JSR C

E-ISSN: 2717-8633
Sayı(Number): 7
Ağustos(August) 2024

JOURNAL OF SCIENTIFIC REPORTS-C

Journal of Scientific Reports-C Sayı(Number) 7 Ağustos(August) 2024

gate of science

Kutahya Dumlupinar University Scientific Reports C
Evliya Celebi Campus Tavsanli Road 10 KM. 43270 Kutahya
Phone : (0274) 443 19 29 - 30
E-mail : joursrc@gmail.com
www.gsjsrcc.com

Dumlupinar University Press

Kütahya Dumlupınar Üniversitesi
Lisansüstü Eğitim Enstitüsü
Sayı 7, Ağustos 2024

Journal of Scientific
Reports-C
E-ISSN: 2717-8633
Number 7, August 2024

Sahibi
Kütahya Dumlupınar Üniversitesi adına
Prof. Dr. Süleyman KIZILTOPRAK (Rektör)
Lisansüstü Eğitim Enstitüsü adına
Doç. Dr. Eray ACAR (Enstitü Müdürü)

Owner
On Behalf of Kütahya Dumlupınar University
Prof. Dr. Süleyman KIZILTOPRAK (Rector),
On Behalf of Institute of Graduate Studies
Assoc. Prof. Dr. Eray ACAR (Director)

Yayın Kurulu / Editorial Board

JSR C
Journal of Scientific Reports

Journal of Scientific Reports-C, Sayı 7, Ağustos 2024
Journal of Scientific Reports-C, Number 7, August 2024

Journal of Scientific Reports-C dergisi, yayın hayatına 2000 yılında başlayan Dumlupınar Üniversitesi Fen Bilimleri Enstitüsü Dergisinden ayrılmış olup, Nisan, Ağustos ve Aralık aylarında olmak üzere yılda düzenli olarak 3 kez yayımlanan uluslararası hakemli bir dergidir. Derginin yazım dili Türkçe ve İngilizce'dir. Dergiye gönderilen makaleler, editör kurulu tarafından seçilen ve konusunda uzman en az iki hakem tarafından değerlendirilmektedir. Dergiye sunulan bütün makaleler çift-körleme yöntemiyle değerlendirilmektedir. Değerlendirilmek üzere dergimize gönderilen makalelerin, daha önce yayınlanmamış, yayınlanmak üzere kabul edilmemiş ve yayınlanmak için başka bir dergide değerlendirilme sürecinde olmaması gerekmektedir. Dergide yayınlanan yazıların her türlü sorumluluğu yazar(lar)ına aittir.

Dergi, fen ve mühendislik bilimlerinde ulusal ve uluslararası düzeyde yapılan bilimsel çalışmaları bilim insanları ve kamuoyu ile paylaşmayı amaçlar. Dergiye, fen ve mühendislik bilim dallarında yapılan, özgün araştırma makaleleri, derleme makaleleri ve kısa notlar kabul edilir. Özgün araştırma makalelerinin başka dergilerde yayınlanmamış olması, teorik ve deneysel sonuçlar içermesi beklenir. Derleme makalelerinde ise belirli bir konu üzerinde bilimsel, teknolojik ve güncel gelişmelerin geniş bir kaynakça kullanılarak yansıtılması ve bunların doyurucu bir değerlendirilmesinin yapılması aranır. Kısa notlar, özgün bir çalışmanın ilk bulgularının duyurulması amacına yönelik hazırlanan kısa yazılar olmalıdır.

İçerik Politikası

Dergimiz açık erişim dergisi olup, makale değerlendirme süresi 1-2 aydır

Yazışma Adresi: Kütahya Dumlupınar Üniversitesi Evliya Çelebi Yerleşkesi Lisansüstü Eğitim Enstitüsü 43270 KÜTAHYA
Telefon: 0 274 443 19 42 **Faks:** 0 274 265 20 60
E-posta: joursrc@gmail.com **Web Sayfası:** https://dergipark.org.tr/tr/pub/jsrc

Journal of Scientific Reports-C was separated from Journal of Science and Technology of Dumlupınar University which started its publication life in 2000 and is a international peer-reviewed journal published regularly third times a year in April, August and December. The language of the journal is Turkish and English. Articles submitted to the journal are evaluated by at least two referees who are experts in the subject and selected by the editorial board. All articles submitted to the journal are evaluated by the double-blind method. Articles submitted to our journal for review should not be previously published, accepted for publication and in the process of being evaluated for publication in another journal. All responsibility for the articles published in the journal belongs to the author(s).

The journal aims to share scientific studies carried out in the fields of science and engineering at national and international level with scientists and the public. Original research articles, review articles and short notes in science and engineering disciplines are accepted for the journal. Original research articles are expected to contain theoretical and experimental results and should not be published in other journals. In the review articles, it is expected that scientific, technological and current developments on a specific subject are reflected by using an extensive bibliography and made a satisfying evaluation of these. Short notes should be brief writings prepared to announce the first findings of an original study.

Journal of Scientific Reports

Journal of Scientific Reports-C, Sayı 7, Ağustos 2024
Journal of Scientific Reports-C, Number 7, August 2024

Editorial Policy

The journal is open access and the article evaluation period is between 1-2 months.

Correspondence Address: Kütahya Dumlupınar Üniversitesi Evliya Çelebi Yerleşkesi Fen Bilimleri Enstitüsü 43270 KÜTAHYA

Phone: 0 274 443 19 42
Fax: 0 274 265 20 60
E-mail: joursrc@gmail.com
Webpage: https://dergipark.org.tr/en/pub/jsrc

JSR C
Journal of Scientific Reports

Journal of Scientific Reports-C, Sayı 7, Ağustos 2024
Journal of Scientific Reports-C, Number 7, August 2024

Bölüm Editörleri / Section Editors

JSR C
Journal of Scientific Reports

Journal of Scientific Reports-C, Sayı 7, Ağustos 2024
Journal of Scientific Reports-C, Number 7, August 2024

Danışma Kurulu / Advisory Board

Journal of Scientific Reports-C, Sayı 7, Ağustos 2024
Journal of Scientific Reports-C, Number 7, August 2024

JOURNAL OF SCIENTIFIC REPORTS-C

E-ISSN: 2717-8633

İÇİNDEKİLER / CONTENTS

ARAŞTIRMA MAKALELERİ / RESEARCH ARTICLES

Contents lists available at *Dergipark*

Journal of Scientific Reports-C

journal homepage: *https://dergipark.org.tr/en/pub/jsrc*

E-ISSN: 2717-8633 ***Sayı(Number) 7, Ağustos(August) 2024***

ARAŞTIRMA MAKALESİ/RESEARCH ARTICLE

Geliş Tarihi (Receive Date): 07.06.2023 *Kabul Tarihi (Accepted Date): 20.02.2024*

Akciğer kanseri tanısı için derin öğrenme modellerinin karşılaştırılması ve uygulanması

Ekrem Gökberk Koç [a,*], Durmuş Özdemir [b]

[a] *Kütahya Dumlupınar Üniversitesi, Mühendislik Fakültesi, Bilgisayar Mühendisliği Bölümü, Kütahya, ORCID: 0009-0000-3589-2692*
[b] *Kütahya Dumlupınar Üniversitesi, Mühendislik Fakültesi, Bilgisayar Mühendisliği Bölümü, KütahyaORCID: 0000-0002-9543-4076*

Öz

Akciğer kanseri, dünya genelinde yaygın bir sağlık sorunu haline gelmiştir. Erken teşhis ve doğru tedavi, hastalığın seyrini önemli ölçüde etkileyebilmektedir. Bu çalışmada, akciğer tomografisi (CT) görüntülerini kullanarak akciğer kanserinin erken teşhisini yapabilmek amaçlanmıştır. Bu teşhisi yapabilmek için derin öğrenme modellerinin karşılaştırılması ve uygulanması üzerine odaklanılmıştır. CNN, DenseNet ve ResNet gibi üç popüler derin öğrenme modeli kullanılarak, akciğer kanseri tanısı için performansları değerlendirilmiştir. Ayrıca eğitim verileri için 1440 akciğer tomografisi görüntüsü, test verileri için 174 akciğer tomografisi görüntüsü ve doğrulama verileri için 36 adet akciğer tomografisi görüntüsü kullanılmıştır. Sonuçlar değerlendirildiğinde en başarılı modelin ResNet (%96.55), bir sonraki başarılı modelin CNN (%89.08) ve son olarak DenseNet modelinin (%88.51) başarısı olduğu gözlenmiştir.

Anahtar Kelimeler: Derin Öğrenme, Akciğer Kanseri, Erken Teşhis, Performans Değerlendirmesi

Comparison and application of deep learning models for diagnosis of lung cancer

Abstract

Lung cancer is a widespread health issue globally. Early detection and proper treatment can greatly impact the progression of the disease. This study aimed to identify lung cancer at an early stage using lung tomography (CT) images. The focus was on comparing and applying deep learning models for this diagnosis. The performance of three popular deep learning models - CNN, DenseNet, and ResNet - was evaluated for lung cancer diagnosis. The training data consisted of 1440 lung tomography images, while 174 images were used for testing and 36 for validation. Upon evaluation, it was observed that the most successful model was ResNet (96.55%), followed by CNN (89.08%), and finally the DenseNet model (88.51%).

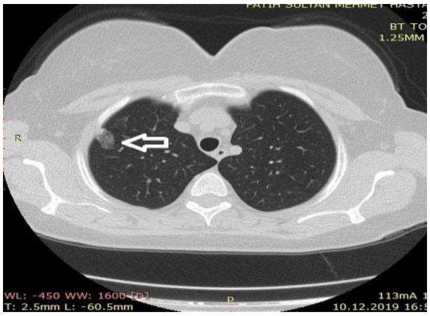
Keywords: Deep Learning, Lung Cancer, Early Diagnosis, Performance Evaluation

---

* Corresponding author. Tel.: +90 530 246 96 48
E-mail address: ekrem.koc@ogr.dpu.edu.tr

1. Giriş

Tüm kanser türleri arasında en yaygın tür olan akciğer kanseri tüm dünyada kanser türleri arasında, erkeklerde en sık ölüme neden olan birinci, kadınlarda ise ikinci kanser türüdür ve tüm dünyada her yıl yaklaşık 1,6 milyon can kaybına neden olmaktadır [1]. Erken teşhis ve doğru tedavi, hastalığın seyrini önemli ölçüde etkileyebilmekte ve hastaların yaşam sürelerini artırabilmektedir. Bu nedenle, akciğer kanserinin erken teşhisi büyük bir öneme sahiptir. Geleneksel olarak, akciğer kanseri tanısı için radyologlar tarafından yapılan görüntüleme yöntemleri kullanılmaktadır. Bunlar arasında en sık kullanılanı akciğer tomografisi (CT) görüntülemesidir. Ancak, akciğer CT görüntülerinin incelenmesi zaman alıcı ve subjektif bir süreç olabilir. Bu nedenle, otomatik ve objektif bir tanı yönteminin geliştirilmesi büyük bir gereksinim haline gelmiştir [2]. Şekil-1'de örnek olarak akciğer kanseri hastasına ait bir CT görüntüsü sunulmuştur.



Şekil 1. Akciğer kanseri hastası CT görüntüsü [3]

Derin öğrenme, son yıllarda tıbbi görüntü analizinde büyük bir ilgi odağı haline gelmiştir. Derin öğrenme modelleri, büyük veri setleri üzerinde eğitilerek karmaşık yapıları algılayabilen ve yüksek doğrulukla sınıflandırma yapabilen yapay sinir ağlarıdır. Bu nedenle, akciğer kanseri tanısı için derin öğrenme modellerinin kullanımı, otomatik ve hassas bir tanı yöntemi sağlayabilir [4]. Derin öğrenme, yapay sinir ağları ile oluşturulan ve karmaşık veri yapılarını analiz etmek ve öğrenmek amacıyla kullanılan bir makine öğrenme yöntemidir. Bu yöntem, bilgisayar sistemlerinin veriye dayalı kararlar alabilmesinde rol oynar. Aynı zamanda birçok uygulama alanında büyük başarılar elde ettiği görülmüştür. Özellikle görüntü işleme, doğal dil işleme, ses tanıma ve otonom sürüş gibi alanlarda derin öğrenme modelleri büyük ilgi görmektedir [5]. Derin öğrenme modelleri, çoğunlukla çok katmanlı sinir ağları olarak tasarlanır ve büyük miktarda veriyle beslenerek öğrenme yeteneklerini geliştirirler. Bu modeller, veri setlerindeki karmaşık desenleri algılayabilir ve bu desenlere dayalı olarak tahminlerde bulunabilir. Özellikle görüntü işleme alanında, derin öğrenme modelleri, piksellerin düşük seviyeli özelliklerinden yüksek seviyeli özelliklere kadar aşamalı olarak öğrenme yeteneğine sahiptir. Bu sayede nesne tanıma, yüz tanıma, nesne tespiti gibi görevlerde oldukça etkili sonuçlar elde edilebilir [6]. Derin öğrenme, akciğer kanseri teşhisi gibi sağlık alanındaki hastalık teşhislerinde de büyük başarıya sahiptir. Akciğer tomografisi (CT) gibi görüntüleme yöntemleri kullanılarak elde edilen veriler, derin öğrenme modelleri tarafından analiz edilebilir ve akciğer kanserinin erken teşhisinde önemli bir rol oynayabilir. Derin öğrenme modelleri, pulmoner nodüllerin tespiti ve sınıflandırılması gibi görevleri gerçekleştirebilir ve radyologlara hızlı ve doğru sonuçlar sunabilir. Ayrıca, derin öğrenme modelleri, akciğer kanserine ilişkin genetik verilerin analizinde de kullanılabilir ve kişiye özgü tedavi yöntemlerinin belirlenmesinde yardımcı olabilir [7].

Derin öğrenme, büyük veri setleriyle beslenerek öğrenme yeteneklerini sürekli olarak geliştirme potansiyeline sahiptir. Ayrıca, derin öğrenme modelleri, transfer öğrenme ve hızlı öğrenme gibi tekniklerle farklı veri setleri ve uygulama alanlarına da genişletilebilir. Ancak, derin öğrenme modellerinin karmaşıklığı ve hesleme gücü gereksinimi, eğitim sürecinde yüksek kaynak ve hesaplama gücü gerektirebilir.Sonuç olarak, derin öğrenme, akciğer kanseri teşhisi gibi ciddi sağlık sorunlarına çözüm olabilecek etkili bir araçtır. Görüntü işleme, genetik veri analizi gibi alanlarda derin öğrenme modellerinin kullanılması, akciğer kanseri tanısı ve tedavisinde önemli bir ilerleme sağlayabilir. Ancak, daha fazla araştırma ve geliştirme gerekmektedir ve derin öğrenme modellerinin klinik uygulamalara entegrasyonu için daha fazla çalışma yapılmalıdır [8].

Literatür incelendiğinde, Ayrık Dalgacık Dönüşümü (ADD) yaklaşımı ile 6053 akciğer tomografi veri seti kullanarak, VGG-16, Inception v4, MobileNet v3 ve AlexNet yöntemi ile görüntülerde kanser hastalığı tespiti yapılmıştır. En başarılı performansı AlexNet'in %99,86 ile sağladığı görülmüştür [9]. U-Net mimarisi kullanılarak yapılan piksel temelli görüntü segmentasyon modelinin avantajını sunan bir başka çalışmada, eğitim görüntüsü az olsa dahi klasik modellerden daha başarılı sonuç verdiği vurgulanmaktadır. 138 sol ve sağ akciğer bölgesinin GXI görüntülerini içeren veri setinde bulunan görüntüler %80 eğitim, %10 doğrulama ve %10 test olarak rastgele bölünmüştür. Modelin performansı Dice katsayısı ölçülerek 0,9763 Dice değeri elde edilmiştir [10].

Liu ve Lee, 37 hastanın biyopsi görüntülerini kullanarak kanserli ve kanser olmayan hastaları belirlemek için birden fazla derin öğrenme modelini kullanmışlardır. Çalışmada geleneksel derin öğrenme modellerinden CNN mimarisi tabanlı; AlexNet, VGG, ResNet ve SqueezeNet modelleri ince ayar yapılarak uyarlanmıştır. Derin öğrenme modelinin AUC' si daha makuldür (0,8808–0,9121). Yani genellikle modeli sıfırdan eğitmek daha iyi bir sonuç vermektedir. Fakat ResNet50 modeli için durum farklıdır, bu durumda önceden eğitilmiş modele ince ayar yapmak daha sağlıklı sonuç vermektedir [11].

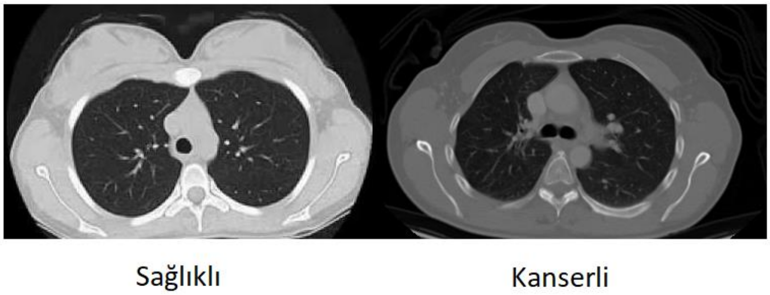
Literatür incelendiğinde bir başka çalışmada InceptionV3 temel alınarak geliştirilen ISANET adlı sınıflandırma modeli kullanılmıştır. Model, kanal dikkati ve mekansal dikkat mekanizmalarını içererek patolojik bölgelere odaklanmayı amaçlamaktadır. ISANET'in geleneksel modellere (AlexNet, VGG16, InceptionV3, MobilenetV2 ve ResNet18) göre üstün doğruluk elde ettiğini göstermektedir. Bu deneylerin sonuçları, ISANET'in akciğer kanserini sınıflandırmada etkili bir model olduğunu doğrulamaktadır, %95,24 ve %98,14 başarı oranı elde edilmiştir[12].

Bu araştırmanın amacı, bu derin öğrenme modellerinin akciğer kanseri tanısı için performanslarını karşılaştırmak ve değerlendirmektir. Bu çalışma, akciğer kanseri tanısında derin öğrenme modellerinin etkili bir şekilde kullanılabileceğini ve potansiyel olarak mevcut yöntemleri tamamlayabileceğini göstermektedir. Derin öğrenme tekniklerinin kullanımıyla, akciğer kanseri tanısında erken teşhisin mümkün olabileceği ve hastaların tedavi sürecinde avantaj sağlanabileceği düşünülmektedir. Bu çalışmada, akciğer kanseri tanısı için derin öğrenme modellerinin karşılaştırılması ve uygulanması üzerine odaklanılmıştır. CNN, DenseNet ve ResNet gibi üç popüler derin öğrenme modeli kullanılarak, akciğer CT görüntülerinden elde edilen veriler üzerinde eğitim ve test işlemleri gerçekleştirilmiştir. Eğitim veri seti olarak 1440 akciğer CT görüntüsü kullanılırken, test veri setinde 174 görüntü ve doğrulama veri setinde 36 görüntü bulunmaktadır.

2. Materyal ve Yöntem

2.1. Veri seti

Araştırmada yer alan veri setine dair bilgiler şu şekildedir: Veri setinde akciğer CT görüntüleri bulunmaktadır bu görüntülerin etiketleri kanserli ve saglikli şeklinde etiketlenmiştir. Kanserli olarak etiketlenen 876 görüntü, saglikli olarak etiketlenen 564 adet görüntü vardır [13]. Toplamda 1440 adet eğitim verisi(876 kanserli 564 sağlıklı), 174 adet test verisi (120 kanserli 54 sağlıklı) ve 36 adet doğrulama verisi (23 kanserli 13 sağlıklı) olmak üzere ayrılmıştır [14]. Şekil 2' de temsili olarak sağlıklı ve kanserli akciğer CT görüntüleri paylaşılmıştır.



Şekil 2. Sağlıklı ve Kanserli akciğer CT görüntüleri [3]

2.2. Kullanılan modeller

2.2.1. Resnet50 modeli

ResNet50, Residual Neural Network (ResNet) ailesine ait bir derin öğrenme modelidir. İsmi, 50 adet katman içermesinden kaynaklanmaktadır. Bu model, özellikle görüntü sınıflandırma ve nesne tanıma gibi görevler için kullanılmaktadır. ResNet50'nin katmanları ve özellikleri şu şekildedir [15].Giriş katmanında ilk katman, görüntülerin girişini alır ve boyutunu belirler. Genellikle RGB renk kanallarını temsil etmek için 3 kanala sahip olur. Bu katman, görüntülerin doğrudan alınmasından sorumludur ve verileri ağın geri kalanına iletmek için herhangi bir işlem yapmaz. Giriş katmanı, görüntü verilerinin doğru boyut ve formatlara sahip olduğundan emin olmak için önemlidir. Örneğin, piksel değerlerini normalize etmek gibi ön işleme adımları da bu katmanda gerçekleştirilebilir. Giriş katmanı, ağın temelini oluşturan ve verilerin ağa uygun bir şekilde aktarılmasını sağlayan önemli bir bileşendir. ResNet50 modeli, giriş katmanının yanı sıra birçok derinlikte konvolüsyonel ve toplama (addition) katmanlarından oluşur. Bu yapı, modelin daha derin ağlarda da başarılı olabilmesini sağlayan kendine has bir özelliktir. ResNet50'nin geri kalan katmanları, bu derin ağ yapısını oluşturmak, görüntülerin özelliklerini öğrenmek ve önemli desenleri yakalamak için optimize edilmiştir. Evrişim katmanında ardışık olarak yer alan katmanlarda, görüntüler üzerinde özellik haritaları oluşturulur. Bu katmanlar, farklı boyutlarda filtreleri kullanarak görüntünün farklı özelliklerini algılar. ResNet50'de 16 adet evrişim katmanı bulunur. Evrişim katmanlarının ardından havuzlama (pooling) katmanları gelir. Bu katmanlar, özellik haritalarını küçültür ve özelliklerin ölçeklenebilirliğini artırır. Çoğunlukla maksimum veya ortalama havuzlama kullanılır. Ardından özellik haritaları tam bağlantılı (fully connected) katmanlara verilir. Bu katmanlar, çıktıları düzleştirir ve sınıflandırma veya tanıma için kullanılacak özellik vektörünü oluşturur. Son katman olan çıkış katmanına gelindiğinde, sınıflandırma veya tanıma amacıyla kullanılan nöronları içerir. Akciğer kanseri tanısında, bu katman, kanserli veya kansersiz olarak sınıflandırma yapmak için kullanılır [16]. ResNet50 modelinin akciğer kanseri tanısıyla bağlantısı, derin öğrenme modelinin akciğer CT görüntülerinde kanserli bölgeleri doğru bir şekilde tanımlama ve sınıflandırma yeteneğiyle ilgilidir. ResNet50'nin evrişim ve havuzlama katmanları, akciğer CT görüntülerinin önemli özelliklerini algılar ve kanserli bölgeleri tespit eder. Tam bağlantı katmanları, bu özellik vektörlerini kullanarak kanserli veya kansersiz sınıflandırmasını gerçekleştirir. ResNet50, yüksek doğruluk oranları ve genelleme yeteneğiyle akciğer kanseri tanısında etkili bir araç olabilir. Model, görüntülerdeki kanserli bölgeleri hassas bir şekilde tespit ederek erken teşhisin sağlanmasına katkıda bulunabilir. Ayrıca, derin ağ yapısı sayesinde geniş bir veri setiyle eğitilmiş olan

ResNet50, daha az veriyle çalışırken yüksek performans sergileyebilir ve klinik uygulamalarda radyologlara ciddi bir destek sunabilir.

2.2.2. Cnn modeli

CNN (Convolutional Neural Network) modeli, akciğer kanseri tanısı için kullanılan ve görüntü işleme görevlerinde başarıyla kullanılan bir derin öğrenme modelidir. Modelin katmanları şu şekildedir. Evrişim katmanı (Conv2D) ile modelin girişine (150, 150, 3) boyutunda olan ve RGB renk kanallarını içeren görüntüler verilir. Bu katmanda 32 adet 3x3 boyutunda filtre kullanılır ve aktivasyon fonksiyonu olarak ReLU (Rectified Linear Unit) kullanılır. Evrişim katmanı, görüntüler üzerinde farklı özellikleri vurgulayan özellik haritalarını oluşturur.Havuzlama katmanı (MaxPooling2D) ile evrişim katmanından elde edilen özellik haritaları üzerinde boyut küçültme işlemleri yapılır. Bu katmanda 2x2 boyutunda bir havuzlama filtresi kullanılır ve maksimum değeri alarak özellik haritalarının boyutunu küçültür. İkinci evrişim katmanıyle önceki evrişim katmanının çıktılarına 64 adet 3x3 boyutunda filtre uygulanır ardından tekrar ReLU aktivasyon fonksiyonu kullanılır. Bu katmanda da farklı özelliklerin vurgulanması sağlanır. İkinci havuzlama katmanı ile ikinci evrişim katmanının çıktılarına aynı şekilde 2x2 boyutunda bir havuzlama filtresi uygulanır ve özellik haritalarının boyutu daha da küçültülür. Üçüncü evrişim katmanıyle önceki katmanlardaki işlemler tekrarlanır. Bu sefer 128 adet 3x3 boyutunda filtre kullanılır ve ReLU aktivasyon fonksiyonu uygulanır. Üçüncü havuzlama katmanına gelindiğinde üçüncü evrişim katmanının çıktılarına yine 2x2 boyutunda bir havuzlama filtresi uygulanır ve boyut küçültme işlemi yapılır. Dördüncü evrişim katmanında önceki adımlarda olduğu gibi 128 adet 3x3 boyutunda filtre kullanılır ve ReLU aktivasyon fonksiyonu uygulanır. Dördüncü havuzlama katmanıyla dördüncü evrişim katmanının çıktılarına 2x2 boyutunda bir havuzlama filtresi uygulanır ve boyut küçültme işlemi yapılır. Düzleştirme katmanı (Flatten) ile havuzlama katmanlarının çıktıları düzleştirilir ve tek boyutlu bir vektör elde edilir. Bu vektör, sonraki tam bağlantılı katmanlara giriş olarak kullanılır. Tam bağlantılı katman (Dense) ile de 512 nöron içeren bir tam bağlantılı katmandır. ReLU aktivasyon fonksiyonu kullanılır ve özelliklerin daha spesifik kombinasyonlarını öğrenmeye yardımcı olur. Çıkış katmanı (Dense) ile son olarak, tek bir nöron içeren bir çıkış katmanı yer alır. Bu katmanda sigmoid aktivasyon fonksiyonu kullanılır ve kanserli veya kansersiz sınıfını tahmin etmek için kullanılır. CNN modeli, akciğer CT görüntülerindeki kanserli bölgelerin tespiti ve sınıflandırılması için kullanılır. Evrişim katmanları, görüntüler üzerindeki özellikleri vurgulayarak kanserli bölgeleri belirler. Havuzlama katmanları ise boyut küçültme işlemi yaparak özelliklerin ölçeklenebilirliğini artırır. Tam bağlantılı katmanlar, özellik vektörünü oluşturarak sınıflandırma yapar. Çıkış katmanı ise kanserli veya kansersiz sınıfını tahmin eder. Bu şekilde, CNN modeli akciğer kanseri tanısında etkili bir şekilde kullanılabilir ve hastaların erken teşhis ve tedaviye yönlendirilmesine yardımcı olabilir [17] [18].

2.2.3. Densenet modeli

DenseNet, yoğun bağlantılı bloklar ve geçiş blokları adı verilen iki temel yapıyı içeren bir derin öğrenme modelidir. Modelin katmanları şu şekildedir. Giriş katmanında, modelin giriş verilerini alan ve işlemeye başlamak için ilk adımı atan bir katmandır. Giriş Katmanı, genellikle görüntüler için RGB (3 kanal) veya siyah-beyaz (1 kanal) gibi belirli bir giriş boyutuyla tanımlanır. Bu katman, ağa giriş verilerini aktarırken aynı zamanda boyut ve format ayarlamaları yapabilir. Örneğin, RGB görüntülerde her bir kanalı ayrı ayrı temsil edebilir ve siyah-beyaz görüntülerde yalnızca tek bir kanalı kullanabilir. Giriş Katmanı aynı zamanda giriş verilerini normalize etmek veya ön işleme adımlarını uygulamak için kullanılabilir.

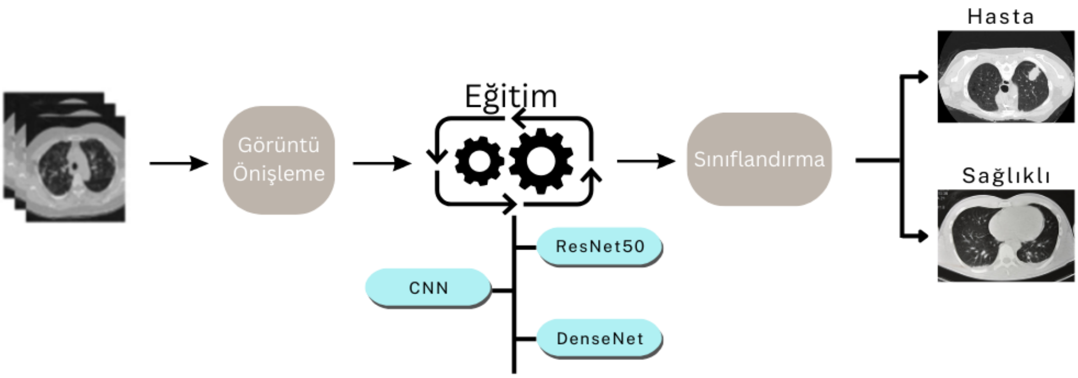
Giriş Katmanı, modelin temelini oluşturan ilk katmandır ve verilerin ağ içindeki diğer katmanlara doğru iletilmesini sağlar. Bu katman, veri akışının başlangıcını belirler ve diğer katmanların üzerinde çalışacağı uygun bir giriş formatı sağlar. Giriş Katmanı, modelin performansını etkileyen önemli bir bileşen olarak görülür ve giriş verilerinin doğru şekilde işlenmesi ve aktarılması için dikkatli bir şekilde tasarlanır. Ardından başlangıç konvolüsyon katmanı ile giriş verileri, konvolüsyon işlemi kullanılarak işlenir. Bu katmanda filtrelerle konvolüsyon yapılır ve aktivasyon fonksiyonu (genellikle ReLU) uygulanır. Bu adım, özellik çıkarımının başlamasını sağlar.

Yoğun bloklara gelindiğinde Yoğun bloklar, ardışık katmanların yoğun bağlantılarla birleştirildiği bloklardır. Her katman, önceki tüm katmanların çıktılarına sahip olur. Bu bağlantılar, bilgi akışını kolaylaştırır ve gradient kaybını azaltır. Yoğun bloklar, bir dizi yoğun katmandan oluşur. Her katmanda, girişe ek olarak birer konvolüsyon, toplama işlemi ve aktivasyon fonksiyonu uygulanır. Hemen sonra geçiş bloklarına geçilir, yoğun bloklar arasında yer alır ve boyut küçültme işlemi yapar. Bu katmanlar, özellik haritalarının boyutunu azaltarak derinliği kontrol eder. Tipik olarak, havuzlama (pooling) veya konvolüsyon (convolution) işlemleri ile boyut küçültme sağlanır. Global average pooling ile yoğun blokların ardından, özellik haritaları global ortalama havuzlama işlemine tabi tutulur. Bu işlem, her özellik haritasının ortalamasını alır ve vektörleştirir. Bu sayede, boyut azaltma ve özelliklerin özeti elde edilir. Son olarak tam bağlantılı katmanlarıyla vektörleştirilmiş özellikler, tam bağlantılı (fully connected) katmanlara aktarılır. Bu katmanlar, sınıflandırma işlemi için kullanılır. Genellikle ReLU aktivasyon fonksiyonu ve çıkış sınıf sayısına uygun bir aktivasyon fonksiyonu (genellikle softmax) kullanılır. DenseNet modeli, akciğer kanseri tanısı için kullanıldığında, yoğun bloklar kanserli bölgelerin tespit edilmesi ve özelliklerinin vurgulanması için kullanılır. Geçiş blokları ise boyut küçültme işlemiyle ölçeklenebilirliği artırır. Bu sayede, model akciğer CT görüntülerinde kanserli bölgeleri tespit etmek ve sınıflandırmak için kullanılabilir [19] [20].

3. Önerilen model ve Bilgiler

Akciğer kanseri tanısı için derin öğrenme modelleri son derece etkili ve güçlü araçlar olarak kabul edilmektedir. Bu çalışmada, akciğer kanseri tanısı için üç farklı derin öğrenme modeli kullanılmıştır.

Şekil 3, incelendiğinde 1440 adet eğitim verisi (876 kanserli, 564 sağlıklı), 174 adet test verisi (120 kanserli, 54 sağlıklı) ve 36 adet doğrulama verisi (23 kanserli, 13 sağlıklı) olmak üzere ayrılmıştır. Görüntüler 224x224 boyutuna yeniden boyutlandırılmış ve piksel değerleri 0-1 aralığına ölçeklendirilmiştir. Bu ölçeklendirme işlemi, görüntülerin işlenmesini kolaylaştırmak için yapılmıştır. Veri seti sınırlı sayıda görüntü içerdiği için veri artırma teknikleri kullanılmıştır. Görüntüler yatay olarak çevrilmiş, 0.2 oranında kaydırılmış ve 0.2 oranında yakınlaştırılmıştır. Bu işlemler, veri setinin çeşitliliğini artırarak modelin genelleme yeteneğini geliştirmeyi hedeflemiştir. Şekil 3'te kullandığımız modellerin süreci sunulmuştur.



Şekil 3. Çalışmada önerdiğimiz modelin çalışma yapısı

CNN, DenseNet ve ResNet50 modeli, giriş katmanı, konvolüsyon katmanları, havuzlama katmanları, tam bağlantılı katmanlar gibi temel yapıları içerir. Bu modeller, akciğer tomografisi (CT) görüntülerinden özellik çıkarımı yaparak kanserli bölgeleri tespit etmeyi amaçlar. DenseNet modeli ise yoğun bağlantılı bloklar ve geçiş blokları kullanır. Yoğun bloklar, bilgi akışını artırır ve gradient kaybını azaltırken, geçiş blokları da boyut küçültme işlemiyle ölçeklenebilirliği artırır. Son olarak, ResNet modeli, derin ağlarda ortaya çıkan gradient kaybı sorununu çözmek için rezidüel bağlantıları kullanır. Bu sayede, daha derin ağların eğitimi daha kolay hale gelir. Her bir modelin performansı değerlendirildiğinde, ResNet modelinin en yüksek başarıya (%96.55) ulaştığı görülmüştür. CNN modeli %89.08, DenseNet modeli ise %88.51 başarı elde etmiştir. Bu sonuçlar, derin öğrenme modellerinin akciğer kanseri tanısında önemli bir rol oynayabileceğini ve erken teşhis için değerli bir araç olabileceğini göstermektedir.

4. Performans metrikleri

Metriklerin sonuçlarını karşılaştırarak algoritmanın performansını değerlendirdik. Metrikler, Python Scikit-learn paketi kullanılarak hesaplandı. Duyarlılık, özgüllük, kesinlik, F1 puanı ve alıcı çalışma karakteristik eğrisinin altındaki alan (AUROC) olmak üzere beş metrik kullanıldı ve duyarlılık, özgüllük, doğruluk ve F1 puanı şu şekilde hesaplandı:

$$Sensitivity = \frac{TP}{TP+FN} \quad (1)$$

$$Specificity = \frac{TN}{TN+FP}, \quad (2)$$

$$Accuary = \frac{TP+TN}{TP+FP+TN+FN}, \quad (3)$$

$$F1score = \frac{2}{\frac{1}{Precision}+\frac{1}{Recall}}. \quad (4)$$

Burada TP, doğru kanserli sayısı; TN, doğru sağlıklı sayısı; FP, yanlış pozitif kanserli sayısı; FN, yanlış sağlıklı sayısı; kesinlik (precision) = TP / (TP + FP) ve hatırlama (recall) = duyarlılık olarak hesaplanmıştır.

Table 1. Elde edilen bulgular

Modeller	Görüntü boyutu	Duyarlılık	Özgüllük	Kesinlik	AUROC	F1 puanı
DenseNet	150 × 150	0.80	0.90	0.80	0.88	0.76
ResNet50	224 × 224	0.84	0.95	0.90	0.96	0.84
CNN	150 × 150	0.71	0.77	0.64	0.89	0.70

En başarılı modelin ResNet50 olduğu (%96.55), CNN modelinin ikinci sırada geldiği (%89.08) ve DenseNet modelinin üçüncü sırada olduğu (%88.51) görülmüştür. Veri setinin büyüklüğüne ve kalitesine göre özellikle F1 puanı ve diğer metrikler etkilenmektedir.

5. Sonuçlar ve tartışma

Bu çalışmanın sonuçları, akciğer kanseri tanısında derin öğrenme modellerinin etkili bir şekilde kullanılabileceğini göstermektedir. Her bir modelin performansı detaylıca incelenmiştir. ResNet modelinin performansı akciğer kanseri tanısında %96.55 doğruluk elde ederek yüksek bir performans sergilemiştir. Ayrıca, modelin hassasiyeti, özgüllüğü ve F1 skoru diğer modellere göre daha yüksek bulunmuştur. ResNet modelinin başarısı, literatürdeki benzer çalışmalarla tutarlıdır ancak en yüksek başarı oranına sahip değildir [21]. CNN modeli ise %89.08 doğruluk oranı ile ikinci sırada yer almıştır. Bu model, daha hızlı eğitim süreleri ve düşük hesaplama gücü gereksinimi gibi avantajlar sunmaktadır. CNN tabanlı modellerin geniş uygulama alanları ve etkileyici sonuçları, önceki literatürde de sıkça vurgulanmıştır [22]. DenseNet modeline gelince, %88.51 doğruluk oranı ile üçüncü sırada yer almıştır. Bu modelin, daha karmaşık yapıları anlamak ve öğrenmek için etkili olabileceği gözlemlenmiştir ayrıca DenseNet'in, benzer çalışmalarda da kullanılarak başarı elde ettiği literatürde belirtilmiştir [23]. Bu çalışmanın sonuçları, akciğer kanseri tanısı alanında derin öğrenme modellerinin potansiyelini vurgulamakta olup, önceki araştırmalarla uyumludur. Bu sonuçlar, akciğer kanseri tanısı alanında derin öğrenme modellerinin gelecekteki klinik uygulamalar ve araştırmalar için önemli bir temel oluşturabileceğini göstermektedir. Ancak, daha büyük ve çeşitli veri setlerinin kullanıldığı gelecekteki çalışmaların, bu modellerin genelleştirilebilirliği ve klinik uygulamalardaki etkinliği üzerinde daha fazla bilgi sağlayabileceği unutulmamalıdır.

Teşekkür

Araştırma süresince sürekli destek ve geri bildirimleri için Doç. Dr. Durmuş Özdemir'e minnettarım. Ayrıca Kütahya Dumlupınar Üniversitesi Bilgisayar Mühendisliği bölümüne teşekkürlerimi sunarım.

Kaynaklar

[1] I. Tunali, R. J. Gillies, ve M. B. Schabath, "Application of radiomics and AI for lung cancer precision medicine," Cold Spring Harbor Perspectives in Medicine, vol. 11, no. 8, Jan. 2021, doi: 10.1101/cshperspect.a039537.

[2] F. Binczyk, W. Prazuch, P. Bozek, ve J. Polanska, "Radiomics and artificial intelligence in lung cancer screening," Translational Lung Cancer Research, vol. 10, no. 2, pp. 1186-1199, Feb. 2021, doi: 10.21037/tlcr-20-708.

[3] P. Batırel, «drhasanbatirel,» 2019. [Online]. Available: https://www.drhasanbatirel.com/erken-evre-akciger-kanserinde-cerrahi/.

[4] Y. Xu vd. "Deep learning predicts lung cancer treatment response from serial medical imaging," Clinical Cancer Research, vol. 25, no. 11, pp. 3266-3275, 2019, doi: 10.1158/1078-0432.CCR-18-2495.

[5] Y. LeCun, Y. Bengio, ve G. Hinton, "Deep learning," Nature, vol. 521, no. 7553, pp. 436-444, 2015, doi: 10.1038/nature14539.

[6] P. P. Shinde ve S. Shah, "A review of machine learning and deep learning applications," in 2018 Fourth International Conference on Computing Communication Control and Automation (ICCUBEA), IEEE, pp. 1-6, Aug. 2018, doi: 10.1109/ICCUBEA.2018.8697857

[7] F. Binczyk, W. Prazuch, P. Bozek, ve J. Polanska, "Radiomics and artificial intelligence in lung cancer screening," Translational Lung Cancer Research, vol. 10, no. 2, pp. 1186, Feb. 2021, doi: 10.21037/tlcr-20-708.

[8] J. Chamberlin vd. "Automated detection of lung nodules and coronary artery calcium using artificial intelligence on low-dose CT scans for lung cancer screening: accuracy and prognostic value," BMC Medicine, vol. 19, no. 1, pp. 1-14, Mar. 2021, doi: 10.1186/s12916-021-01928-3.

[9] M. A. CİFCİ, "Derin Öğrenme Metodu ve Ayrık Dalgacık Dönüşümü Kullanarak BT Görüntülerinden Akciğer Kanseri Teşhisi," Mühendislik Bilimleri ve Araştırmaları Dergisi, vol. 4, no. 2, pp. 141-154, 2022, doi: 10.46387/bjesr.1114243.

[10] N. KARACA ve A. KARACI, "DERİN ÖĞRENME VE GÖRÜNTÜ İŞLEME YÖNTEMLERİNİ KULLANARAK GÖĞÜS X-IŞINI GÖRÜNTÜLERİNDEN AKCİĞER BÖLGESİNİ TESPİT ETME," International Journal of 3D Printing Technologies and Digital Industry, vol. 6, no. 3, pp. 459-468, 2022, doi: 10.46519/ij3dptdi.1140171.

[11] L. Liu ve C. Li, "Comparative study of deep learning models on the images of biopsy specimens for diagnosis of lung cancer treatment," Journal of Radiation Research and Applied Sciences, vol. 16, no. 2, pp. 100555, Jun. 2023, doi: 10.1016/j.jrras.2023.100555.

[12] Z. Xu, H. Ren, W. Zhou, ve Z. Liu, "ISANET: Non-small cell lung cancer classification and detection based on CNN and attention mechanism," Biomedical Signal Processing and Control, vol. 77, pp. 103773, 2022, doi: 10.1016/j.bspc.2022.103773.

[13] H. F. Al-Yasriy, «kaggle,» 2020. [Online]. Available: https://www.kaggle.com/datasets/hamdallak/the-iqothnccd-lung-cancer-dataset.

[14] A. Mahimkar, «kaggle,» 2021. [Online]. Available: https://www.kaggle.com/datasets/adityamahimkar/iqothnccd-lung-cancer-dataset.

[15] K. He, X. Zhang, S. Ren, ve J. Sun, "Identity mappings in deep residual networks," in Computer Vision–ECCV 2016: 14th European Conference, Amsterdam, The Netherlands, October 11–14, 2016, Proceedings, Part IV 14, ss. 630-645, Springer International Publishing, Sep. 2016, doi: 10.1007/978-3-319-46493-0_38.

[16] «TensorFlow ResNet50 documentation,» [Online]. Available: https://www.tensorflow.org/api_docs/python/tf/keras/applications/ResNet50.

[17] W. Alakwaa, M. Nassef, ve A. Badr, "Lung cancer detection and classification with 3D convolutional neural network (3D-CNN)," International Journal of Advanced Computer Science and Applications, vol. 8, no. 8, 2017, doi: 10.14569/IJACSA.2017.080853.

[18] C. J. Lin, S. Y. Jeng, ve M. K. Chen, "Using 2D CNN with Taguchi parametric optimization for lung cancer recognition from CT images," Applied Sciences, vol. 10, no. 7, pp. 2591, 2020, doi: 10.3390/app10072591.

[19] G. Huang, Z. Liu, L. Van Der Maaten, ve K. Q. Weinberger, "Densely connected convolutional networks," in Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, pp. 4700-4708, 2017, doi: 10.1109/CVPR.2017.243.

[20] K. Team, «DenseNet,» [Online]. Available: https://keras.io/api/applications/densenet/.

[21] M. Šarić, M. Russo, M. Stella, ve M. Sikora, "CNN-based method for lung cancer detection in whole slide histopathology images," in 2019 4th International Conference on Smart and Sustainable Technologies (SpliTech), pp. 1-4, IEEE, Jun. 2019, doi: 10.23919/SpliTech.2019.8783041.

[22] N. Faruqui, M. A. Yousuf, M. Whaiduzzaman, A. K. M. Azad, A. Barros, ve M. A. Moni, "LungNet: A hybrid deep-CNN model for lung cancer diagnosis using CT and wearable sensor-based medical IoT data," Computers in Biology and Medicine, vol. 139, pp. 104961, Dec. 2021, doi: 10.1016/j.compbiomed.2021.104961.

[23] Z. Tao, H. Bingqiang, L. Huiling, Y. Zaoli, ve S. Hongbin, "NSCR-based DenseNet for lung tumor recognition using chest CT image," BioMed Research International, vol. 2020, Dec. 2020, doi: 10.1155/2020/6636321.

Contents lists available at *Dergipark*

Journal of Scientific Reports-C

journal homepage: *https://dergipark.org.tr/en/pub/jsrc*

E-ISSN: 2717-8633 ***Sayı(Number) 7, Ağustos(August) 2024***

ARAŞTIRMA MAKALESİ/RESEARCH ARTICLE

Geliş Tarihi (Receive Date): 18.02.2024 *Kabul Tarihi (Accepted Date): 09.05.2024*

Design of a Model Satellite Consisting of Container and Payload for the Teknofest 2023 Competition

Cemil Özgültekin[a], Yasin Turanlı[b], Şerif Ali Sadık[c]*

[a]*Kutahya Dumlupınar University, Faculty of Engineering, Electrical and Electronics Engineering Dept., 43100, Kutahya, Turkey, ORCID: 0009-0009-5115-4740*

[b]*Kutahya Dumlupınar University, Faculty of Engineering, Computer Engineering Dept., 43100, Kutahya, Turkey, ORCID: 0000-0003-2316-9151*

[c]*Kutahya Dumlupınar University, Faculty of Engineering, Software Engineering Dept., 43100, Kutahya, Turkey, ORCID: 0000-0003-2883-1431*

Abstract

This work presents the design of a model communication satellite featuring an autonomously separable mission mechanism. Focusing on originality and efficiency, the model satellite is designed in two parts: the container and the payload. The model satellite is configured with software and necessary mechanical-electronic components to gather relevant data with the sensors placed on the payload. The design emphasizes mobility and simplicity to meet the requirements of Teknofest model satellite competition 2023. The development process adhered to specific work packages, culminating in the configuration of components to meet vehicle requirements. Subsequent to hardware and mechanical development, the software development process commenced in three distinct phases: hardware integration, communication software, and ground station software, each essential for autonomous missions.

Keywords: Model Satellite, Payload, Container, Telemetry Transmission, Satellite Structure, Mechanical Design, Hardware Design, Software Design

---

* Corresponding author. Tel.:+90 274 443 4330; fax: +90 274 265 20 13.
E-mail address: serifali.sadik@dpu.edu.tr

.

Teknofest 2023 Yarışması için Taşıyıcı ve Faydalı Yükten Oluşan Bir Model Uydu Tasarımı

Öz

Bu çalışma, otonom olarak ayrılabilen bir görev mekanizmasına sahip model bir haberleşme uydusunun tasarımını sunmaktadır. Özgünlük ve verimliliğe odaklanan model uydu, taşıyıcı ve faydalı yük olmak üzere iki parça halinde tasarlanmıştır. Model uydu, faydalı yük üzerine yerleştirilen sensörlerle, ilgili verileri toplamak için yazılım ve gerekli mekanik-elektronik bileşenlerle yapılandırılmıştır. Tasarım, Teknofest Model Uydu Yarışması 2023'ün gerekliliklerini karşılamak için mobilite ve basitliği vurgulamaktadır. Geliştirme süreci, belirli iş paketlerine bağlı kalarak, araç gereksinimlerini karşılamak için bileşenlerin yapılandırılmasıyla sonuçlandırıldı. Donanım ve mekanik geliştirmenin ardından, yazılım geliştirme süreci de donanım entegrasyonu, iletişim yazılımı ve yer istasyonu yazılımı adımlarında üç ayrı fazda gerçekleştirildi.

Anahtar Kelimeler: Model Uydu, Görev Yükü, Taşıyıcı, Telemetri Iletimi, Uydu Yapısı, Mekanik Tasarım, Donanım, Yazılım

1. Introduction

In accordance with the Turkish Space Agency (TUA), a Satellite is a compact celestial object traversing an orbital trajectory around a celestial body. These satellites manifest in two primary classifications: Natural Satellites, and Artificial Satellites. The latter encompasses a spectrum of specialized categories, including Communication Satellites, Meteorology Satellites, and Astronomy Satellites [1].

The popularity of satellites in modern applications is conspicuous, with communication and observation emerging as the foremost domains of their utilization [2], [3]. One of Turkey's first steps in satellite research took place on 23 April 1979 with the inauguration of AKA-1 (Ankara-1), the first indigenous satellite ground station. A milestone in Turkey's venture into satellite technology was the launch of Turksat 1A, the nation's first domestic satellite, on January 24, 1994. After this historic event, Turkey has witnessed a progression in satellite initiatives. This pivotal establishment laid the groundwork for subsequent advancements, including the achievement of data transfer at a velocity of 140Mb/s, employing a 1310nm wavelength through fiber optic cables. This breakthrough not only amplified channel capacity in communication but also played a pivotal role in augmenting public awareness about Satellite Systems [1], [4], [5].

Satellite Systems, instrumental in diverse sectors such as communication and imaging, have evolved into indispensable components of contemporary technology. The integration of distinct containers and mission mechanisms has further enhanced their efficacy. Concurrently, the relentless march of technology has engendered the design and implementation of autonomous functionalities, expanding the spectrum of tasks that Satellite Systems can autonomously undertake on a daily basis [6], [7].

Today, model satellite technology is appreciated and promoted. Various model satellite competitions are organized in Turkey and worldwide:

- TEKNOFEST Model Satellite Competition: Organized as part of TEKNOFEST, Turkey's largest technology festival, this competition has been held since 2018 and is the most prestigious model satellite competition in Turkey. Teams launch their own designed and manufactured model satellites to perform various tasks that meet the competition requirements.

- Istanbul Technical University (ITU) Model Satellite Competition: This competition has been organized by ITU since 2004 and is one of the oldest model satellite competitions in Turkey. Teams launch their own designed and manufactured model satellites to perform various tasks.
- Middle East Technical University (METU) Model Satellite Competition: Organized by METU since 2007, is one of the most prestigious model satellite competitions in Türkiye. Participants are expected to design a model satellite that will fulfill the specified missions.
- CanSat is organized by NASA and is known as the oldest model satellite competition with a history dating back to 1999. Participating teams are expected to design a Can-sized model satellite and are also asked to fulfill the specified tasks.
- CubeSat Design Competition: The CubeSat competition has also been organized since 1999. The model satellites that will participate in the competition are expected to be 10 cm x 10 cm x 10 cm in size and are expected to fulfill various tasks.

In model satellite competitions, participating students are expected to acquire skills such as electronic circuit modeling, control software design, mechanical calculations and design, project management, teamwork and effective presentation during the design and prototype production of a model satellite.

In this study, a model satellite design was realized for Teknofest 2023 Model Satellite competition. The model satellite designed in the study has functionalities to meet the competition qualifications. After the model satellite ascends with a rocket or drone and descends to a height of approximately 400 meters at medium speed, it is divided into two parts as container and payload. In addition to transferring parameters such as speed, position, pressure and temperature to the ground station via sensors on the payload, the model satellite has real-time imaging capability through a built-in camera and is designed to continuously transmit images to the ground station throughout its operational phase. In addition, the data from the sensors on the payload can be sent to the ground station without any interruption and visualized at the ground station through the designed software user interface.

1.1. Literature Review

In a study focusing on very small-scale satellites, two innovative model satellite designs called "SpaceChip" and "PCBSat" were proposed. These designs introduced the concept of very small model satellites and emphasized the miniaturization and cost reduction of satellites. The "SpaceChip" integrates all components on a single microchip and the "PCBSat" utilizes mass-produced printed circuit boards. Initial evaluations have shown significant cost savings compared to existing technologies [8].

In 2011, researchers analyzed the various uses of satellites and their miniature models, highlighting applications in communications, weather observation, data collection and even military purposes. That study emphasized the advantages of model satellites, such as fast and low-cost development processes and simpler launch procedures. In the study, a successful model satellite measuring altitude-dependent temperature and pressure variations was demonstrated with a low-budget design [9].

Bulut et al. successfully designed and built a model satellite named "Vecihi" in accordance with the CanSat 2013 competition requirements. Vecihi transmitted sensor data wirelessly during its orbital flight and stored additional sensor and image data on the model satellite. Simple and cost-effective solutions were prioritized in the design of the model satellite, and the innovative aspects included an adapted quadcopter aerodynamic braking system for increased durability and a protection system inspired from egg [10].

Also in 2013, a study emphasized the critical role of ground stations in the success of CanSat. A new, platform-independent ground station software designed specifically for CanSats was presented. Built using C#, the station offers enhanced reliability and functionality and enabled users to monitor multiple parameters and send control commands simultaneously [11].

Kızılkaya et al. introduced a novel descent control system designed for a CanSat participating in the 2016 International CanSat Competition's Mars Glider theme. Prioritizing simplicity and reliability, the system ensured no interference with the CanSat's electronics. The authors proposed its adaptation for other glider projects and highlight the educational value gleaned through competition participation. The proposed system have earned the Tenderfoot Award at CanSat 2016 [12].

In 2019 Islam et al. proposed a satellite design packed within the limited space for the CanSat competition. Their novel design featured an independent parachute recovery system and successfully accomplished the primary mission of real-time atmospheric parameter sensing (temperature, pressure, altitude) and a secondary mission of image capture for later analysis [13].

In another work, the researchers focused on the design of the container and payload of a CanSat. Polylactic Acid (PLA) carbon fiber was chosen as material with its advantages of lightness and strength. Also, as a novelty, a blade mechanism was integrated into the structure for controlled descent. The achieved results showed that the chosen structure for the container and payload successfully completed the mission. [14].

In another study focused on minimizing satellite structural mass with particularly aluminum honeycomb panels, the authors investigated various configurations to achieve mass reduction. They compared the performance of the novel hexagonal structure formed from honeycomb panels with conventional container designs and the proposed hexagonal design resulted in a significant 15% mass reduction [15].

A more recent study focused on designing a small satellite for the 2021 CanSat Competition. The proposed model satellite was designed to have the capabilities of real satellites, such as real-time telemetry and measurement of environmental data such as temperature, altitude or atmospheric pressure. The design had novelties such as cost-effectiveness and small scale. The model successfully completed the competition missions [16].

In a recent study presented in 2023, researchers aimed to minimize the body weight of a model satellite without sacrificing robustness through an optimization study. Designing the optimization problem to include the calculation of static and dynamic loads acting simultaneously on the model satellite at launch, the researchers achieved a 30% mass reduction in the satellite structure with this novel approach [17].

2. Materials and Methods

The main task of the participating teams in The Teknofest Model Satellite competition is as follows. The model satellite should be designed as two parts: Container and Payload. The model satellite will be lifted to an altitude of 500-700 m and released. After a fall from a height of up to 400 m, the payload and the container will be separated. The payload will send a telemetry packet to the ground station every second from the time it is powered on until it lands on the ground. Additionally, the data will be saved to an SD card on the payload. In addition, data coming to the ground station will be plotted in real time and video images from the payload can be watched simultaneously. The Teknofest Model Satellite Competition consists of the following stages: Plan and Organization Review (POR), Preliminary Design Review (PDR), Critical Design Review (CDR), Qualification Review (QR), Flight Readiness Review (FRR) and Post Flight Review (PFR). This study has met the requirements within the scope of POR, PDR and CDR reports. In the POR phase, the project plan is created, and the team organization is determined. During the PDR phase, preliminary designs were studied and tests to be carried out at the equipment, subsystem and system levels were planned. In the CDR phase, the details of the model satellite design were determined, and the equipment and subsystems were tested.

Under the PDR and CDR stages, initially, the selection of sensors and electronic components for the project was finalized. Subsequently, attention was directed towards the development, and testing of the mechanical subsystem, followed by the study of the landing control system design. The fourth phase entailed the design of the communication and data processing subsystem. Following this, the electrical subsystem was devised in the fifth phase, while the flight software was developed in the sixth phase. Lastly, the ground station interface program was designed to complete the project.

2.1. Electronic component and sensor selection

In this study, the design of an original model communication satellite model was performed. Alongside transmitting essential data such as speed, location, pressure, and temperature, our model satellite design incorporates a live imaging capability, enabling continuous transmission of images to the ground station during operation via an onboard camera. The developed software is geared towards enabling the model satellite to execute targeted tasks by employing algorithms that process sensor-derived data and relay it to the ground station. Data obtained by the model satellite's sensors is relayed to our designed ground station for collection and subsequent analysis. Furthermore, the ground station facilitates real-time tracking of satellite movements, with graphical representations and images of instant tracking data also transmitted to the ground station. The electronic components utilized in this study are given in Table 1.

Table 1. List of electronic components.

Components	Payload	Container
GPS	UBLOX M-8N GPS	-
Temperature	Adafruit BNO055 9-DOF Integrated Circuit	-
Pressure	BMP-280 Pressure Sensor	BMP-280 Pressure Sensor
Autogyro	Adafruit BNO055 9-DOF Integrated Circuit	-
Camera	Arducam Mega 5MP	-
Communication	RFD900X Telemetry	Holybro 3DR Telemetry
Processor	Raspberry Pi Zero	Raspberry Pi Zero
Battery	3s 2000mAh 30C	2s 1250mAh 30C
Antenna	15-50dB gain, 1.5dB noise factor, passive antenna (M8N) 868-900MHz Quarter wave monopole 2.1dBi (RFD900X)	433MHz active antenna, ~5dBi
Subsystem	Arduino SD card module	-
Subsystem	MG90 servomotor	-
Other	Buzzer	Buzzer
Other	Voltage Sensor	Voltage Sensor

After the model satellite gains altitude with a rocket or Unmanned Aerial Vehicle (UAV) and passively descends to an altitude of 400 m (+/- 10) at a speed of 12-14 m/s, the container and the payload on the model satellite are autonomously separated by a mechanism. Then, the telemetry data generated from the sensors in the payload mechanism is transferred to the ground station without interruption, and the determined task is successfully carried out. Data collection and transmission tasks set for the model satellite require high processing power. For this reason, Raspberry Pi Zero was chosen as the microcomputer on which the software will be developed. Single Board Computer (SBC) with ARM11 core provides high performance in data processing with its 1 GHz frequency and 512MB SDRAM hardware. In addition, the computer's communication ports (I2C, SPI, UART), CSI and USB connections for the camera, Mini-HDMI and MicrosSD ports for 1080P60 analog video transfer were preferred. Another feature in choosing the controller is that it has dimensions of 65mm×30mm×5mm. Thus, the controller can be easily placed inside the small satellite model and a compact structure will be created.

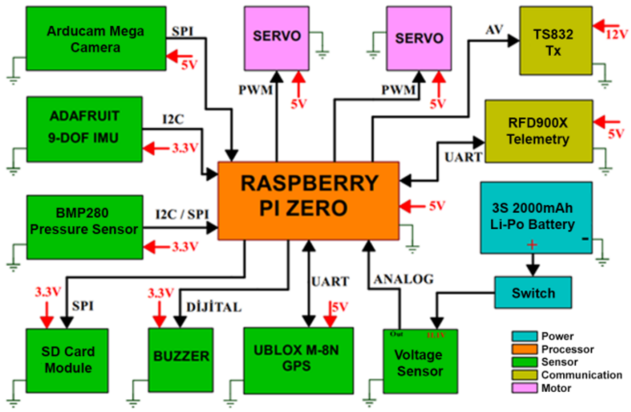


Fig. 1. Block diagram of the payload system.

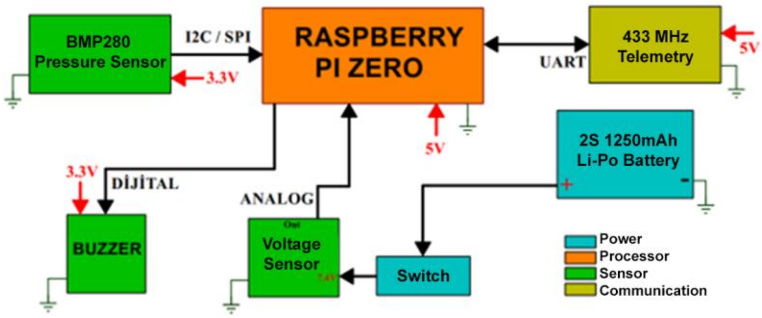


Fig. 2. Block diagram of the container system.

In the payload section, the Arducam Mega camera module was used to transmit the environmental image live to the ground station. The camera, which will be connected to Raspberry Pi Zero via Serial Peripheral Interface (SPI) protocol, can obtain images up to 2592×1944 (UHD) resolution and 30fps. The module, which has a speed of 8MHz, has low power consumption and weight.

For the precise positioning capability of the designed satellite, a 72-channel Ublox GYGPSV1 NEO M-8N GPS module was used. Location control and tracking can be done using GPS with the universal asynchronous receiver-transmitter (UART) protocol, and it is possible to obtain location information with high precision. The module, which has an accuracy range of 2-2.5 m, met the desired requirements in the model satellite project and was easily integrated into the microcontroller, providing comfortable use.

Telemetry was used to transmit data generated from the sensors on the model satellite to the ground station in real time. In this context, RFD900X telemetry module was chosen to use in the payload. The most important factor in choosing the specified telemetry is the ability to transmit up to 40 kilometers with a properly configured system. Transmission can be made uninterruptedly and at high speeds with the transmitter with 1000mW high output power. The module, which sends packet data via MAVLink protocol, is compatible with many RF modules and has open-source software, providing great ease of use. 433MHz YRRC Radio telemetry module is used for the container. Telemetry, which can transmit data up to 5000 m under maximum conditions, communicates with the UART protocol and can be easily integrated into the ground station software. The transmission power of the telemetry transmitter is 1000mW. In addition, the fact that the module is compatible with many RF modules and has open-source software provides great ease of use.

AutoGyro sensor was added to the system to generate the data that the payload will transfer to the ground station with the telemetry module. The sensor, connected via I2C protocol, produces pressure, altitude, altitude difference, descent speed, temperature, roll, pitch and yaw values and transmits them to the ground station via the RFD900X telemetry module. Adafruit BNO055 9-DOF 9-axis model was preferred as the Inertial measurement unit (IMU) Sensor. By using this sensor, absolute position, angular velocity vector, acceleration vector, magnetic field intensity vector, linear acceleration vector, gravity vector and temperature data can be obtained quickly and with high precision. Since the sensor has dimensions of 20 mm×27 mm×4 mm and a mass of 3 g, it is easily integrated into the system.

High accuracy DF-Robot BMP280 digital pressure sensor was preferred to obtain pressure values on the container and payload. In addition to pressure measurement, this sensor can measure temperature with an accuracy of 0.01 ℃ and a range of 0 ℃ - 65 ℃. Working with I2C protocol, the sensor produces pressure data in the range of 300~1100 hPa with ± 1 hPa absolute and ± 0.12 hPa relative accuracy.

When the payload is separated from the container, it is separated by a separation mechanism consisting of 2 servo motors. The preferred MG90S Model servo has a torque of 2 kg/cm and a rotation angle of 180 degrees. Servo motors, with their small size and mass of 13 g, support mass and space optimization.

TS832 Transmitter and RC832 Receiver were used to transfer camera images from the payload to the ground station. The operating distance of this receiver and transmitter, which has a capacity of 48 channels, is 5 kilometers. The TS832 Transmitter has 60mW output power and is compatible with 5.8GHz receivers. All images received via the model satellite can be transmitted uninterruptedly to the ground station via the RC832 Receiver.

A voltage sensor based on the voltage divider principle was used to read the voltage values of the batteries of the container and the payload and send them to the microcontroller. The sensor, connected to the microcontroller via analog ports, supports input voltages in the range of 0-25V. SD card module was used to save sensor data depending on the task load to the SD card. The module was connected to Raspberry Pi Zero via the SPI protocol. The buzzer component was preferred so that the payload and container can be easily found after passive landing.

Lithium Polymer batteries were preferred to provide the necessary power to the system. Leopard-Power 3S 2000mAh 30C capacity batteries were used in the container, and 2S 1250mAh 30C capacity batteries were used in the mission load. The required power calculations for the systems were made in the electrical subsystem design section.

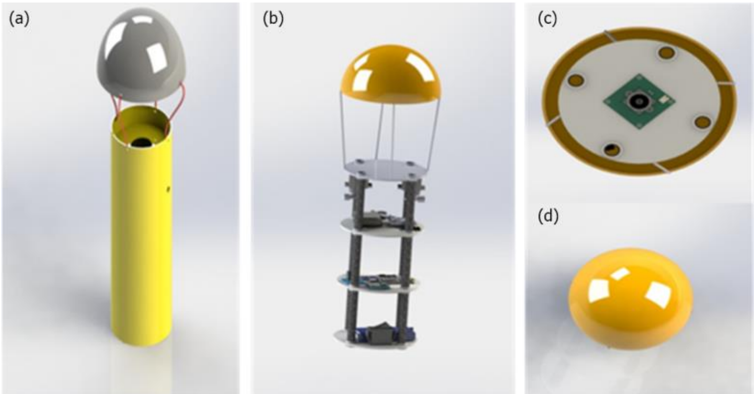


Fig. 3. Render images of (a) the container (b) the payload (c) the bottom view of the payload and (d) the upper view of the payload.

2.2. Development of the mechanical subsystem

The container is produced from PLA material using a 3D printer and coated with glass fiber and polyester. Glass fiber increases the strength and ensures that the container has a rigid structure. Glass fiber does not conduct electricity, thus preventing damage to electronic devices and does not disrupt the transmission of electromagnetic waves (Fig.3).

The electronic equipment housing in the payload was accommodated within circular cross-section plates crafted from PLA material via a 3D printer. These plates were secured together using metric 3 (M-3) bolts and nuts, forming a tight fit connection with carbon fiber pipes. PLA was chosen for the chassis due to its effective vibration damping properties, ease of production, and cost-effectiveness. Carbon fiber pipes were selected for their high strength, rigid structure, and capacity to support stable task execution. Parachute attachment was facilitated through holes drilled on the plate above the payload system (Fig.3).

The separation mechanism, designed for simplicity and optimal performance, ensures stability and cost-effectiveness in fulfilling its designated function. The separation mechanism works by rotating the drive shaft 180º, that is, half a turn, by means of two servo motors. Thus, the circular shaft retracts and separates from the holes in the container mechanism, causing the duty load to fall in free fall (Fig.4). The parachute on the free-falling payload opens because of the air currents that occur during the fall, and a healthy passive landing is achieved. The parachute was stacked neatly on the container and the parachute ropes were connected through the holes drilled on the container cylinder. The container has a length of 300 mm, an outer diameter of 113 mm and an inner diameter of 108 mm. For the separation mechanism, holes with a diameter of 8.5 mm were drilled on both sides.

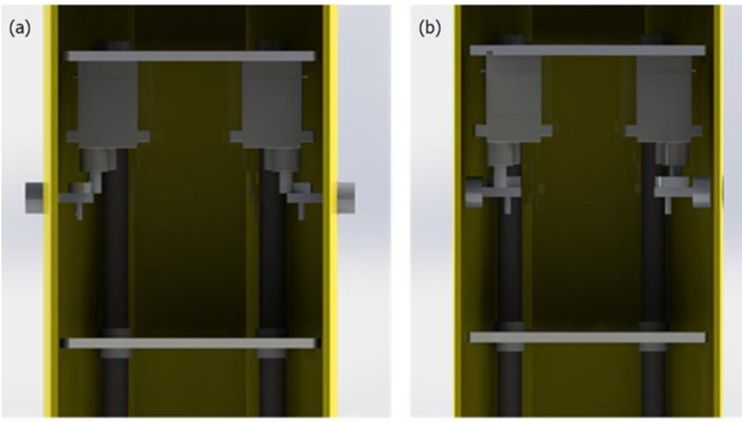


Fig. 4. Render images showing (a) the engagement and (b) the separation states of the separation mechanism.

Table 2. Mass budget of the payload and the container.

Section	Components	Mass (g)	Source of Information
Payload	Payload plates	82	Application Result
	Payload carbon fiber pipes	14	Application Result
	Separation mechanism	12	Application Result
	Servo motor x 2	13x2	Datasheet
	Raspberry Pi Zero	9	Datasheet
	Arducam mega camera	15	Datasheet

	Adafruit BNO055	5	Datasheet
	UBLOX M-8N GPS	17	Datasheet
	Voltage sensor	1	Datasheet
	RFD900X telemetry	16	Datasheet
	Buzzer	3	Datasheet
	SD card module	5	Datasheet
	TS832 transmitter	14	Datasheet
	3S 2000mAh Li-Po battery	126	Datasheet
	Power distribution card	12	Datasheet
	Power control switch	20	Datasheet
	Total Mass:	**379 g**	
Container	Container load	241	Application Result
	STM32F4 BlackPill	9	Datasheet
	BMP280 pressure sensor	2	Datasheet
	Voltage sensor	1	Datasheet
	Holybro 3DR Telemetry	10	Datasheet
	Buzzer	3	Datasheet
	2S 1250mAh Li-Po Battery	58	Datasheet
	Power distribution card	12	Datasheet
	Power control switch	20	Datasheet
	Total Mass:	**356 g**	

In the mechanical subsystem design studies, the mass budget of the container and payload was also calculated. A mass budget was created by calculating the datasheet data of the equipment to be used in the design and the material masses of the body designs. As a result of the designs and optimization studies, the total mass of the container and payload was found to be 735 g (Table 2). The total mass of the designed model satellite met the requirements of the competition which is 730 g +/- 20 g.

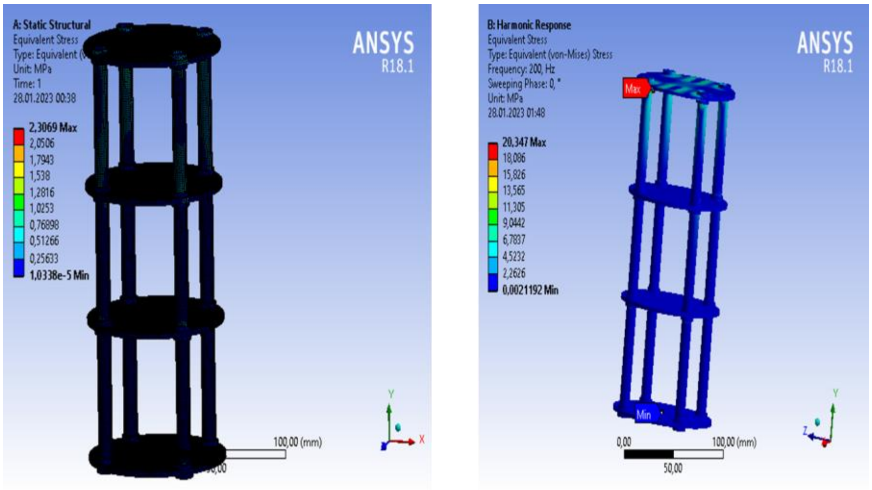


Fig.5. Static and Modal (Vibration) Analysis with Ansys Workbench.

Before production, the system that was designed underwent static, modal, and harmonic response analyses using a CAE program. The analysis was performed on the Ansys Workbench program (Fig.5). This allowed for the identification of potential mechanical and structural issues before production, enabling revisions to the design. In the analysis phase, attention was paid to meshing processes and was checked based on element quality and skewness values. Boundary conditions were accurately defined to reduce the margin of error in the analysis. The analysis concluded that no deformation would occur in the material. To ensure the robustness of our design, we analysed mechanical performance using Ansys software. This analysis focused on also withstanding an 8G force. Ansys software analysis verified that the mechanical design meets the key requirement of withstanding 8G forces.

2.3. Landing control system design

During the design phase of the landing control system, separate parachute dimension calculations were conducted for both the payload and the container, based on the mass specifications established in the mechanical subsystem design phase. Parachute surface area was calculated according to Eq. 1:

$$Sp = \frac{2 \times m \times g}{v^2 \times \rho \times Cd} \tag{1}$$

In the equation, *Sp* denotes the surface area, *m* represents the total mass, *g* signifies the gravitational acceleration (9.81 m/s^2), *v* denotes the speed, *ρ* represents the air pressure (1.225 kg/m^3), and *Cd* symbolizes the drag coefficient (0.5). This equation is used to ensure that the parachute descends slowly to the ground and minimizes damage to the rocket. It provides the balance between the weight of the rocket and the drag force [18]. The diameter of the parachute represents the area within this equation, and a circular parachute is generally considered. With calculated total masses of 735 g and 356 g, and the expected speeds of 13 m/s^2 and 7 m/s^2, the corresponding parachute surface areas were determined as 0.1364 m^2 and 0.2183 m^2, respectively, for the total system and the payload separately.

2.4. Communication and data processing subsystem

The RFD900X telemetry module in the payload is equipped with an 868-900MHz Quarter Wave Monopole antenna. We opted for a single antenna to minimize mass and ensure reliable communication. However, the system supports the use of two antennas if needed. The antenna, featuring a Reverse Polarity SubMiniature version A (RP-SMA) connection, has a signal gain of 2.1dBi, enabling transmission distances of up to 40 km under optimal conditions. In comparison, the Holybro Telemetry antenna has a transmission distance of 3-4 km under similar conditions.

We also conducted comparisons between dipole and monopole antennas for telemetry. The monopole antenna, covering half the area of the dipole antenna, boasts nearly twice the gain (5.2 dBi). However, it has a radiation resistance of 36.5Ω, half that of the dipole antenna. Following these comparisons, we determined that the Quarter Wave Monopole antenna best ensures continuous and robust communication, which is critical for our application.

All the data that is carried on a telemetry packet is shown at Table 3.

Table 3. Telemetry packet format and its description.

Veri Formatı	**Data Example**	**Description**
<PACKET_NUMBER>	<2>	Number of each telemetry packet
<SATELLITE_STATUS>	<4>	A numerical value that shows the state of the model satellite at the time of mission. (0-7)
<ERROR_CODE>	<0>	The telemetry data of possible errors that may occur. (0-5)
<TIME>	<12:43:26>	Real time clock data. (Hour:Minute:Second)
<PRESSURE1>	<1079.2>	Pressure data from the payload (pascal)
<PRESSURE2>	<1032.3>	Pressure data from the container (pascal)
<HEIGHT1>	<320>	The height of the payload above the ground. (m)
<HEIGHT2>	<125>	The height of the container above the ground. (m)
<HEIGHT_DIFF>	<195>	Difference between HEIGHT1 and HEIGHT2 (m)
<LANDING_SPEED>	<6>	Landing speed daya (m/s)
<TEMPERATURE>	<23>	Temperature data from the payload (°C)
<BATTERY_VOLTAGE>	<10.65>	Voltage value of the battery (V)
<GPS1_LATITUDE>	<39.48137>	The latitude of the payload.
<GPS1_LONGITUDE>	<29.89837>	The longitude of the payload.
<GPS1_ALTITUDE>	<324>	The altitude data of the payload taken from GPS.
<GPS2_LATITUDE>	<39.48695>	The latitude of the container.
<GPS2_LONGITUDE>	<29.89529>	The longitude of the container.
<GPS2_ALTITUDE>	<129>	The altitude data of the container taken from GPS.
<PITCH>	<80>	The angle of inclination of the payload on the pitch axis. (°)
<ROLL>	<45>	The angle of inclination of the payload on the roll axis. (°)
<YAW>	<60>	The angle of inclination of the payload on the yaw axis. (°)
<TEAM_NUM>	<211334>	Model satellite competition team number

2.5. Electrical subsystem design

During the electrical subsystem design phase, our primary objective was to establish a power budget. This budget was formulated by analyzing the power requirements of the components installed on both the container and the payload. Subsequently, the selection of batteries to power the entire system was carefully determined.

Table 4. Power budget of the payload and the container.

Section	Components	Voltage (V)	Peak Current (mA)	Max. Power (W)	Min. Power (W)	Tolerance (W)	Mission time (s)
Payload	BMP280 press. sens.	1.7 – 3.6	1.12	0.0041	0.0192	0.0021	132
	Adafruit BNO055	3.3 – 5	50	0.25	0.165	0.085	132
	UBLOX M-8N GPS	3.3 – 5	23	0.115	0.0759	0.0391	132
	Voltage sensor	3	1.12	2.13	-	-	132
	RFD900X telemetry	5	1000	5	2.8	1.6	132
	Raspberry pi zero	5V	1000	5	5	-	132
	Servo motor	4.8 – 6.2	400	2.4	0.096	0.024	10
	SD card module	3.3 – 5	200	1	0.0165	0.0085	132
	Arducam mega cam.	3.3 – 5	154	0.77	0.66	0.34	132
	TS832 transmitter	12	200	2.4	-	-	132
	Buzzer	3.3	20	0.066	-	-	30
	Total Power:			**19.135 W**			
Container	Raspberry pi zero	5V	1000	5	5	-	132
	Voltage sensor	3	1.12	2.13	-	-	132
	BMP280 press. sens.	1.7 – 3.6	1.12	0.0041	0.0192	0.0021	132
	Voltage sensor	3	1.12	2.13	-	-	132
	Holybro 3DR Telemetry	3.3 – 5	100	0.5	0.33	0.17	132
	Buzzer	3.3	20	0.066	-	-	30
	Total Power:			**7.700 W**			

As a result of the calculations, the maximum power required for the payload was determined to be 19.135W. To power the payload system for 1 hour, the battery capacity was calculated as $(19.135W/11.1V) \times 1h = 1.724\ Ah$. Consequently, a 2000mAh 30C Li-Po battery was selected, which met the calculated requirements.

The power required for the container is calculated as 7.700 W. To power the system for 1 hour, the battery capacity is calculated as $(7.700W/7.4V) \times 1h = 1.04\ Ah$ For the container, we decided to use a 1250mAh 30C Li-Po battery, which can meet the calculated requirements.

2.6. The flight software

The flow diagram of the flight software for the model satellite is illustrated in the Fig.6. The flight control software was developed using the C language in both Visual Studio and Arduino IDE environments. Upon receiving the "System calibration" command from the ground station, the software initiates a series of tasks: it resets the sensors, sets the reference altitude to zero, resets the inclination angles, and calibrates the system. The software then proceeds to collect camera images and telemetry data from the model satellite's sensors, saving this information to the onboard SD card. Concurrently, all collected data is transmitted in real-time to the ground station.

After completing its readiness checks, the model satellite is launched via rocket and released at an altitude of 500-700 meters. The payload is separated from the container by a designated mechanism at an altitude of 400 meters (±10 meters). As an additional communication performance test, a 500 kByte video packet is transmitted from the ground station to the model satellite and stored on the SD card. Subsequently, the same video packet is transmitted from the model satellite to another ground station computer. Upon successful landing, the data transmission continues for an additional 10 seconds, during which the buzzer is activated.

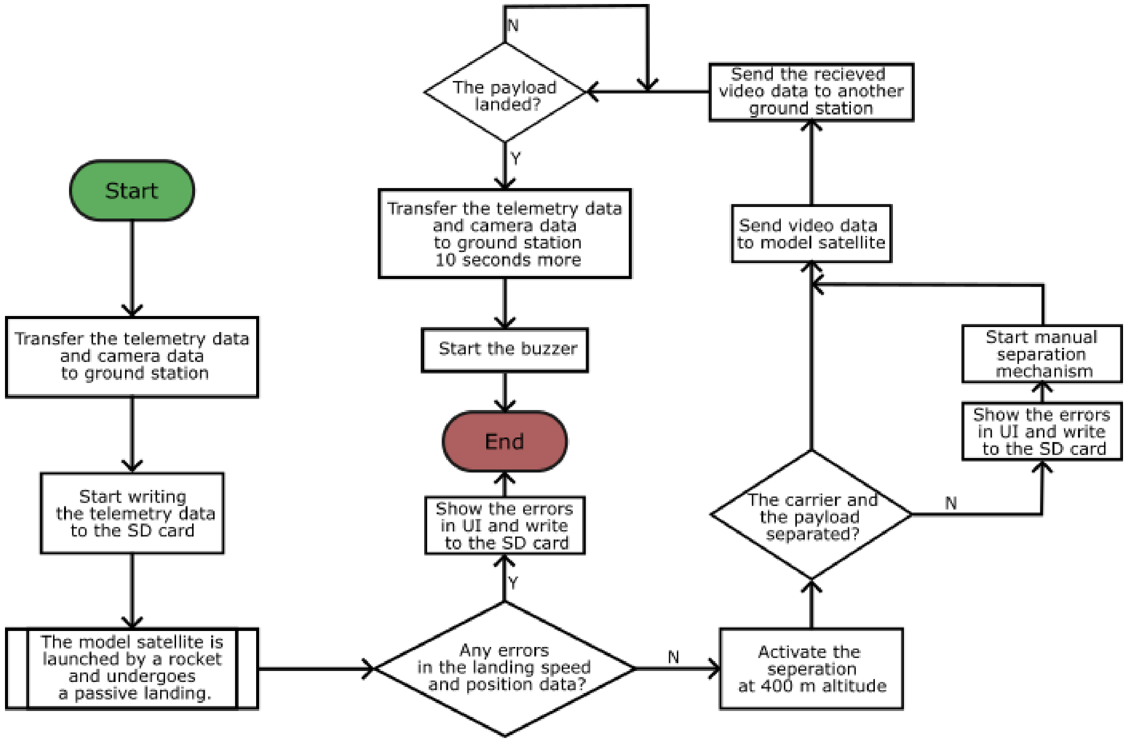


Fig. 6. The flow diagram of the flight software.

2.7. The ground station user interface

A user interface program was developed in C# using the .NET platform and Visual Studio Code environment. This interface allows manual control and tracking of the model satellite from the ground station when necessary, and it visualizes the data sent from the model satellite. Figure 7 illustrates a screenshot from this interface program.

The interface enables users to issue Start, Stop, and Calibration commands for the model satellite mission. Additionally, in the event of an error in the automatic separation mechanism, a manual separation command can be issued. Real-time data from the sensors onboard the model satellite is visualized within the interface, providing users with immediate insights. Moreover, the interface allows users to view camera images transmitted by the model satellite.

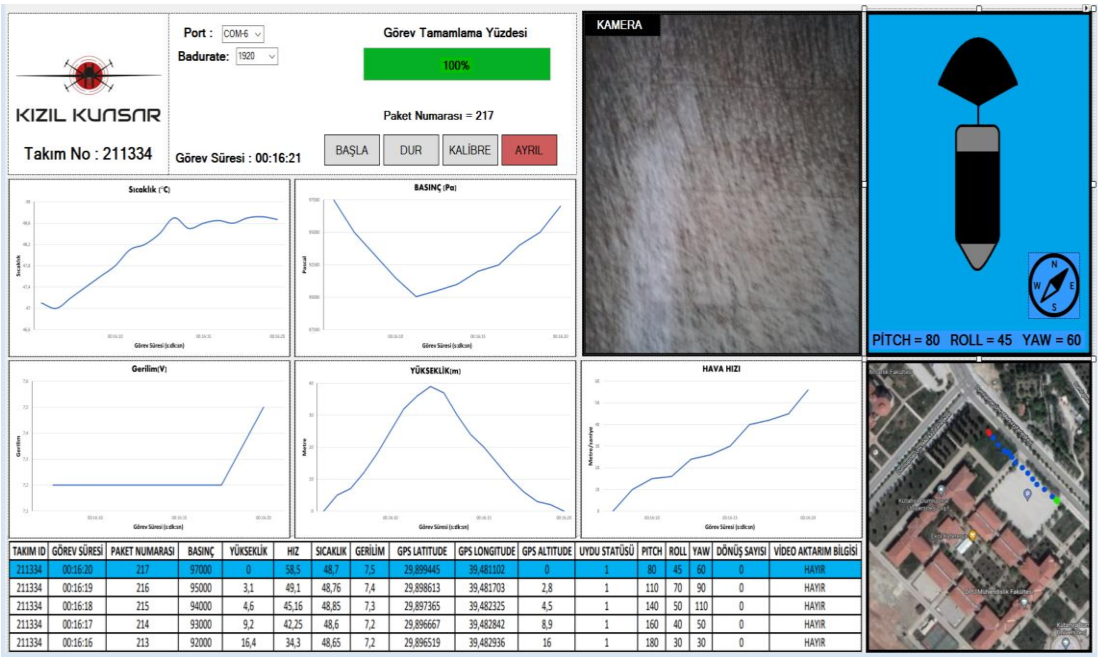


Fig. 7. The user interface of the ground station.

3. Results and Discussion

This study focused on the design and development of a model communication satellite with an autonomously separable mission mechanism for the Teknofest Model Satellite Competition 2023. The project prioritized originality, efficiency, and reliability, resulting in a satellite equipped with reliable software and suitable mechanical and electronic components with the Teknofest Model Satellite Competition requirements. The emphasis on mobility and simplicity ensured ease of transportation and deployment.

The development process followed a structured approach determined by the competition committee, from the initial hardware and mechanical design to the subsequent software integration and testing phases. In the PDR phase, the first designs were carried out by determining and selecting the electronic components. The design of electronic subsystems and the design steps of the mechanical body and subsystems were carried out at the CDR stage. Mechanical and electronic designs were made considering the requirements determined by the Teknofest competition committee. The mechanical performance and durability simulations of the subsystems were carried out using Ansys software and it was observed that the design met the critical requirements. A parachute design was prepared to control the landing of the subsystems of the design. The design of the communication module was also carried out in accordance with the telemetry package format determined to meet the competition requirements. The flight control software was developed in both Visual Studio and Arduino IDE environments using C language. Finally, the ground station interface programme was designed in C# using the .NET platform and Visual Studio Code environment. The first three phases of the competition were thus successfully completed, but the flight phase could not be started due to difficulties in meeting the deadlines.

Acknowledgements

There is no conflict of interest with any person/institution in the prepared article. This work was financially supported by the Scientific Research Projects of Kutahya Dumlupinar University, project number 2023/11. Collaboration with the Unmanned Systems Community, particularly the Kızıl Quasar UAV Team of Kutahya Dumlupınar University, enabled the project's participation in the Model Satellite competition at Teknofest 2023.

References

[1] L. Kuzu, "Türkiye'de Uydu Teknolojilerinin Bugünü ve Geleceği," *Turkish Journal of Astronomy and Astrophysics*, vol. 1, no. 2, p. 483-483, 2020.
[2] M. N. Sweeting, "Modern small satellites-changing the economics of space," *Proceedings of the IEEE*, vol. 106, no. 3, pp. 343–361, 2018.
[3] L. Kuzu, A. F. Yagli, M. Gokten, and V. Yanikgonul, "Reliability analysis of TUSAT satellite communication payload," in *2012 IEEE First AESS European Conference on Satellite Telecommunications (ESTEL)*, 2012, pp. 1–5. doi: 10.1109/ESTEL.2012.6400167.
[4] A. Baygeldi, "Ülkemizde Uydu ve Uzay Teknolojileri Alanında Faaliyetler ve Türkiye Uzay Ajansı Kurulum Çalışmaları," in *Turkish Journal of Astronomy and Astrophysics*, Türk Astronomi Derneği, 2020, pp. 445–447.
[5] Ş. Kutlu, "Uydu-Uzay Teknolojilerinin Geliştirilmesinde Türkiye'nin Yönetim Anlayışı ve Dünya Ölçeğinde Karşılaştırmalı Bir Analiz," *Havacılık ve Uzay Çalışmaları Dergisi*, vol. 1, no. 1, pp. 70–92, 2020.
[6] Ş. Gülgönül, E. Köklükaya, İ. Ertürk, and A. Y. Teşneli, "Aya: Haberleşme Uydusu Faydalı Yük Sistemi Akıllı Yedekleme Algoritması," *Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi*, vol. 29, no. 1, 2014.
[7] J. Praks *et al.*, "Aalto-1, multi-payload CubeSat: Design, integration and launch," *Acta Astronaut*, vol. 187, pp. 370–383, 2021, doi: https://doi.org/10.1016/j.actaastro.2020.11.042.
[8] D. J. Barnhart, T. Vladimirova, and M. N. Sweeting, "Very-small-satellite design for distributed space missions," *J Spacecr Rockets*, vol. 44, no. 6, pp. 1294–1306, 2007.
[9] C. Çabuloğlu *et al.*, "Mission analysis and planning of a CANSAT," in *Proceedings of 5th International Conference on Recent Advances in Space Technologies - RAST2011*, 2011, pp. 794–799. doi: 10.1109/RAST.2011.5966951.
[10] S. N. Bulut *et al.*, "Model satellite design for CanSat Competition," in *2013 6th International Conference on Recent Advances in Space Technologies (RAST)*, IEEE, 2013, pp. 913–917.
[11] M. E. Aydemir, R. C. Dursun, and M. Pehlevan, "Ground station design procedures for CANSAT," in *2013 6th International Conference on Recent Advances in Space Technologies (RAST)*, 2013, pp. 909–912. doi: 10.1109/RAST.2013.6581343.
[12] M. Ö. Kizilkaya, A. E. Oğuz, and S. Soyer, "CanSat descent control system design and implementation," in *2017 8th International Conference on Recent Advances in Space Technologies (RAST)*, 2017, pp. 241–245. doi: 10.1109/RAST.2017.8002947.
[13] T. Islam, A. Noureen, M. R. Mughal, and M. A. Nadeem, "Design and Development of a Weather Monitoring Satellite, CanSat," in *2019 15th International Conference on Emerging Technologies (ICET)*, 2019, pp. 1–6. doi: 10.1109/ICET48972.2019.8994718.
[14] R. P. Ramadhan, A. R. Ramadhan, S. A. Putri, M. I. C. Latukolan, Edwar, and Kusmadi, "Prototype of CanSat with Auto-gyro Payload for Small Satellite Education," in *2019 IEEE 13th International Conference on Telecommunication Systems, Services, and Applications (TSSA)*, 2019, pp. 243–248. doi: 10.1109/TSSA48701.2019.8985514.
[15] A. Aborehab, M. Kassem, A. Nemnem, M. Kamel, and H. Kamel, "Configuration design and modeling of an efficient small satellite structure," *Engineering Solid Mechanics*, vol. 8, no. 1, pp. 7–20, 2020.
[16] P. Shukla, R. Mishra, U. A. Sardar, and B. Mohapatra, "Satellite Design for CANSAT with Autorotatig payloads," in *2022 4th International Conference on Advances in Computing, Communication Control and Networking (ICAC3N)*, 2022, pp. 2385–2392. doi: 10.1109/ICAC3N56670.2022.10074552.
[17] A. Aborehab, M. Kassem, A. F. Nemnem, and M. Kamel, "Structural optimization of a small earth remote sensing satellite," *Noise & Vibration Worldwide*, vol. 54, no. 10–11, pp. 539–556, 2023.
[18] B. W. McCormick, *Aerodynamics, aeronautics, and flight mechanics*. John Wiley & Sons, 1994.

Contents lists available at *Dergipark*

Journal of Scientific Reports-C

journal homepage: *https://dergipark.org.tr/en/pub/jsrc*

E-ISSN: 2717-8633 ***Sayı(Number) 7, Ağustos(August) 2024***

ARAŞTIRMA MAKALESİ/RESEARCH ARTICLE

Geliş Tarihi (Receive Date): 23.03.2024 *Kabul Tarihi (Accepted Date): 22.04.2024*

An analysis of coal mining accidents in Türkiye: A decade of incidents

El Hassen Diahah[a]*, Oktay Şahbaz[b]

[a]*Kütahya Dumlupınar University, Faculty of Engineering, Department of Mining Engineering, 43000 Kütahya, Türkiye, ORCID: 0009-0003-6787-6584*

[b]*Kütahya Dumlupınar University, Faculty of Engineering, Department of Mining Engineering, 43000 Kütahya, Türkiye, ORCID: 0000-0003-0945-9048*

Abstract

This article presents the critical issue of coal production accidents in Türkiye within the last decade, providing a comprehensive analysis of these accidents to shed light on the safety and challenges of coal production. Beginning with setting the stage for the inquiry on coal's significance as a primary source of energy, the research compares Türkiye and the USA’s coal production sector accident rates and revealing high contrasts changes within the same period. The past decade underground mine accidents examinations identified key contributing factors to these incidents, enriched by insights from leading experts specializing in Occupational Health and Safety (OHS) within the Turkish coal mining sector. Moreover, the analysis of safety measures and regulatory changes over the timespan, revealed the reactive nature of these amendments rather than proactive, which could have served in mitigating these accidents or anticipating the hazards responsible for these tragedies. This study concludes with a discussion of lessons learned from these accidents, proposing a set of forward-thinking suggestions that aim to reduce accident rates, enhance safety protocols, and prevent future tragedies. This investigation not only illuminates the urgent need for proactive and preventive strategies in mine risk management but also calls on decision-makers, industry shareholders, and the global community to put the lives and well of workers in this field above all else. Through the balanced combination of the available methods used in this research, this article aims to contribute deeply to improving coal production safety standards in Türkiye and the world.

Keywords: Accidents, coal mining, occupational health and safety, Türkiye, risk management.

Türkiye'deki kömür madenciliği kazalarının analizi: On yıllık kazalar

Öz

Bu makale, Türkiye’de son on yılda meydana gelen kömür üretim kazalarını ele alarak, bu kazaların kapsamlı bir analizini sunmakta ve kömür üretimindeki güvenlik ve zorluklara ışık tutmaktadır. Kömürün birincil enerji kaynağı olarak öneminin sorgulanmasına zemin hazırlayarak başlayan araştırma, Türkiye ve ABD’nin kömür üretim sektörü kaza oranlarını karşılaştırmakta ve aynı dönemdeki yüksek kontrast değişimlerini ortaya koymaktadır. Son on yılda meydana gelen yeraltı maden kazaları incelenerek, bu kazalara öncülük eden temel faktörler tespit edilmiş ve Türkiye kömür madenciliği sektöründe İş Sağlığı ve Güvenliği (İSG) alanında uzmanlaşmış önde gelen uzmanların görüşleriyle zenginleştirilmiştir. Ayrıca, söz konusu zaman aralığında alınan güvenlik önlemleri ve mevzuat değişikliklerinin analizi, bu kazaların hafifletilmesine veya bu trajedilerden sorumlu tehlikelerin öngörülmesine hizmet edebilecek bu değişiklikleri proaktif olmaktan ziyade reaktif niteliğini ortaya koymuştur. Bu çalışma, kazalardan çıakrılan derslerin tartışılmasıyla sona ermekte ve kaza oranlarını azaltmayı, güvenlik protokollerini geliştirmeyi ve gelecekteki trajedileri önlemeyi amaçlayan bir dizi ileri görüşlü öneri sunmaktadır. Bu araştırma, maden risk yönetiminde proaktif ve önleyici stratejilere duyulan acil ihtiyaca ışık tutmakla kalmayıp, aynı zamanda karar vericileri, sektör paydaşlarını ve küresel toplumu bu alandaki çalışanların hayatlarını ve refahını her şeyin üstünde tutmaya çağırmaktadır. Bu araştırmada kullanılan mevcut yöntemleri dengeli bir şekilde bir araya getirilmesiyle, bu makale Türkiye’de ve dünyada kömür üretimi güvenlik standartlarının iyileştirilmesine derin bir katkı sağlamayı amaçlamaktadır.

Anahtar Kelimeler: Kazalar, kömür madenciliği, iş sağlığı ve Güvenliği, Turkiye, risk yönetimi

1. Introduction

According to the International Labor Organization, nearly 2.3 million individuals, both men and women, globally lose their lives due to work-related accidents or occupational diseases on an annual basis, which equates to an alarming daily average of over 6,000 fatalities. The world witnesses approximately 340 million work-related accidents and around 160 million cases of individuals suffering from occupational illnesses every year, and these statistics, unfortunately, tend to grow [1].

One of the most accident- prone industries is mining, especially coal mining. Coal plays a crucial role in numerous industrial procedures and is a fundamental element in 70% of global steel manufacturing, it holds a crucial position in global electricity production [2]. Currently, coal-fired power stations supply 37% of the world's electricity, and estimations from the International Energy Agency (IEA) indicate that coal will continue providing 22% of the world's electricity in 2040 [3]. Despite its bad reputation due to the hazardous structure of mining and processing, coal is predominantly used to produce electrical power and industrial heating. Türkiye’s 2022 total coal reserve estimation is 20.84 billion tons, including 19.32 billion tons of lignite, asphaltite and approximately 1.52 billion tons of hard coal [4], with a total beneficiation, from 800tons traded in the same year, that surpassed 128M $ [5].

The top three countries with the highest fatal occupational accident rate values in the world are India, Russia, and Türkiye, which increased substantially in the last decade. Coal production-related activities, which involve extraction and processing, are one of the riskiest working lines within industries in Türkiye [6, 7, 8]. The occurrence of occupational accidents unfolds at a rate of approximately one incident every 7 minutes, resulting in a tragic loss of an employee's life roughly every eleven hours, with another employee experiencing disability approximately every 6 hours [9].

Analysis of the Social Security Institution (SGK) statistical data between 2001 and 2020 shows that the mining sector in Türkiye has the highest death rate, with an average of 0.81 per 10,000 employees [10]. Moreover, according to the Türkiye Kömür İşletmeleri Kurumu (TKI), the accident severity rate average between 2013-2022 stands at 0.431, which makes it one the riskiest, if not the riskiest, work in terms of accident severity [11].

Thus, minimizing or preventing coal production catastrophic accidents demands a long-term commitment to safety, comprehensive regulations, training, and education, improving community awareness, accountability, investment in hazard detection technologies and risk management & analysis. Immediate actions are essential to protect the well-being of workers and minimize the environmental and social impact of such accidents. This study aims to shed light on the last decade of accidents in the coal production industry, analyzes the root causes of the incidents, and offer recommendations and insights to support the countermeasures that could prevent any similar situations from happening in the future.

2. Overview of major accidents

Türkiye has one of the most severe occupational accidents, which are primarily deadly since the activities in the coal production line are considered significantly hazardous. Historically, officials and non-governmental organizations reported a substantial number of accidents (Table 1) [12, 13].

Table 1. Major coal mining accidents in Türkiye (1992-2012).

Year	Location	Fatalities	Root cause
1992	Kozlu, Zonguldak	263	Firedamp explosion
1995	Sorgun, Yozgat	37	Firedamp explosion
2003	Aşkale, Erzurum	8	Firedamp explosion
2003	Ermenek, Karaman	10	Firedamp explosion
2004	Bayat, Çorum	3	Firedamp explosion
2005	Gediz, Kütahya	18	Firedamp explosion
2006	Dursunbey, Balıkesir	17	Firedamp explosion
2009	M.Kemalpaşa, Bursa	19	Firedamp explosion
2010	Dursunbey, Balıkesir	13	Firedamp explosion
2010	Karadon, Zonguldak	30	Firedamp explosion
2011	Elbistan, K.Maraş	11	Slope failure

As seen in the table, these incidents always leave an enormous number of fatalities which makes a bad reputation for the coal sector.

The total death toll in the twenty years before 2012, sadly reached at least 429. Whether it was a state agency, a public participation, a contractor company, or a private company, unfortunately, all these incidents included the loss of many lives. In comparison with the USA, the mine safety and health administration reported for the same time period 733 deaths [14] (fig. 1).

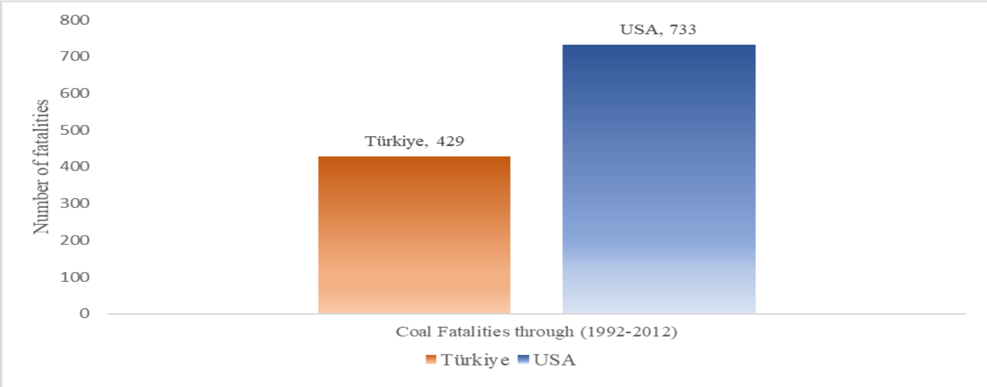


Fig. 1. Coal production fatalities in Türkiye and U.S.A through (1992-2012).

When comparing the coal mining sector in Türkiye with the USA's sector through the last ten years, we can notice a huge difference (fig. 2). For instance, comparing yearly death rates per million tons of coal produced we instantly observe the high death rates among Turkish coal workers for each million tons. These rates reached enormous peak (nearly 5 miners for each million tons), in the year 2014 due to the tragic event of Soma disaster, ranking that year as the highest in terms of occupational fatalities, which have led to increased scrutiny of mining practices and regulations in the country. Besides, we can clearly see that even with the large production values of the USA, which attained double of the Turkish ones in some of the years, the fatality rates are incomparable.

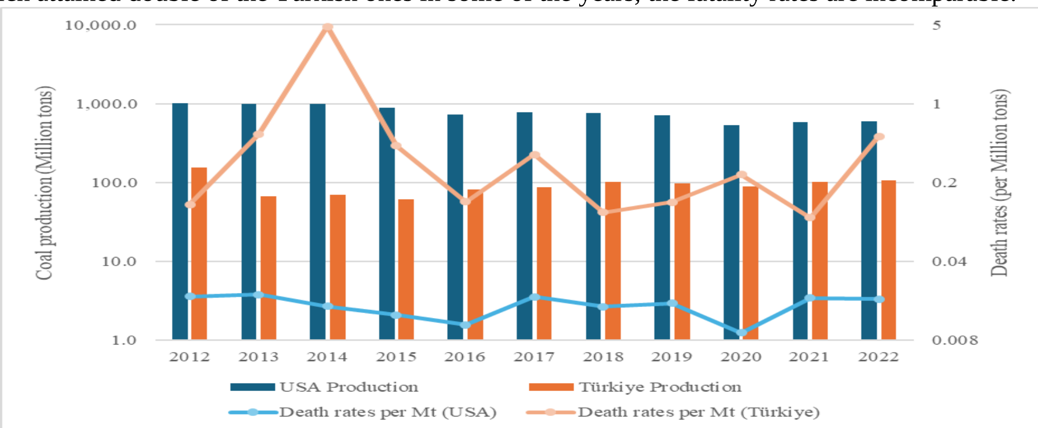


Fig. 2. Türkiye and USA coal production and death toll rates within the last decade [15, 14, 16, 17, 18, 19].

In the same context of comparison, when analyzing the incidence rates (IR) in the two countries within the same time span, we notice a clear difference between the two (fig. 3). We notice an increasing trend toward high numbers in terms of incidence for 200000 working hours in Türkiye's coal production sector. In contrast, the USA's incidence rates trend is miraculously constant and low, given the high production numbers, mentioned earlier.

IR is one of the indicators that can help measure occupational accidents occurrences rates, taking into account several parameters such as the workforce, their total working hours, and the number of accidents that occurred during a specific time period. It is calculated as follows:

$$IR=\frac{Number\ of\ occupational\ accidents}{Total\ exposure\ hours}\times 200{,}000 \quad (1)$$

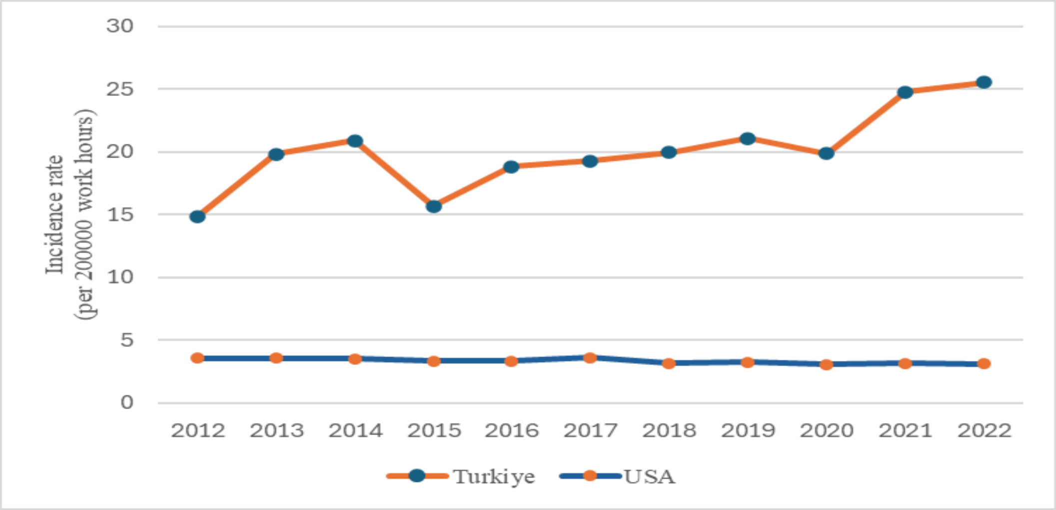


Fig. 3: Incidence rates in Türkiye and U.S.A coal production sector within the last decade.

Today, Türkiye's production of coal, from the last data available, reached 140 million tons, but the price was 54 workers, unfortunately [4]. On the other hand, the USA coal production attained 539 million tons, with a death toll that reached 11 workers [14, 20, 18].

According to statistical reports from the Social Security Institution of Türkiye (SGK) 104,099 coal and lignite production-related workers have been exposed to work accidents or occupational diseases within the last decade (fig. 4) [21].

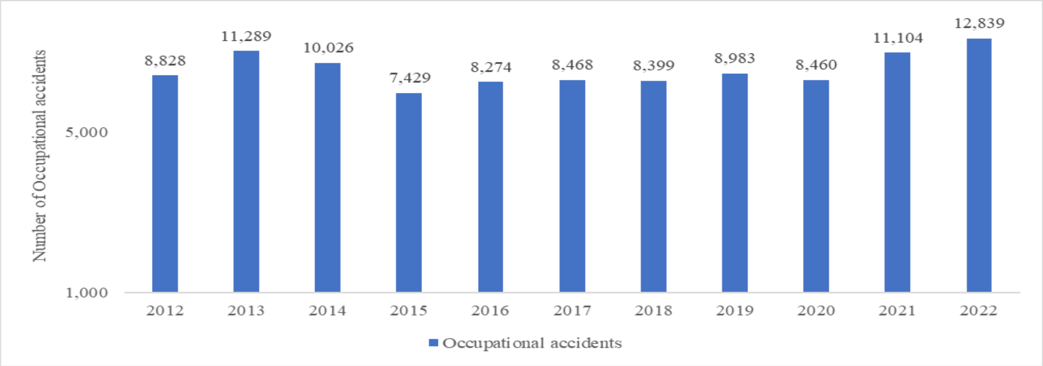


Fig. 4. Insured workers having or exposed to occupational accidents in Türkiye Coal and Lignite production sector within the last decade.

The statistics for sure show a massive increase in the last couple of years, even though the Turkish mining sector has faced criticism over the years for its safety standards which, as we can see, still completely insufficient to cope with the high production levels.

The same statistics reveal frightening numbers of deaths and permanent incapacity among workers that occurred due to work accidents related to coal production activities in the same period (fig. 5) [21].

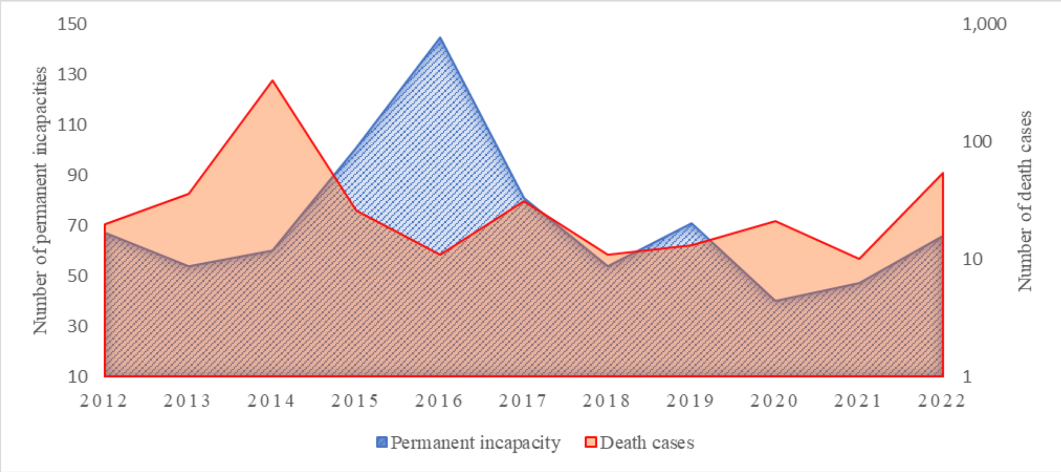


Fig. 5. Insured workers deceased/permanent incapacity due to occupational accidents in Türkiye's Coal and Lignite production sector within the last decade.

These statistics reveal that, unfortunately, 786 workers were permanently incapacitated, and a death toll of 568 among workers in the coal and lignite sector within the same period.

Generally, accidents frequency rates (AFR) and accidents severity rates (ASR) are used to get a deeper understanding and evaluation of the data collected from occupational accidents. To clarify, these rates are used to measure past performance indicating how repeatably and how severe these accidents were withing a defined timeframe. To calculate these rates, the following formulas are used:

$$AFR = \frac{Total\ number\ of\ accidents}{Total\ exposure\ hours} \times 1{,}000{,}000 \quad (2)$$

$$ASR = \frac{Total\ number\ of\ Lost\ workdays}{Total\ exposure\ hours} \times 1{,}000 \quad (3)$$

AFR & ASR show an increasing trend in recent years, except when AFR reach low values 74.04 accidents for every million working hours and 78.37 accidents for every million working hours in 2012 and 2015, respectively (fig. 6). These values are considered to be the lowest within the last decade, yet these values are still very high compared to other countries. The rate has reached its max in 2022 within the last ten years, according to the last data available, with more than 127.64 accidents for every million working hours.

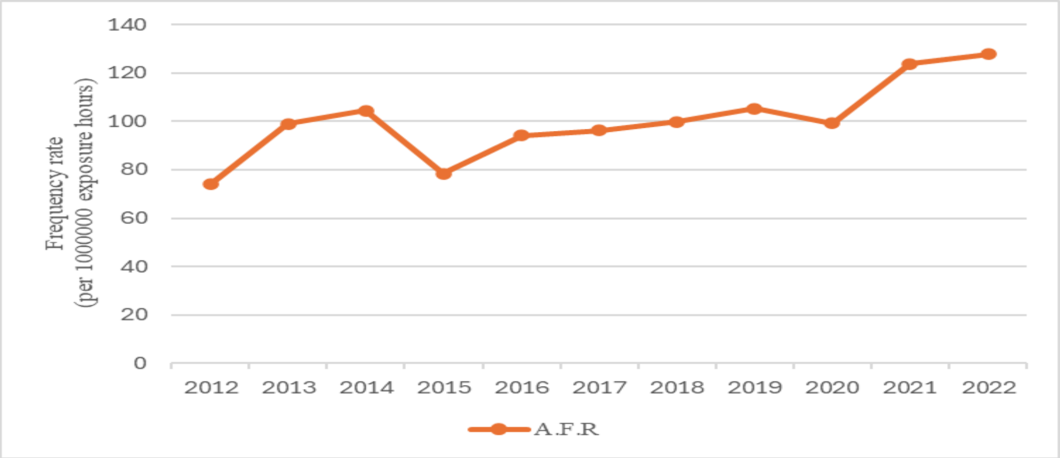


Fig. 6: Coal & lignite mining accidents frequency rates in Türkiye within the last decade.

While ASR reached its lowest, 0.875 lost workday per 1000 working hours, in the year 2018. Which is due to the significant decrease in total days lost within that year. The highest recorded severity rate within the past decade is surely the last two years, with 1.785 and 1.788 lost workday per 1000 working hours in 2021 and 2022, respectively (fig. 7).

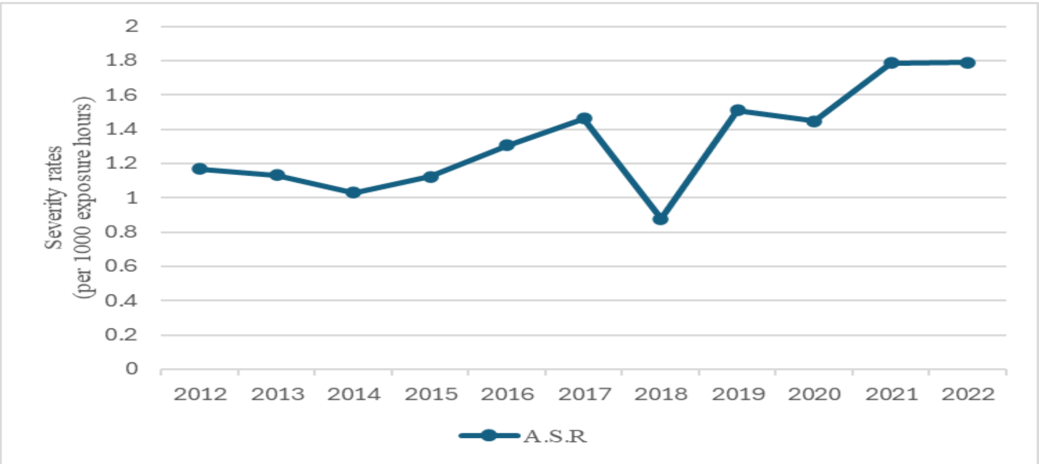


Fig. 7: Coal & lignite mining accidents severity rates in Türkiye within the last decade.

The chronological summary of the deadliest coal accidents in the last decade, with their key details, are as follows (Table 2) [13, 19, 22].

Table 2. Chronological summary of the deadliest coal occupational accidents in the last decade.

Year	Location	Fatalities	Root causes
2012	Soma, Manisa	1	N/A

2013	Kozlu, Zonguldak	8	Sudden Methane discharge.
2014	Soma, Manisa	301	Firedamp explosion/Toxic gasses.
2014	Ermenek, Karaman	18	Flooding.
2017	Kemer, Antalya	2	Firedamp explosion.
2017	Şırnak	7	Landslide
2017	Kilimli- Zonguldak	2	Roof collapse.
2020	Soma - Manisa	3	Roof collapse.
2022	Amasra, Bartin	41	Firedamp explosion.

Moreover, on 13 Sept. 2023, the disaster and emergency presidency (AFAD) reported that at least one person passed and 4 were seriously injured after a coal mine collapse in Armutçuk, Zonguldak, as 4 other workers were still trapped under the rubble.

In addition, it's important to acknowledge the minor incidents, which are not the focus of the present work, however, will be discussed further with insights from the experts and can still significantly impact the health and safety of the workers involved which contribute to the overall safety record of the mining industry.

All of this gives a clear message that lethal coal mine accidents are still in the picture if not treated properly from their root causes. It is vital to note that the previous list has only the major occupational accidents reported in the last decade, however, the number of injuries, traumas, and bad reputation of coal mining especially is immense.

3. Accidents analysis

Coal workers face a range of hazards that make their workplace one of the most dangerous, if not the most dangerous. The spontaneous combustion and high explosion probability properties of coal make it one of the most hazardous earth resources to extract and process.

In underground coal mining, the most frequent accidents occur due to collapses, pillar outbursts, firedamp explosions, gas and dust explosions, blasting and shock waves, roof falls, floodings, transportation and hoisting [23, 9, 24, 25]. Mechanical failure has been a leading contributor to accidents in recent years due to the sensitivity of features. Poor design of features such as tailing dams, ventilation systems, shaft systems, blasting and explosive equipment, and transportation machines could also lead to disasters [26, 27, 28].

On the other hand, preparation plants face other types of hazards, these hazards can be fire hazards, chemical exposure, falling, tripping, slipping, being squeezed under a pile, or hitting a limb while dealing with equipment. Electric shocks, noise and vibration, coal dust which can cause suffocation and skin issues, or skeletal shocks due to carrying high loads [29, 30, 6].

3.1. Factors contributing to accidents

According to a study conducted on research trends in mining accidents between 2015 and 2019, the selected articles were from ten countries, and they managed to identify 57 studies related to mining accidents (fig. 8). Under the theme of "Main causes of mine accidents", half of these articles were subdivided into sixteen main causes. Along with risk management factors (Safety management, Leadership behavior of supervisors, Unsafe behavior, and Lack of safety training etc.), the statistical results of these research trends show that mechanical failures are the dominant factor in contributing to accidents in the coal mining industry [31].

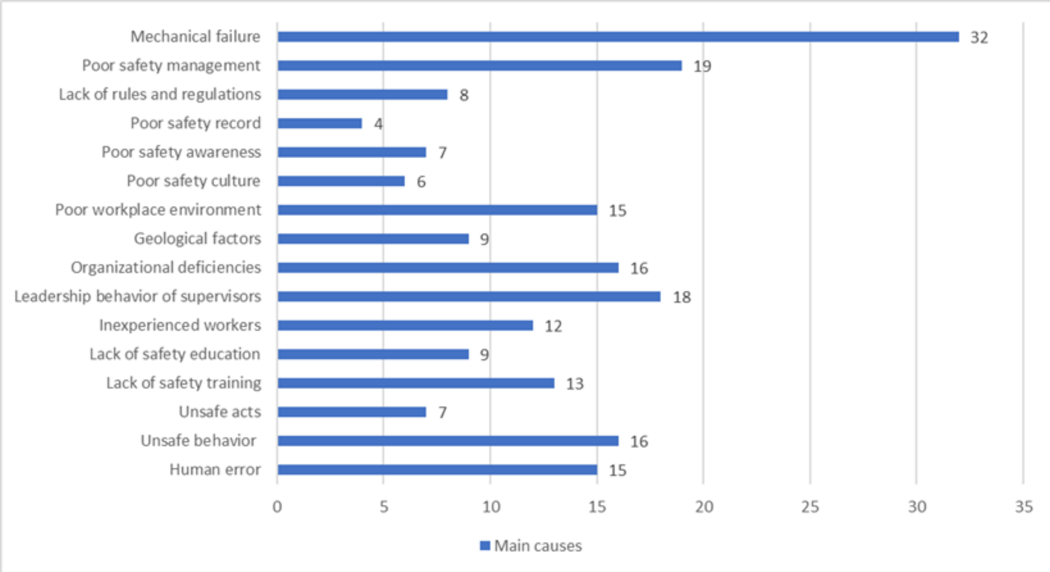


Fig. 8. Main causes of mining accidents in published research (2015-2019).

Investigation on safety culture nowadays is a new area of interest when it comes to accidents prevention by identifying the influence of the cultural factors, such as safety culture. A group of researchers conducted an analysis combining OHS reports from five different countries and more than 900 references, representing a 50-year data set. Their ultimate goal was to respond to the question if/how this concept historically influenced mining accidents. The themes found to be of potential to provide insights into their role in accidents, are subdivided into two main frames (a) Individual and (b) Organization, role in safety culture (Table 3) [32].

Table 3: Key safety culture themes related to main frames (a) Individual (b) Organization.

Individual	Organization
Attitude	Belief
Competence	Safety Culture
Norms	
Patterns	

This analysis identified how the concept of safety culture was framed in the post accidents reports within 50-years of research, which could provide insights on how each of these themes could contribute to understanding and preventing future accidents. For instance, the role of an individual in safety culture is influenced by many factors which consist of the worker's attitude towards safety, how the worker's characteristics add to how he should behave, and his technical competence. On the other hand, the organizational role in safety culture is driven beyond individuals to the larger context of organizational practices. This context is influenced by the commitment from all stakeholders to safety through sharing responsibilities, persuaded by the dominant social practices, and attention.

The chronological summary of the major accidents that occurred during the last decade in Türkiye, shows that firedamp explosions, roofs and wall collapses, ventilation problems, and flooding were the direct reasons that caused these disasters (fig. 9).

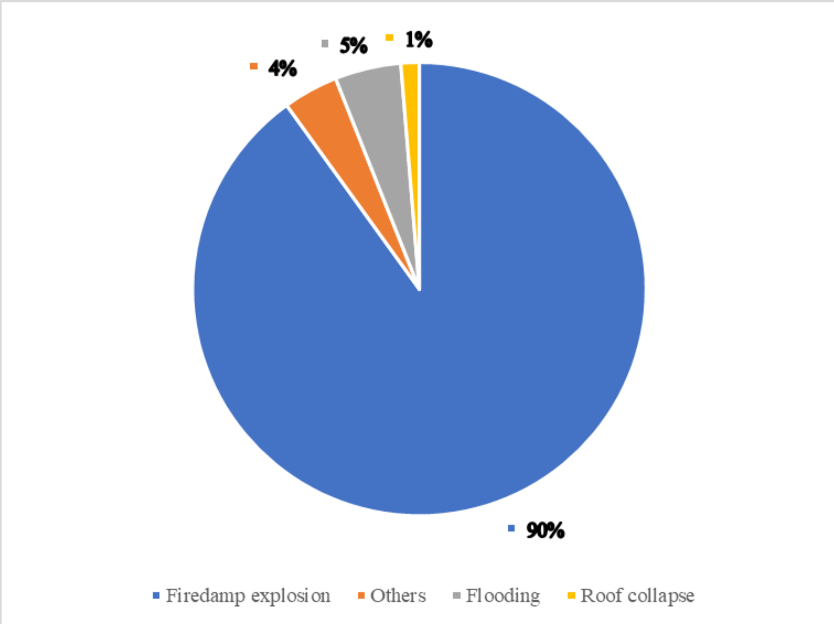


Fig. 9. The proportions on major accidents root causes in the last decade.

When analyzed, the distribution accidents that led to deaths indicate that causes related to gas explosions are the highest in terms of death toll with a percentage of 90%, which is far from other causes due to its presence in the Soma and Amasra disasters.

Methane, emitted throughout the coal mining process, encompasses gases released before, during, and after mining activities, constituting a massive portion of the mine atmosphere. It combines with water vapour, coal or rock dust, and various hazardous gases, creating a complex and potentially perilous mining environment. The origin of these gases spans diverse sources within the mine. Factors such as mineral oxidation, wood degradation, oxygen displacement, and instances like fires and explosions contribute to generating hazardous gases. Among these, methane (CH4) is a primary concern due to its explosive nature and widespread presence in coal mines. Additionally, gases like carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (N2), hydrogen sulfide (H2S), and sulfur dioxide (SO2) pose significant health and safety risks to miners, forming toxic, flammable, or suffocating gas combinations like firedamp and blackdamp (Table 4) [33, 13].

Table 4. Risks for main toxic gases in mines [9, 34].

Gases	Risks
CH4	Explosion, Firedamp and Asphyxiation (Suffocation)
CO	Asphyxia (Suffocation), Explosion
CO2	Suffocation
H2S	Eye and respiratory infections
O2 Shortage	Anoxia (lack of oxygen in the body tissues)
Diesel engines gazes	Respiratory infections, Lung cancer

This investigation, along with many others, attributes a large number of accidents to methane, which can be a key factor in firedamp explosions, with its varying concentrations and conditions creating volatile and potentially catastrophic environments. This gas emanates from diverse sources within the mine, notably ventilation air, pre-mining gas drainage, and post-mining areas. Ventilation air, despite containing lower methane concentrations, significantly contributes to coal mine methane emissions, particularly in gassy coal mines, highlighting its role in the risk profile of mining operations. These reasons can conceal indirect causes as discussed in studies and accidents reports, such as [34]:

- Poor uncertified electrical equipment, wiring and engines.
- Insufficient licensed firefighters, gas detectors, and ventilation in the mine.
- Poor safety plan, safety culture and training.
- Inadequate safety measurements such as gas measurements.
- Poor control and recording of sensors.
- Untrained and unexperienced personnel supervising critical safety posts.

3.2. Expert Insights

We managed to conduct interviews to get a comprehensive view through the insights that were given by the experts and decoding the challenges from different perspectives on preventing coal mining disasters. By connecting our data with insights from experts, which serves as a bridge connecting statistical data of past accidents with the experiential knowledge of those who confront these risks daily, thus offering a more holistic insights on what the statistical data couldn't provide. We asked the experts, from their point of view and experience, three fundamental questions:

- What are the main reasons for occupational deaths in coal mines?
- What are the main reasons for injuries and loss of limbs in coal mines?
- What are the main reasons for minor accidents in coal mines?

OHS experts, MINER 1 and 2, are leading experts in mining safety with several years of experience in the field, were interviewed on the 9th of January 2024. They contributed significantly through supervision of occupational health and safety protocols in the coal company they're working in.

- In response to the first question, MINER 1 stated that, "When fatal work accidents are examined, fortification, ventilation (underground gases), ground water, methane explosion, accidents with mechanical vehicles, falling, blocking, decline, public fall, compressed air hit, accidents while exploding dynamite, wagon crash, rope breaking in descending, etc., accidents caused by electricity or electrical equipment are listed also." While MINER 2, added "Multiple deaths are usually due to fuel explosions, coal dust explosion after ignition, collapses, CO exposure, and falling from heights etc."

They emphasize on the complex nature of coal mining accidents that causes death or multiple death cases. their response highlights the relationship between hazardous environmental factors and dangerous human behavior.

- Going to the second question, MINER 1 answers, "The reasons of work accidents causing limb loss and occupational diseases, along with all the aforementioned reasons, coal dust usually causes occupational diseases, although the risk of occupational disease is low compared to chemical and biological risks because coal is organic."

They both agreed that “Loss of a limb is caused by movement machines and equipment, for example, belt drums, chain conveyor jamming, etc.”

MINER 1 adds, “The first precaution, to prevent the formation of dust at the source, it is to prevent dust from coming up during hole drilling, excavation, and blasting.” In terms of effective preventive measures for these problems, he remarked, “For this, preventing dust by drilling with wet drilling and preventing dust formation by using wet tightening cartridge. When dust forms for any reason, effective ventilation is provided as a precaution and dust is removed from the environment. As a last precaution, the person's exposure is reduced by using a dust mask, when drilling and blasting, in which workers are mostly exposed to dust, in order to reduce exposure, only the driller and his assistant are present. Transportation and other persons are kept in another section to ensure that they are not exposed to dust.” These insights point to the best available precautions from his point of view.

From their point of view, the machinery movement poses a major challenge which requires a high vigilance and safety culture among workers that are exposed to such risk. However, MINER 1 expressed that the main challenge is the prevention of coal dust inhalation which can cause Pneumoconiosis problems. He suggested prevention strategy expresses the complexity of interaction between technological and risk management factors in mining safety. It also highlights the necessity for a holistic safety approach, resonating with present OHS theories that support modern risk management practice.

- Lastly, for the third question, they agreed that “When near miss accidents or accidents with minor injuries are examined, they are usually due to falls due to slippery floor, accidents with hand tools, hit of the air hose, accidents occurring while fortification, accidents while carrying masts, inclined roads, descended stairs. As well as filling the wagon while standing, which can lead to waist injury.”

In terms of preventive actions, MINER 1 says, “Following the same logic, precautions are taken with personal protection first at the source, then in the environment and then in the person. When risks arise from the environment, those risks can be removed.”

As we can clearly notice that, that these minor accidents usually occur due to the overlooked daily work hazards, which surely include inadequate maintenance, high complexity of routine operations, and minor technical deviations. Their responses highlight the crucial significance of minor accidents as an indicator of potential major risks. The importance of these routine hazards, points to the need for continuous vigilance and regular review of safety standards and operational procedures in the mines.

3.3. Safety Measures and regulatory changes

The aforementioned tragedies come as a part of a pattern of accidents in Türkiye, often attributed to inadequate safety measures and regulatory supervision in the coal production industry. Occupational health and safety act (No. 6331) from Türkiye official newspaper (No. 2833) was accepted and implemented on the 20th of June 2012. Its purpose was to ensure OHS in workplaces and to improve safety conditions by regulating duties, authorities, responsibilities, rights and obligations of employees and employers.

The law came with several definitions, from which it defines the work accident as “Any accident that occurs at the workplace or due to the execution of work , causing death or damaging the integrity of the body mentally or physically”, risk as “The possibility of loss , injury or other harmful consequences arising from danger”, and Hazard class “ the hazard group determined for the workplace, taking in account characteristics of work, substances used at every stage, equipment, production forms and methods, and other work related environment and conditions” [35].

The Ministry of Labor and Social Security published, in the official newspaper (No. 28509) dated 26th of Dec. 2012, an annex listing the workplace hazard classification according to economical activities (Table 5).

Table 5. Hazardous Coal related activities (workplace hazard classes list) [36].

NACE Rev.2 Code	NACE Rev.2 Work Definition	Hazard Class
05.10.01	Hard coal mining	Very Dangerous
05.20.01	Lignite mining	Very Dangerous
19.10.10	Manufacture of coke oven from lignite and peat.	Very Dangerous
19.10.11	Manufacture of coke oven from hard coal	Very Dangerous
19.20.12	Fuel obtained by coal dust pressure	Very Dangerous

Coal related activities have always been considered as one of the most, if not the most, dangerous in workplace hazard classification related to Occupational Health and Safety. Consequently, over the past decade, Türkiye has been engaged in the process of reforming its nation's OHS regulatory system, to harmonize it with the regional and international standards.

- 29th May 2013 the government issued law (No. 6485) concerning participation in OHS development framework convention, which was already adopted by the International Labor Organization ILO [37].
- 19th Sept. 2013, a regulation within the scope of the previous law (No. 6331) on OHS in mining workplaces. This regulation came with some general obligations of employers and employees, protection from explosion and harmful ambient air, rescue, communication and warning systems, health surveillance, employee participation, and minimum health and safety requirements, which was well in this amendment [38].
- 24th Sept. 2014, after the SOMA mine disaster a regulation on amending the OHS in mining workplaces, was published in the Turkish official newspaper number (No. 29129). This amendment brought some additional articles to the previous regulations concerning evacuation and rescue process [39].
- 23rd April 2015, (Law No. 6645) major changes were made in the decision provisioning related to regulatory laws of Occupational Health and Safety decrees, such as providing guidance and consultancy to the employer on issues related to OHS, accountability of employers who exposes employees to fatal work accidents, suspension of workplaces that didn't change conditions after work accidents occurred [40].
- 24th March 2016, the ministry of Labor and Social Security made some changes to OHS regulations in the official newspaper (No. 29663), tackling the enforcement of a tracking and monitoring system of employees during their presence in the workplaces, some new definitions of equipment and materials, and some details concerning escape and rescue plans [41].
- 18th Sept. 2017, another regulatory changes (No. 30244), from the Ministry of Labor and Social Security, was published. These changes were concerning technical materials within the mines that may ignite fires and explosions, dealing with certain rescue and evacuation situations and their alternatives [42].
- 24th May 2018, new regulatory amendments were introduced in the official newspaper number (No. 30430), on the principles of regulations regarding procedure of OHS training of employees. This amendment insists on issues such as OHS training of employees, ensuring their participation by recording and documentation reports of training workshops, emphasizing on the responsibility of employers/sub-employers providing OHS training to their employees. It even defined the minimum training time requirement assigned for each level of hazardous workplaces [43].

From that time until now there was no significate amendment or regulations regarding the occupational health and safety, which causes Turkish mining sector to face criticism over the years for its safety standards. Tragic events like the Amasra, Bartin Province mine explosion in lately, have led to increased scrutiny of mining practices and regulations in the country. The accidents often lead to calls for improved safety measures, better regulation, and more stringent enforcement of existing laws to protect miners.

4. Lessons learned and recommendations

Preventing or limiting coal-related activities and accidents demands a long-term commitment to safety, comprehensive regulations, training/education, improving community awareness, accountability, investment in hazard detection technologies and risk management strategies to be implemented.

The preventive actions should start from the root of all administrative and regulatory failures. Implementing and rigorously enforcing robust safety regulations specific to coal mining and processing operations. These regulations should address areas such as ventilation, equipment maintenance, hazard identification, and safe work practices. Moreover, according to the analysis, employees working in the coal mining industry were found to be one the topmost exposed to work accidents and fatality numbers in this particular industry cannot be tolerated. Lessons collected from each incident highlight the critical need for a multifaced approach regarding the enhancement of safety standards. Besides, as we can notice clearly from the measures and regulatory changes section, that regulations and amendments are exclusively implemented almost predominantly after the occurrence of a tragedy, such as SOMA, rather than as pre-action mitigation measures which revels a reactive rather than proactive approach in managing risk. Even though it is commonly used in many industries and countries, the reactive approach is increasingly considered as outdated in risk management practices.

Compliance with international occupational health and safety standards such as OHSAS 18001 and recent standards such as ISO 31000 & ISO 45001, which describes a more advanced management system than OHSAS 18001, with terms, definitions, roles, and scope defined more clearly. The standard's compliance with other management system standards such ISO 9001 and ISO 14001 will provide a great advantage for organizations. ISO 45001 establishes an organizational context, which describes factors (external and internal) that can affect the organization's overall responsibility for OHS in a positive or negative sense. Moreover, the updated standard emphasis on the planning aspect within this section, specifying that organizations are to precisely plan control measures by delineating risks related with both routine and non-routine activities [44]. Furthermore, performance evaluation is previously mentioned in the ISO 18001, but it was highlighted in the new standard that monitoring & performance documentation should be crucial to organizations [45].

Developing and implementing comprehensive training and education programs for coal miners is imperative. These programs should not only cover the fundamental aspects of identifying risks, safe machinery operation, and effective emergency response but also delve into advanced techniques and evolving industry best practices. Moreover, specialized skill enhancement modules should be incorporated into these programs, focusing on specific roles and responsibilities within the mining environment. A study on the relationship between coal workers subjective wellbeing and unsafe behavior concluded that the wellbeing of miners plays a significant role when in it comes to unsafe behavior in terms of, positive, negative emotions and life satisfaction of miners [46]. An investigation of learning needs in the mining industry concluded that, training interventions prepared in the three considered macro-areas with the aim of increasing knowledge, skills, and attitudes on not only a strictly cognitive and technical scientific level, but also socio-psychological level which have been confirmed to be of crucial significance when it comes to coal mining accidents. This approach translates into a skills development plan, wherein socio-constructivist strategies and methodologies will be implemented, with a particular focus on the proactive engagement of workers in their educational journey [47].

Engaging with local communities to raise awareness about the potential risks associated with coal mining and processing, emphasizing the importance of safety measures and the role of the community in supporting a safe working environment. A study analyzed work accidents and occupational diseases occurring in the mining sector in Türkiye, identified that, in recent years, both governmental authorities and employers have undertaken notable and promising initiatives aimed at mitigating work-related accidents in the mining sector. Particular attention has been dedicated to increasing safety measures and promoting safety-oriented culture within mining operations. Consequently, a noticeable but modest trend towards a reduction in work-related accidents has been observed. To augment this positive trend, the authors put forth some recommendations designed to increase the decline in work-related accidents [48].

In terms of accountability, the penalty and reward approach which typically refers to a mechanism of consequences and motivations designed to encourage safety and prevent such tragedies especially for coal mining companies. A study from China found that static penalty approach has a clear impact in promptly decreasing safety hazards and enhancing the immediate state of coal-mine safety production. On the other hand, the dynamic penalty strategy proves effective as mitigation measure and to lower safety risks coming from uncertainty [49]. Alternatively, it's of major importance to have the balance between imposing punishment for violations and disobedience of safety regulations while keeping rewards that motivate those who encourage positive safety behaviour. A group of researchers conducted an analysis of coal safe production under a tripartite evolutionary game model to provide ultimately a reference for an effective reward and punishment mechanism. They found that governmental rewards for coal mining enterprises encourage them to adopt safe production methods, simultaneously, the increase in rewards for local governments boosts the probability of strictly implementing coal safety supervision policy. Moreover, punishment of enterprises for unsafe actions and rent-seeking behaviour of local governments, with an increasing number of fines on both, leads to raising the local government's sternness in implementing safety supervision. Furthermore, increasing sales revenue and rent-seeking costs can lead also to the implementation of coal safe production [50].

Investments in state-of-the-art monitoring and sensing technologies to continuously assess conditions in mines, including gas levels, structural stability, and air quality, and remember early detection of potential hazards is critical for accident prevention. A case study on, the use of sensors in occupational health and safety applications, it was remarkably observed that the utilization of sensors in post-accident risk assessments, employing the 5x5 L-type matrix method, resulted in a significant 75% reduction in the probability of work-related accidents [51].

Risk management and risk analysis protocols are vital, preventing coal mining and processing accidents. This requires conducting thorough risk assessments to identify and evaluate potential hazards within the mining and processing operations. Risk analysis is practical approach in the sense that it deals exclusively with potential accidents, which is the opposite to an accident investigation, which is a reactive approach that seeks to determine the causes and circumstances of accidents that have already happened. Integrating risk management and risk analysis into the training and education programs for coal miners. Again, as we mentioned in the training and education preventive measures, this empowers workers to recognize and respond to potential risks effectively [52]. This assessment needs to be integrated in any project plan that involves any level of occupational risks and should encompass geological, mechanical, and operational factors that may pose risks to worker safety. Developing and implementing risk mitigation strategies based on the findings of the risk assessment. This includes engineering controls, administrative measures, personal protective equipment to reduce the likelihood and severity of accidents, continuous monitoring mechanisms to assess the effectiveness of risk mitigation measures and to adapt to evolving risk factors, and strategies for preventing similar incidents in the future, by analyzing root causes to identify the underlying factors and systemic issues that contributed to the incident.

The mentioned recommendations come as part of the commitment that coal mining companies, central government, local communities, and workers in the coal production field, should comply with the ultimate aim to increase vigilance, improve coal labor conditions, and prevent forthcoming tragedies.

5. Conclusion

This study presents an analysis of coal mining accidents in Türkiye, with the main focus on the last decade (2012-2023), which have highly impacted the reputation of the coal sector negatively. It sheds light on major accidents such as Soma mine disaster, towards minor incidents, which remind us to take serious actions towards the prioritization of safety in coal mining and processing operations.

The historical overview on major accidents revealed that coal fatalities is not to be considered as recent issue, shocking numbers in terms of fatalities were presented only in the twenty-years before 2012, more than four-hundred workers, unfortunately, lost their lives. As in the same period, U.S.A's fatality rates were twice more. However, in recent years, even though with the increase of coal production from the U.S.A which triples Türkiye's production, the number of fatalities is less than the one observed in Türkiye. Which questions the application of safety protocols, standards, and the challenges of safety culture.

The analysis of these accidents revealed multiple factors contributing to the list of root causes. It revealed that ninety percent of these incidents were directly caused by firedamp explosions, which has a long history of being the main trigger of these accidents as we seen in the previous years. The rising of gas content in underground mines produces the necessity to increase airflow rates. This points out the need for more adequate and well-designed ventilation systems that should be considered prior to exploitation phase, during mine development stage. Besides, if the need increases production plans should be modified based on the ventilation requirements. In addition, floodings and roof collapses come in minor percentages. Moreover, other direct and indirect causes, as mentioned in multiple sources, for instance, mechanical failures, poor safety management, lack of safety culture and poor design of mechanical parts, contributed to such accidents. It stretches also to other indirect factors that represent the concept of safety culture which can be grouped as organizational and/or personal factors. From this point, we tracked the regulatory changes that may have occurred in response to these accidents. We found that the foremost general nature of these regulations and amendments were reactive rather than the proactive approach, which serves as a pre-occurrence action to prevent such disasters in the future.

Finally, this study discusses a set of future recommendations drawn from the lessons learned of similar situations and investigations, to ensure the fostering of a strong safety mentality that should be adopted by workers in this field, governmental branches, and stakeholders. Again, following these suggestions from the proactive implementation and enforcement of safety regulations, compliance with the safety international standards, enforcement of safety education on companies, raising safety awareness among workers and local communities, investments in monitoring and safety technologies, to the development of risk management practices, can draw the way for a secure and more sustainable environment for all of those working in the coal production industry in Türkiye.

Acknowledgements

This study is a part of a master thesis carried out by El Hassen Diahah at the Mining Engineering Department of Kütahya Dumlupınar University.

References

[1] ILO, "World statistic," Inter. Labor Org., 13 July 2011. [Online]. Available: https://www.ilo.org/moscow/areas-of-work/occupational-safety-and-health/WCMS_249278/lang--en/index.htm#:~:text=The%20ILO%20estimates%20that%20some,of%20work%2Drelated%20illnesses%20annually. [Accessed 27 Oct. 2023].
[2] WCA, "Coal's contribution," World Coal Assoc., [Online]. Available: https://www.worldcoal.org/coal-facts/coals-contribution/. [Accessed 27 Oct. 2023].
[3] IEA, "Global coal production, (2000-2025)," Inter. Energy Agen., 16 Dec. 2022. [Online]. Available: https://www.iea.org/data-and-statistics/charts/global-coal-production-2000-2025. [Accessed 27 Oct. 2023].

[4] MTA, “2022 faaliyet raporu,” Maden Tetkik ve Arama Genel Müd., Ankara, Turkiye, 2022.
[5] MTA, “Madencilik sektörüne ait temel ekonomik göstergeler,” MTA Genel Müd., Ankara, Turkiye, 2022.
[6] P. E. Fındıkçıoğlu, “Investigation of workplace accidents in coal and mineral processing plants: unsafe acts, safety culture and safety leadership [Ph.D. - Doctoral Program],” 2018. [Online]. Available: https://open.metu.edu.tr/handle/11511/27236. [Accessed 15 Feb. 2023].
[7] K. Koçali, “Sosyal güvenlik kurumu’nun 2012-2020 yillari arasi iş kazalari,” Akad. Yaklaş. Dergisi, vol. 12, no. 2, pp. 302-327, 2021.
[8] C. Hüseyin and al., “High-risky sectors in terms of work accidents in Turkey,” Int. Journal of Eng. and Dev., vol. 14, no. 1, pp. 45-57, 31 Jan. 2022.
[9] F. Küçük and A. Ilgaz, “Causes of coal mine accidents in the world and Turkey,” Turk Thor. Jour., vol. 16, no. 1, pp. 9-14, 2015.
[10] S. Sadid and A. Konuk, “Türkiye madencilik sektörü iş kazalarının yoğunlaşma analizleriyle değerlendirilmesi,” AKU Jour. Sci. Eng., vol. 23, no. 2, pp. 487-502, 21 Mar. 2023.
[11] TKI, “Faaliyet Raporu 2022,” Türkiye Kömür Işletmeleri Kurumu (TKI), Ankara, Turkiye, 2022.
[12] TMMOB, “Soma faciasi ön raporu,” Maden Mühendisleri Odası, Ankara, Turkiye, 2014.
[13] A. E. Dursun, “An analysis and countermeasures of fatal accidents caused by firedamp explosions in underground coal mines in Turkey,” Bilim. Maden. Dergisi, vol. 58, no. 4, pp. 299-310, Jun. 2019.
[14] MSHA, “Coal fatalities for 1900 through 2022,” Mine Saf. and Health Admin., [Online]. Available: https://arlweb.msha.gov/stats/centurystats/coalstats.asp. [Accessed 12 Dec. 2023].
[15] SGK, “İş kazasi ve meslek hastaliği istatistikleri (4-1/a),” Sosyal Güvenlik Kurumu (SGK), Ankara, Turkiye, 2022.
[16] TÜİK, “Industrial production index,” Türkiye İstatistik Kurumu (TÜİK), 11 Dec. 2023. [Online]. Available: https://data.tuik.gov.tr/Bulten/Index?p=Sanayi-%C3%9Cretim-Endeksi-Ekim-2023-49707&dil=1. [Accessed 18 Dec. 2023].
[17] T.C. enerji ve tabii kaynaklar bakanlığı, “Coal,” Ministry of Energy and Natural Res., 20 June 2023. [Online]. Available: https://enerji.gov.tr/bilgimerkezi-tabiikaynaklar-komur#:~:text=Maden%20ve%20Petrol%20%C4%B0%C5%9Fleri%20Genel,37%20milyon%20ton%20olarak%20ger%C3%A7ekle%C5%9Fmi%C5%9Ftir. [Accessed 15 04 2024].
[18] MSHA, “Mine injury and worktime reports 2012-2022,” Mine Saf. and Health Admin., Arlington, VA, 2023.
[19] TMMOB, “Madencilikte yaşanan iş kazalari raporu (2010-2020),” TMMOB, Maden Mühendisleri Odası, Ankara, Turkiye, 2010-2020.
[20] EIA, “Annual coal report,” U.S Energy Info. Admin., 03 Oct. 2023. [Online]. Available: https://www.eia.gov/coal/annual/#:~:text=Highlights%20for%202022,million%20short%20tons%20(MMst). [Accessed 18 Dec. 2023].
[21] SGK, “İş kazasi ve meslek hastaliği istatistikleri,” Sosyal Güvenlik Kurumu (SGK), Ankara, Turkiye, 2012-2022.
[22] TBMM, “Amasra maden kazası araştırma komisyonu raporu,” TBMM kaza araştırma komisyonu, Ankara, Turkiye, 2022.
[23] H. Chen and al., “Characteristics of direct causes and human factors in major gas explosion accidents in chinese coal mines: case study spanning the years 1980-2010,” Journal of Loss Prev. in the Proc. Indust., vol. 26, no. 1, pp. 38-44, Jan. 2013.
[24] H. H. Erdoğan, “A quantitative risk assessment methodology for occupational accidents in underground coal mines: a case of Turkish hard coal enterprises [Ph.D. - Doctoral Program],” 2016. [Online]. Available: https://open.metu.edu.tr/handle/11511/26151. [Accessed 8 Nov. 2023].
[25] Y. Zhu and al., “A statistical analysis of coal mine fires and explosions in china,” Proc. Safety & Environ. Protection, vol. 121, p. 357–366, Jan. 2019.
[26] A. Dash and al., “Lessons learnt from Indian inundation disasters: an analysis of case studies,” Inter. Journal Disas. Risk Red., vol. 20, pp. 93-102, Dec. 2016.
[27] Y. Zhang and al., “Analysis 320 coal mine accidents using structural equation modeling with unsafe conditions ofthe rules and regulations as exogenous variables,” Accid. Anal. Prev., vol. 92, p. 189–201, Jul. 2016.
[28] L. Wang and al., “Research on the influencing factors in coal mine production safety based on the combination of DEMATEL and ISM,” Safety Sci., vol. 103, p. 51–61, Mar. 2018.
[29] MSHA, “Injury experience in coal mining, 2012,” Mine Saf. and Health Admin., Colorado, USA, 2013.
[30] P. McKennis, “Report of investigation preparation plant fatality (plate press accident),” West Virginia Office of Miners Health, Safety and Training, Oak Hill, USA, 2013.
[31] S. N. Ismail and al., “Research trends in mining accidents study: a systematic literature review,” Safety Sci., vol. 143, no. 105438, p. 105438, 2021.
[32] E. J. Tetzlaff and al., “Safety culture: a retrospective analysis of occupational health and safety mining reports,” Safety and Health at Work, vol. 12, no. 2, pp. 201-208, 2021.
[33] S. S. and al., “An assessment of mine methane mitigation and utilisation technologies,” Prog. in Energy and Comb. Sci., vol. 31, no. 2, p. 123–170, 30 Mar. 2005.
[34] A. E. Dursun, “Statistical analysis of methane explosions in Turkey’s underground coal mines and some recommendations for the prevention of these accidents: 2010–2017,” Nat. Hazards, vol. 104, p. 329–351, Jul. 2020.
[35] Resmî-Gazete, “30 haziran 2012 tarihli ve 28339 sayılı resmî gazete,” 30 June 2012. [Online]. Available: https://www.resmigazete.gov.tr/eskiler/2012/06/20120630-1.htm. [Accessed 24 Dec. 2023].
[36] Resmî-Gazete, “26 aralık 2012 tarihli ve 28509 sayılı resmî gazete,” 26 Dec. 2012. [Online]. Available: https://www.resmigazete.gov.tr/eskiler/2012/12/20121226-11.htm. [Accessed 24 Dec. 2023].
[37] Resmî-Gazete, “29 mayıs 2013 tarihli ve 28661 sayılı resmî gazete,” 29 May 2013. [Online]. Available: https://www.resmigazete.gov.tr/eskiler/2013/05/20130529-10.htm. [Accessed 24 Dec. 2023].
[38] Resmî-Gazete, “19 eylül 2013 tarihli ve 28770 sayılı resmî gazete,” 19 Sept. 2013. [Online]. Available: https://www.resmigazete.gov.tr/eskiler/2013/09/20130919-3.htm. [Accessed 24 Dec. 2023].
[39] Resmî-Gazete, “24 eylül 2014 tarihli ve 29129 sayılı resmî gazete,” 24 Sept. 2014. [Online]. Available:

https://www.resmigazete.gov.tr/eskiler/2014/09/20140924-2.htm. [Accessed 24 Dec. 2023].
[40] Resmî-Gazete, "23 nisan 2015 tarihli ve 29335 sayılı resmî gazete," 23 April 2015. [Online]. Available: https://www.resmigazete.gov.tr/eskiler/2015/04/20150423-3.htm. [Accessed 24 Dec. 2023].
[41] Resmî-Gazete, "24 mart 2016 tarihli ve 29663 sayılı resmî gazete," 24 March 2016. [Online]. Available: https://www.resmigazete.gov.tr/eskiler/2016/03/20160324-5.htm. [Accessed 24 Dec. 2023].
[42] Resmî-Gazete, "18 kasım 2017 tarihli ve 30244 sayılı resmî gazete," 18 Nov. 2017. [Online]. Available: https://www.resmigazete.gov.tr/eskiler/2017/11/20171118-26.htm. [Accessed 24 Dec. 2023].
[43] Resmî-Gazete, "24 mayıs 2018 tarihli ve 30430 sayılı resmî gazete," 24 May 2018. [Online]. Available: https://www.resmigazete.gov.tr/eskiler/2018/05/20180524-1.htm. [Accessed 24 Dec. 2023].
[44] P. C. ISO, "ISO 45001:2018 (F)," Int.l Org. for Stand., Geneva, Switzerland, 2018.
[45] U. M. and al., "Change in occupational health and safety management system: ISO 45001:2018," in 5th Inter. Proj. and Const. Manag. Conference (IPCMC2018), North Cyprus, 2018.
[46] Y. Zhang and al., "Relationship research between subjective well-being and unsafe behavior of coal miners," EURASIA Jour. of Math., Sci. & Tech. Edu., vol. 13, no. 11, pp. 7215-7221, 2017.
[47] S. Miranda and al., "An Investigation of learning needs in the mining industry," Edu. Sci., vol. 13, no. 10, p. 1036, 2023.
[48] N. Bilim and al., "Ülkemizdeki maden sektöründe meydana gelen iş kazası ve meslek hastalıklarının analizi," BEU Journal of Sci., vol. 7, no. 2, pp. 423-432, Nov. 2018.
[49] Q. Liu and al., "Effectiveness research on the multi-player evolutionary game of coal-mine safety regulation in china based on system dynamics," Safety Sci., vol. 111, pp. 224-233, 2019.
[50] K. Zhou and al., "Tripartite evolutionary game and simulation analysis of coal mining safe production supervision under the chinese central government's reward and punishment mechanism," Math. Problems in Eng., vol. 2021, p. 17, 2021.
[51] S. Şimşek and al., "İş sağliği ve iş güvenliği uygulamalarinda sensör kullaniminin incelenmesi," İAÜ journal, vol. 12, no. 1, pp. 41-53, 01 Jan. 2020.
[52] M. Rausand., Risk assessment: theory, methods, and applications, vol. Part 2, NJ, USA: John wiley & sons, Inc., 2011.