 5. It can be

realized how extreme temperature indices create a change in coastal areas. For both scenarios, an increase in the number of CHT is expected in the coastal and inland areas in the near and distant future.

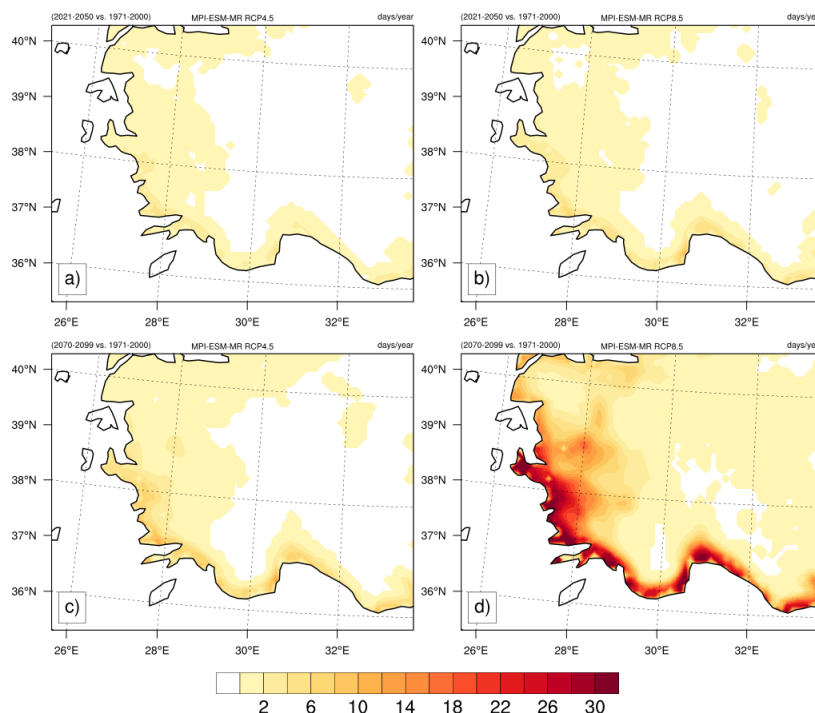


Figure 5. Changes in the number of CHT, a) RCP4.5 for 2021-2050; b) RCP8.5 for 2021-2050; c) RCP4.5 for 2070-2099; d) RCP8.5 for 2070-2099

On a provincial basis, an increase in the number of CHT is foreseen for all provinces for each scenario and period (Table 4). The lowest increase is expected in Balıkesir and the highest increase in Muğla. An annual average increase of 0.04-1.44 days is predicted for the RCP4.5 scenario in the near future and 0.28-3.45 days in the distant future for the same scenario.

Under RCP8.5, an annual average increase of 0.12-1.90 days is expected in the near future and 3.94-17.11 days in the distant future. According to the RCP8.5 scenario, Balıkesir is expected to experience the lowest increase (3.94 days), while Aydın is projected to have the highest increase (17.11 days) in the distant future. Overall, Muğla is projected to have the highest annual average increase across all periods and scenarios.

Table 4. Annual changes in the number of CHT on a provincial basis

Provinces	RCP4.5		RCP8.5	
	2021-2050	2070-2099	2021-2050	2070-2099
Antalya	0.51	1.93	1.31	9.47
Aydın	0.77	2.41	1.09	17.11
Balıkesir	0.04	0.28	0.12	3.94
İzmir	0.91	2.69	1.28	16.29
Muğla	1.44	3.45	1.90	16.17

3.4. Changes in the number of days with dangerous apparent temperature

A slight increase is observed in the number of days with dangerous apparent temperature in the coastal areas in the RCP4.5 scenario compared to the reference period of 1971-2000. However, this increase is more pronounced in the RCP8.5 scenario since the number of

days with dangerous apparent temperature increases in touristic coastal areas. It shows that the number of days above 40.6 °C, which represents the dangerous starting point of heat-related disturbances, has been increasing. Principally, the increase in the number of days for AT in the Aegean Region for the RCP8.5 scenario in the distant future is striking (Figure 6).

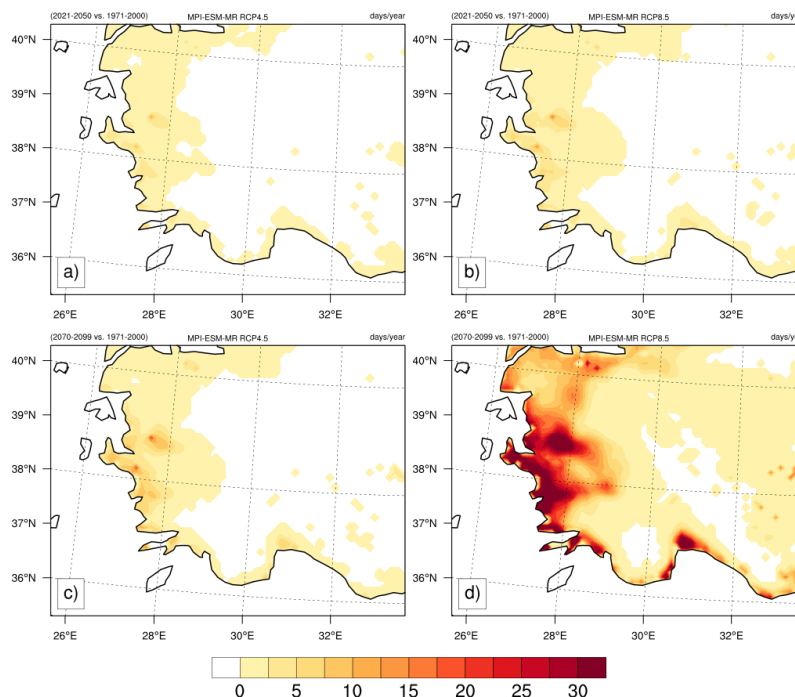


Figure 6. Changes in the number days for AT, a) RCP4.5 for 2021-2050; b) RCP8.5 for 2021-2050; c) RCP4.5 for 2070-2099; d) RCP8.5 for 2070-2099

An increase in the number of days for AT is foreseen for all provinces in each scenario and period (Table 5). The lowest increase is expected in Antalya and the highest increase in İzmir and Aydın. For the RCP4.5 in the near future, the annual average expected increase is at most 1 day. However, an annual average increase of up to 3 days is foreseen in the distant future.

Although the annual average expected to increase for the RCP8.5 scenario in the near future is still less, an increase of 4-20 days is expected for the RCP8.5 scenario in the distant future. The lowest increase is expected in Antalya (4 days), the highest increase in İzmir (19 days), and Aydın (20 days). In general, the highest annual average increase is expected to be in Aydın and İzmir, followed by Muğla, Balıkesir, and Antalya.

Table 5. Annual changes in the number of days for AT on a provincial basis

Provinces	RCP4.5		RCP8.5	
	2021-2050	2070-2099	2021-2050	2070-2099
Antalya	0.12	0.49	0.24	4.75
Aydın	0.96	2.81	1.66	20.71
Balıkesir	0.07	0.65	0.43	7.27
İzmir	1.14	3.31	1.97	19.92
Muğla	0.52	1.46	0.71	11.33

IV. DISCUSSION AND CONCLUSIONS

Tourism activities, which are vitally important for the countries on the Mediterranean coast and their economies, are vulnerable to climate change as they are sensitive to rising temperatures [80-82]. The potential comfort and health effects arising from predicted high temperatures in a changing climate should be taken into consideration.

According to the findings of the study, an increase in the number of hot summer days and tropical nights and the number of days with dangerous apparent temperature is expected in the future in the 5 provinces studied on the Turquoise Coast. Some studies about the regions close to Türkiye have found similar outcomes. For example, in a study on heatwaves in Europe, it is stated that an increase in hot days will be in the future

(2071-2100) [83]. There will be an increase in hot summer days for the 2070-2099 period in the future due to the increase in the frequency and intensity of droughts and extremely hot weather conditions [72]. Furthermore, an increase of 30 days in the number of hot summer days is expected as well as 2-4 weeks increase in the number of tropical nights for the period of 2031-2060 relative to 1961-1990 [84]. Using the 25 °C threshold for tropical nights, as in the case with this article, another study project an increase in the number of tropical nights in the Eastern Mediterranean and the Middle East for the end of the 21st century [73]. Evaluating the impact of extreme heat events in Europe, an increase in the number of tropical nights under 1.5 °C, 2 °C, and 3 °C global warming scenarios is expected [42]. Hot summer days and tropical nights may even lead to an increase in death rates. For example, in the period towards the end of the severe heatwave that hit France in the summer of 2003, deaths were mainly due to the extremely high value of tropical nights [85]. A series of high-resolution regional climate simulations was analyzed, and it was found that that summer heatwaves in Europe will become more frequent and severe this century, consistent with the trend observed in the past decades [8]. Therefore, the findings specific to Türkiye are consistent with the findings for Europe, the Mediterranean, and the Middle East regions.

An increase in the number of days with dangerous apparent temperature, another index examined in this study, is also expected in the 5 provinces on the Turquoise Coast in the future. Considering that apparent temperature aims to describe the body's ability to cool itself through perspiration and evaporation, the increase in apparent temperature upsets this ability. Studying the apparent temperature during the hot summer months in the Portuguese cities of Lisbon and Oporto, it was found that increases in apparent temperatures increase the rates of heart diseases and even death [86]. Furthermore, examining the increase in the number of days with dangerous apparent temperature for the Iberian Peninsula and Mediterranean coasts, an increase in the number of days with dangerous apparent temperature for the future periods of 2021-2050 and 2071-2100 was projected [8]. This study also states that an increase in the number of days with dangerous apparent temperature will have adverse health effects.

Our study did not analyze the effects of the increase in the number of hot summer days and tropical nights and in the number of days with dangerous apparent temperature, but it reveals the possible effects of increases in these indices on human comfort and health. Stating that climate change not only increases the ambient temperature but also causes population movements, climate change has implications for travel and disease risk [13]. Tourists may be at risk of disease

due to factors in their country of origin and destination. The tourist climate comfort has already deteriorated in coastal countries and on the coasts of Türkiye, and this situation has worsened with warmer hinterlands and nights [12].

Considering the importance of coastal tourism, adaptive measures should be taken due to the vulnerability of the relationship between climate change and coastal tourism. Destinations can preserve their natural coastal environments and become more resilient and attractive to tourists, provided they have flexibility and foresight. A study, which relates developments in the history of the tourism industry to climate change, states that the mistakes of the past should not be repeated, and lessons should be learned from them in adapting the industry to the effects of climate change [87]. The main adaptation strategies are increasing scientific and social awareness, establishing early warning systems, and developing emergency response and adaptation processes.

The natural resources and climate of a destination are crucial economic drivers of tourism. Therefore, any change in the environment or climate creates both opportunities and challenges for the tourism industry. Due to the tourism sector's vulnerability to climate change impacts, it is necessary to investigate and implement adaptation methods and policies for the sector's exposure to the effects of climate change. It is believed that adaptation is the best course of action to lessen the industry's sensitivity to climate change [82,88-90]. Although the tourism sector needs to adapt to climate change, it is not fully recognized in the literature [91]. When the potential consequences of climate change are recognized, concentrating on adaptation measures can be simpler and more effective. The research on tourism has begun this phase recently.

For those who are especially at risk from the effects of climate change, better surveillance and control measures are required. Education initiatives regarding the dangers of exposure to high temperatures are needed [89]. It is crucial to collaborate with other organizations and sectors to advance urban green infrastructure that is appropriate for Mediterranean Basin countries [92]. It is important to work not only with the tourism industry but also with other industries associated with it, especially the health sector, regarding the health, environment and ecological threats that rising temperatures can pose. For instance, one area that needs to be expanded initially is the capacity of the health system, which will need to serve a capacity above the typical population during the summer tourist season. Planned adaptation may be the best course of action in light of the hazards posed by climate change. The planned adaptation process, on the other hand, should include risk management planning, funding the adaptation process, prioritizing research

and development activities, training, and effective communication, as well as accepting responsibility for each stakeholder, from local residents to governmental organizations.

The natural and cultural environments, as well as other resources that are important to the tourism industry, must be safeguarded. Policies created through inclusive processes are required to achieve it. Most research on tourism industry adaptation and policies highlight attempts to diversify products or shift places as the adaptation responses that have been most successful. Taking into account Türkiye's tourism strategy, the Development Plans launched in 1963 included various regulations that addressed the industry. These are associated with spending much more on advertising and promotion, diversifying tourist-related activities, raising tourism income, enticing investments and creating infrastructure facilities, and education tourism staff. None of the reports before 2019, however, make any specific mention of climate change; instead, they concentrate on raising the accommodation capacity and travel-related services. In the eleventh and final development plan covering the 2019-2023 targets, climate change, food security and water management issues and the importance of adaptation were mentioned, but specific targets related to these issues were not included [93]. Environmental goals including attempting to stop the exploitation and pollution of natural resources and preserving the ecological balance should be incorporated into the tourism policy [94]. Therefore, the growth of tourism can be accomplished in a way that ensures the preservation of natural and cultural resources for both present and future uses. Unplanned tourism development can result in issues like the degradation and alteration of the physical environment, the destruction of historical and cultural resources, crowding and noise in the tourist area, pollution of the environment, and traffic issues. These issues arise during the busy tourist season in 5 provinces that were the subject of this study.

Countries such as Türkiye, which heavily rely on tourism revenue, may face the potential for substantial financial losses due to climate change if they fail to implement adequate measures to mitigate risks and adapt to the changing climate. Adaptation is an appropriate response to reduce the tourism industry's vulnerability to climate change. Adapting to climate change is an imperative need, but this need is not fully understood in the tourism sector. Focusing on adaptation strategies can be easier and more efficient when the potential impacts of climate change are known. Examining the effects of climate change on a system is important for studies that evaluate and understand vulnerabilities and related adaptation measures. It is recommended that future research focus on adaptation solutions based on impact studies such as this research.

In conclusion, flexible and participatory approaches should be used to incorporate climate change into sustainable tourism policies. Effective control systems are also needed to ensure the implementation of these integrated policies. Additionally, education on climate change and its impacts is essential for all stakeholders, including governments, the private sector, and the public. Moreover, economic incentives can be provided for the implementation of climate change adaptation measures, including both tax breaks and taxation for tourism industry.

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Effects of Spreading Parameters on Powder Bed Quality

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Abstract

Powder bed-based additive manufacturing processes such as laser powder bed fusion, binder jetting, and electron beam melting are commonly utilized in various critical areas such as medical, aviation, and energy. Common to all these operations, the powders are first spread onto the build platform in a layer-by-layer fashion and selectively fused or bound with a suitable method. The quality of the process depends on several parameters, including how the powders are spread onto the build platform. The powder spreading operation, which involves spreading powders on a powder bed with a roller or spreader, is an important step in these operations and can affect various process outputs. In this study, powder spreading is numerically investigated using the discrete element method to determine the effects of layer thickness, rotation, and translation velocities, selected as parameters with a powder spreader roller. To account for the relationship between powder spreading parameters and the powder volume packing fraction, as well as the interactions between particles themselves and between the particles and the build plate, the Hertz-Mindlin contact model, including normal tangential forces, as well as the Johnson-Kendall-Roberts (JKR) contact model, including the effects of surface energy, were added to the numerical model. A Design of Experiment combined with analysis of variance (ANOVA) was utilized to gain a broader understanding of the relationship between process parameters, green density, and dynamic angle of repose.

Keywords: Additive Manufacturing, Powder Spreading, Discrete Element Method, ANOVA

Öz

Lazerle toz yatağında füzyon, bağlayıcı püskürtme ve elektron ışını ile ergitme gibi toz yatağı tabanlı yöntemler, tıbbi, havacılık ve enerji gibi çeşitli kritik alanlarda yaygın olarak kullanılmaktadır. Bu işlemlerin hepsinde ortak olarak, tozlar önce katman üretim platformuna yayılır ve uygun bir yöntemle seçici olarak ergitilir veya bağlanır. Sürecin kalitesi, tozların üretim platformuna nasıl yayıldığı da dahil olmak üzere birçok süreç parametresine bağlıdır. Bir merdaneyle veya yayıcı ile tozların toz yatağına serilmesi işlemi olan toz yayma operasyonu, bu işlemlerde önemli bir adımdır ve yoğunluk, yüzey pürüzlülüğü gibi çeşitli süreç çıktıları üzerinde etkili olabilir. Bu çalışmada, toz yayma, katman kalınlığı, dönüş ve geçiş hızlarının parametre olarak seçildiği bir toz yayıcı silindiri ile, ayırık elemanlar yöntemi kullanılarak sayısal olarak incelenmiştir. Toz yayma parametreleri ile toz hacim paketleme oranı arasındaki ilişki, partiküllerin kendileri arasında ve partikül ile üretim plakası arasındaki etkileşimleri dikkate almak için normal ve teğetsel kuvvetleri içeren Hertz-Mindlin temas modelinin yanında yüzey enerjisinin etkilerini içeren Johnson-Kendall-Roberts (JKR) temas modeli sayısal modele eklenmiştir. Deney Tasarımı ve varyans analizi (ANOVA) ile birleştirilmiş olarak, süreç parametreleri ile yoğunluk ve dinamik yığın açısı arasındaki ilişkiyi daha geniş bir anlayış kazanmak için kullanılmıştır.

Anahtar Kelimeler: Eklemeli imalat, Toz Serpme, Ayırık Elemanlar Yöntemi, ANOVA

I. INTRODUCTION

Additive manufacturing has been proven to be an effective and versatile approach to produce intricate geometries from a variety of materials [1]. Its geometric capabilities are beyond comparison with traditional techniques. Among additive manufacturing processes, powder bed-based processes such as laser/electron beam powder bed fusion and binder jetting have found numerous critical applications in many industries [2]. In these processes, powder fed to the system with either a piston-based or hopper-based system is spread onto the build platform using a spreader. The powder is then selectively melted or bound together by a suitable means depending on the manufacturing type used. In general, the spreading operation is employed using either a roller, knife, or brush. Depending on the spreading conditions, final part quality may be affected. Thus, it is imperative to understand the effects of powder spreading conditions on powder bed quality [3].

Although the final geometry is obtained after melting the powder in fusion-based powder bed processes or after sintering in binder jetting operations, it has been shown that the powder bed quality can affect the final part [4]. The powder bed quality also has a detrimental effect on energy absorption in powder bed fusion [5]. In binder jetting, it can significantly affect the powder-binder interaction, sintering, and infiltration behavior [6]. The quality of the powder layer in the powder spreading process is influenced by the geometry, motion, and material properties of the spreading tool. Additionally, the powder feedstock and its characteristics play a significant role, impacting both the powder layer quality and, consequently, the final product's properties and overall quality.

Several studies have examined various aspects of powder spreading in additive manufacturing using both experimental and numerical methodologies. For instance, Onler et al. explored the impact of powder spreading parameters, alongside other process variables, in binder jet additive manufacturing. They found that factors such as layer thickness, roller rotation direction, and roller transverse velocity significantly affect both green part densities and quality [7]. Gilebart et al. highlighted the importance of both assembling procedures and contact laws in determining the properties of cohesive powders. Through detailed simulations, they provided insights that can be used to better control and predict the behavior of these materials in practical applications [8]. Maximenko et al. investigated the influence of powder spreading parameters on part distortion during binder jetting using the discrete element method. Their findings suggested that the distortion of previously deposited layers depends on factors such as the amount of powder removed during spreading, the thicknesses of the deposited layers, and the dimensions of the manufactured components. Through modeling and simulation, they provided insights and guidelines for optimizing the powder spreading process, contributing to better control over the final dimensions and quality of binder-jetted parts [9]. Zhang et al. integrated the discrete element method with neural networks to develop a powder spreading process map. Their study highlighted the dominant role of the rotational speed of the roller in determining the surface roughness of the spread layer [10]. Additionally, Miyanaji et al. demonstrated the importance of powder characteristics in the binder jetting process, showing that particle size, shape, distribution, and flowability significantly affect the quality and properties of the fabricated parts. By optimizing these powder characteristics, manufacturers can achieve better control over the binder jetting process and produce high-quality parts. They also presented a comprehensive study on optimizing the binder jetting process for printing green parts, highlighting the importance of binder saturation, layer thickness, and powder characteristics. By fine-tuning

these parameters, manufacturers can achieve high-quality green parts, paving the way for improved final products after sintering [11,12].

The discrete element method (DEM), pioneered by Cundall and Strack, has been widely utilized for particle analysis and simulations across various systems. Given the difficulties and expenses associated with experimentally investigating powder spreading, DEM offers a cost-effective and powerful platform for understanding powder spreading in additive manufacturing. For instance, Parteli and Paschel developed a numerical workbench to analyze the effects of surface roughness due to these parameters. They demonstrated the utility of particle-based simulations in studying and optimizing the powder application process in additive manufacturing. By analyzing the effects of particle properties and spreading mechanisms, their study provides valuable insights for achieving better control over powder layer quality, ultimately enhancing the performance and reliability of additive manufacturing processes [13]. Meanwhile, Mindt et al. monitored the load during the spreading process of titanium alloy powder. They highlighted the often-overlooked importance of powder bed layer characteristics as a primary input in additive manufacturing. By demonstrating how these characteristics influence final part quality, their study calls for improved control and optimization of the powder bed layer to achieve better outcomes in AM processes [14]. Haeri et al. investigated the effects of speed parameters on coating and plate displacement, revealing that cylindrical spreaders are superior to blade types in terms of powder packing density. Their study demonstrates the potential of using DEM simulations to optimize blade-type spreaders for powder bed preparation in additive manufacturing. By identifying the optimal blade design and operational parameters, they provide valuable insights for improving the uniformity and quality of powder layers, ultimately enhancing AM process performance [15]. Chen et al. and Meier et al. employed DEM-based numerical models to investigate particle dynamics and the powder recoating process, respectively, validating their findings with experiments [16]. Nan et al. studied friction-induced jamming in powders experimentally and incorporated these findings into simulations [17]. Fouda et al. analyzed the effects of particle material and spreader type on packing density, emphasizing process parameters and system mechanisms. Their study examines the behavior of powder particles during the spreading process and identifies factors influencing the uniformity and density of the powder layer. Key findings highlight the importance of particle size, shape, and cohesion in achieving a consistent powder bed, which is crucial for the quality of the final manufactured parts. Their results provide insights for optimizing the spreading process to improve additive manufacturing outcomes [18]. Han et al. developed a systematic approach to determine the optimal layer

thickness considering packing density, correlating it with microstructure and tensile strength. Their study investigates how parameters such as particle size distribution and spreading speed affect the thickness and uniformity of the powder layer. The findings indicate that optimal control of these parameters can lead to more consistent layer thickness, which is essential for high-quality additive manufacturing parts [19]. Phua et al. calibrated particle properties using DEM-based models, matching experimental measurements. Their results demonstrate how surface roughness and features impact the uniformity of new powder layers [20]. Gurnon et al. proposed a multi-layer DEM model, contrasting with single-layer studies, and validated it experimentally. Their findings emphasize that precise control of spreading dynamics is essential for achieving high-quality powder layers, which in turn influence the final part properties [21]. Chen et al. introduced a counterclockwise rotating roller in DEM-based analysis, offering new insights into physical mechanisms [22], while Valerio et al. elucidated spreading operations using a numerical DEM model [23].

As summarized above, powder spreading plays a crucial role in powder bed-based additive manufacturing processes. Although various aspects of powder spreading have been comprehensively investigated in the literature, discrete element-based approaches can be further useful for improving powder spreading without incurring experimental costs. Hence, this study focuses on the statistical analysis of spreading parameters on powder bed quality. To achieve this, a full factorial design of experiment-based DEM simulations has been carried out. Analysis of Variance (ANOVA)-based statistical investigations were performed to identify the relationship between spreading parameters and both powder density and the dynamic angle of repose.

The optimization of powder spreading in powder bed-based additive manufacturing processes is crucial for ensuring high-quality output in critical applications such as medical implants, aerospace components, and energy systems. Despite the significant role of powder spreading, there is limited understanding of how specific parameters like layer thickness, roller rotation and translation velocities impact the final product's quality. This study addresses this gap by employing the discrete element method (DEM) to numerically investigate these effects, incorporating advanced contact models to capture the intricate interactions between particles and the build platform using a design of experiment, ANOVA and response surface method (RSM) based statistical approaches. This study approach provides deeper insights into the mechanics of powder spreading, enabling better control and optimization of additive manufacturing processes, ultimately leading to enhanced product performance and reliability.

II. METHOD

2.1. Discrete Element Method

The Discrete Element Method (DEM) is a powerful numerical technique employed to simulate systems composed of numerous discrete particles [18]. A typical DEM simulation begins with the initialization phase, where particles are spatially oriented and assigned initial velocities. This is followed by the explicit time-stepping phase, where forces acting on each particle are computed based on initial conditions, physical laws, and contact models. Nearest neighbor sorting is periodically conducted during this phase to reduce computational complexity by limiting the number of potential contact pairs. Forces considered in macroscopic simulations include friction, contact plasticity or recoil, gravity, and various attractive potentials such as cohesion, adhesion, liquid bridging, and electrostatic attraction.

2.2. Governing Equation

A 'super-spherical approach' was used for the particle type because powders exhibit very dense particle flow and require effective layering during the spreading process [22,24]. In this layering process, the motion of powder particles is governed by Newton's second law of motion, which describes the individual translational and rotational motion of particles. As depicted in Figure 1, the equations governing the motion of each particle in the system at time 't', arising from interactions with other particles 'j' present in the system or with other components, can be expressed as follows:

$$m_i \frac{du_i}{dt} = G_i + \sum_j (F_{ij}^n + F_{ij}^t) \quad (1)$$

$$I_i \frac{d\omega_i}{dt} = \sum_j (T_{f,ij} + T_{r,ij}) \quad (2)$$

Where u_i , I_i , m_i and ω_i are, respectively, translational velocity, moment of inertia, the mass, and rotational velocity of particle i ; F_{ij}^n and F_{ij}^t are, respectively, the normal and tangential interaction forces between particle i and j . G_i is the gravitational force of particle i . The normal and tangential forces inherent in the system can be derived directly from the contact and damping force formulas, i.e., $F_{ij}^n = F_{c,ij}^n + F_{d,ij}^n$ and $F_{ij}^t = F_{c,ij}^t + F_{d,ij}^t$. Then, the model proposed by Tsuji et al [25], this model is also based on the Hert-Mindlin contact force model, simplified for ease of use, which makes an acceptable accuracy demonstrate of the particle dynamic behavior during the particle contacts [26], is applied to calculate the damping forces ($F_{d,ij}^n$ and $F_{d,ij}^t$) and tangential contact forces $F_{c,ij}^t$ as a result of the deformation of the particles. $T_{f,ij}$ is the torque which is formed by the contact forces driving the other particle which cause particle i to rotate, and $T_{r,ij}$ is the rolling friction torque that opposes to the rotation of particle i .

Van der Waals forces begin to dominate when the diameters of the particles in the system are smaller than 100 microns. Consequently, calculating cohesion forces between particles becomes necessary. The JKR contact model addresses this requirement. The JKR contact model is essentially an extension of the Hertz-Mindlin contact model, designed to calculate contact forces acting on elastic and adhesive particles. Equations 3 and 4 are used to determine the contact radius and pull-off force, respectively.

$$a = \frac{a^2}{R^*} - 2 \left(\frac{\pi \gamma a}{E^*} \right)^{1/2} \tag{3}$$

$$F_n = \frac{4E^* a^3}{3R^*} - 4(\pi \gamma E^* a^3)^{1/2} \tag{4}$$

Where a , γ and E are circular are of radius, surface energy and young modulus, respectively.

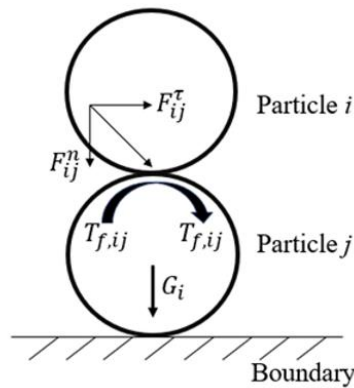


Figure 1. Illustration of force and torque for two interacting super-spherical particles

2.3. Material

To simulate particle dynamic behaviors and their fundamentals using DEM, the material properties and conditions must be accurately described and input into the program as parameters and boundaries. Although some of these parameters are challenging to measure [27], they are often sourced directly from the literature [18,28].

In this study, Ti6Al4V (Titanium Alloy), which is widely used in additive manufacturing, is employed to provide a common basis for comparison. The physical and mechanical properties of the particulate material required for the simulations are listed in Table 1. These properties are characterized by their specific applications and have been defined in previous studies. Commercial steel is chosen as the material for the build plate [29].

Table 1. Properties and input parameters of Ti6Al4V (Titanium Alloy) material [18]

Properties	Clearance
Particle Material Density (kg/m ³)	4300
Walls Material Density (kg/m ³)	8500
Particle Shear Modulus (MPa)	1
Particle Poisson Ratio	0.3
Wall Shear Modulus (MPa)	1
Wall Poisson Ratio	0.3
Particle-Particle Coefficient of Restitution	0.5
Particle-Wall Coefficient of Restitution	0.5
Particle-Particle Coefficient of Sliding Friction	0.5
Particle-Wall Coefficient of Sliding Friction	0.5
Particle-Particle Coefficient of Rolling Friction	0.01
Particle-Wall Coefficient of Rolling Friction	0.1

2.4. Particle Size Distribution and Layer Thickness

Particle size distribution is a critical parameter for the spreading operation and has both positive and negative effects on packing fraction. Various particle distribution methods are used in the literature, such as random, half-normal, log-normal, and linear-normal distributions. For a more precise simulation, gas-atomized Ti-6Al-4V powders were considered. Particle size distributions were measured using a particle size analyzer (Mastersizer-2000, Malvern), and particle morphology was assessed using scanning electron microscopy (XL30 SFEG, Philips). As shown in Figure 2, the particle diameter distribution is approximately 50 microns, with particles close to this diameter occupying most of the total volume. Among the investigated particle distributions, the log-normal size distribution was found to be more representative of the actual conditions than the others. Therefore, the particle diameter distribution was chosen based on the log-normal size distribution [30].

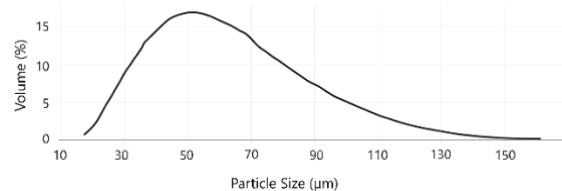


Figure 2. A sample particle size distribution of Ti-6Al-4V powders considered in the simulation

In this study, the particle diameter was set to 50 microns, and the log-normal size distribution was defined with a standard deviation of 0.05 and a mean of zero for all materials. As shown in the scanning electron microscopy images in Figure 3, the particles are predominantly spherical, with a small number of

satellite-shaped particles. Therefore, super-spherical-shaped particles were modeled, consistent with approaches used in the literature [8].

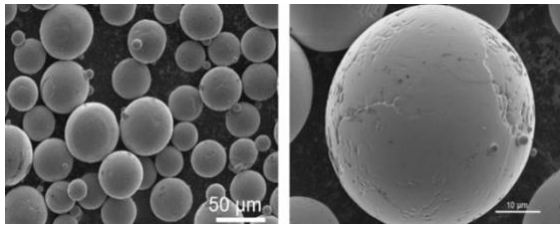


Figure 3. Scanning Electron Microscopy images of Ti-6Al-4V particles considered in the study

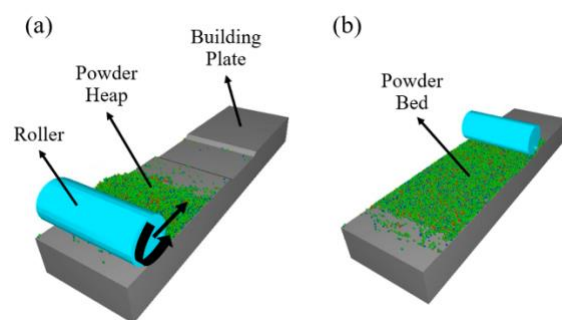


Figure 4. DEM simulation set-up showing roller, feedstock and building plate (a) before, and (b) after the spreading operation for one layer

2.5. Simulation Setup

A powder spreading system, featuring a spreader and a build plate, is commonly used in production methods such as Selective Laser Melting (SLM), Binder Jetting (BJ), and Selective Electron Beam Melting (SEBM). This system, modeled as shown in Figure 4, consists of three main components: the roller, the powder heap, and the build plate, which defines the layer geometry by providing the desired depth. As illustrated in Figure 4(a), powders are produced at a rate of ten thousand units per second using a virtual plate positioned appropriately within the system. These powders are deposited in front of the roller under the influence of gravity, forming a heap. After the heap is formed by the virtual plate, the roller rotates at a specific angular velocity and moves forward at a set translational speed to fill the gap created by the layer thickness on the build plate, thereby forming the powder bed, as shown in Figure 4(b). Another critical physical parameter is the vertical gap between the roller and the build plate, which directly impacts the system. This gap affects the packing density of the deposited powder and its surface roughness, which corresponds to the vertical resolution of the 3D printed component. In the simulations performed for this study, the gap was maintained at a constant 50 microns, a standard value used in typical electron beam melting (EBM) machines [31,32]. This standardization ensures consistency and allows

meaningful comparisons between simulation results and real-world manufacturing processes.

The discrete element method (DEM) is a numerical technique well-suited for predicting the motion of individual powder particles and their dynamics during the powder spreading process. Due to these capabilities, DEM has been used extensively in simulations. In this paper, varying simulations were conducted using the DEM software EDEM® provided by Altair. To achieve more accurate results, the Hertz-Mindlin and Johnson-Kendall-Roberts (JKR) contact models were employed to determine interactions between particles and between particles and walls.

2.6. Simulation Parameters

In this study, we employed a full factorial design of experiments approach, incorporating layer thickness, rotational speed, and translational speed as key factors. The layer thickness values chosen were 100, 120, 130, and 140 µm. The roller rotational velocities were set at 150, 200, and 250 rpm, while the roller translational velocities were set at 10, 20, and 30 mm/sec. These parameter choices were informed by previous studies [18,23,33]. With 4 levels of layer thickness and 3 levels each of rotational and translational velocities, a total of 36 simulations were conducted to thoroughly explore the parameter space and analyze their effects on the system.

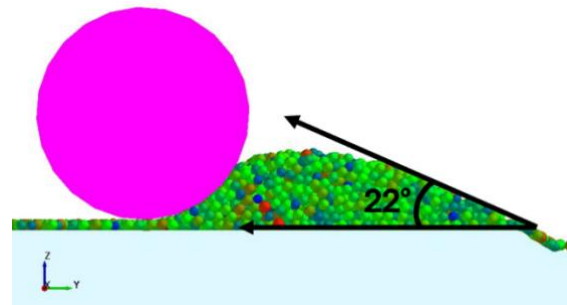


Figure 5. Virtual measurement of dynamic angle of repose

2.6.1. Dynamic angle of repose and packing fraction measurements

The dynamic angle of repose for different rotational and translational velocities at each layer thickness was measured by capturing screenshots at various time intervals, ensuring that the rollers were in identical positions. To pinpoint the precise moment for determining the dynamic angle of repose, all time steps of the simulation were carefully reviewed. The specific moment when the powders first filled the space designated for the layer thickness, as shown in Figure 5, was identified as the time to reach the steady state, as suggested by [34]. This approach enabled a precise assessment and analysis of the dynamic angle of repose under the varying experimental conditions.

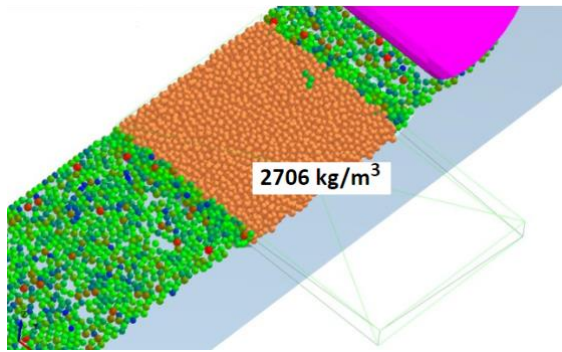


Figure 6. Virtual box employed for measurement of volume packing fraction

In this study, the volume packing fraction defined as the percentage of the total volume of powders within a given unit volume was measured for different rotational and translational velocities at each layer thickness. This measurement was conducted using a virtual box within the EDEM simulation environment, as shown in Figure 6. The density sensor box was designed to fully encompass the layer thickness to ensure accurate density measurements. The positioning of the layer thickness for density determination was carefully aligned to cover the entire layer thickness, in accordance with established practices [16,35]. This approach enabled a precise and thorough assessment of the volume packing fraction under various experimental conditions.

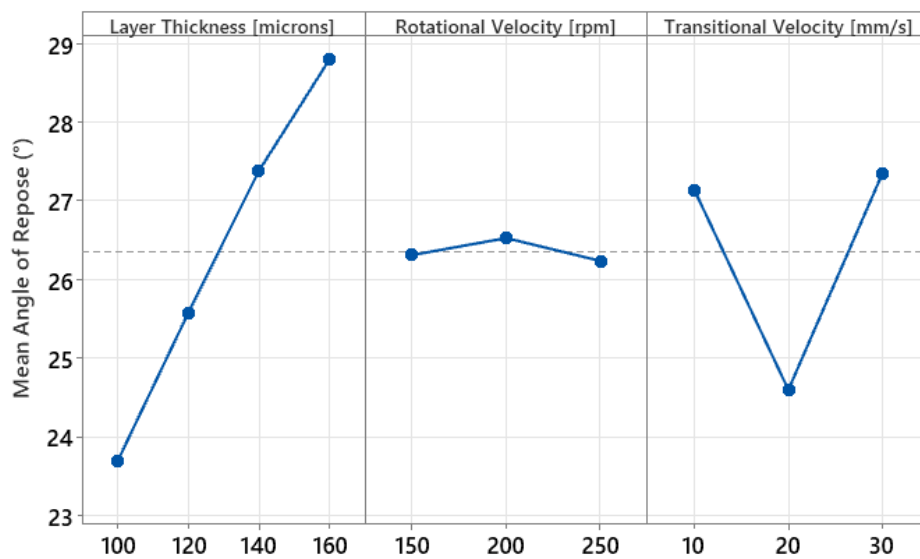


Figure 7. Virtual box employed for measurement of volume packing fraction

2.6.2. Analysis of Variance

To assess the impact of the examined parameters, we utilized a commonly employed statistical method known as Analysis of Variance (ANOVA). ANOVA is frequently used to ascertain if there are any statistically significant distinctions among the means of various groups. Statistical comparisons were conducted using a two-tailed Student's t-test, with a significance threshold of $p < 0.05$. Additionally, to better interpret the ANOVA outcomes beyond mere statistical significance, we calculated the relative contributions of spreading parameters and their interactions [36]. The ANOVA results pertaining to parameters with substantial contributions were subsequently tabulated and graphically represented.

III. RESULTS

3.1 Dynamic Angle of Repose

Figure 7 illustrates the main effects of how spreading parameters influence the dynamic angle of repose, which consistently ranges from 23° to 32° under various conditions. In this figure, the y axis shows the mean of the simulations results generated using the

identical individual simulation parameter. For instance, the first point corresponding to $100\ \mu\text{m}$ layer thickness considers all the rotational and translational velocity combinations with $100\ \mu\text{m}$ layer thickness. The angle of repose was found to increase linearly with layer thickness. In contrast, rotational and translational velocities did not show a consistent trend in the angle of repose. To validate these observations, an Analysis of Variance (ANOVA) presented in Table 2 assessed the effects of three key parameters: layer thickness, rotational velocity, and translational velocity. In this table, DF represents degree of freedom, Adj SS represents adjusted sum of squares and adj MS represents adjusted mean of squares. The F-value is the ratio of the variance between the group means to the variance within the groups. The p-value, or probability value, is a measure used in statistical hypothesis testing to determine the significance of the observed results [37]. A significance level of 0.05 is used to determine the significance of the investigated factor. Layer thickness was identified as the most significant factor, accounting for 55.91% of the total variation, with a highly significant F-value of 110.55 ($p < 0.001$). Rotational velocity, however, had minimal impact,

contributing only 0.01% of the variation with a non-significant F-value of 0.03 ($p = 0.868$). Translational velocity similarly contributed 0.11% of the variation, supported by an insignificant F-value of 16.580 ($p = 0.645$). Additionally, the squared term of translational velocity showed a significant effect with an F-value of 46.46 ($p = 0.000$), accounting for 23.45% of the variation. The unexplained variation, indicated by the error term contributing 13.15%, highlights the complexity of the analysis. Overall, these findings emphasize the substantial influence of layer thickness on the dynamic angle of repose, consistent with existing literature [23], and underscore the minimal effect of rotational velocity in this context.

According to the results in the table, a response surface method equation was found to be as follows:

$$\begin{aligned}
 AoR = & 30,1 + 0,051LT + 0,0118RV - 1,526TV \\
 & - 0,000292LT * LT \\
 & - 0,000102RV * RV \\
 & + 0,02642TV * TV + 0,000201LT \\
 & * RV + 0,00353LT * TV \\
 & + 0,000103RV * TV
 \end{aligned} \quad (5)$$

Table 2. Analysis of variance for dynamic angle of repose (AoR).

Source	DF	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	9	86,85%	206,005	22,889	19,08	0,000
Linear	3	56,03%	132,907	44,302	36,93	0,000
Layer Thickness (LY)	<u>1</u>	<u>55,91%</u>	<u>132,612</u>	<u>132,612</u>	<u>110,55</u>	<u>0,000</u>
Rotational Velocity (RV)	1	0,01%	0,034	0,034	0,03	0,868
Translational Velocity (TR)	1	0,11%	0,261	0,261	0,22	0,645
Square	3	23,97%	56,856	18,952	15,80	0,000
LT*LT	<u>1</u>	<u>0,21%</u>	<u>0,492</u>	<u>0,492</u>	<u>0,41</u>	<u>0,527</u>
RV*RV	1	0,22%	0,517	0,517	0,43	0,517
TV*TV	1	23,54%	55,847	55,847	46,56	0,000
2-Way Interaction	3	6,85%	16,242	5,414	4,51	0,011
LT*RV	1	0,51%	1,211	1,211	1,01	0,324
LT*TV	1	6,32%	14,989	14,989	12,50	0,002
RV*TV	1	0,02%	0,042	0,042	0,04	0,853
Error	26	13,15%	31,188	1,200		
Total	35	100,00%				

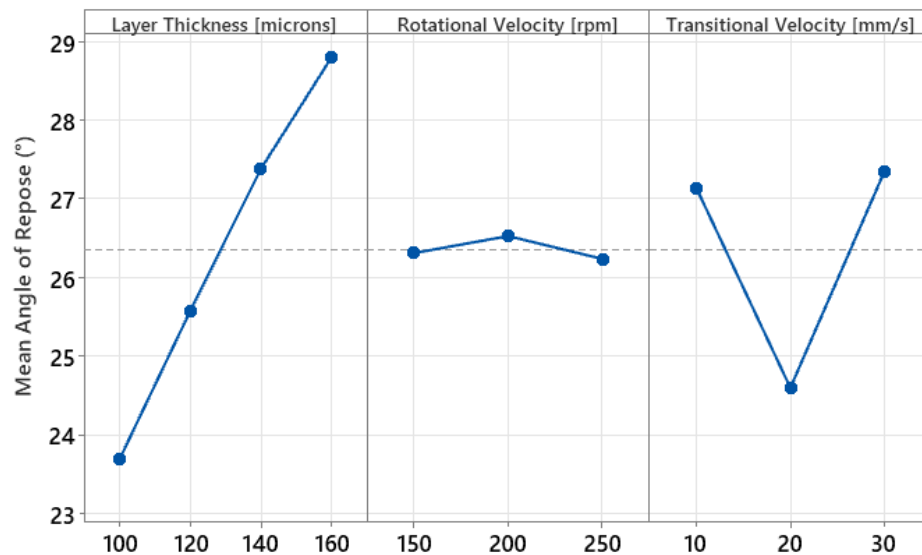


Figure 8. Parameters effect on volume packing fraction [%]

3.2. Bulk Density/Packing Fraction

Figure 8 provides insight into the main effects of volume packing fraction revealing that, under the investigated simulation parameters, increasing layer thickness and translational velocity lead to a significant decrease in volume packing fraction, while rotational velocity tends to increase it, consistent with findings by Haeri et al. [15] Zhang et al [30]. In their study, the translational velocities ranged from 40 mm/s to 160 mm/s and the volume packing fractions corresponding to these velocities ranged from 0.53 to 0.45, respectively. In the same study, when the effect of layer thickness on the volume packing fraction is considered, the volume packing fraction increases between 0.15 and 0.5, corresponding to a layer thickness of 50 microns and a layer thickness of 175 microns. However, the effect of rotational speed on volume packing fraction was found to be very small compared to other parameters. Fouda et al. also revealed similar findings. In their study, volume packing fractions corresponding to translational velocity speeds between 10 mm/s and 100 mm/s ranged between 47.5% and 25%. It is clearly seen that the increasing of translational velocity of roller reduces the packing volume fraction [18]. A similar situation was also found in this, the upper and lower values of volume packing fraction are determined to be 2800 kg/m³ and 2600 kg/m³, respectively. Table 3 presents the ANOVA results for volume packing fraction, offering further clarity on the influencing factors. Layer thickness emerges as a significant contributor, explaining 18.29% of the total variation with a highly significant F-Value of 124,28 ($p < 0.001$). Although rotational velocity demonstrates statistical significance, its impact is relatively modest, accounting for 3.69% of the variation (F-Value = 25.09, $p = 0.007$). In contrast, translational velocity emerges as the most influential factor, explaining a substantial 65.90% of the total variation, supported by a remarkably high F-Value of 447,86 ($p < 0.001$). Despite its lesser significance,

rotational velocity still plays a discernible role. Overall, this analysis underscores the significant influence of layer thickness and translational velocity on volume packing fraction, highlighting the complexity of the system.

According to the results in the table, a response surface method equation was found to be as follows:

$$\begin{aligned}
 VPF = & 70,03 + 0,0766RV - 0,5128TV + 0,000257LT \\
 & * LT - 0,000082RV * RV \\
 & + 0,00522TV * TV - 0,000181LT \\
 & * RV + 0,001881LT * TV \\
 & - 0,000589RV * TV
 \end{aligned} \quad (6)$$

The literature commonly suggests that the dynamic angle of repose tends to increase with higher translational velocities. This trend typically indicates more challenging particle flow, leading to increased volume fraction and decreased production quality [38,39]. However, contrary to these expectations, this study did not yield clear statistical results regarding the dynamic angle of repose concerning the primary parameters. Notably, only the influence of layer thickness on the dynamic angle of repose was evident. As depicted in Figure 8, the effect of spreading parameters on volume packing fraction shows a very clear distribution, whereas no clear results were obtained for the effect on the dynamic angle of repose. Consequently, a direct correlation between increased layer thickness and the rise in the dynamic angle of repose is established. Nevertheless, despite this insight, a definitive relationship with volume packing fraction remains elusive.

In contrast to the statistical analysis regarding the dynamic angle of repose, notable findings emerge from the volume packing fraction analysis, demonstrating distinct results based on the parameters. The analysis reveals significant changes according to the three

primary parameters considered, suggesting meaningful relationships. As summarized in Figure 7, translational velocity notably influences volume packing fraction more than other factors. This observation aligns with

findings from numerous studies in the literature (e.g., [4,21,40,41]), further emphasizing the substantial impact of translational velocity on volume packing fraction.

Table 3. Analysis of variance for volume packing fraction (VPF)

Source	DF	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	9	96.17%	110.268	122.520	72.63	0.000
Linear	3	87.88%	100.756	335.852	199.08	0.000
Layer Thickness (LY)	1	<u>18.29%</u>	<u>20.967</u>	<u>209.669</u>	<u>124.28</u>	<u>0.000</u>
Rotational Velocity (RV)	1	<u>3.69%</u>	<u>4.233</u>	<u>42.333</u>	<u>25.09</u>	<u>0.000</u>
Translational Velocity (TR)	1	<u>65.90%</u>	<u>75.555</u>	<u>755.554</u>	<u>447.86</u>	<u>0.000</u>
Square	3	2.53%	2.895	0.9651	5.72	0.004
LT*LT	1	0.33%	0.379	0.3792	2.25	0.146
RV*RV	1	0.29%	0.338	0.3379	2.00	0.169
TV*TV	1	<u>1.90%</u>	<u>2.178</u>	<u>21.783</u>	<u>12.91</u>	<u>0.001</u>
2-Way Interaction	3	<u>5.77%</u>	<u>6.617</u>	<u>22.058</u>	<u>13.08</u>	<u>0.000</u>
LT*RV	1	0.86%	0.983	0.9832	5.83	0.023
LT*TV	1	<u>3.70%</u>	<u>4.246</u>	<u>42.457</u>	<u>25.17</u>	<u>0.000</u>
RV*TV	1	1.21%	1.389	13.885	8.23	0.008
Error	26	3.83%	4.386	0.1687		
Total	35	100.00%				

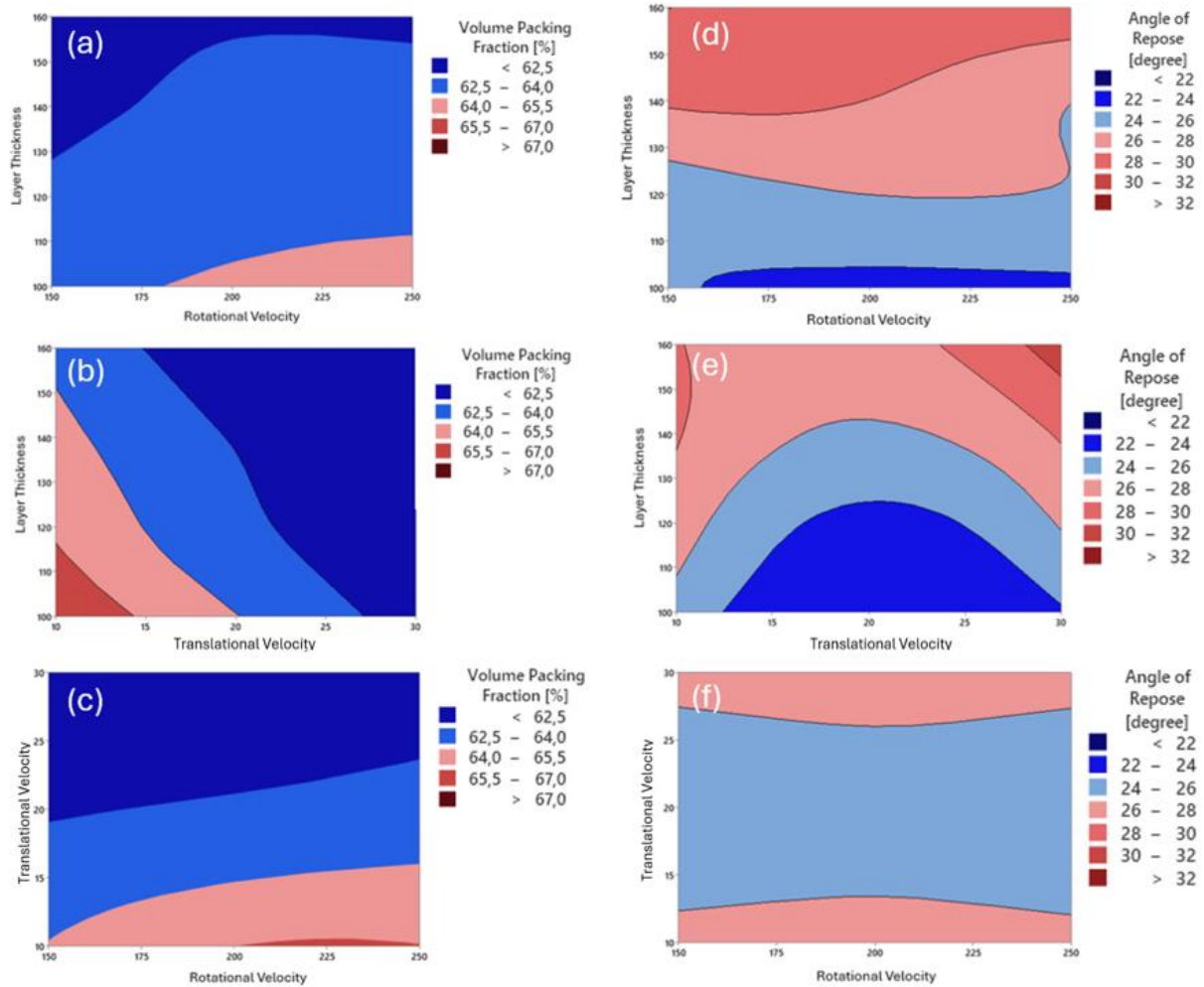


Figure 9. 2D contour plot for parameters effects on volume packing fraction a) Layer Thickness-Rotational Velocity, b) Layer Thickness -Translational Velocity, c) Translational Velocity -Rotational Velocity and Angle of Repose d) Layer Thickness – Rotational Velocity, e) Layer Thickness – Translational Velocity, f) Translational Velocity -Rotational Velocity

IV. CONCLUSIONS

This study numerically investigates the powder spreading behavior of Ti-6Al-4V alloy using the discrete element method, considering full factorial combinations of four levels of layer thickness, three levels of rotational velocity, and three levels of translational velocity. The simulation results were further evaluated using ANOVA. In conclusion, our investigation into the dynamic angle of repose and volume packing fraction reveals the intricate interplay between spreading parameters and material characteristics. Regarding the dynamic angle of repose, our findings align with existing literature, highlighting the pronounced influence of layer thickness and translational velocity. Notably, while rotational velocity showed statistical insignificance, layer thickness and translational velocity significantly affected the dynamic angle of repose, with translational

velocity emerging as the most influential factor. However, contrary to expectations, no clear statistical results were obtained for the dynamic angle of repose concerning the main parameters, underscoring the complexity of the system. In contrast, our analysis of volume packing fraction reveals distinct results based on the parameters, with translational velocity exerting the most significant influence. Increasing layer thickness and translational velocity led to a notable decrease in volume packing fraction, while rotational velocity tended to increase it, consistent with previous research. These observations highlight the multifaceted nature of volume packing fraction determination, with translational velocity emerging as a key determinant. Overall, our study emphasizes the importance of considering multiple factors in understanding both the dynamic angle of repose and volume packing fraction.

It provides valuable insights into the complex dynamics of granular materials used in additive manufacturing. Further research into areas such as powder morphology variation and binder/powder interactions during spreading could enhance our understanding of particle behavior and inform the optimization of production processes. This study examined the spreading of the first layer in general. In fact, powder bed additive manufacturing methods involve the formation of multilayers and after each layer is spread, the binder is sprayed in binder jetting, while in applications such as electron beam melting and laser beam melting, each spread layer is molten. As a result of spraying the binder or melting the powder, the volume packing fraction of the layer changes and even the layer thickness decreases. Even such changes can be parameterized and added to the model. Improving the model used and studying this multilayer formation can lead to much more accurate results. In addition, due to the use of metal powders in this type of application, there is a magnetic attraction or repulsion between the powders. This may even occur between the powders and the binder. Such effects can also be added to the numerical model to produce better simulations that converge to reality.

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CuS/CuInS₂/TiO₂ ile Fotokatalitik Hidrojen Üretimi: Fotokatalizör Sentez Yönteminin Etkisi

Photocatalytic Hydrogen Production by CuS/CuInS₂/TiO₂: Effect of Photocatalyst Synthesis Method

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Öz

Fotokatalitik hidrojen üretimi, uygun fotokatalizörler kullanılarak güneş enerjisini kimyasal enerjiye dönüştürme konusunda önemli bir potansiyele sahip, temiz ve yenilenebilir bir enerji üretim süreci olarak bilinmektedir. Bu çalışmada, solar ışık altında H₂ üretimini arttırmak için CuS/CuInS₂/TiO₂ nanokompozitinin sentezlenmesini hedeflenmiştir. CuS/CuInS₂/TiO₂ katı-katı sentez ve yerinde sentez olmak üzere iki farklı sentez metodu ile hazırlanmıştır; H₂ üretiminin en yüksek olduğu fotokatalizör kompozisyonu ve fotokatalizör sentez metodu belirlenmiştir.

Anahtar Kelimeler: Fotokatalizör, TiO₂, CuS, CuInS₂, solar, hidrojen

Abstract

Photocatalytic hydrogen production is known as a clean and renewable energy production process with significant potential to convert solar energy into chemical energy by using suitable photocatalysts. In this study, it was aimed to synthesize CuS/CuInS₂/TiO₂ nanocomposite to increase H₂ production under solar light. CuS/CuInS₂/TiO₂ was prepared by two different synthesis methods, solid-solid synthesis and in situ synthesis; the photocatalyst composition and photocatalyst synthesis method with the highest H₂ production were determined.

Keywords: Photocatalyst, TiO₂, CuS, CuInS₂, solar, hydrogen

I. GİRİŞ

Suyun ayrışması yoluyla fotokatalitik hidrojen (H₂) üretimi, uygun fotokatalizörler kullanılarak güneş enerjisini kimyasal enerjiye dönüştürme konusunda önemli bir potansiyele sahip, temiz ve yenilenebilir bir enerji üretim süreci olarak bilinmektedir. TiO₂'in düşük maliyeti, toksik olmaması, kimyasal stabilitesi ve yüksek verimliliği nedeniyle fotokatalitik hidrojen üretiminde en çok dikkate alınan malzemelerden biridir. Fakat TiO₂'in fotokatalitik hidrojen üretimi aktivitesinin düşük olmasına sebep olan önemli dezavantajları vardır. Bu dezavantajlar, zayıf solar ışık absorpsiyonu ve foton ile üretilen elektron-boşluk çiftlerinin hızlı rekombinasyonudur. Geniş bant aralığı enerjisine sahip olan TiO₂ (yaklaşık 3,2 eV) güneş ışığı spektrumunun sadece yaklaşık %5'ini oluşturan UV ışınmasıyla aktif hale gelebilir. TiO₂'in performansını artırmak için kimyasal katkılama ve fiziksel iyon yerleştirme yöntemleriyle katyonlar, anyonlar, değerli metaller, metal oksitler ve metal sülfürler gibi bileşenlerin az miktarlarda eklenmesiyle görünür ışığa duyarlı hale getirilmesini ve daha düşük elektron-boşluk rekombinasyonu sağlayan birçok çalışma mevcuttur [1-5]. TiO₂'e katılan bu yapılardan metal sülfürler, dar bant boşlukları, geniş spesifik yüzey alanları ve uygun bant pozisyonları gibi hidrojen üretiminde ihtiyaç duyulan fotoelektronik özellikleri nedeniyle çok dikkat çekmektedir [6, 7]. TiO₂'in düşük bant aralıklı yarı iletken metal sülfürler ile kullanımı, yalnızca ışık absorpsiyon arttırmayı aynı zamanda foton ile üretilen yük taşıyıcılarının rekombinasyonunu baskılayarak hidrojen üretim miktarı açısından önemli sonuçlara ulaşılmasını sağlamıştır. CdS, MoS₂, CuS, PbS, Sn₂S, ZnS, Bi₂S₃, In₂S₃ ve FeS gibi birçok farklı ikili metal sülfürlerin TiO₂ ile kullanıldığında fotokatalitik hidrojen üretim performansını arttırdığı ortaya konmuştur [8]. ZnIn₂S₄, AgInS₂, CuInS₂ gibi üçlü metal sülfürler de genellikle yüksek aktiviteye, uygun kimyasal stabiliteye, esnek element bileşimlerine ve ayarlanabilir bir bant yapısına ve görünür ışık fotokatalize karşılık gelen bant aralığına sahiptir [9]. 2019 Yılında rapor edilen bir çalışmada TiO₂/ZnIn₂S₄ nanoyapılı heteroeklem kompozit yapısı ile tek başına

TiO₂'in ürettiğinden 26 kat fazla ve tek başına ZnIn₂S₄'ün ürettiğinden 2,3 kat fazla hidrojen üretimi sağlanmıştır [10]. Yine 2019'da %1CuInS₂/TiO₂ ile tek başına TiO₂ ile üretilenden 1,68 kat fazla olarak 785,4 µmol g⁻¹ h⁻¹ hidrojen üretimi kaydedilmiştir [7]. Literatürdeki bu çalışmaların yanısıra ikili metal sülfürlerin ve üçlü metal sülfürlerin TiO₂'e birlikte yüklenmesi ile oluşturulan kompozitlerin hidrojen üretiminde üstünlük sağladığı çalışmalar da dikkat çekmektedir. CuInS₂ kuantum noktaları/TiO₂/MoS₂ fotokatalizörü ile 1034 µmol g⁻¹ h⁻¹ hidrojen üretimi kaydedilmiştir [11].

Bütün bu bilgiler ışığında, bu çalışma kapsamında CuS/CuInS₂/TiO₂ fotokatalizörleri katı-katı sentez metodu ve yerinde sentez metodu olmak üzere iki farklı yöntemle sentezlenmiştir. Fotokatalizörlerin sentez yönteminin ve içerdikleri metal sülfür oranlarının hidrojen üretimine etkisi incelenmiştir.

II. MATERYAL VE YÖNTEM

2.1. TiO₂ Nanopartiküllerinin Sentezlenmesi

Belli oranlarda titanyum tetra-izopropoksit ve susuz propanol karıştırılarak A çözeltisi hazırlanır. Yine susuz propanol ve belli oranlarda deiyonize su ve asetik asit karıştırılarak B çözeltisi oluşturulur. Her iki çözelti de hazır edildikten sonra B çözeltisi, karıştırma altında damla damla A çözeltisine ilave edilerek şeffaf bir çözelti elde edilir. Çözelti birkaç saat sonra oda sıcaklığında süt kıvamına geldikten sonra birkaç saat daha beklenir ve jel kıvamı elde edilir. Daha sonra, çözücülerini uzaklaştırmak için 5 saat boyunca 120°C'de bir kurutma adımı gerçekleştirilir ve ardından agat havanda öğütülür. Nihai TiO₂ partiküllerine çökeltinin 500°C'de 2 saat boyunca kalsine edilmesiyle ulaşılır.

2.2. Katı-katı Sentez Metodu ile CuS/CuInS₂/TiO₂ Hazırlanması

Öncelikle CuS, tek başına hidrotermal yöntemle çöktürülerek sentezlenir. Bakır nitrat trihidrat (Cu(NO₃)₂·3H₂O) ve tityürenin (CH₄N₂S) 1:1 oranında alınarak deiyonize suda çözülür. Çözelti teflon kaplamalı paslanmaz çelik otoklava aktarılır. Otoklav etüvde 180°C sıcaklıkta, 5 saat boyunca bekletilir. Otoklav doğal olarak oda sıcaklığına geldikten sonra içinde CuS partiküllerinin çöktüğü gözlemlenir, çökelti filtre edilerek ayrılır ve defalarca deiyonize su ile yıkanır. 80°C'de kurutulur.

Ayrıca CuInS₂, tek başına hidrotermal yöntemle çöktürülerek sentezlenir. Bakır nitrat trihidrat (Cu(NO₃)₂·3H₂O), indiyum (III) klorit tetrahidrat (InCl₃·4H₂O) ve tityürenin (CH₄N₂S) sırasıyla 1:1:2 oranında alınarak deiyonize suda çözülür. Çözelti teflon kaplamalı paslanmaz çelik otoklava aktarılır. Otoklav etüvde 180°C sıcaklıkta, 5 saat boyunca bekletilir. Otoklav doğal olarak oda sıcaklığına geldikten sonra içinde partiküllerinin çöktüğü gözlemlenir, çökelti filtre edilerek ayrılır ve defalarca

deiyonize su ile yıkanır. 80°C'de kurutulur. CuS/CuInS₂/TiO₂ fotokatalizörleri katı halde karışım olarak ile bir araya getirilmiştir [25]. CuS ve CuInS₂ oranları kütlece CuS (%3) ve CuInS₂ (%5, %10 ve %20) ve geri kalan kısım TiO₂ olacak şekilde tartılarak birleştirilip agat havanda 2 saat süre ile öğütülmüştür. Toz karışımın üstüne birkaç damla etanol ilave edilerek toz numunenin daha iyi karışması sağlanmıştır ve elde edilen numune tekrar kurutulmuştur. Numunelerin isimlendirilmesi sistemi takip eden şekilde yapılmıştır: katı-katı sentez metodu ile hazırlanan %3CuS/%20CuInS₂/TiO₂ numunesi 3CS20CIST(K) olarak kodlanmıştır.

2.3. Yerinde Sentez Metodu ile CuS/CuInS₂/TiO₂ Hazırlanması

Yerinde sentez metodu ile CuS/CuInS₂/TiO₂ hazırlanmasında, önceden hazırlanmış TiO₂ nanopartikülleri, uygun oranlarda bakır nitrat trihidrat (Cu(NO₃)₂·3H₂O), indiyum (III) klorit tetrahidrat (InCl₃·4H₂O) ve tityürene (CH₄N₂S) başlangıç maddeleri katılarak su içinde süspansiyon edilir. Süspansiyon teflon kaplamalı paslanmaz çelik otoklava aktarılır. Otoklav etüvde 180°C sıcaklıkta, 5 saat boyunca bekletilir. Otoklav doğal olarak oda sıcaklığına geldikten sonra içindeki çökelti filtre edilerek ayrılır ve defalarca deiyonize su ile yıkanır. 80°C'de kurutulur.

Fotokatalizörler CuS ve CuInS₂ oranları kütlece CuS (%3) ve CuInS₂ (%5, %10 ve %20) ve geri kalan kısım TiO₂ olacak şekilde hazırlanmıştır. Numunelerin isimlendirilmesi sistemi takip eden şekilde yapılmıştır: yerinde sentez metodu ile hazırlanan %3CuS/%20CuInS₂/TiO₂ numunesi 3CS20CIST(Y) olarak kodlanmıştır.

2.4. Fotokatalitik Hidrojen Üretimi Testleri

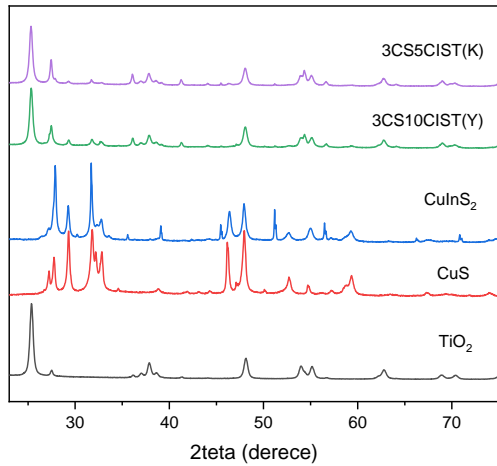
0,25M Na₂S - 0,35M Na₂SO₃ Çözeltisi kuvars tabanlı reaktöre yüklenerek fotokatalitik hidrojen üretim reaksiyonları gerçekleştirilmiştir. Her deneyde 50 mg fotokatalizör ve 150 ml reaktan çözeltisi kullanılmıştır. Işık kaynağı olarak HAL-320 Compact Xenon Işık Kaynağı Güneş Simülatörü kullanılmış ve ışık yoğunluğu 1000 W m⁻² olarak ayarlanmıştır. Elde edilen gaz miktarını ölçmek için bir su manometresi kullanılmıştır. Toplanan gaz, GC (Agilent 6890) ile analiz edilmiştir; H₂ kalitatif olarak tanımlanmıştır.

III. SONUÇLAR VE TARTIŞMA

3.1. Karakterizasyon

Sentezlenen fotokatalizörlerin fazları X-ışını kırınımı difraktometrisi analizi ile tespit edilmiştir; Şekil 1'de X-ışını kırınım desenleri görülmektedir. Sentezlenen TiO₂ örneğinin X-ışını kırınım diyagramında 25,40°, 38,00°, 48,23° ve 55,30° açılarında görülen karakteristik pikler sırasıyla anataz fazının (101), (112), (200) ve (211) düzlemlerine karşılık gelmektedir [7]. Ayrıca 27,65°, 54,17°, 63,00°, 69,16° ve 70,64° açılarında görülen pikler ise sırasıyla rutil fazının (110), (211), (002), (301) ve (112) düzlemlerine karşılık

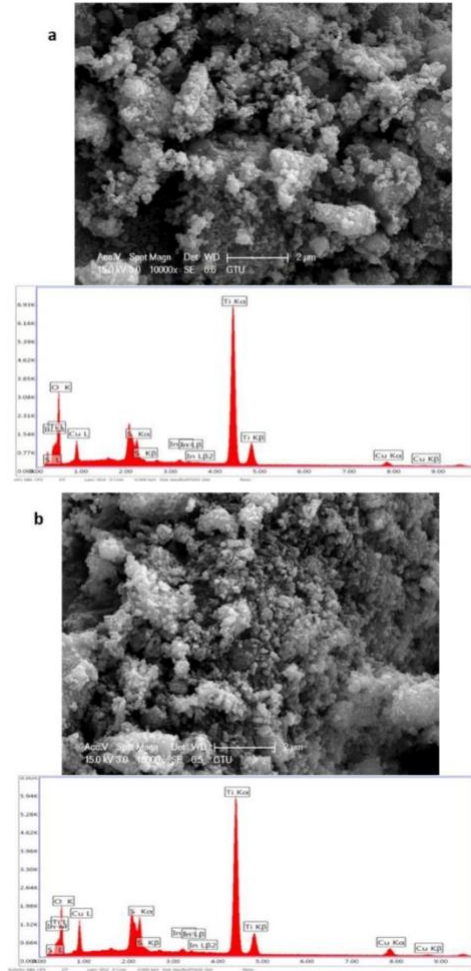
gelmektedir [12]. Anataz ve rutil fazlarının bağıl ağırlıklarını tespit etmek için Spurr Myers denklemleri kullanılmıştır [12, 13]. Bu çalışmada sentezlenen TiO₂ için %85,5 anataz ve %14,4 rutil fazı bulunduğu tespit edilmiştir. Sentezlenen CuS örneğinin X-ışını kırınım diyagramında 27,34°, 29,46°, 31,82°, 32,10° ve 48,11° açılarında görülen karakteristik pikler sırasıyla kovelit fazının (101), (102), (103), (006) ve (110) düzlemlerine karşılık gelmektedir [14, 15]. Sentezlenen CuInS₂ örneğinin X-ışını kırınım diyagramında 27,86°, 31,70°, 47,90° ve 56,42° açılarında görülen karakteristik pikler sırasıyla (112), (200), (220) ve (312) düzlemlerine karşılık gelmektedir [16]. Katı-katı sentez metodu ile sentezlenen %3CuS/%5CuInS₂/TiO₂ örneğinin ve yerinde sentez metodu ile sentezlenen %3CuS-%10CuInS₂-TiO₂ örneğinin X-ışını kırınım diyagramında görülen ana pikler TiO₂ fazına ait olmakla birlikte 29,40° ve 31,80° açılarında görülen küçük pikler CuS varlığını göstermektedir; 56,60° açısında görülen pik ise CuInS₂ varlığını göstermektedir.



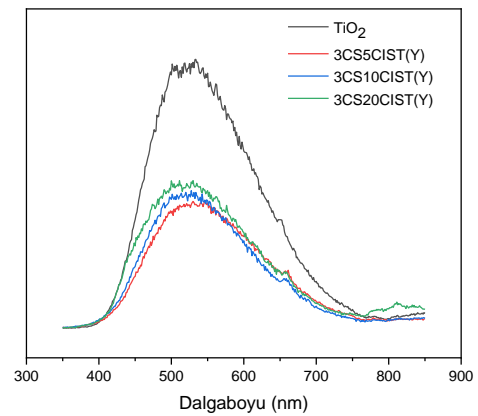
Şekil 1. Fotokatalizör numunelerinin X-ışını kırınım desenleri

Şekil 2’de katı-katı sentez metodu ile sentezlenen %3CuS/%5CuInS₂/TiO₂ örneğinin ve yerinde sentez metodu ile sentezlenen %3CuS/%10CuInS₂/TiO₂ örneğinin SEM-EDS analiz sonuçları verilmiştir. Fotokatalizördeki elementel Cu, In, S, Ti, O analiz sonuçları XRD sonuçlarını destekler niteliktedir. SEM görüntüleri incelendiğinde katı-katı sentez metodu ile hazırlanan örnekte topaklanmanın daha fazla olduğu gözlemlenmiştir, yerinde sentez metodu ile hazırlanan örnekte daha homojen bir dağılımdan bahsedilebilir. Şekil 3’te yerinde sentez metodu ile sentezlenen CuS/CuInS₂/TiO₂ örneklerinin fotoluminesans analizi sonuçları verilmiştir. En yüksek PL şiddeti tek başına TiO₂ örneğine aittir; CuS/CuInS₂ katkısı yapıldığında PL şiddetinin düştüğü gözlemlenmiştir. Böylelikle CuS/CuInS₂ katkısı ile elektron – boşluk çiftlerinin rekombinasyon hızının düşmesi sağlanmıştır. Fotokatalizördeki CuInS₂ oranının artmasıyla PL

şiddeti de artmıştır; dolayısıyla CuInS₂ oranı en az olan %5CuInS₂ içeren 3CS5CIST(Y) örneği en düşük elektron – boşluk rekombinasyon hızına sahip olan örnek olarak belirlenmiştir.



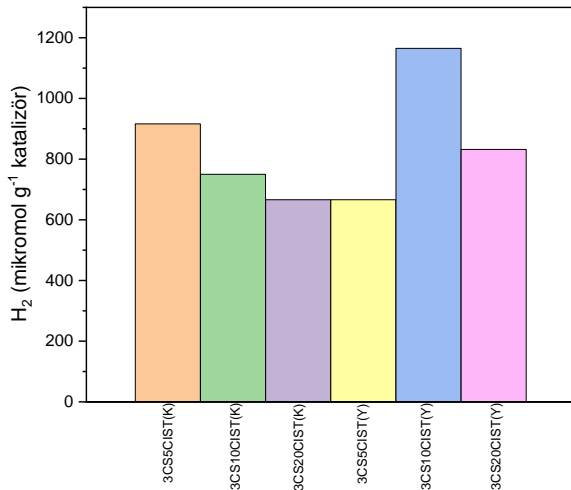
Şekil 2. (a) 3CS5CIST(K) örneğinin ve (b) 3CS10CIST(Y) örneğinin SEM-EDS analiz sonuçları



Şekil 3. Yerinde sentez metodu ile hazırlanan CuS/CuInS₂/TiO₂ fotokatalizör örneklerinin fotoluminesans spektrumları

3.2. Fotokatalitik Aktivite Sonuçları

Şekil 4’de iki farklı sentez metodu ile hazırlanan fotokatalizörlerin 8 saat reaksiyon sonundaki hidrojen üretimi sonuçları verilmiştir. Katı-katı sentez metodu ile hazırlanan örneklerde en iyi sonucu veren örnek 916 $\mu\text{mol g}^{-1}$ kat. hidrojen üretimi sağlayan %3CuS/%5CuInS₂/TiO₂ (K) örneğidir. Fotoluminesans analiz sonuçlarını destekler nitelikte fotokatalizördeki kütlece %5 in üzerinde CuInS₂ oranı arttıkça fotokatalitik aktivite düşmüştür. Katı-katı sentez yönteminde kullanılacak maksimum CuInS₂ oranı %5 olabilir. Yerinde sentez metodu ile hazırlanan örneklerde en iyi sonucu veren örnek 1165 $\mu\text{mol g}^{-1}$ kat. hidrojen üretimi sağlayan %3CuS/%10CuInS₂/TiO₂ (Y) örneği olmuştur. Yerinde sentez metodu ile daha homojen bir yapı sağlandığından bu fotokatalizör setinde maksimum fotokatalitik hidrojen üretimi bakımından optimum CuInS₂ oranı %10 olarak bulunmuştur.



Şekil 4. Farklı iki sentez yöntemiyle hazırlanmış CuS/CuInS₂/TiO₂ fotokatalizör örnekleri ile 8 saat reaksiyon sonrasında elde edilen hidrojen miktarları

IV. SONUÇ

Fotokatalitik hidrojen üretimi, solar ışığın kullanıldığı fotokatalitik bir süreçle suyun parçalanması yoluyla hidrojen gazının üretilmesidir. Bu çalışmada TiO₂ bazlı fotokatalizörler kullanılmıştır; ancak TiO₂ yarı iletkeninin düşük solar ışık emilimi ve elektron-boşluk çiftlerinin hızlı rekombinasyonu nedeniyle, bu fotokatalizöre aktiviteyi arttırmak amacıyla CuS ve CuInS₂ metal sülfürleri iki farklı sentez metodu ile eklenmiştir. Yapılan denemeler sonucunda en yüksek hidrojen üretim miktarı yerinde sentez metodu ile hazırlanan %3CuS/%10CuInS₂/TiO₂ fotokatalizörü ile 1165 $\mu\text{mol H}_2 \text{ g}^{-1}$ kat. olarak bulunmuştur.

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On a Simple Characterization of Conformally Flat 4-Dimensional Spaces of Neutral Signature

4–Boyutlu Nötr Metrik İşaretli Konformal Düz Uzayların Basit Bir Karakterizasyonu Üzerine

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Abstract

In this work, the full characterization of 4-dimensional conformally flat spaces of neutral signature is given by using methods based on holonomy structure. Possible holonomy types are obtained for the spaces in question and several remarks are made. Various examples are presented related to this investigation.

Keywords: Weyl conformal curvature tensor, Conformally flat space, Neutral signature, Holonomy

I. INTRODUCTION

Conformally flat spaces are one of the important research topics not only in differential geometry but also in physics. Such spaces are commonly used in general relativity, for example, describing Friedmann–Lemaître–Robertson–Walker metric. The classification of conformally flat spaces has been a subject of interest for many years and so it is not possible to mention about all these works (among them see, e.g., [1-9]). Our goal in the present study is to provide a systematic examination of holonomy types in 4 –dimensional conformally flat spaces admitting a metric of signature $(+, +, -, -)$ referred to as *neutral signature*. Such studies for Lorentz and positive definite signatures have been carried out by Hall and Lonie in [3] and by Hall in [4], respectively. Adding to these works, the present paper is intended to explore the problem further for neutral signature which is the most complicated metric signature as there are orthogonal null vectors that are independent and there are pairs of timelike 2 –spaces that are orthogonal. The holonomy algebras for 4 –dimensional spaces of neutral signature are known and the labelings given in [10] will be used in the present work.

The rest of the paper is organized as in the following: Some basic notions of the study and the description of holonomy groups of 4 –dimensional spaces of signature $(+, +, -, -)$ are recalled in Section II for further consideration. The main result of the paper is presented in Section III. To illustrate the results of the study, several examples are given in Section IV. Finally, further remarks and conclusion are discussed in Section V.

II. PRELIMINARIES

Let \mathcal{M} be a 4 –dimensional manifold such that it is smooth, connected, simply connected and equipped with a metric g being smooth and having neutral signature $(+, +, -, -)$. The Levi-Civita connection of g will be symbolised by ∇ . Let the notations W , $Riem$, $Ricc$ and r respectively represent the Weyl conformal curvature tensor, Riemann curvature tensor, Ricci tensor and scalar curvature of \mathcal{M} . We shall assume that $Riem$ is not identically zero on \mathcal{M} by saying that the structure (\mathcal{M}, g) is not flat. The Weyl curvature tensor of type $(0,4)$ is given by

$$W_{ijkh} = R_{ijkh} + \frac{1}{2}(g_{jk}R_{ih} - g_{jh}R_{ik} + g_{ih}R_{jk} - g_{ik}R_{jh}) + \frac{r}{6}(g_{ik}g_{jh} - g_{ih}g_{jk}), \quad (1)$$

where W_{ijkh} , $R_{ijkh} \equiv g_{im}R^m{}_{jkh}$ and $R_{ik} \equiv R^j{}_{ijk}$ are the components of W , $Riem$ and $Ricc$, respectively. If W vanishes in $\dim \mathcal{M} \geq 4$, then (\mathcal{M}, g) is named as *conformally flat* meaning that there is a neighbourhood \mathcal{V} of each $p \in \mathcal{M}$ on which g , restricted to \mathcal{V} is conformal to a flat metric.

If \mathcal{M} is Ricci-flat, in other words, if $Ricc \equiv 0$ on \mathcal{M} , one can observe from Equation (1) that $W \equiv Riem$. For this reason, we shall study conformally flat spaces provided that \mathcal{M} is not Ricci-flat. Let $\mathcal{T}_p\mathcal{M}$ be the tangent space of \mathcal{M} at p and $v \cdot \omega$ be the inner product of tangent vectors $v, \omega \in \mathcal{T}_p\mathcal{M}$. A non-zero tangent vector $\omega \in \mathcal{T}_p\mathcal{M}$ is named as *spacelike*, *timelike*, *null* (or *lightlike*) if $\omega \cdot \omega > 0$, $\omega \cdot \omega < 0$, $\omega \cdot \omega = 0$ hold, respectively. For neutral metric, we can set up a (pseudo)-orthonormal basis of $\mathcal{T}_p\mathcal{M}$ shown as $\{x, y, s, t\}$ which satisfies $x \cdot x = y \cdot y = 1$ (x, y being spacelike) and $s \cdot s = t \cdot t = -1$ (s, t being timelike). Besides, an associated null basis $\{l, n, L, N\}$ can be constructed in the way that $l = \frac{1}{\sqrt{2}}(x + t)$, $n = \frac{1}{\sqrt{2}}(x - t)$, $L = \frac{1}{\sqrt{2}}(y + s)$, $N = \frac{1}{\sqrt{2}}(y - s)$ where the relations $l \cdot n = 1$ and $L \cdot N = 1$ are satisfied and the other products between these null vectors are all zero. Moreover, a 2-dimensional subspace \mathcal{U} , named as a 2-space, of $\mathcal{T}_p\mathcal{M}$ can be classified by the following items: (i) *spacelike*: every non-zero element of \mathcal{U} is timelike or every non-zero element of \mathcal{U} is spacelike (ii) *timelike*: \mathcal{U} involves precisely two, null 1-dimensional subspaces that are referred to as directions (iii) *null*: \mathcal{U} involves precisely one null direction (iv) *totally null*: every non-zero element of \mathcal{U} must be null and so any two non-zero elements must be orthogonal. Now, let $\Lambda_p\mathcal{M}$ be the space of all bivectors at the point p . A non-zero bivector F with components $F^{ij} (= -F^{ji})$ has even rank which can be either 2 or 4. The case when the rank of F equals 2, it is referred to as a *simple bivector* and in the other case, it is named as a *non-simple bivector*. In the former case it can be expressed as $F^{ij} = 2v^{[i}\omega^{j]}$ for $v, \omega \in \mathcal{T}_p\mathcal{M}$ in which square brackets surrounding indices are used to indicate the ordinary anti-symmetrisation of the indices. In that case, the *blade* of F , which will be written as $v \wedge \omega$, is the 2-space generated by $v, \omega \in \mathcal{T}_p\mathcal{M}$. If the blade of F is *spacelike* (in order of, *timelike*, *null* or *totally null*) 2-space at p as defined above, then (the simple bivector) F is named as *spacelike* (in order of, *timelike*, *null* or *totally null*). Note that F is simple including $0 \neq v \in \mathcal{T}_p\mathcal{M}$ in its blade provided that $F_{[ij}v_{h]} = 0$.

It is also remarked that one can define the *curvature map* denoted by $\tilde{f}: \Lambda_p\mathcal{M} \rightarrow \Lambda_p\mathcal{M}$ given by $F \rightarrow R^i{}_{jkh}F^{kh}$, [11]. On the other hand, it is advantageous to express the decomposition of *Riem* as follows (see, e. g., [11]):

$$R_{ijkh} = W_{ijkh} + E_{ijkh} + \frac{r}{6}G_{ijkh} \tag{2}$$

where

$$E_{ijkh} = \tilde{R}_{i[k}g_{h]j} + \tilde{R}_{j[h}g_{k]i}, \quad G_{ijkh} = g_{i[k}g_{h]j},$$

$$\tilde{R}_{ij} = R_{ij} - \frac{r}{4}g_{ij} = E^m{}_{imj}. \tag{3}$$

It is clear from Equation (3) that the tensor with components are \tilde{R}_{ij} is tracefree and $E = 0 \Leftrightarrow \tilde{R} = 0 \Leftrightarrow R_{ij} = \frac{r}{4}g_{ij}$ meaning that (\mathcal{M}, g) is an *Einstein manifold*.

Let Φ be the holonomy group of (\mathcal{M}, g) which is a Lie group formed by the collection of all linear isomorphisms on $\mathcal{T}_p\mathcal{M}$ arising from the parallel transfer of each tangent vector of $\mathcal{T}_p\mathcal{M}$ around a smooth, closed curve c at p (for details on holonomy group, see [12]).

When the metric is of neutral signature, the Lie algebra of Φ is subalgebra of $o(2,2)$, which will be denoted by ϕ . By using the matrix characterization of this algebra, one achieves a bivector representation of ϕ for this signature. The labelings that were tabulated in [10] are utilized in Table 1 containing exactly 23 types. All these holonomy types are shown in columns 1 and 3 together with the generators in bivector representation respectively indicated in columns 2 and 4. The dimension of each holonomy type can easily be seen from its label. Note that these holonomy algebras are the ones arising for a metric connection and they are not all of the subalgebras of $o(2,2)$.

It is noted that one can define 3-dimensional subspaces of $\Lambda_p\mathcal{M}$ denoted by $\overset{+}{S} = \{F \in \Lambda_p\mathcal{M}: F^* = F\}$ and $\overset{-}{S} = \{F \in \Lambda_p\mathcal{M}: F^* = -F\}$ where $*$ is the Hodge duality operator. The dual of $F \in \Lambda_p\mathcal{M}$, shown as F^* , is described by $F^*_{ij} = \frac{1}{2}\epsilon_{ijkh}F^{kh}$ with $\epsilon_{ijkh} = \sqrt{\det g} \delta_{ijkh}$ being the classical pseudo-tensor, δ being the standard alternating symbol. One has $F^{**} = F$ for neutral signature. In Table 1, $\overset{+}{B} = \langle l \wedge n - L \wedge N, l \wedge N \rangle$, $\overset{-}{B} = \langle l \wedge n + L \wedge N, l \wedge L \rangle$ where the symbol $\langle \rangle$ denotes a spanning set. Furthermore, $\eta, \zeta \in \mathbb{R}$ and $\eta \neq \pm\zeta$ are valid for types 2(h) and 3(d) whilst for type 2(j), both of them are non-zero. A basis of $\overset{+}{S}$ is $\{l \wedge N, l \wedge n - L \wedge N, n \wedge L\}$.

An essential concept in the theory of holonomy is the Ambrose-Singer theorem [13] which states that if one fixes $p \in \mathcal{M}$ and for arbitrary $p' \in \mathcal{M}$ calculates the range space of the curvature map, $Rg(\tilde{f})$, and parallel transports the range space to p throughout a curve $\alpha: p' \rightarrow p$ and carry on doing this for every p' and α , the collection of bivectors acquired at p generates ϕ .

Table 1. Holonomy types relevant for neutral signature are indicated

Type	Generators	Type	Generators
1(a)	$l \wedge n$	2(j)	$l \wedge N, \eta(l \wedge n - L \wedge N) + \zeta(l \wedge L)$
1(b)	$x \wedge y$	2(k)	$l \wedge y, l \wedge n$ (or $l \wedge s, l \wedge n$)
1(c)	$l \wedge y$ (or $l \wedge s$)	3(a)	$l \wedge N, l \wedge n, L \wedge N$
1(d)	$l \wedge N$	3(b)	$l \wedge N, l \wedge n - L \wedge N, l \wedge L$
2(a)	$\overset{+}{B}$	3(c)	$x \wedge y, x \wedge t, y \wedge t$ (or $x \wedge s, x \wedge t, s \wedge t$)
2(b)	$l \wedge n, L \wedge N$	3(d)	$l \wedge N, l \wedge L, \eta(l \wedge n) + \zeta(L \wedge N)$
2(c)	$l \wedge n - L \wedge N, l \wedge L + n \wedge N$	4(a)	$\overset{+}{S}, l \wedge n + L \wedge N$
2(d)	$l \wedge n - L \wedge N, l \wedge L$	4(b)	$\overset{+}{S}, l \wedge L + n \wedge N$
2(e)	$x \wedge y, s \wedge t$	4(c)	$\overset{+}{B}, \overset{-}{B}$
2(f)	$l \wedge N + n \wedge L, l \wedge L$	5	$\overset{+}{S}, \overset{-}{B}$
2(g)	$l \wedge N, l \wedge L$	6	$o(2,2)$
2(h)	$l \wedge N, \eta(l \wedge n) + \zeta(L \wedge N)$		

Then, $Rg(\tilde{f})$ is a subspace of ϕ and the Riemann curvature tensor may always be expressed as a symmetrized sum of products of bivectors of ϕ (see, [11]).

Finally, it will be useful to give a remark on parallel and recurrent vector fields. A vector field v is said to be *recurrent* on an open and connected subset $\mathcal{U} \neq \emptyset$ of \mathcal{M} if $\nabla v = q \otimes v$ for some 1-form q . If q vanishes on \mathcal{U} , in other words, the case when $\nabla v = 0$ on \mathcal{U} , v is named as *parallel* on \mathcal{U} . If v is parallel, it is either non-null everywhere or null everywhere.

In the sense of holonomy theory, if $0 \neq v \in \mathcal{T}_p\mathcal{M}$ is an eigenvector of *all* bivectors of ϕ , then on some neighbourhood of $p \in \mathcal{M}$, there exists a smooth vector field which is recurrent and whose value at p is v (for details, see, e.g., [11]). Further, if every eigenvalue of v is zero for all $F \in \phi$, then it is eligible as a parallel vector field. Therefore, as \mathcal{M} is simply connected, all recurrent and parallel vector fields (if any) can be detected by considering Table 1 for every holonomy type (see [14]).

For instance, for holonomy type 3(c) with its one of the generators presented in Table 1, it can be checked that $\nabla s = 0$ (or $\nabla y = 0$), in other words, s (or y) causes a parallel vector field whilst for type 4(c), l turns out a recurrent vector field on \mathcal{U} .

III. THE MAIN RESULT

Let us now look for the potential holonomy types for conformally flat spaces with a metric of neutral signature. Assume that (\mathcal{M}, g) is conformally flat (but it is neither flat nor Ricci-flat). For this case, one gets from Equation (1) that

$$R_{ijkh} = \frac{1}{2}(g_{jh}R_{ik} - g_{ih}R_{jk} + g_{ik}R_{jh} - g_{jk}R_{ih}) - \frac{r}{6}(g_{ik}g_{jh} - g_{ih}g_{jk}). \tag{4}$$

First of all, assume that \mathcal{M} contains a non-zero parallel vector field v . In this case, the Ricci identity implies that $R_{ijkh}v^h = 0$ and thus, $R_{jh}v^h = 0$. Contracting Equation (4) by v^jv^h and using the Ricci identity, we obtain

$$\frac{1}{2}R_{ik}v_hv^h + \frac{r}{6}(v_iv_k - g_{ik}v_hv^h) = 0. \tag{5}$$

Case 1: If v is null, then we get from Equation (5) that $r = 0$ and vice versa. Contracting Equation (4) by v^h , one can get the following equation:

$$R_{ik}v_j = R_{jk}v_i. \tag{6}$$

The condition (6) is equivalent to $Ricc = \lambda(v \otimes v)$ for some nowhere zero function $\lambda: \mathcal{M} \rightarrow \mathbb{R}$, where the Segre type of $Ricc$ is $\{(211)\}$ with zero eigenvalue (for the Segre classification, see, e. g., [11, 14]). As $r = 0$,

we also obtain from Equation (2) that $Riem = E$. Moreover, as the tensor E has the duality properties $*E_{ijkh} = -E^*_{ijkh}$, we have $*R_{ijkh} = -R^*_{ijkh}$. It then follows that if a bivector F is in the range of the curvature map, so is its dual F^* . Plugging $Ricc$ into Equation (4), a direct computation shows that $Riem$ can be written in terms of a pair of totally null bivectors whose blades contain v . More explicitly, for that case the causal character of the bivectors in $Riem$ is preserved by parallel transporting them from each $p' \in \mathcal{M}$ to a fixed point $p \in \mathcal{M}$ and considering the Ambrose-Singer theorem (see Section II). Moreover, since v is parallel, it remains as null under parallel translation and stays in the blades of these bivectors. By the aid of Table 1, it can be seen that Φ must be of type $2(g)$ admitting l as a parallel vector field as this type is generated by the bivectors $l \wedge N$ and $l \wedge L$ for both of which l is an eigenvector corresponding to the zero eigenvalue.

Case 2: Assume that v is non-null. Then $v_k v^k \neq 0$ and it can be deduced from Equation (5) that $Ricc$ takes the following form:

$$R_{ij} = \frac{r}{3} \left(g_{ij} - \frac{1}{v_k v^k} v_i v_j \right) \tag{7}$$

where the Segre type of $Ricc$ is $\{1(111)\}$ and $r \neq 0$. Let F be an arbitrary bivector at p satisfying the condition $F_{ij} v^j = 0$. In this case, putting Equation (7) into (4) and multiplying the resulting equation by F^{kh} , we get that $R_{ijkh} F^{kh} = \frac{r}{3} F_{ij}$. It then follows that F is an eigenvector of the Riemann curvature tensor corresponding to eigenvalue $r/3$. Moreover, such bivectors must be simple and they form a 3-dimensional subspace of $\Lambda_p \mathcal{M}$ such that the dual subspace to it is generated by three bivectors each of which annihilates $Riem$ and that they are independent, simple, and v is in their blades. This yields that the rank of $Riem$ is 3 at p . Moreover, as the holonomy admits a parallel vector field v which is non-null, the dimension of the holonomy algebra is at most 3. Combining these findings, it is achieved that $\dim \phi = 3$. Hence, it can be observed from Table 1 that Φ must be of type $3(c)$ as for this type the basis members, as being simple bivectors, are $F_1 \equiv x \wedge y$, $F_2 \equiv x \wedge t$, $F_3 \equiv y \wedge t$ (or $G_1 \equiv x \wedge s$, $G_2 \equiv x \wedge t$, $G_3 \equiv s \wedge t$) and they have a common annihilator s (or y) which is timelike (or spacelike) and parallel. Note that if $Ricc$ takes the form (7), then such a manifold is known as *quasi-Einstein manifold* in the literature.

Next, let \mathcal{M} contains a null vector field v which is recurrent, more explicitly, for some 1-form q , one has $\nabla v = q \otimes v$. From the Ricci identity, we get the following:

$$\begin{aligned} \nabla_k \nabla_j v_i - \nabla_j \nabla_k v_i &= v^h R_{hijk} \\ &= v_i (\nabla_k q_j - \nabla_j q_k). \end{aligned} \tag{8}$$

By using the identity $R_{h[ijk]} = 0$ and Equation (8), one gets that the bivector $F_{jk} \equiv \nabla_k q_j - \nabla_j q_k$ is simple whose blade contains v . In this case, a contraction of Equation (4) with $v^i v^k$ shows that $r \equiv 0$ for (\mathcal{M}, g) and so $Riem = E$ and the curvature range is *dual invariant*. From Table 1, potential holonomy types admitting (real or complex) recurrent vector fields are $1(a)$, $1(b)$, $2(a)$, $2(b)$, $2(c)$, $2(d)$, $2(e)$, $2(f)$, $2(h)$, $2(j)$, $2(k)$, $3(a)$, $3(b)$, $3(d)$ ($\eta \neq 0$) and $4(c)$. However, (\mathcal{M}, g) cannot be conformally flat for $1(a)$ and $1(b)$ as for these types $r \neq 0$ and the condition (4) forces $Riem$ to be zero. Moreover, $G = l \wedge n - L \wedge N \in \overset{+}{S}$, $H = l \wedge N \in \overset{+}{S}$ generate the holonomy type $2(a)$ yielding the recurrence of l and N . But it was proven in [14] that (\mathcal{M}, g) is automatically Ricci-flat, i.e., $Ricc \equiv 0$. Thus, the condition (4) gives flatness and so $2(a)$ is not possible for a conformally flat space according to our assumption. For holonomy types $2(b)$ and $2(e)$, the cross term in $Riem$ vanishes by considering the identity $R_{i[jkh]} = 0$ and so, $Riem$ is of the form $R_{ijkh} = \psi F_{ij} F_{kh} + \rho F_{ij} F_{kh}^*$ for some smooth functions ψ , ρ and a dual pair (F, F^*) . For these types, the condition (4) is satisfied if $\psi = -\rho$. For the type $2(c)$ where ϕ is generated by $l \wedge L + n \wedge N \in \overset{+}{S}$, $l \wedge n - L \wedge N \in \overset{+}{S}$, conformal flatness is possible if the coefficient of cross term in $Riem$ is not zero and other coefficients are zero. In this case, $R_{ij} = \vartheta (l_i L_j + L_i l_j - n_i N_j - N_i n_j)$ for a nowhere zero function ϑ and $r = 0$ so that $Ricc$ has a special Segre type denoted by $\{(zz)(\bar{z}\bar{z})\}$ (complex eigenvalues with degeneracies) occurring only for neutral signature. On the other hand, considering that l and L are recurrent for the type $2(d)$ and applying Equations (4) and (8), it is obtained that (\mathcal{M}, g) could be conformally flat if the coefficient of cross term, say ρ , in $Riem$ is not zero and other coefficients are zero where $Ricc$ is of the form $R_{ij} = -2\rho (l_i L_j + L_i l_j)$ (Segre type $\{(22)\}$ with eigenvalue zero). Analogously, for holonomy type $2(f)$, conformal flatness is possible so that $Ricc$ is of type $\{(22)\}$ having zero eigenvalue. Considering the generators from Table 1, it can be seen that holonomy type $2(h)$ admits recurrent vector field(s) but it does not give rise to a conformally flat space as the conditions $\eta \neq \pm \zeta$ and Equation (4) force $Riem$ to be zero. Similar comments can be made for types $2(j)$ and $2(k)$. For types $3(a)$, $3(b)$ and $4(c)$ admitting recurrent vector fields (which are l, N for $3(a)$, l for $3(b)$ and $4(c)$), the condition (4) is satisfied when $r = 0$ as for these cases, by taking into account the generators presented in Table 1 it yields that if $F \in \Lambda_p \mathcal{M}$ is in the range of the curvature map, so is its dual F^* . For $3(d)$ ($\eta \neq 0$), the condition (4) imposes $Rg(\tilde{f})$ to be generated by the bivectors $l \wedge N$ and $l \wedge L$ which gives rise to the contradiction by using the Ambrose-Singer theorem. Furthermore, there can be conformally flat spaces which admit no parallel or

recurrent vector fields. The above argument shows that if the space is conformally flat with $r = 0$, the range of $Riem$ is dual invariant. Therefore, considering the Ambrose-Singer theorem one also gets potential types $4(a), 4(b), 5$ satisfying Equation (4) as the generators of these types are members of either \bar{S} or \bar{S}^+ . In conclusion, the following result is proven:

Theorem 1. *Let \mathcal{M} be a connected and simply connected 4 –dimensional space admitting a metric g of neutral signature. Suppose that (\mathcal{M}, g) is not Ricci-flat. If (\mathcal{M}, g) is a conformally flat space, then the holonomy group Φ of \mathcal{M} is one of the types $2(b), 2(c), 2(d), 2(e), 2(f), 2(g), 3(a), 3(b), 3(c), 4(a), 4(b), 4(c), 5$ or 6 .*

It will be useful to interpret what is proved in Theorem 1 and compare the results achieved for the neutral signature with the case when g has Lorentz signature $(+, +, +, -)$. Certain remarks and interpretations can be given as follows:

Remark 1. For the Lorentz case, a bivector and its dual bivector must be independent, but this is not true for neutral signature (for example, one can consider the members of \bar{S}^+ and \bar{S}). This implies that for Lorentz signature, if the space is conformally flat with $r = 0$, $\dim\phi$ must be even. Nevertheless, it is *false* for neutral signature as proved in Theorem 1. For instance, 3 –dimensional types $3(a)$ and $3(b)$ yield recurrent vector fields and ϕ is dual invariant but it is not even-dimensional for these types.

Remark 2. It can be observed from Theorem 1 that even if no parallel or recurrent vector fields arise in the holonomy, (\mathcal{M}, g) could be conformally flat, e.g., the case when Φ is one of the types $4(a), 4(b)$ or 5 .

Remark 3. For a conformally flat space of dimension $n \geq 4$, it is known that the Cotton tensor whose components are given by

$$C_{jkh} = \nabla_h R_{jk} - \nabla_k R_{jh} + \frac{1}{2(n-1)} (\nabla_k r g_{jh} - \nabla_h r g_{jk}) \tag{9}$$

vanishes. The steps and calculations carried out in the proof of Theorem 1 indicated that r is zero unless Φ is one of the holonomy types $3(c)$ or 6 . It then follows from Equation (9) that in cases where the potential holonomy types $2(b), 2(c), 2(d), 2(e), 2(f), 2(g), 3(a), 3(b), 4(a), 4(b), 4(c)$ and 5 satisfy the conformally flat condition (4), $Ricc$ must be a Codazzi tensor, i.e., the condition $\nabla_h R_{jk} = \nabla_k R_{jh}$ holds.

Finally, suppose that (\mathcal{M}, g) is a proper Einstein space, in other words, $Ricc = \xi g$ where $0 \neq \xi = \frac{r}{4}$, and $E = 0$ in Equation (3). Then, Segre type of $Ricc$ is $\{(1111)\}$, r is constant and $\nabla Ricc = 0$. In this case, it

was proven in [14] that Φ could be one of the types $2(b), 2(c), 2(e), 2(f), 3(a), 3(b), 4(a), 4(b), 4(c), 5$ or 6 . Moreover, if the space is also conformally flat, then it is clear from Equation (4) that $\nabla Riem = 0$ and it has constant sectional curvature. Bringing together the aforementioned result and Theorem 1, the following corollary can be stated:

Corollary 1. *Let \mathcal{M} be a connected and simply connected 4 –dimensional proper Einstein space equipped with a neutral metric g . If (\mathcal{M}, g) is also a conformally flat space, then it has constant sectional curvature and possible holonomy types could be $2(b), 2(c), 2(e), 2(f), 3(a), 3(b), 4(a), 4(b), 4(c), 5$ or 6 .*

IV. EXAMPLES

This section is devoted to give some examples of conformally flat 4 –dimensional spaces of neutral signature.

Example 1. Consider the following metric on $\mathcal{M} = \mathbb{R}^4$ with coordinates (u, v, x, y) :

$$ds^2 = a(u)(x^2 + \epsilon y^2)du^2 + 2dudv + dx^2 + \epsilon dy^2 \tag{10}$$

where a is a nowhere zero function. If $\epsilon = 1$, the metric (10) has Lorentz signature which is known as the *plane wave metric* in the general relativity theory (see [11] pages 248–249) whilst it has neutral signature if $\epsilon = -1$ (see also [15]). It can be calculated that such a space is conformally flat and that the rank of $Riem$ is 2. In addition, the vector field $\frac{\partial}{\partial v}$ is parallel and the Ricci tensor is given as $Ricc = -2a(u)dudu$. Therefore, it has Segre type of $\{(211)\}$ (with eigenvalue zero). In that case, the holonomy group of (\mathcal{M}, g) is $2(g)$ (for $\epsilon = -1$).

Example 2. Consider now the product manifold $\mathcal{M} = \mathbb{R}^4 = \mathbb{R}^2 \times \mathbb{R}^2$ with the following metric

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu + g'_{ab} dx^{a'} dx^{b'} \tag{11}$$

where $\mu, \nu = 1, 2$ and $a, b = 3, 4$ and also, $g_{\mu\nu}$ and g'_{ab} denote the components of the metrics g and g' in the coordinates x^μ and $x^{a'}$, respectively (in other words, the $g_{\mu\nu}$ are independent of x^3, x^4 and the g'_{ab} are independent of x^1, x^2). Suppose that the 2 –dimensional manifolds (\mathbb{R}^2, g) and (\mathbb{R}^2, g') have constant curvatures and that the metrics g and g' both have Lorentz signatures $(+, -)$. On the other hand, if we denote the metric given in Equation (11) by \tilde{g} , then $\tilde{g} = g \times g'$ and it has neutral signature. Now, one can set up a null basis $\{l, n, L, N\}$ in some neighbourhood of $p \in \mathcal{M}$ so that l, n are tangent to the manifold admitting the metric g , and L, N are tangent to the manifold admitting the metric g' . In this case, $Riem$ can be expressed as follows:

$$R_{ijkl} = \gamma(l_i n_j - n_i l_j)(l_k n_h - n_k l_h) + \lambda(L_i N_j - N_i L_j)(L_k N_h - N_k L_h) \tag{12}$$

where $\gamma = -\lambda \neq 0$ and the simple bivectors $H \equiv l \wedge n$, $K \equiv L \wedge N$ are dual pairs. It follows from Equation (12) that *Ricc* has Segre type $\{(11)(11)\}$ and $r = 0$ and that $W \equiv 0$. In this case, the bivectors H and K generate the range of the curvature map. Therefore, the holonomy of $(\mathbb{R}^4, \tilde{g})$ is $2(b)$ from Table 1. Besides, the simple bivectors H and K are parallel and their blades are also orthogonal.

Example 3. Next, consider the following metric expressed in a coordinate system $(t, \tau, \theta, \varphi)$:

$$-dt^2 + (1 - \Lambda\tau^2)^{-1}d\tau^2 + \tau^2(d\theta^2 - \sin^2\theta d\varphi^2) \quad (13)$$

where Λ is a non-zero positive constant. Firstly, it is useful to note that the metric (13) is the neutral signature equivalent of the *Einstein static universe* metric in the theory of general relativity, that is, the case when (\mathcal{M}, g) is a space-time (see [11], page 249). For the metric (13), it is true that $W \equiv 0$, more precisely, the space is conformally flat having a non-zero, parallel vector field $\frac{\partial}{\partial t}$ which is timelike and also, $r = 6\Lambda$. It then follows that Φ is of holonomy type $3(c)$.

V. CONCLUSION

In this study, 4 –dimensional conformally flat spaces with a metric of neutral signature were described by the holonomy structure. Besides the remarks given in Section III, it is useful to briefly mention about the cases Lorentz and positive definite signatures as well. Regarding conformally flat space-times, it is found in [3] that if (\mathcal{M}, g) is conformally flat (but not flat), then it can be one of the holonomy types $R_7, R_8, R_{10}, R_{13}, R_{14}$ or R_{15} where the labelings (up to isomorphism) are tabulated in [16]. Several examples were also presented in [3]. It is useful to note that the standard Friedmann-Robertson-Walker space-time is of holonomy type R_{15} , the Einstein static universe metric yields the holonomy type R_{13} which are both conformally flat (for details, see, [3]).

Finally, for positive definite signature, if (\mathcal{M}, g) is conformally flat (but not flat and not Ricci-flat), then the holonomy group Φ of \mathcal{M} is one of the types S_2, S_3, S_4 or S_6 where the labelings (up to isomorphism) are tabulated in [17].

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