



14-17 October 2026

6th

**GLOBAL CONFERENCE on
ENGINEERING RESEARCH**

Proceedings Book

ISBN: 978-625-92493-2-2

PROCEEDINGS BOOK

6th GLOBAL CONFERENCE on ENGINEERING RESEARCH

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Induction Heating of Thermoplastic Adhesives for Bonding of Double-Strap Joints

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Abstract In this study, the effect of induction temperature on the strength of double-strap metal joints with thermoplastic adhesives was investigated. Thermoplastic polyurethane (TPU) and polylactic acid (PLA) were used as adhesives. The induction temperatures used for PLA were 170°C and 200°C, while the TPU induction heating process was carried out at 190°C and 200°C. The strength of thermoplastic adhesive joints was compared to that of the methyl methacrylate (MMA) adhesive joint. Maximum load values of 2279 N and 1349 N were obtained for PLA and TPU joints, respectively. The MMA adhesive joint had a higher load capacity than the induction-heated joints.

Keywords: Induction heating, Steel, PLA, TPU, Joint

I. INTRODUCTION

In joints where two surfaces are held together by an adhesive, both the joint geometry and the adhesive properties are important in determining the joint strength. It is generally preferable for the joint to fail under shear stress, as this is the scenario in which adhesives can achieve their maximum load-bearing capacity. Double-strap joint geometry is favoured for both material assembly and the repair of damaged joints [1]. They reduce bending stresses by preventing axial misalignment at the joint interface [2]. Thanks to its double-sided support, it can transmit higher loads than joints with single-sided support. They can be used reliably in joints with dissimilar adherends. The type of adhesive used is another factor that affects joint strength. It is as important as joint geometry. Structural adhesives with various formulations are now commonly used for load transfer in joints. A previous study on thermoplastic adhesives has demonstrated that materials in this group can be used as alternatives to structural adhesives. [3]. Thermoplastic adhesives are suitable for the induction heating process. The other advantages of these adhesives are their recyclability and the speed of joint assembly. Various studies on joint preparation using the induction method can be found in the literature. These studies have examined the debonding and rebonding of joints, the curing behaviour of ferromagnetic particle-modified adhesives, and the joining of carbon fiber-reinforced thermoplastic composites [4-7].

In the current study, steel sheets were used for double-strap joints. The joints were manufactured using induction heating. PLA and TPU thermoplastic polymer films, which were fabricated using the solution casting method, were used as adhesives in the overlap region of the joints. The strength of the thermoplastic adhesive joints was then compared to that of the methyl methacrylate adhesive joint. An axial tensile test was performed on the joints to determine their failure behaviour and load capacity.

II. MATERIALS AND METHODS

The PLA and TPU thermoplastic films were used as thermoplastic adhesives in the

induction-heated joints. MMA adhesive was used for the adhesive joint. DIN C75 was selected as steel adherend. Thermoplastic films were manufactured by solution casting method. Dimethyl formamide and dichloromethane were used as solvents for TPU and PLA, respectively. The thermoplastic solution is poured into a mould and left in an oven for four hours. Fig. 1 shows molded thermoplastic films in the oven.



Fig. 1. Molded thermoplastic films.

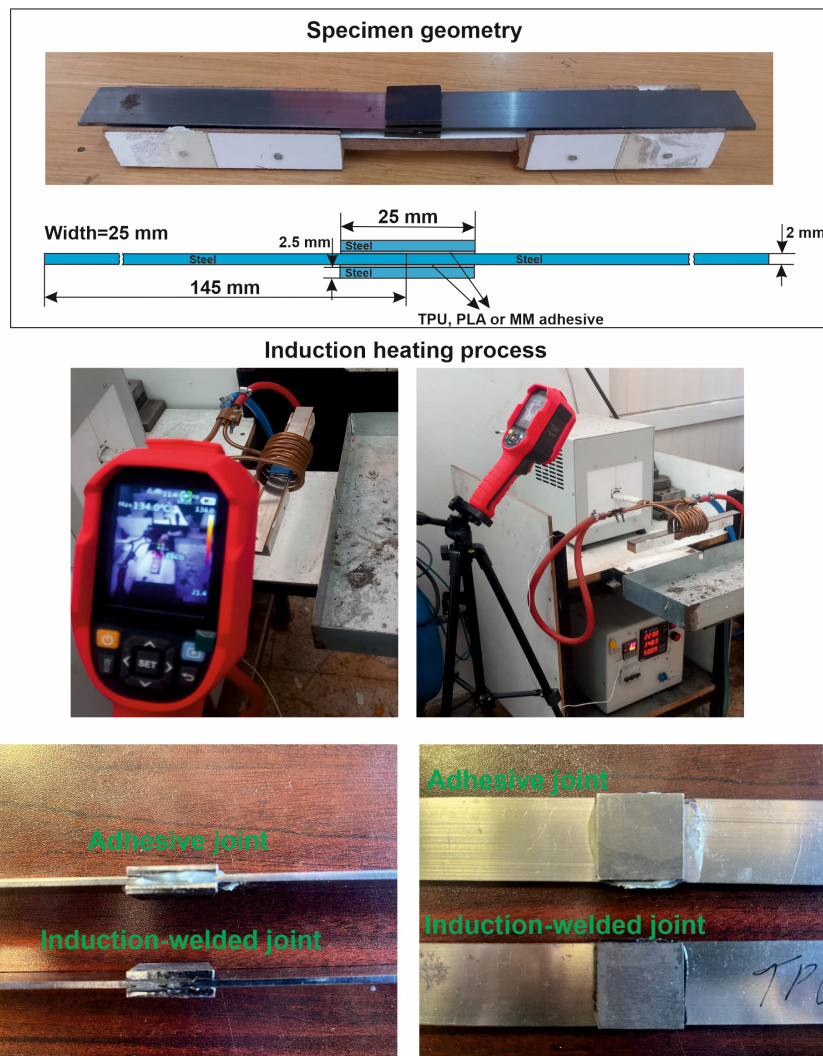


Fig. 2. Joint preparation processes.

The metal sheet surfaces were cleaned with acetone, but no surface preparation process was applied. The induction temperatures used for PLA were 170°C and 200°C, while the TPU induction heating process was carried out at 190°C and 200°C. The induction heating

temperature used for thermoplastic adhesives is above their melting points [8,9]. Fig. 2 shows induction heating process and the details of double-strap joint geometry. During the induction heating process, temperature measurements were taken at the overlap zone. Once the target temperatures were reached, the joint was removed from the coil. It was then allowed to cool under pressure. The MMA adhesive joint was left to cure at room temperature for 24 hours after the adhesive was applied.

Fig. 3 shows tensile test setup for joints.



Fig. 3. Tensile test setup.

The tensile load was applied to each joint at a loading speed of 1 mm/min. The load was continued until the joint was damaged.

III. RESULTS AND DISCUSSIONS

The load-displacement diagrams and failures of induction-heated joints and adhesive joints are shown in Figs. 4-6.

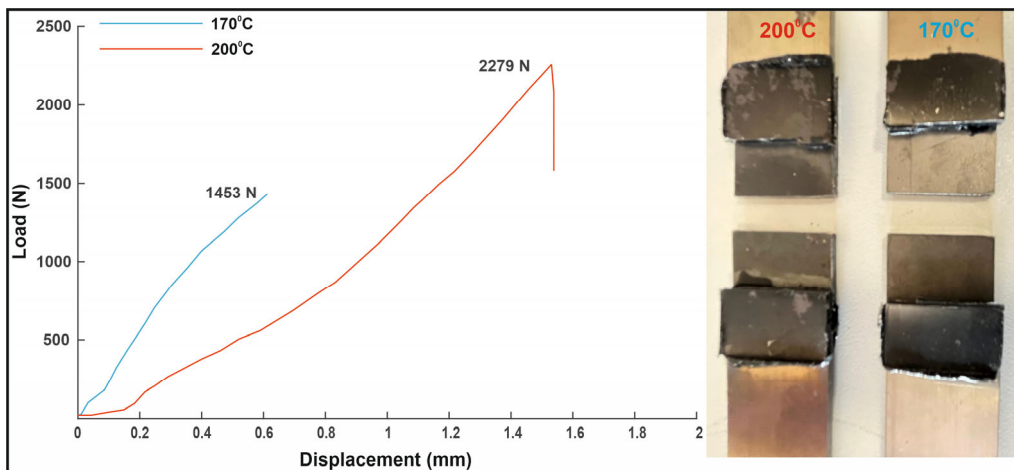


Fig. 4. Load-displacement diagrams and failures of PLA joints.

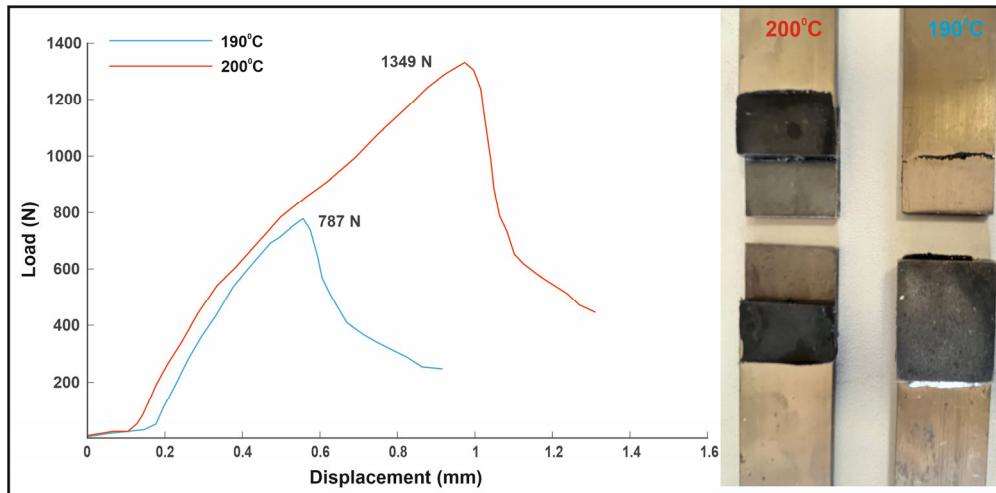


Fig. 5. Load-displacement diagrams and failures of TPU joints.

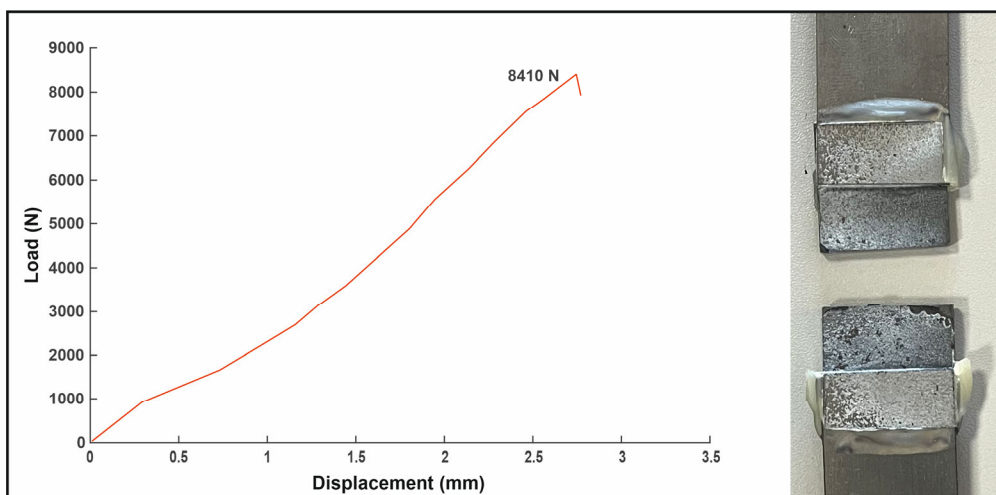


Fig. 6. Load-displacement diagram and failure of adhesive joint.

It was observed from Figs. 4 and 5 that an increase in temperature enhanced the strength of joints prepared via induction heating. The increase in strength associated with the rise in temperature was calculated as 56.8% for the PLA joint and 71.4% for the TPU joint. Maximum load values of 2279 N and 1349 N were obtained for PLA and TPU joints, respectively. The load value for the adhesive-bonded joint is significantly higher than that of the induction-heated joints. A failure load of 8410 N was achieved with the adhesive-bonded joint. The lower strength values observed in the PLA and TPU joints can be attributed to insufficient adhesion forces between the thermoplastic adhesives and the steel adherends due to a lack of surface preparation. The strength of joints bonded with thermoplastic adhesives can be increased by using the correct surface preparation methods. In the case of the adhesive bonded joint, bonding to the surface occurred despite the absence of surface preparation, leading to a significant increase in strength compared to the induction-heated joints. The lack of extensive surface pretreatment did not adversely affect the joint strength of MMA adhesive. When MMA adhesive was used, cohesive failure occurred, demonstrating that high adhesion forces were achieved across the entire overlap area. Although thermoplastic adhesive joints have lower strength values than MMA adhesive, they can be used for joints that require low load transmission and short processing times.

IV. CONCLUSION

In this study, the effect of induction temperature on the strength of double-strap metal joints with thermoplastic adhesives (TPU and PLA) was investigated. The induction temperatures used for PLA were 170°C and 200°C, while the TPU induction heating process was carried out

at 190°C and 200°C. Maximum load values of 2279 N and 1349 N were obtained for PLA and TPU joints, respectively. Observed joint failure modes indicated that surface preparation is essential for PLA and TPU joints. In cases where no surface treatment is performed, adhesive joints with PLA and TPU adhesives can be used when low load transmission is required, and a rapid bonding process is needed.

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C++ Ortamında Konteyner Servis Yapılandırılmalarının Güvenli Round-Trip Düzenlenmesi

Safe Round-Trip Editing of Container Service Configurations in C++

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Özet: Docker Compose dosyaları, geliştiricilerin yanı sıra CI/CD hatları ve dağıtım araçları tarafından da programatik olarak değiştirilmektedir. Bu dosyaları genel amaçlı YAML belgeleri gibi ele alan ayrıştır–değiştir–serileştir döngüleri; kullanıcı tanımlı $x-*$ alanlarını, yeni Compose sürümleriyle gelen modellenmemiş özellikleri, kısa ve uzun sözdizimi biçimlerini ve YAML tipini etkileyen tırnak bilgisini kaybedebilir. İncelediğimiz C++ kütüphaneleri arasında, Compose alanları için sınıf tabanlı bir API sunarken bilinmeyen ve $x-*$ alanlarının korunmasını sistematik round-trip deneyleriyle doğrulayan bir kütüphaneye rastlanmamıştır. Bu bildiride, Compose alanlarına tip-farkında erişim sağlayan, değişiklikleri mevcut YAML düğüm ağacı üzerinde gerçekleştiren ve dosyaları atomik olarak kaydeden C++20 kütüphanesi ComposeMorph tanıtılmaktadır. Yaklaşım; 38 kontrollü ve GitHub’dan derlenen 647 gerçek dünya Compose dosyası üzerinde yürütülen yedi deneyle doğruluk, yapı koruma, değişiklik yerelliği, Docker Compose CLI doğrulaması ve performans açısından değerlendirilmiştir. Hedeflenen tek alanlık bir düzenlemede dosyalara eklenen 802 bilinmeyen özelliğin ve 1.203 $x-*$ alanının tamamı korunmuş; kaydetmenin taban gürültüsü düşüldüğünde ölçülen on özelliğin tamamında düzenlemenin kendi katkısı tek satırla sınırlı kalmıştır. Değerlendirme ayrıca yaml-cpp tabanlı serileştirmede sessiz bir tip değişimi kusuru ortaya çıkarmıştır: tırnaklı skalerler tırnaksız yazıldığında docker compose config çıktılarının yalnızca %38,1’ini kabul ederken, ayrıştırıcının sakladığı tırnak bilgisini kullanan serileştirme başarı oranını %100’e (892/892) çıkarmıştır. Bu düzeltme ölçülebilir bir performans bedeli oluşturmamış; eşleşik ölçümde tırnak koruyan serileştirici yaml-cpp’nin kendi serileştiricisinden %4–18 daha hızlı çalışmış ve en büyük dosyalarda yükle–değiştir–kaydet toplamının medyanı yaklaşık 15,23 milisaniye olmuştur. Koruma metinsel değil yapısaldır: yorumlar ve boş satırlar korunmadığından, değişiklik yapılmadan kaydedilen dosyaların yalnızca %4,0’ü bayt düzeyinde aynı kalmıştır. Düzenlenen alt ağacı yeniden kuran ham yaml-cpp kodunun ölçülen hiçbir vakada servisin kardeş alanlarını koruyamaması, bu kazanımın API tasarımından kaynaklandığını göstermektedir. Tüm veri kümeleri, betikler ve ham sonuçlar tek komutla yeniden üretilebilecek biçimde yayımlanmıştır.

Anahtar Kelimeler: Docker Compose, YAML Round-Trip Düzenleme, Kod Olarak Yapılandırma, Yapı Koruma, C++

Abstract: Docker Compose files are increasingly modified programmatically by CI/CD pipelines and deployment tools. Generic parse–modify–serialize cycles can discard user-defined $x-*$ fields, unmodeled properties introduced by newer Compose Specification versions, short-and long-syntax forms, and quoting information that affects YAML types. Among the C++ libraries reviewed, none combines a class-based API for Compose fields with preservation of unknown and $x-*$ properties validated through systematic round-trip experiments. We present

ComposeMorph, a C++20 library that provides type-aware access to Compose fields, edits the existing YAML node tree in place, and saves files atomically. We evaluate the approach in seven experiments over 38 controlled files and 647 real-world Compose files collected from GitHub, measuring correctness, structure preservation, change locality, Docker Compose CLI validation, and performance. All 802 injected unknown properties and all 1,203 $x-*$ fields survive a targeted single-property edit; after baseline save noise is subtracted, the edit itself is confined to one line for all ten measured properties. The evaluation also exposes a silent type-coercion defect in yaml-cpp-based serialization: when quoted scalars are emitted without quotes, docker compose config accepts only 38.1% of the outputs, whereas serialization driven by the quote information retained by the parser raises validation success to 100% (892/892). This correction introduces no measurable performance cost: in paired measurements, the quote-preserving serializer is 4–18% faster than yaml-cpp's serializer, and the median load–modify–save time is approximately 15.23 ms even for the largest files. Preservation is structural rather than textual: because comments and blank lines are not retained, only 4.0% of files are byte-identical after an unmodified save. A direct yaml-cpp implementation that rebuilds the edited subtree preserves the service's sibling fields in none of the measured cases, indicating that the observed preservation follows from the API design. All datasets, scripts, and raw results are published for one-command reproduction.

Keywords: Docker Compose, YAML Round-Trip Editing, Configuration As Code, Structure Preservation, C++

I. GİRİŞ

Docker Compose dosyaları, uygulamanın nasıl çalıştırılacağını tanımlayan teknik belgeler olmanın yanında geliştiriciler, CI/CD hatları ve dağıtım araçları arasında paylaşılan bir sözleşmedir [1, 2]. Otomatik bir aracın yaptığı küçük bir güncellemenin ilgisiz alanlara yansması, kod incelemesini güçleştirir ve çalışan bir yapılandırmayı fark edilmeden bozabilir. Bu nedenle programatik düzenlemede temel beklenti, yalnızca istenen değişikliğin yapılması ve dosyanın geri kalanının anlamının korunmasıdır.

Bu beklentiye karşılık, YAML'ı okuyup yeniden yazmaktan daha kapsamlı bir problemidir. Compose Specification zamanla genişler; aynı kavram farklı sözdizimleriyle ifade edilebilir ve düzenleyici, henüz tanımadığı alanlarla karşılaşabilir. Buna karşın C++ ekosisteminde, Compose kavramlarını doğrudan temsil eden ve bu çeşitliliği yeniden kullanılabilir bir arayüz arkasında yöneten ortak bir kütüphane bulunmamaktadır.

Bu çalışma, sınıf tabanlı bir Compose API'sinin mevcut belge ağacı üzerinde yerinde değişiklik yaparak bu gereksinimi karşılayıp karşılayamayacağını inceler. Bu amaçla geliştirilen ComposeMorph; hedef alanı düzenlerken belgenin modellenmeyen bölümlerini aynı ağaçta tutar ve kaydetme aşamasında YAML değerlerinin anlamını korumayı amaçlar. Yaklaşım, birbirini tamamlayan kontrollü ve gerçek dünya veri kümelerinde doğruluk, koruma, değişiklik yerelliği, ileriye dönük uyumluluk ve performans bakımından sınanmıştır.

Bu bildirinin katkıları şunlardır:

1. Compose alanları için sınıf tabanlı API, modellenmeyen alanlara genel erişim ve atomik kaydetme sunan yeniden kullanılabilir bir C++ kütüphanesi.
2. Modellenmeyen Compose ve $x-*$ alanlarını koruyan yerinde düzenleme yaklaşımının gerçek dünya dosyalarıyla değerlendirilmesi.
3. Sessiz tip değişimi ile kısa sözdiziminin istemeden mapping biçimine dönüşmesi sorunlarının belirlenmesi ve giderilmesi.
4. İki veri kümesini, yedi deneyi ve yeniden üretim betiklerini içeren açık değerlendirme paketi.

II. ALTYAPI VE MOTİVASYON

A. Docker Compose Specification

Compose Specification [1], bir uygulamanın servislerini ve bunların ağlarını, volume'larını, config ve secret tanımlarını YAML biçiminde tanımlar. Belgenin üst seviyesinde `services`, `networks`, `volumes`, `configs`, `secrets` gibi bölümler ile `x-` önekli extension fields (`x-*`) bulunur. Extension fields, spesifikasyonun araçlara ayırdığı resmî genişletme noktalarıdır: şema bunları serbest bırakır, ancak `x-` öneki taşımayan tanınmayan anahtarları reddeder. Spesifikasyon ayrıca aynı bilgiyi iki biçimde ifade etmeye izin verir. Örneğin portlar kısa sözdiziminde `"8080:80"` biçiminde bir dizi elemanı, uzun sözdiziminde ise `target/published` anahtarlarını taşıyan bir eşleme (mapping) olarak yazılabilir; `environment`, `labels`, `extra_hosts` ve `volumes` için de benzer ikilikler vardır. Bir düzenleme kütüphanesi her iki biçimi de bozmadan taşımak zorundadır.

B. YAML skalerleri ve örtük tip çözümlemesi

YAML'da bir skaler değerin tipi, tırnak kullanımına bağlıdır. Tırnaksız (plain) yazılmış `3.8` bir kayan noktalı sayı, `true` bir boolean, `8080` bir tam sayı olarak çözülür; aynı değerler tırnak-landığında string olur. YAML 1.1 çözümleme kuralları bu kümeyi `yes/no/on/off` gibi boolean eşdeğerlerini, onaltılık ve sekizlik tam sayıları, `1:30` biçimindeki altmışlık (sexagesimal) sa-yıları ve tarih/zaman damgalarını da içerecek biçimde genişletir. Dolayısıyla tırnak, YAML'da biçimsel bir tercih değil, anlam taşıyan bir işarettir: `version: "3.8"` ile `version: 3.8` farklı belgelerdir ve Compose şeması `version` alanının string olmasını şart koşar.

YAML ayrıca yorum satırları, boş satırlar, girinti tercihleri, `anchor/alias` (`&ad`, `*ad`) ve birleştirme anahtarı (`<<`) gibi, belgenin veri içeriğine değil sunumuna ait öğeler barındırır. Bu öğelerin bir kısmı ayrıştırma sırasında veri modeline hiç taşınmaz.

C. Round-trip düzenleme problemi

Bir yapılandırma dosyasını programatik olarak düzenlemenin temel akışı *ayrıştır* → *değiştir* → *serileştir* biçimindedir. Dosyanın bu döngü sonunda ne ölçüde korunacağı, ayrıştırıcı tarafından tutulan ara temsile bağlıdır. Somut sözdizimi ağacı (İng. Concrete Syntax Tree, CST) kulla-nan araçlar, kaynak metindeki sözdizimsel ayrıntıları da saklayabildiği için yalnızca değiştirilen bölümü yeniden yazabilir. `ruamel.yaml` [4] ve `eemeli/yaml` [5] bu yaklaşım sayesinde yorum ve biçim bilgisinin önemli bölümünü korur. `yaml-cpp` [3] ise belgeyi düzenlenebilir bir YAML düğüm ağacına dönüştürür. Bu model belge yapısını, anahtar sırasını ve değerleri korusa da yorum, boş satır, girinti ve bazı skaler gösterim ayrıntılarını tam olarak saklamaz. Bu nedenle dosya kaydedilirken belgenin tamamı yeniden serileştirilir ve hedeflenen değişikliğin dışındaki satırlarda da fark oluşabilir. Daha önemlisi, serileştirme sırasında tırnak bilgisinin kaybedilmesi bazı skalerlerin YAML tipinin sessizce değişmesine neden olabilir.

D. İleriye dönük uyumluluk

Compose Specification gelişmeye devam etmektedir. Bir düzenleme kütüphanesinin nesne mo-del, spesifikasyonun her sürümünü takip edemez. Bu nedenle kütüphanenin bilmediği alanları *kaybetmemesi*, yani modellenmemiş her yapıyı olduğu gibi taşıması pratik bir gerekliliktir. Şema temelli (`dataclass/Pydantic` benzeri) yaklaşımlar bu noktada dezavantajlıdır: model, tanımadığı bir alanı saklayacak bir yere sahip değilse serileştirmede o alan kaybolur.

III. İLGİLİ ÇALIŞMALAR

Bu bölüm, Docker Compose yapılandırmalarının programatik olarak düzenlenmesiyle ilişkili araç ve kütüphaneleri karşılaştırmaktadır.

A. YAML kütüphaneleri

İncelenen C/C++ kütüphaneleri yorum ve biçim koruyan round-trip düzenlemeyi desteklenen bir özellik olarak belgelememektedir. yamll-cpp [3] yorumları atar ve ilgili talep 2015'ten beri açıktır [8, 9]; libyaml yorum belirteci üretmez [10, 11]. rapidyaml'da skaler tip sadakatini bozan ters yönlü bir tırnaklama hatasının daha önce giderilmiş olması [12,13], tırnak kararlarının genel bir hata kaynağı olduğunu göstermektedir. fYAML da round-trip koruma iddiası taşımaz [14].

B. Yorum koruyan ve CST tabanlı araçlar

ruamel.yaml [4], eemeli/yaml [5] ve Rust yaml-edit [15] CST veya kayıpsız ağaçlarla yorum ve biçimi koruyabilir; benzer yaklaşım LibCST ve cstree'de görülür [16, 17]. Ancak bu araçlar genel amaçlıdır, Compose nesne modeli sunmaz ve C++ değildir.

C. Kubernetes ve Docker Compose araçları

Kubernetes kyaml [7] yapıyı ve yorumları korumayı hedeflese de go-yaml kaynaklı yorum ka-yıpları bildirilmiştir [18]. Compose'un başvuru kütüphanesi compose-go [6] yükleme ve doğ-rulamaya odaklanır. fishfinger, compose-py ve docker-compose-yaml-parser programatik dü-zenleme sunar [19–21], ancak bilinmeyen alan ve x-* korumasını ölçülmüş bir garanti olarak belgelemez.

D. Ampirik çalışmalar

GitHub tabanlı çalışmalar Compose kullanımını ve kompozisyon örüntülerini incelemiştir [2, 22]; YAML'ın model yönetimi dilleriyle işlenmesi de model düzeyinde ele alınmıştır [23]. Bu bildirinin odağı ise mevcut dosyanın en az yan etkiyle düzenlenmesidir.

E. Konumlandırma

Taramada, Compose'u C++ ile tipli bir API üzerinden düzenlerken modellenmeyen alanların korunmasını deneysel olarak değerlendiren bir kütüphaneye rastlanmamıştır. ComposeMorph bu boşluğu hedefler; yorum ve tam biçim koruyan bir CST düzenleyicisi değildir.

IV. TASARIM

A. Nesne modeli

Kütüphanenin giriş noktası ComposeFile sınıfıdır: bir dosyayı yükler, servislere ve üst seviye koleksiyonlara erişim verir, dosyayı kaydeder. service(ad) çağrısı bir Service nesnesi döndürür; Service de Compose kavramlarını doğrudan yansıtan alt nesneler sunar (Environment sınıfı labels için de kullanılır). Service üzerinden Environment, ExtraHosts, Ports, Volumes, Networks, BuildConfig, HealthCheck, DependsOn ve DeployConfig nesnelerine erişilir. ComposeFile ayrıca NetworkCollection, VolumeCollection, ConfigCollection ve SecretCollection üst seviye koleksiyonlarını sunar.

Bu sınıfların hiçbirisi veriyi kendi içinde kopyalamaz; her biri, altta yatan YAML düğüm ağacı'nın ilgili düğümüne tutunan ince bir görünümdür. Bir Service nesnesi, servisin düğümüne bir tutamaçtır; üzerinde yapılan her değişiklik doğrudan ağaçta gerçekleşir. Böylece kütüphanenin modellemediği kardeş alanlar, düzenleme sırasında hiçbir zaman okunup yeniden yazılmaz.

B. Tipli API ile genel alan API'nin ilişkisi

Tipli API, spesifikasyonun sık kullanılan alanlarını adlandırılmış işlemlerle sunar; örneğin bir imaj etiketini güncellemek tek satırdır:

```
compose.service("api")  
.setImage("company/api:2.0");
```

Modellenmemiş her alan için aynı nesne, nokta gösterimli genel bir özellik API'si sağlar:

```
api.set("x-company-security.hsm",  
"enabled"); auto v = api.get<std::string>(  
"logging.options.max-file");  
api.remove("deploy.placement.constraints");
```

İki API aynı ağaç üzerinde çalışır ve birbirinin yerine geçebilir: tipli işlemler, genel alan API'nin yapacağı düğüm yazma işleminin adlandırılmış ve tip kontrollü bir kısayoludur. Bu ilişki, ileriye dönük uyumluluğun kaynağıdır. Spesifikasyona yarın eklenecek bir alan için kütüphanenin güncellenmesi gerekmez; alan genel alan API ile okunup yazılabilir, hiç dokunulmasa bile dosyada aynen kalır.

C. Kısa ve uzun sözdizimi

Ortam değişkenleri, etiketler ve ek host kayıtları için kullanılan sınıflar, altlarındaki düğümün liste mi yoksa eşleme mi olduğunu çalışma zamanında tespit eder ve dosyanın mevcut biçimi-mini korur. Örneğin ortam değişkenleri kısa sözdiziminde, yani KEY=value biçimindeki liste girdileri olarak yazılmışsa, bir değişkeni güncelleyen çağrı ilgili girdiyi yerinde değiştirir ya da listenin sonuna yeni bir girdi ekler; bölümü eşlemeye dönüştürmez. Ports, Volumes ve Networks yardımcıları da uzun sözdizimli (eşleme) girdileri hata vermeden işler.

D. Hata yönetimi ve güvenli kaydetme

Ayrıştırılamayan dosya, bulunamayan servis ve iş kuralı ihlali, her biri kendi istisna türüyle bildirilir; örneğin olmayan bir servise erişim ServiceNotFoundException fırlatır. Kaydetme varsayılan olarak atomiktir: içerik önce geçici bir dosyaya yazılır, ardından hedefin üzerine rename ile taşınır; böylece yazma sırasında oluşan bir kesinti mevcut dosyayı yarım bırakmaz. İsteğe bağlı olarak .bak yedeği alınabilir.

V. ROUND-TRIP DÖNÜŞÜM YAKLAŞIMI

A. Ayrıştırma modeli ve neyin korunduğu

ComposeMorph, belgeyi yaml-cpp'nin değiştirilebilir düğüm ağacına ayrıştırır. Bu bir CST değildir: kaynak metnin karakter aralıkları saklanmaz. Ağaçta korunan bilgi şunlardır: belge yapısı, eşlemelerde anahtar sırası, koleksiyonların akış/blok stili, skaler değerlerin metni, anchor ile paylaşılan düğümlerin kimliği ve — bu çalışma için kritik olan — skalerin kaynakta tırnaksız yazılıp yazılmadığını gösteren *belirtisiz etiket*: tırnaksız (plain) skalerler ?, tırnaklı ve blok (|, >) skalerler ise ! etiketi taşır. Ayrıştırmada kaybolan bilgi ise yorumlar, boş satırlar, girinti genişliği, tek/çift tırnak ayrımı, blok skaler stili ve anchor adlarıdır.

B. Değişiklik izleme ve çakışmalar

Kütüphane bir değişiklik günlüğü tutmaz. Her düzenleme, ilgili düğüme doğrudan yazar; do-layısıyla birleştirilecek iki sürüm ve çözülecek bir çakışma durumu oluşmaz. Modellenmemiş alanlar hiçbir aşamada okunmaz, kopyalanmaz veya yeniden inşa edilmez; kaydetmede ağaçta ne varsa o yazılır. Bilinmeyen özelliklerin ve x-* alanlarının korunması, ek bir mekanizmanın değil bu tasarım kararının sonucudur.

C. Serileştirme

yaml-cpp'nin varsayılan serileştiricisi bir skaleri tırnaksız yazmanın güvenli olup olmadığına yalnızca metnine bakarak karar verir: 0.8.0 sürümünde IsValidPlainScalar işlevi değeri null benzeri değerlere (null, ~, boş string) ve sözdizimsel olarak sakıncalı karakterlere karşı sınar, fakat boolean veya sayı gibi görünmesini dikkate almaz. Ayrıca ayrıştırmada üretilen ! etiketi serileştirmede yok sayılır. Sonuç, giriş bölümünde örneklenen

davranıştır: version: "3.8" tırnaksız yazılır ve yeniden okunduğunda artık string değil kayan noktalı sayıdır.

Bu nedenle ComposeMorph, kaydetmeyi kendi ağaç yürütücüsü üzerinden yapar. Yürütücü, yaml-cpp'nin kendi düğüm serileştiricisiyle aynı çıktıyı üretir (aynı anchor/alias numaralandır-ması, aynı etiketler, aynı akış/blok stili, aynı anahtar sırası); tek farkı skaler yazma kararıdır:

1. **Birinci geçiş.** Ağaç dolaşarak her düğümün kaç kez referans edildiği sayılır. Bir düğüme birden çok yoldan ulaşılıyorsa o düğüm anchor gerektiriyor demektir. Kimlik karşılaştı-rması düğüm kimliği üzerinden yapılır; arama uzayını daraltmak için düğümler kaynaktaki konumlarına göre kovalara ayrılır.

2. **İkinci geçiş.** Ağaç yeniden dolaşılır ve yazılır. Birden çok referanslı bir düğüme ilk ulaşıldığında bir anchor atanır, sonraki ulaşım-larda alias yazılır. Eşlemeler ve diziler için düğümün stili (akış/blok) uygulanır.

3. **Skaler yazma kuralı.** Düğüm ! etiketi taşıyorsa (yani kaynakta tırnaklı ya da blok skaler olarak yazıldıysa) değer çift tırnakla yazılır; aksi hâlde yazma kararı yaml-cpp'nin var-sayı-lan davranışına bırakılır. Böylece kaynakta tırnaksız yazılmış sayılar ve boolean'lar tırnaksız kalır, tırnaklı yazılmış string'ler string olarak kalır.

D. API üzerinden yazılan değerler

Round-trip sadakati, yalnızca dosyadan gelen değerleri kapsar. API üzerinden yazılan bir string de aynı tuzağa düşebilir: örneğin `setCommand({"run", "--workers", "4"})` çağ-rısında "4" tırnaksız yazılırsa Compose şeması `command` dizisinin tüm elemanlarının string olmasını beklediği için dosya reddedilir. Bu nedenle string alan her setter, yazdığı değeri bir belirsizlik sınamasından geçirir: değer tırnaksız yazıldığında YAML 1.1 veya YAML 1.2 çekir-dek şemasına göre null, boolean, tam sayı, kayan nokta, altmışlık sayı, zaman damgası ya da birleştirme anahtarı olarak çözümlenecekse düğüm ! ile işaretlenir ve yukarıdaki kural gereği tırnaklı yazılır. Sınama kasıtlı olarak geniş tutulmuştur: gereksiz tırnaklamanın bedeli estetik-tir, eksik tırnaklamanın bedeli sessiz tip değişimidir.

Mevcut bir değer-in üzerine yazıldığında etiket korunduğu için, kaynakta tırnaklı olan bir alan güncellendikten sonra da tırnaklı kalır; kaynakta tırnaksız olan bir alan ise değeri belirsiz olma-dıkça tırnaksız kalır.

E. Desteklenmeyen YAML özellikleri

Yorumlar ve boş satırlar ayrıştırmada kaybolduğu için çıktıda bulunmaz. Anchor/alias yapıları korunur — somut değerlere genişletilmez — ancak anchor adları ayrıştırmacı tarafından saklan-madığından çıktıda otomatik üretilmiş sayısal adlarla (&1, *1) yeniden yazılır. Tek tırnaklı skalerler çift tırnakla yazılır. Blok skalerlerin (|, >) içeriği korunur, ancak stil bilgisi saklan-madığından değer kaçış dizileri içeren tek satırlık çift tırnaklı bir string olarak yazılır (örneğin `"echo one\necho two\n"`); Veri Kümesi B'deki 647 dosyanın 55'inde (%8,5) en az bir blok skaler bulunmaktadır. Bu davranışlar ölçümleriyle birlikte bulgular (Bölüm VIII.) ve kısıt-lamalar (Bölüm XI.) bölümlerinde raporlanmaktadır.

VI. GERÇEKLEŞTİRİM

ComposeMorph C++20 ile yazılmıştır ve GCC 11 veya Clang 13 ve üzeri derleyicilerle kuru-labilir; değerlendirmede GCC 14.2 kullanılmıştır. Derleme sistemi CMake (≥ 3.16), tek dış bağımlılık yaml-cpp'dir ($\geq 0.7.0$; ölçümlerde 0.8.0). Birim testleri GoogleTest ile yazılmış ve CTest'e bağlanmıştır; paket şu anda 55 test içermektedir.

Kütüphane kodu toplam 2.471 satırdır (1.832 satır .cpp kaynak kodu ve 639 satır baş-lık). Değerlendirme altyapısı ayrıca beş adet C++ ölçüm aracı (toplam 557 satır) ve on iki

Python betiği (toplam yaklaşık 4.140 satır) içerir. Depoda `src/` ve `include/` kütüphaneyi, `benchmarks/` ölçüm araçlarını, `datasets/` iki veri kümesini, `scripts/` deney sürücülerini, `results/` ham çıktıları, tabloları ve figürleri, `paper/` ise bu bildiriye barındırır.

Docker Compose ile bütünleşme iki düzeydedir. Kütüphane içinde

`ComposeFile::validate()` yaygın alanlar için iş kuralı denetimleri yapar: servis adının biçimini ve servis düğümünün eşleme olmasını; `extends` kullanan servisler dışında `image` ya da `build` alanlarından en az birinin bulunmasını; `ports`, `volumes`, `networks` ve `environment` gibi temel alanların YAML türlerini; `port` ve `volume` girdilerinin biçimini ve yinelenmesini; liste biçimli `environment` girdilerindeki ve `networks` başvurularındaki tekrarları ve üst seviyede `networks` bölümü bulunan dosyalarda tanımsız ağlara yapılan başvuruları denetler. İnterpolasyon içeren değerler (örneğin `"${PORT}:80"`) çalışma zamanında çözüldüğünden denetim dışında bırakılır. Asıl doğrulama ise dış araçla yapılır: üretilen her çıktı `docker compose config` komutundan geçirilir (Bölüm VII.).

VII. DENEYSEL YÖNTEM

A. Araştırma soruları

- **RQ1 (Doğruluk):** Kütüphane gerçek Compose dosyalarını ayrıştırıp değiştirdikten sonra geçerli Compose dosyaları üretiyor mu?
- **RQ2 (Koruma):** Yalnızca belirli bir alan değiştirildiğinde, değişiklikle ilgisi olmayan yapılandırma bilgisinin ne kadarı korunuyor?
- **RQ3 (Değişiklik yerelliği):** Hedeflenen alan değiştirilirken dosyada ne kadar gereksiz değişiklik oluşuyor?
- **RQ4 (İleriye dönük uyumluluk):** Nesne modelinde tanımlanmamış Compose özellikleri kaybedilmeden taşıyor mu?
- **RQ5 (Performans):** Yükleme, değiştirme ve serileştirme maliyeti gerçek kullanım için kabul edilebilir mi?

B. Veri kümeleri

Veri Kümesi A (kontrollü), elle yazılmış 38 dosyadan oluşur: 24 dosya Compose özelliklerini tek tek (`build`, kısa ve uzun sözdizimli `environment/ports/volumes`, `networks`, `depends_on`, `healthcheck`, `deploy`, `configs`, `secrets`, `labels`, `profiles`, `logging`, `sysctls`, `ulimits`, `devices`, `x-*` alanları, modellenmemiş alanlar ve iç içe genel özellikler) izole eder; 2 dosya bunları birlikte içerir; 10 dosya sınır durumlarını (`anchor/alias` ve birleştirme anahtarı, tırnaklı skaler biçimleri, yalnızca `build` içeren servis, Unicode içerik, `null` ve boş değerler, `external` kaynaklar, `extends`, `include`, yalnızca büyük/küçük harfle ayrıışan anahtarlar) sınar; 2 dosya ise koruma deneylerinin işaretçi kalıplarını taşır.

Veri Kümesi B (gerçek dünya), açık kaynak GitHub projelerinden iki adımda otomatik olarak toplanmış 647 Compose dosyasından oluşur. İlk adımda GitHub kod arama API'sinin `filename:docker-compose.yml` sorgusundan 597, depo aramasının `topic:docker-compose` sorgusundan 3 dosya alınmıştır; adaylar depo ve dosya yolu düzeyinde tekilleştirilmiş, yalnızca geçerli YAML olarak ayrıştırılan ve bir `services` eşlemesi içeren dosyalar tutulmuştur. Bu dosyaların satır sayısı medyanı 36, en büyüğü ise 405 satırdır; büyük dosya grupları hiç temsil edilmemektedir. Bu nedenle ikinci adımda, çok servisli yığınlar barındırma olasılığı yüksek depolarda (`homelab`, `self-hosted`, izleme yığınları) tüm dosya ağacı taranarak 500 satırın üzerindeki 47 Compose dosyası ayrıca eklenmiştir. Dolayısıyla korpus büyük dosyalar yönünden bilinçli olarak zenginleştirilmiştir. Toplama ve analiz betikleri depoda yayımlanmıştır. Birleşik korpus yine de literatürdeki gözlemlerle uyumlu biçimde küçük dos-

yalara eğilimlidir: satır sayısı medyanı 39 (en büyük dosya 2.591 satır), servis sayısı medyanı 2 (en fazla 56), üst seviye bölüm sayısı medyanı 2, YAML iç içelik derinliği medyanı 4 ve $x-*$ alanı sayısı medyanı 0'dır. Son değer, $x-*$ ve modellenmemiş alan deneylerinde neden kontrollü işaretçi enjeksiyonuna başvurduğumuzu açıklar: bu alanlar gerçek dosyalarda doğal olarak nadirdir.

C. Deneyler

Yedi deney yürütülmüştür: (1) kimlik round-trip (değişiklik yapmadan yükle-kaydet), (2) hedefli değişiklik ve değişiklik yerelliği (on ayrı özellik üzerinde), (3–4) modellenmemiş alan ve $x-*$ alan koruma, (5) docker compose config ile doğrulama, (6) ham yaml-cpp ile karşı-laştırma, (7) performans. Her deney her iki veri kümesi üzerinde de koşulmuştur. Deney 6'da üç araç karşılaştırılır: ComposeMorph; düğümü yerinde değiştiren *dikkatli* ham yaml-cpp kodu; ve aynı düzenlemeyi ilgili alt ağacı yeniden inşa ederek yapan *saf* ham yaml-cpp kodu. Deney 2'de kütüphane ports, extra_hosts ve networks için yerinde değiştirme değil yalnızca ekleme ve çıkarma işlemi sunduğundan, bu üç özellikteki hedefli değişiklik listeye tek bir girdi eklemektir. volume-source düzenlemesinde en az bir kısa sözdizimli volume girdisi bulu-nan servisler uygun kabul edilmiş, volume girdilerinin tamamı uzun sözdizimli olan servisler deneyden dışlanmıştır. Dikkatli araç yaml-cpp'nin varsayılan serileştiricisini kullandığından, Deney 5 ve tırnak analizinde aynı zamanda “düzeltme öncesi” sütununu sağlar; bu eşdeğerlik ölçülmüştür (Bölüm VIII.).

D. Metrikler ve istatistiksel değerlendirme

Metinsel koruma, girdi ile çıktı arasındaki değişen satır sayısı, değişen satır oranı, satır düzeyinde Levenshtein uzaklığı ve normalize edilmiş düzenleme uzaklığı ile ölçülür. Değişiklik yerelliği için *beklenen değişen satır / gerçekleşen değişen satır* oranı kullanılır; beklenen değer tek alanlık bir düzenleme için 1'dir. Aynı dosyanın değişiklik yapılmadan kaydedilmesindeki taban gürültü, düzeltilmiş oranda gerçekleşen satır sayısından düşülür. Anlamsal koruma iki bağımsız doğrulama mekanizmasıyla ölçülür: docker compose config (Compose şemasının kendi doğrulayıcısı) ve PyYAML ile yeniden yükleme (değerlerin YAML tiplerinin korunup korunmadığı). Performans ölçümleri her dosya için 30 yinelemeyle yapılır; medyan, ortalama, standart sapma ve p95 raporlanır. İki serileştirici karşılaştırılırken ölçümler aynı süreçte, aynı ağaç üzerinde ve yineleme başına sıra değiştirerek eşleşik biçimde alınır; dağılım varsayımı yapmamak için Wilcoxon işaretli sıralar testi (normal yaklaşım) kullanılır.

E. Ortam ve tekrarlanabilirlik

Ölçümler 12. nesil Intel Core i7-1255U (12 mantıksal çekirdek), 15,3 GiB RAM, Debian GNU/Linux 13 (çekirdek 6.12), GCC 14.2.0, Release derleme, C++20 ve Docker Compose 2.26.1 ortamında yapılmıştır. Tüm deneyler depodaki tek bir komutla yeniden üretilebilir:

`./scripts/run-all-experiments.sh`. Ham çıktılar, tablolar ve figürler `results/` altında yayımlanmıştır; düzeltme öncesi tablolar karşılaştırma için `results/pre-fix/` altında saklanmıştır.

Tablo I. Docker Compose doğrulama başarı oranı (Veri Kümesi B)

Çıktı	ComposeMorph	Karşılaştırma sürümü
Kimlik round-trip	491/491 (%100)	187/491 (%38,1)
Hedefli image düzenlemesi	401/401 (%100)	153/401 (%38,2)
Toplam	892/892 (%100)	340/892 (%38,1)

VIII. BULGULAR

Bulgular, deney çıktılarından otomatik olarak üretilen özetlere dayanmaktadır. “Karşılaştırma sürümü” sütunları, aynı düzenlemeleri yaml-cpp’nin varsayılan serileştiricisiyle gerçekleştiren dikkatli ham yaml-cpp aracına aittir. Bu araç, düzeltme öncesi ComposeMorph ile 100 dosyanın tamamında bayt düzeyinde aynı çıktıyı üretmiştir.

A. RQ1 — Doğruluk

Veri Kümesi B’deki 647 dosyanın tamamı ayrıştırılmış (647/647), kaydedilmiş ve kaydedilen çıktı yeniden ayrıştırılabilmektedir (647/647). Veri Kümesi A’da da 38/38 dosya için aynı sonuç alınmıştır.

Asıl ayırım dış doğrulamada ortaya çıkar. Korpustaki 647 dosyanın 491’i (%75,9) docker compose config tarafından zaten geçerli kabul edilmektedir; kalanlar eksik .env dosyaları, tanımsız interpolasyon değişkenleri veya bozuk sözdizimi gibi kütüphaneden bağımsız nedenlerle reddedilir ve aşağıdaki oranların dışında tutulur. Tablo I, bu geçerli girdilerden üretilen çıktıların doğrulama sonuçlarını göstermektedir.

Karşılaştırma sürümünde geçersizleşen 552 çıktının 548’i, tırnaklı bir skalerin tırnaksız yazılması sonucu string olması gereken bir alanın sayıya veya boolean’a dönüşmesinden kaynaklanmaktadır. Kalan 4 vakada çıktı, Docker’ın YAML ayrıştırıcısı için sözdizimsel olarak dahi geçerli değildir: kaynakta " : 80 " biçiminde tırnaklanmış bir değer, akış dizisi içinde tırnaksız yazıldığında PyYAML ve go-yaml tarafından okunamamaktadır. ComposeMorph’un tırnak koruyan serileştiricisiyle bu vakaların tamamı ortadan kalkmıştır. Veri Kümesi A’da da ComposeMorph çıktılarının tamamı geçerlidir (64/64); karşılaştırma sürümünde yalnızca tırnaklı skaler biçimlerini sınavan dosyanın iki çıktısı reddedilmektedir (62/64).

B. RQ2 — Koruma

Koruma üç ayrı düzeyde ölçülmüştür.

Yapısal koruma. Gerçek dosyalara kontrollü olarak eklenen ve kütüphanenin modellemediği alanlar, ilgisiz bir alan değiştirildikten sonra tüm vakalarda korunmuştur: 802/802 modellenmemiş alan ve 1.203/1.203 $x-*$ alanı örneği (Veri Kümesi A’da 96/96 ve 144/144). Kontrollü sınır durumlarının altısı da (null değerli $x-*$, skaler değerli $x-*$, liste değerli $x-*$, liste biçiminde bilinmeyen üst seviye bölüm, tipli bir bölümün içine gömülü bilinmeyen alan, başka bir bilinmeyen bloğun içine iki düzey gömülü $x-*$) korunmuştur.

Değer tipleri. Korpustaki 617 dosyada açıkça tırnaklanmış 9.807 skaler değer tespit edilmiştir. ComposeMorph ile round-trip sonrasında bunların hiçbirisi tip değiştirmemiştir. Karşılaştırma sürümünde ise 452 dosyada (tırnaklı skaler içeren dosyaların %73,3’ü) 2.570 değer tip değiştirmektedir: tam sayı görünümlü değerlerin %99,9’u, kayan nokta görünümlülerin %100’ü ve boolean kelimelerinin %99,5’i. Buna bağlı olarak, çıktının girdiyle PyYAML’a göre birebir aynı veriye çözümlenme oranı 33/100’den 100/100’e çıkmaktadır.

Metinsel koruma. Buna karşılık çıktı bayt düzeyinde girdinin aynısı değildir: değişiklik yapılmadan kaydedilen dosyaların yalnızca %4,0’ü (26/647) özdeştir; değişen satır oranının medyanı 0,167’dir (düzeltme öncesi %0,77 ve 0,250). Satır düzeyinde Levenshtein uzaklığının medyanı 7, normalize edilmiş düzenleme uzaklığının medyanı 0,167’dir. Kalan farklar yorumların ve boş satırların kaybindan, girinti normalizasyonundan, tek tırnağın çift tırnağa ve blok skalerlerin tek satırlık çift tırnaklı string’e dönüşmesinden kaynaklanır. Anchor/alias ve birleştirme anahtarı yapıları somut değerlere genişletilmeden korunur, ancak anchor adları sayısal adlarla yeniden yazılır.

C. RQ3 — Değişiklik Yerelliği

On ayrı özellik üzerinde 1.467 düzenleme senaryosu koşulmuştur. Tek alanlık bir düzenlemede değişen satır sayısının medyanı port için 8; image, env ve volume-source için 9; restart için 10; healthcheck-retries için 13; network için 14; deploy-cpus için 20; hostname için 23 ve extra-host için 36’dır. Ham yerellik oranının medyanı bu

nedenle 0,03–0,13 arasındadır. Bu satırların neredeyse tamamı düzenlemenin kendisinden değil, kaydetmede yorum ve boş satır kaybından ve girinti normalizasyonundan doğan taban gürültüden kaynaklanır. Aynı dosyanın değişiklik yapılmadan kaydedilmesindeki gürültü düşüldüğünde, on özelliğin tamamında düzeltilmiş yerellik oranının medyanı 1,0'dır: düzenlemenin kendi katkısı tek satırla sınırlıdır. Buna karşın kod incelemesinde görülen ham diff taban gürültüyü de içerdiğinden tek satırlık değildir (Bölüm IX.).

Aynı ölçüm, kısa sözdizimi hatasının etkisini de ortaya koyar. Düzeltme öncesinde, liste biçimli `environment` bölümüne sahip 94 servisin 83'ünde düzenleme, gürültü düşüldükten sonra da birden fazla satırı değiştirmekteydi (medyan 3 satır), çünkü tek bir değişkenin güncellenmesi listenin tamamını eşlemeye dönüştürüyordu; `extra_hosts`'a girdi eklemede bu sayı 9/34'tü. Düzeltmeden sonra her iki özellikte de böyle bir vaka kalmamıştır (0/94 ve 0/34). Kısa sözdizimi hatasından etkilenmeyen `image` düzenlemesinde bu sayı önce de sonra da sıfırdır.

Deneyde başarısızlık gözlenmemiştir: on özelliğin tamamında 1.467 düzenlemenin tümü tamamlanmıştır.

D. RQ4 — İleriye Dönük Uyumluluk

Kütüphanenin nesne modelinde bulunmayan alanlar, hem $x-$ önekli $x-*$ alanları hem de gelecekteki spesifikasyon alanlarını temsil eden $x-$ öneksiz modellenmemiş alanlar için tam olarak korunmuştur (RQ2). Ancak koruma ile geçerlilik aynı şey değildir. Yalnızca $x-*$ alanları eklenen dosyaların tamamı `docker compose config` tarafından kabul edilirken (83/83; temel çizgide 33/83), $x-$ öneksiz bilinmeyen alan eklenen dosyaların hiçbirisi kabul edilmemiştir (0/83). Bunun nedeni kütüphane değil, Compose şemasının tanınmayan anahtarlar yalnızca $x-$ öneki taşıdıklarında izin vermesidir. Pratik sonuç şudur: ileriye dönük uyumluluk için ayrılmış resmî mekanizma $x-*$ alanlarıdır ve kütüphane bu mekanizmayı eksiksiz desteklemektedir.

E. RQ5 — Performans

Tablo II, dosya boyutuna göre yükle–değiştir–kaydet sürelerinin medyanlarını vermektedir. Ölçümler, her boyut grubunda alfabetik sıradaki ilk 20 dosyadan `image` düzenlemesine uygun bir servis içerenler üzerinde yapılmıştır. Değiştirme adımının maliyeti diğer iki adımın yanında ihmal edilebilir düzeydedir; toplam süre en büyük dosyalarda bile onlarca milisaniye mertebesinde. Tepe bellek kullanımı 4,7 MiB ile 8,2 MiB arasındadır.

Tırnak koruyan serileştiricinin bir maliyeti olup olmadığını ölçmek için iki serileştirici aynı süreçte, aynı ağaç üzerinde ve yineleme başına sıra değiştirilerek karşılaştırılmıştır. `ComposeMorph`'un serileştiricisi tüm boyut gruplarında `yaml-cpp`'nin kendi serileştiricisinden hızlıdır: medyan oran küçük ve büyük dosyalarda 0,96, orta dosyalarda 0,95, çok büyük dosyalarda 0,82'dir ve fark her grupta istatistiksel olarak anlamlıdır (Wilcoxon işaretli sıralar testi, $p < 10^{-10}$). Her dosyanın ilk yinelemesi soğuk başlangıç maliyetini içerir: sayfa hataları, dosya sistemi ön belleği ve API üzerinden yazılan değerlerin belirsizlik sınavında kullanılan düzenli ifadenin süreç başına bir kez derlenmesi. İlk yinelemede değiştirme adımının medyanı 0,80 ms'dir (59 dosyada en fazla 1,07 ms). Bu yinelemeler istatistiklerden çıkarılmamıştır; bu nedenle ortalama ve p95 değerleri yukarı çekilmiştir ve tipik maliyeti medyan daha iyi temsil eder.

Tablo II. Yükle–değiştir–kaydet süreleri, medyan, ms (Veri Kümesi B'den 59 dosya: 17/20/20/2; dosya başına 30 yineleme)

Grup	Yük le	Değiş tir	Kayd et	Topla m
Küçük (<100 satır)	0,15	0,003	0,15	0,31
Orta (100–500)	0,64	0,007	0,55	1,21
Büyük (500–2000)	2,25	0,019	1,96	4,26
Çok büyük (>2000)	8,62	0,076	6,17	15,23

F. Ham yaml-cpp ile karşılaştırma

Deney 6, ComposeMorph'u iki ham yaml-cpp kullanımıyla karşılaştırır. Serileştirme düzeyinde ComposeMorph ile dikkatli ham kullanım arasındaki çıktı farkı 100 dosyanın 96'sında yalnızca tırnak karakterlerinden ibarettir, 4'ünde çıktı zaten özdeştir; tırnak dışında farklılık yoktur. Düzenleme güvenliği düzeyinde ise fark büyüktür (Şekil 1): alt ağacı yeniden inşa eden saf kullanım, ölçülebilen hiçbir vakada düzenlenen servisin diğer alanlarını koruyamamıştır (image için 0/149, hostname için 0/39, env için 0/116), ComposeMorph ise tümünü korumuştur (149/149, 39/39, 116/116). Aynı durum işaretçi alanlarında da görülür: saf kullanım servis düzeyindeki 200 işaretçinin tamamını kaybederken üst seviyedekilerin tamamını korur; hasar, üzerine yazılan alt ağaçla sınırlıdır.

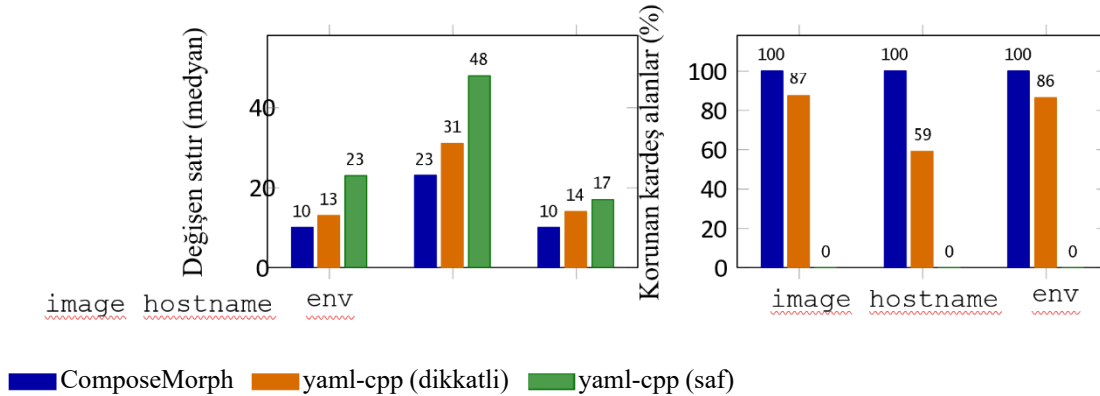
Şekil 1, dikkatli ham kullanımın da kardeş alanları her vakada korumadığını göstermektedir (130/149, 23/39, 100/116). Bu fark yapısal bir kayıp değildir. Korunma, kardeş değerlerin düzenleme öncesi ve sonrasında PyYAML ile karşılaştırılmasıyla ölçülür; dikkatli araç yaml-cpp'nin varsayılan serileştiricisini kullandığından tırnaklı kardeş değerler (ör. "8022:22") tip değiştirir. Bu 51 vakanın 48'inde kardeş alanların tümü çıktıda yerindedir ve yalnızca skaler gösterimleri değişmiştir; kalan 3 vakada çıktı, RQ1 altında açıklanan ":80" sorunu nedeniyle ayrıştırılmaz hâle gelmiştir.

Ergonomi açısından, ComposeMorph'ta on düzenlemenin her biri tek satırdır; aynı düzenlemeleri ham yaml-cpp ile doğru yapmak 1 ile 24 satır arasında kod gerektirir (volume-source için 24, extra-host için 22, env için 18 satır). Satır sayısı hatalı kodu ayırt etmez: env düzenlemesinde bölümün tamamını yeniden kuran saf sürüm (6 satır), doğru sürümün üçte biri uzunluğundadır. image ve hostname için ise doğru sürüm tek satırdır ve saf sürüm (5 ve 3 satır) daha uzundur.

IX. TARTIŞMA

A. Tırnak, biçim değil anlamdır

Tırnak kaybı kozmetik değildir: geçerli girdilerden üretilen çıktıların %62'si Docker tarafından reddedilmiştir. Ayrıştırıcı tırnak bilgisini ! etiketiyle sakladığından düzeltme, mevcut etiket serileştirmede kullanılmasını gerektirir. PyYAML ve Docker bazı skalerleri farklı yorumladığı için iki bağımsız doğrulama mekanizması kullanılmıştır.



Şekil 1. ComposeMorph ile iki ham yaml-cpp kullanımının karşılaştırması (Veri Kümesi B). Solda düzenleme başına değişen satır sayısının medyanı, sağda düzenlenen servisin diğer alanlarının korunma oranı. Alt ağacı yeniden inşa eden saf kullanım hiçbir vakada kardeş alanları koruyamamaktadır (%0, çubuk görünmez). Dikkatli kullanımdaki eksik, tırnak kaybı sonucu tip değişiminden kaynaklanır; kardeş alanlar yapısal olarak yerindedir.

B. Hangi senaryoda ne beklenmeli

ComposeMorph tek alanlı otomasyon değişikliklerinde bilinmeyen alanları korur ve geçerli çıktı üretir. Yorum, boşluk, girinti ve blok skalerlerin metinsel biçiminin korunması gerekiyorsa CST tabanlı bir araç gerekir.

C. Performans ile koruma arasında bir ödünleşme yok

Koruma için performans bedeli ölçülmemiştir: tırnak koruyan serileştirici tüm boyut gruplarında yamll-cpp'den hızlı, düzenleme maliyeti ise yükleme ve kaydetmenin yanında ihmal edilebilir düzeydedir.

D. Compose'a özgü API neden fark yaratıyor?

Doğru yazılmış ham yamll-cpp kodu aynı yapısal korumayı sağlayabilir. ComposeMorph'un katkısı, hedef düğümü yerinde değiştirmeyi ve kısa sözdizimini korumayı varsayılan kullanım hâline getirerek sessiz alan kaybı riskini azaltmasıdır.

X. GEÇERLİLİK TEHDİTLERİ

A. İç Geçerlilik

Deney altyapısı kendi hatalarını ölçümlere taşıyabilir; ilk koşullarda interpolasyonlu imaj adlarını bozan bir ölçüm hatası saptanıp düzeltilmiştir. Koruma deneylerindeki bilinmeyen ve x- * alan-lar sentetiktir; sonuçlar bu kalıplar için geçerlidir. Saf ham yamll-cpp karşılaştırması da gerçek projelerdeki tüm hatalı kullanımları temsil etmez.

B. Dış Geçerlilik

GitHub'dan toplanan 647 dosya özel ve kurum içi kullanımları temsil etmeyebilir. Korpus kü-çük dosyalara eğilimlidir [2, 22]; büyük dosyalar ayrıca eklendiği hâlde 2.000 satırın üzerindeki performans sonuçları yalnızca iki dosyaya dayanır.

C. Yapı Geçerliliği

Değişen satır sayısı anlamsal korumayı tek başına göstermez. Bu nedenle metinsel ölçümler docker compose config ve PyYAML doğrulamasıyla birlikte raporlanmıştır. PyYAML ile go-yamll bazı değerleri farklı çözümlediğinden sonuçlar ayrı tutulmuştur.

D. Sürüm Geçerliliği

Sonuçlar yamll-cpp 0.8.0, Docker Compose 2.26.1 ve ölçüm tarihindeki spesifikasyona bağlıdır. Şema veya serileştirici değiştiğinde oranlar da değişebilir; deneyler bu nedenle tek komutla yeniden çalıştırılabilir.

XI. KISITLAMALAR

Aşağıdaki sınırlar ölçülmüş ve gizlenmemiştir.

- **Yorum satırları korunmaz.** Yorumlar yamll-cpp'nin ayrıştırıcısında veri modeline hiç taşınmadığı için çıktıda bulunmaz. Bu, kütüphanenin düzeltebileceği bir davranış değildir; altta yatan kütüphanede yorum koruma talebi 2015'ten beri açıktır [8].
- **Round-trip bayt düzeyinde özdeş değildir.** Boş satırlar ve girinti tercihleri korunmaz, tek tırnak çift tırnağa dönüşür; dosyaların yalnızca %4,0'ü değişiklik yapılmadan kaydedildiğinde özdeş kalır. Değerlerin YAML tipleri ise korunur.
- **Blok skaler stili kaybolur.** | ve > ile yazılmış çok satırlı değerlerin içeriği korunur, ancak kaçış dizileri içeren tek satırlık çift tırnaklı string olarak yazılır. Bu, çok satırlı command veya sağlık kontrolü betiklerinin okunabilirliğini düşürür; Veri Kümesi B'deki dosyaların %8,5'i (55/647) blok skaler içermektedir.
- **Anchor adları kaybolur.** Anchor/alias ve birleştirme anahtarı yapıları genişletilmeden korunur, fakat adlar ayrıştırıcıda saklanmadığı için çıktıda &1, *1 biçiminde yeniden üretilir.
- **x- öneksiz bilinmeyen alanlar şemaya aykırıdır.** Kütüphane bu alanları eksiksiz ko-

kur, ancak Compose şeması yalnızca x- önekli alanlara izin verdiğinden dosya docker compose config tarafından reddedilir. Bu, kütüphaneden bağımsız bir spesifikasyon kısıtıdır.

- **Doğrulama tam Compose şemasını kapsamaz.** `validate()` yaygın alanları ve iş kurallarını denetler, ancak Compose şemasındaki bütün alanları ve sürüme bağlı bütün kuralları eksiksiz doğrulamaz; tam şema doğrulaması dış araca, yani docker compose config komutuna bırakılmıştır.

- **Platform.** Geliştirme ve ölçümler Linux üzerinde yapılmıştır; Windows ve macOS'ta test edilmemiştir.

XII. SONUÇ

Docker Compose dosyalarının programatik olarak değiştirilmesi, YAML sözdizimini ayrıştır-maktan ibaret değildir: dosyada aracın modellemediği alanlar, kullanıcı tanımlı x-* alanları, farklı sözdizimi gösterimleri ve anlam taşıyan tırnak tercihleri bulunur. Bu bildiride, problemi C++ tarafında ele alan ComposeMorph kütüphanesi sunulmuş; yaklaşımın sağladığı olanaklar ve sınırları 647 gerçek dünya ve 38 kontrollü Compose dosyası üzerinde yürütülen yedi deneyle ölçülmüştür.

Sonuçlar üç noktada toplanabilir. Birincisi, düzenlemeyi düğüm ağacında yerinde yapmak, modellenmemiş alanların korunması için yeterlidir: dosyalara eklenen modellenmemiş alanların ve x-* alanlarının tamamı korunmuştur. İkincisi, düğüm ağacı tabanlı serileştirme sessiz bir tip değişimi kusuru barındırır; ayrıştırıcının sakladığı tırnak bilgisinin serileştirmede kullanılması bu kusuru ortadan kaldırmış ve Docker doğrulama başarısını %38,1'den %100'e çıkarmıştır;

üstelik bunun bir performans bedeli yoktur. Üçüncüsü, koruma davranışı doğru yazılmış ham yaml-cpp koduyla da elde edilebilir; tipli API'nin katkısı, doğru olanı varsayılan yol hâline getirmesidir — ölçümlerimizde makul görünen ama hatalı bir ham kullanım, düzenlenen servisin diğer alanlarını hiçbir vakada koruyamamıştır.

Gelecek çalışmalar için üç yön öne çıkmaktadır. Birincisi, yorum ve boşluk korumasını da kapsayan tam CST tabanlı düzenleme; bu, diğer ekosistemlerde çözülmüş olan problemin C++ tarafındaki karşılığıdır. İkincisi, mevcut doğrulama kapsamının Compose şemasındaki daha fazla alan ve kuralı kapsayacak biçimde genişletilmesi. Üçüncüsü, nesne modelinin Compose Specification ile otomatik eşitlenmesi ve aynı yaklaşımın Kubernetes manifestoları gibi diğer yapılandırma biçimlerine uygulanması.

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Divergence Between Laboratory and In Situ Stiffness Indicators in an Over-consolidated Clayey-Sandy Soil

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Abstract: This study investigates the geotechnical characteristics of foundation soils for a 100-unit public housing project in Cité Selsabil, Batna, Algeria, using a combination of in situ and laboratory investigations. The program included Ménard pressuremeter tests, heavy dynamic penetration tests, boreholes with Standard Penetration Tests (SPT), and laboratory tests for particle-size distribution, Atterberg limits, direct shear, and oedometer consolidation. Laboratory results identified a low-plasticity, moderately compressible, and overconsolidated clay, whereas in situ tests indicated a stiff, dense, and weakly compressible formation. Pressuremeter moduli ($EM = 177\text{--}970$ bar), limit pressures ($PL = 9.9\text{--}30.9$ bar), and SPT values ($N = 56\text{--}65$) consistently confirmed the high stiffness of the soil. The discrepancy between laboratory and in situ results is mainly attributed to sample disturbance. Allowable bearing pressures of 2.30 and 4.59 bar and settlements of 0.54 and 0.21 cm were obtained from laboratory-based and pressuremeter-based approaches, respectively. A conservative allowable pressure of 1.20 bar was ultimately adopted. The results highlight the importance of cross-validating laboratory and in situ data for reliable soil characterization and safe shallow foundation design.

Keywords: *Pressuremeter test, Dynamic penetrometer, Sample disturbance, overconsolidated clay, Bearing capacity, Settlement*

I. INTRODUCTION

This The design of shallow foundations requires reliable estimates of soil bearing capacity and settlement, particularly in fine-grained deposits where laboratory and in situ investigations may provide contrasting assessments of soil stiffness and strength. Laboratory tests provide direct measurements under controlled conditions but are sensitive to sample disturbance, whereas in situ methods characterize the soil in its natural state but generally rely on empirical or semi-empirical correlations to derive mechanical parameters (Mair and Wood 1987; Clarke 1995).

The Ménard pressuremeter test is widely used in French- and Algerian-influenced geotechnical practice and provides both the pressuremeter modulus (EM) and limit pressure (PL), which are valuable indicators of soil deformability and strength (Ménard 1975; Baguelin et al. 1978). The Standard Penetration Test (SPT) provides an independent empirical measure of soil resistance and is commonly used to complement pressuremeter investigations. Numerous correlations between SPT values and pressuremeter parameters have been proposed worldwide; however, their applicability is strongly dependent on local geological conditions. Recent studies on Algerian soils have therefore emphasized the need for site-specific

correlations and caution against direct transfer of relationships developed elsewhere (Bahar et al. 1999, 2012; Mezouar et al. 2017; Letif et al. 2025).

Discrepancies between laboratory and in situ results are particularly relevant for stiff, overconsolidated fine-grained soils, where sample disturbance may lead to an underestimation of the in-situ stiffness and strength (Lunne et al. 2006; Aubeny et al. 2000). A critical comparison of both data sets is consequently necessary to establish reliable and appropriate design parameters.

This study presents an integrated geotechnical investigation for a 100-unit public housing project at Cité Selsabil, Batna, Algeria. The investigation combines laboratory tests with heavy dynamic penetration, Ménard pressuremeter, and SPT soundings. The objectives are to characterize the foundation soil and its physical, mechanical, and chemical properties, compare laboratory and in situ stiffness and strength indicators using published correlations; and evaluate bearing capacity and settlement from both approaches and develop foundation design recommendations in accordance with Algerian technical regulations.

II. MATERIALS AND METHODS

A. Site and Project context

The study concerns the geotechnical investigation for the construction of 100 public rental housing units at Cité Selsabil, in the municipality of Batna, Algeria. A preliminary site visit was carried out to assess surface conditions – topography, vegetation, presence of fill or gullies, and site accessibility – in order to select the most appropriate in situ investigation layout for the project.

B. In Situ Investigation Program

The field campaign comprised four complementary components: heavy dynamic penetrometer testing, Ménard pressuremeter soundings, cored boreholes, and Standard Penetration Tests (SPT). Heavy dynamic penetration tests were performed using a BORRO-type penetrometer, in which a rod string equipped with a conical tip was continuously driven into the ground by repeated hammer blows; the number of blows required for each 20 cm of penetration was recorded and converted into apparent dynamic resistance using the conventional Dutch driving formula, allowing rapid assessment of soil-layer succession, homogeneity, anomalies, and possible hard substrata. Three Ménard pressuremeter soundings (SP01–SP03) were conducted in pre-drilled boreholes according to NF P94-110-1 by inflating a cylindrical probe against the borehole wall and recording the pressure–deformation response at different depths, from which the pressuremeter modulus (EM), limit pressure (PL), and creep pressure (Pf) were determined. Three cored boreholes (SC01–SC03), each 10.00 m deep, were drilled using a SEDIDRILL 1000 rig to characterize the geological formations and recover samples for laboratory testing; the cores were visually logged and preserved in labeled core boxes. Finally, SPT soundings (SPT01–SPT03) were performed within the boreholes using a standard Raymond split-spoon sampler driven by a 63.5 kg hammer falling freely from 76 cm, in accordance with NF P94-116. At each test depth, three successive 15 cm penetration intervals were recorded, and the SPT resistance value (N) was calculated as the sum of the blows required for the second and third intervals.

C. Laboratory testing program

A laboratory testing program was carried out on samples recovered from the cored boreholes, comprising water content and unit weight (oven-drying and hydrostatic weighing), particle-size distribution (sieving and sedimentation, NF P94-057), Atterberg limits (Casagrande cup and thread-rolling methods), consolidated-drained direct shear testing (Mohr–Coulomb interpretation), one-dimensional oedometer consolidation testing, and chemical analysis of

sulfate (SO_4^{2-}) and calcium carbonate (CaCO_3) content.

D. Foundation Design Methodology

Two independent methods, both codified in the Algerian technical regulation DTR-BC 2.331, were used to determine the allowable bearing pressure (Q_{adm}) of a strip footing ($B = 1.80$ m, $D = 1.50$ m): a laboratory-based approach, using Terzaghi's bearing capacity equation with the shear strength parameters obtained from direct shear testing, and a pressuremeter-based approach, using the Ménard–Rousseau method with the net equivalent limit pressure (PL_e^*) derived from the pressuremeter profile and an empirical bearing factor (K_p).

Settlement was similarly evaluated by two independent methods: the layered oedometer method, in which the compressible profile is subdivided into successive layers and the settlement of each layer is computed from its compression index, preconsolidation pressure, and the stress increase ($\Delta\sigma$) induced by the foundation load; and the Ménard–Rousseau pressuremeter settlement method (DTR-BC 2.331), combining a deviatoric settlement component (S_d) and a spherical settlement component (S_c). The coefficient of subgrade reaction (K_v) was additionally derived from the pressuremeter results.

E. Verification of Reported Results

All numerical results extracted from the source geotechnical report were independently re-derived from the underlying raw data prior to inclusion in this article: plasticity indices were recomputed as $IP = WL - WP$; the overconsolidation ratio was recomputed as $OCR = P_c/\sigma_0$; the layered oedometer settlement was recomputed as the sum of the individual layer settlements; the EM/PL ratios were recomputed at every tested depth in SP01–SP03; the SPT N-values were recomputed as $N_1 + N_2$ at every tested interval; and both bearing capacity values (Terzaghi and Ménard–Rousseau) were reconstructed from their respective governing equations and input parameters. All recomputed values were found to be internally consistent with the reported results.

III. RESULTS AND DISCUSSION

A. Stratigraphy

Visual logging of the three cored boreholes revealed a broadly consistent stratigraphic sequence: a thin surficial fill, underlain by dark brown clay to a depth of about 3.6 m, transitioning to brownish-to-yellowish sandy clay that persists to 9–10 m, with a discrete gravel and boulder horizon encountered near the base of SC01 (9.40–10.00 m) and within SC03 (8.00–8.90 m). According to the Algerian technical regulation DTR-BE 1.2, the in-place soils are classified as non-compact to moderately compact formations. Figure 1 presents the simplified lithological logs of the three boreholes, illustrating the near-surface variability (fill and clay thickness) contrasted with the more uniform sandy clay found at depth.

B. Physical Properties

Wet unit weights range from 2.00 to 2.28 t/m^3 and dry unit weights from 1.79 to 2.02 t/m^3 (Table 1), reflecting a dense material overall. Natural water content ranges from 8.96% to 13.17%, with degrees of saturation between 64.1% and 92.1%, indicating a moist to near-saturated condition consistent with the clay-dominated composition identified from the borehole logs.

Table I. Physical Properties of the Investigated Samples

Borehole	Depth (m)	γ_h (t/m^3)	γ_d (t/m^3)	W_n (%)	W_s (%)	S_r (%)
SC01	2.60–2.80	2.28	2.02	12.76	12.48	92.05
SC02	2.00–3.00	2.06	1.82	13.17	17.98	73.22
SC03	1.50–1.70	2.00	1.79	12.17	18.99	64.11
SC03	2.40–2.60	2.16	1.98	8.96	13.55	66.15

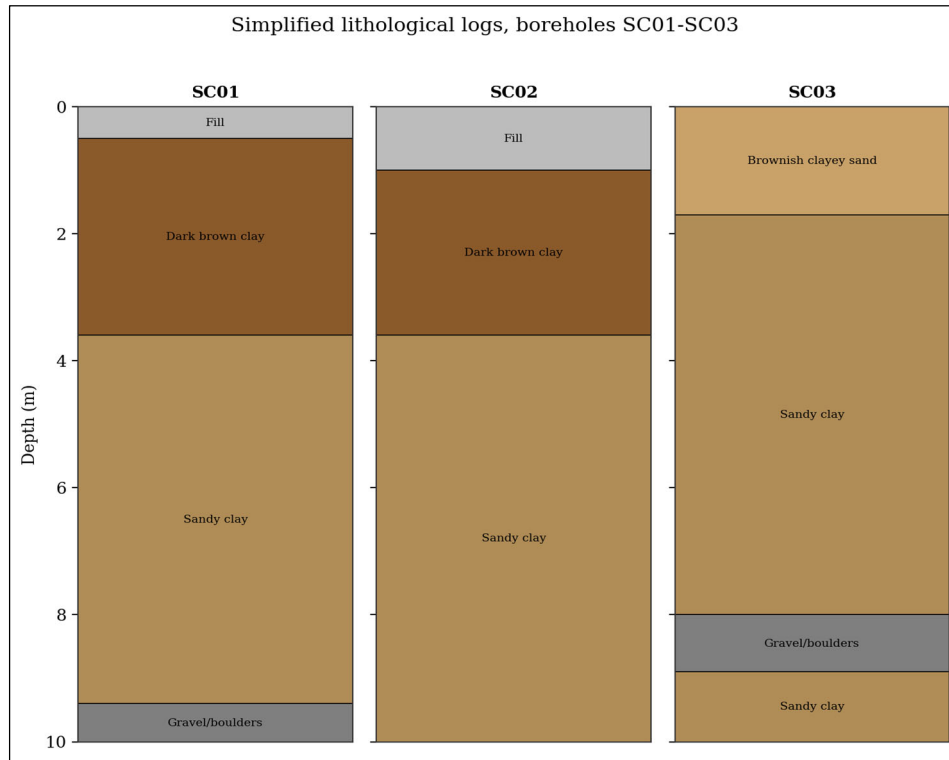


Fig. 1. Simplified lithological logs of boreholes SC01–SC03 (0–10.00 m).

C. Particle-Size Distribution

Grain-size analysis (Figure 2) confirms the predominance of fine particles, with clay content between 48% and 52% and silt between 14% and 24%; combined, the clay and silt fractions represent 66–74% of the total mass. The sand fraction, dominated by fine sand (24–28%), is moderate, and coarse elements (gravel) remain minor, not exceeding 8%, consistent with the sandy clay classification derived from the borehole logs.

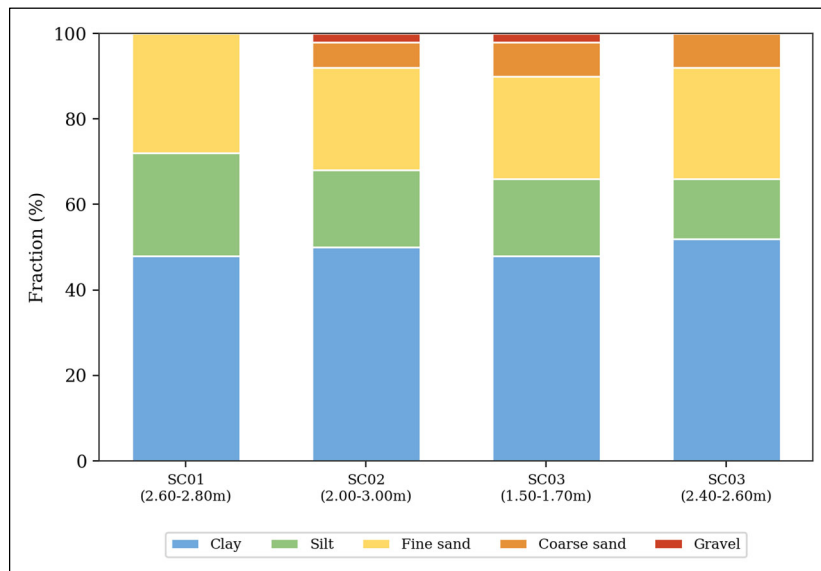


Fig. 2. Grain-size fraction composition of the investigated samples.

D. Atterberg Limits and Plasticity

Liquid limits range from 35.7% to 47.7% and plasticity indices from 13.4% to 20.8%, classifying the fine fraction as a low-plasticity clay across all four samples. As shown on the Casagrande plasticity chart (Figure 3), all four points plot on or immediately above the A-line and below $WL = 50\%$, confirming a CL (low-plasticity clay) classification; the point from

SC03 (2.40–2.60 m) plots very close to the A-line, indicating a borderline clay/silt behavior at that specific depth. Despite the relatively high clay content (48–52%) identified in Section 3.3, the moderate plasticity index suggests that the clay fraction is dominated by low-activity, weakly swelling clay minerals, which is favorable in terms of limiting shrink–swell deformation.

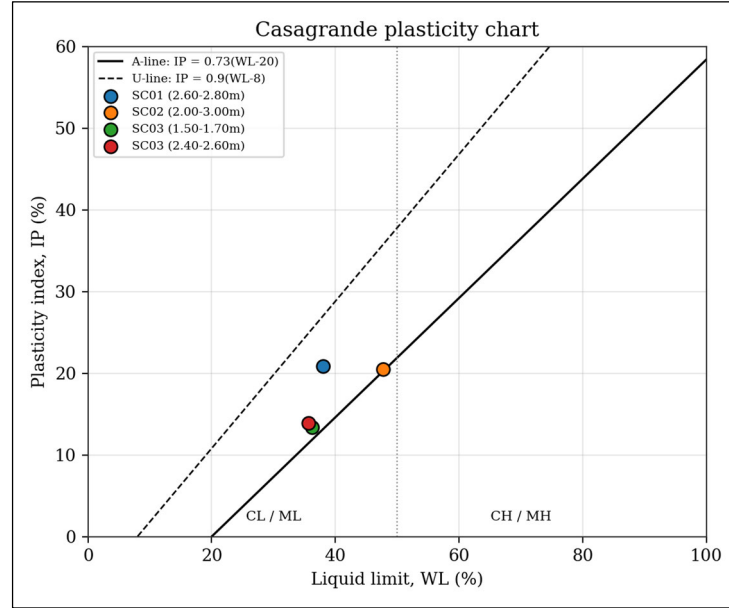


Fig. 3. Casagrande Plasticity Chart for the Investigated Samples.

E. Shear Strength and Consolidation Behavior

Direct shear and oedometer testing (Table 2) yielded a modest cohesion ($C = 8$ kPa) combined with a moderate friction angle ($\phi = 24.9^\circ$), indicating that the shear resistance of the material is governed primarily by internal friction rather than cohesion – consistent with the mixed clay–silt–sand composition identified in Section 3.3. The preconsolidation pressure ($P_c = 1.74$ bar) substantially exceeds the initial effective overburden stress ($\sigma_0 = 0.54$ bar), giving an overconsolidation ratio of approximately 3.22, attributable to past geological overburden, fluctuations of the water table, erosion of overlying layers, or desiccation. The compression index ($C_c = 11.36\%$) indicates a moderate compressibility, while the low swelling index ($C_g = 2.04\%$) confirms the limited shrink–swell potential already suggested by the plasticity results.

Table II. Shear Strength and Consolidation Parameters

Parameter	Value
Cohesion, C	8 kPa (0.08 bar)
Friction angle, ϕ	24.9°
Initial effective stress, σ_0	0.54 bar
Preconsolidation pressure, P_c	1.74 bar
Overconsolidation ratio, $OCR = P_c/\sigma_0$	≈ 3.22
Compression index, C_c	11.36 %
Swelling index, C_g	2.04 %

F. Chemical Aggressiveness

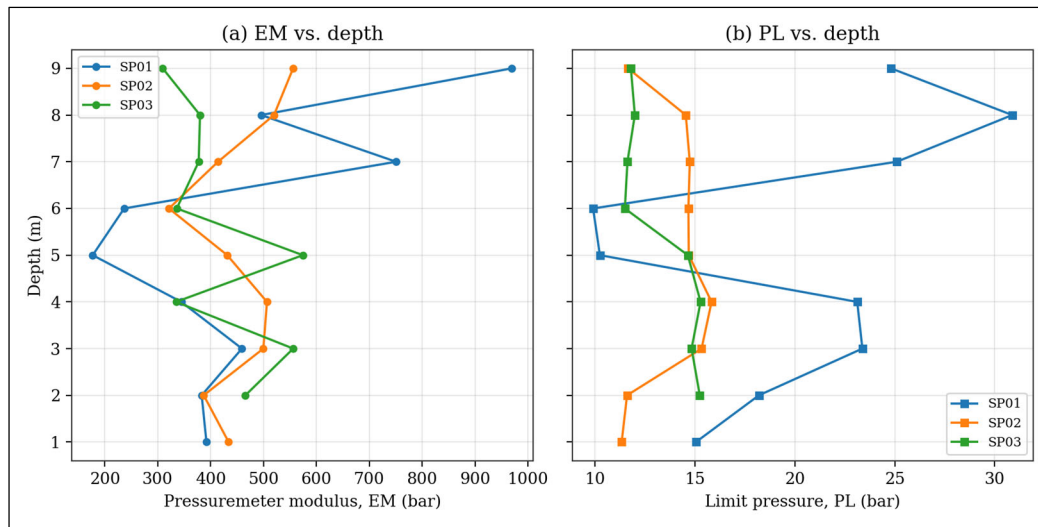
Sulfate contents vary markedly between boreholes (Table 3): SC01 and SC02 show elevated concentrations (6,730 and 9,100 mg/kg, respectively), placing them in aggressiveness class XA2 (moderate), whereas SC03 shows much lower values (200–1,400 mg/kg), corresponding to class XA1 (low). Calcium carbonate contents are consistently high (32–41%) across all boreholes, confirming the calcareous nature of the formation.

Table III. Chemical Test Results and Aggressiveness Classification

Borehole	Depth (m)	SO ₄ ²⁻ (mg/kg)	CaCO ₃ (%)	Class	Aggressiveness
SC01	2.60–2.80	6,730	41.4	XA2	Moderate
SC02	2.00–3.00	9,100	41.2	XA2	Moderate
SC03	1.50–1.70	200	32.0	XA1	Low
SC03	2.40–2.60	1,400	37.2	XA1	Low

G. Pressuremeter Results

The pressuremeter soundings show pressuremeter moduli ranging from 177 to 970 bar and limit pressures from 9.9 to 30.9 bar across the three soundings. SP01 exhibits the greatest variability, with a comparatively soft interval between 5 and 6 m depth followed by a marked stiffening below 7 m (EM up to 970 bar at 9 m), clearly visible as the pronounced peak in Figure 4a. SP02 and SP03 are more homogeneous, with moduli in the 300–575 bar range and limit pressures around 11–16 bar throughout, consistent with the comparatively flat profiles shown in Figure 4. In all three soundings, the EM/PL ratio mostly exceeds 16 – reaching up to 39 – generally interpreted as indicative of an overconsolidated soil (Baguelin et al. 1978), consistent with the OCR obtained from the oedometer tests. No groundwater was encountered during the pressuremeter campaign.

**Fig. 4.** Pressuremeter modulus (EM) and limit pressure (PL) profiles, SP01–SP03.

H. SPT Results

SPT blow counts (Figure 5) range from $N = 56$ to $N = 65$ across all three soundings and all tested depths, classifying the soil as very dense according to conventional consistency criteria. The results are remarkably homogeneous both vertically and laterally, with no interval indicating loose or weak material, and are in close qualitative agreement with the high pressuremeter moduli and limit pressures reported in Section 3.7. As illustrated in Figure 5, all measured N -values fall well within the “very dense” band ($N > 50$) across the full 3–9 m depth range investigated.

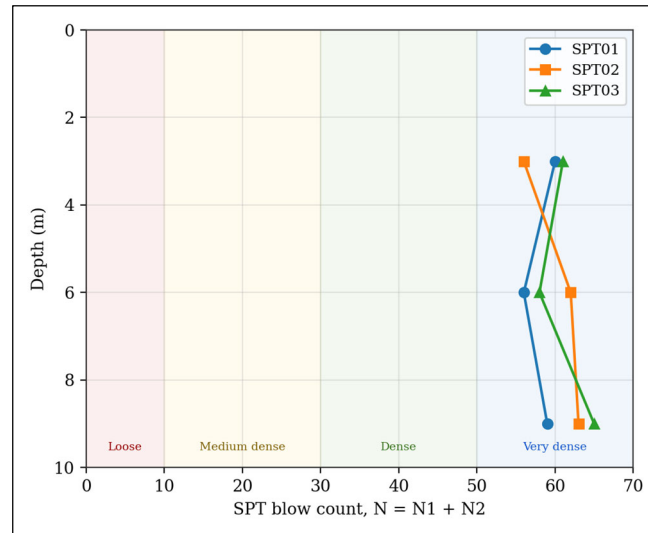


Fig. 5. SPT blow-count (N) profiles, SPT01–SPT03.

I. Divergence between laboratory and in situ stiffness indicators

A clear discrepancy was observed between laboratory and in situ results. Laboratory tests indicated moderate strength ($\phi = 24.9^\circ$, $C = 8$ kPa) and compressibility ($C_c = 11.36\%$), whereas pressuremeter and SPT tests revealed a very stiff and dense soil, with $N = 56$ – 65 and EM/PL ratios up to 39. The close agreement between both in situ methods supports the reliability of these results. The measured EM and PL values are consistent with published SPT–pressuremeter relationships, particularly the strong correlations reported by Cheshomi and Ghodrati (2015), with similar trends observed by Bozbey and Togrol (2010) and Firuzi et al. (2019). For Algerian soils, Letif et al. (2025) emphasized the site-specific nature of these correlations, while Bahar et al. (1999, 2012) reported higher pressuremeter-derived strength in overconsolidated clays. The discrepancy is therefore likely related to sample disturbance during coring and preparation, which can reduce the measured stiffness and strength of stiff, overconsolidated soils (Lunne et al. 2006; Aubeny et al. 2000). These results highlight the importance of combining laboratory and in situ investigations for reliable foundation design.

Table III. Chemical Test Results and Aggressiveness Classification

Reference	Region / soil	Reported relationship	Comparison with present data
Bahar et al. (1999)	Algerian clays (various)	Early in situ–laboratory correlations for Algerian clays	Site data fall within the stiffer end of reported ranges
Bahar et al. (2012)	Algerian clays	Undrained strength from PMT generally exceeds laboratory-derived values in overconsolidated clays	Consistent with the higher in situ strength implied by PL and N at this site
Cheshomi & Ghodrati (2015)	Silty clay, Mashhad, Iran	EM, PL strongly correlated with corrected SPT ($r = 0.94$, 0.89)	Present EM/N and PL/N ratios plot near the stiff end of the reported trend
Letif et al. (2025)	Clayey soils, central northern Algeria (76 boreholes)	Site-specific EM–N, PL–N correlations recommended over generic models	Present site's high N (56–65) and EM/PL (up to 39) are consistent with the stiff, overconsolidated subset of their database

J. Bearing capacity and settlement

The allowable bearing pressure for a strip footing ($B = 1.80$ m, $D = 1.50$ m) computed from laboratory shear strength parameters using Terzaghi's method is 2.30 bar, compared with 4.59 bar obtained from the pressuremeter-based Ménard–Rousseau method (Figure 6a) – a difference consistent with the stiffness contrast. Despite this margin, a conservative design value of $Q_{adm} = 1.20$ bar was ultimately retained for the project, below both computed values, reflecting a cautious design approach that likely accounts for additional factors such as heterogeneity between boreholes, the softer interval identified in SP01, and the sulfate aggressiveness noted locally in SC01/SC02.

Settlement estimates from the two methods (Figure 6b) are both very small and mutually consistent in order of magnitude: 0.54 cm from the layered oedometer method under a service pressure of 1.20 bar, and 0.21 cm (0.06 cm spherical + 0.15 cm deviatoric) from the pressuremeter-based Ménard–Rousseau method. Both values are far below typical serviceability limits for shallow foundations (on the order of 2.5–5.0 cm), confirming that settlement does not govern the design for this site.

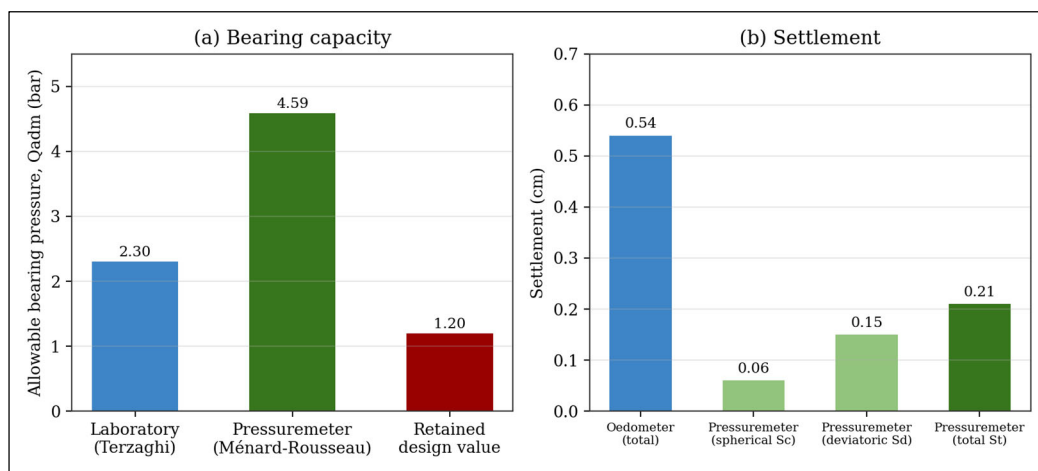


Fig. 6. Comparison of allowable bearing pressure and settlement – laboratory vs. pressuremeter methods.

K. Site Classification, Subgrade Reaction, and Design Recommendations

Based on the pressuremeter results, the site is classified in category S3. According to the Algerian seismic code (RPA99, version 2003), the Batna region falls within seismic zone 1, corresponding to low seismicity. The coefficient of subgrade reaction derived from the pressuremeter data for the strip footing configuration is $K_v = 57,511$ kPa/m, a high value consistent with the dense, stiff character of the formation identified throughout the in-situ campaign. On the basis of the combined investigation, shallow strip footings are recommended, with a minimum embedment depth of 1.50 m and a design allowable bearing pressure of $Q_{adm} = 1.20$ bar. Given the moisture sensitivity of the near-surface clay and the moderate sulfate aggressiveness locally identified in SC01 and SC02, an effective drainage and waterproofing system is recommended, together with the use of sulfate-resisting cement in the vicinity of these boreholes.

IV. CONCLUSION

This study presented a combined laboratory, pressuremeter, SPT, and dynamic penetrometer investigation for a 100-unit public housing project at Cité Selsabil, Batna, Algeria. The investigated soil consists of a fill-capped sequence of dark brown clay overlying brownish-yellowish sandy clay, classified in the laboratory as a low-plasticity, overconsolidated clay ($OCR \approx 3.22$, $C_c = 11.36\%$) of moderate shear strength ($C = 8$ kPa, $\phi = 24.9^\circ$). In contrast,

both the pressuremeter (EM up to 970 bar, EM/PL up to 39) and SPT ($N = 56\text{--}65$) results independently indicate a very dense, rigid formation – a discrepancy that, when benchmarked against published SPT–pressuremeter correlations for Algerian and other clayey soils, is most plausibly explained by sample disturbance affecting the laboratory specimens of this stiff, overconsolidated material, rather than by anomalous or unrepresentative in situ measurements.

Bearing capacity and settlement were computed independently from laboratory data ($Q_{adm} = 2.30$ bar, settlement = 0.54 cm) and from pressuremeter data ($Q_{adm} = 4.59$ bar, settlement = 0.21 cm) for a strip footing embedded at 1.50 m; a conservative design value of $Q_{adm} = 1.20$ bar was retained, and the resulting settlements in both approaches remain well below typical serviceability limits. The site is classified as category S3 with low seismicity (RPA99/2003, Zone 1), and the soil is weakly to moderately aggressive toward buried concrete (XA1/XA2), warranting sulfate-resisting cement locally.

More broadly, these results illustrate the value of combining independent laboratory and in situ methods, not only to cross-validate design parameters when they agree, but also to detect, quantify, and account for discrepancies – such as the stiffness contrast observed here – that could otherwise lead to unconservative or overly conservative designs if only one source of information were used. Comparison with local and regional SPT–pressuremeter correlations proved a useful, low-cost means of assessing the plausibility of such discrepancies before they are attributed to genuine site heterogeneity. For this site, shallow strip footings with the recommended drainage and waterproofing provisions are considered an appropriate and safe foundation solution.

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Yazılım Mimarisi Kararlarının Kurumsal Hafızaya Aktarılmasında Architecture Decision Record Kullanımı: Bookingws Projesi Üzerinden Bir Uygulama

Using Architecture Decision Records to Transfer Software Architecture Decisions into Organizational Memory: An Application through the Bookingws Project

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Özet: Bu çalışmada, yazılım mimarisi kararlarının kurumsal hafızaya aktarılmasını sağlayan Architecture Decision Record (ADR) metodolojisinin yazılım ekipleri açısından kullanım amacı, uygulama biçimi ve sağladığı faydalar incelenmektedir. Çalışmanın amacı, mimari kararların yalnızca sonuçlarının değil, kararların alındığı bağlamın, değerlendirilen alternatiflerin, seçilen çözümün gerekçelerinin ve teknik veya organizasyonel sonuçlarının da kalıcı bir bilgi kaynağı olarak saklanmasını göstermektir. Yöntem olarak ADR yaklaşımı önce kavramsal çerçevede ele alınmış, ardından Bookingws projesinde Passenger Service System (PSS) bağlantısının Message Queue (MQ) tabanlı yapıdan TCP/IP tabanlı doğrudan iletişime dönüştürülmesi örnek olay olarak incelenmiştir. Mevcut ve hedef mimarinin bileşenleri, bağlantı akışları, session yönetimi ve dönüşümün arka planındaki ihtiyaçlar ADR yaklaşımı üzerinden değerlendirilmiştir. Uygulama sonucunda ADR kayıtlarının mimari kararların gerekçelerini koruduğu, legacy sistemlerin anlaşılmasını kolaylaştırdığı, mevcut ve hedef mimarilerin karşılaştırılmasını desteklediği ve yeni ekip üyelerinin sisteme uyumunu kolaylaştırdığı görülmüştür. Ayrıca kararların kişilerin deneyimine bağımlı olmaktan çıkarılarak kurumsal ölçekte erişilebilir ve yeniden kullanılabilir hâle getirilebildiği değerlendirilmiştir. Bununla birlikte ADR hazırlanması, güncel tutulması ve kararların ekip içinde sonuçlandırılması için ek dokümantasyon ve koordinasyon maliyeti oluşturmaktadır. Bu nedenle ADR kullanımının her teknik değişiklik için değil, uzun vadeli etkisi bulunan ve mimari açıdan önemli kararlar için tercih edilmesi önerilmektedir. Çalışma, ADR'nin yalnızca bir dokümantasyon şablonu olmadığını; mimari kararların anlaşılabilir, izlenebilir ve gelecekte yeniden kullanılabilir olmasını destekleyen bir yazılım mühendisliği yaklaşımı olduğunu ortaya koymaktadır. Bu yaklaşımın özellikle uzun ömürlü, çok ekipli ve legacy bileşenler içeren sistemlerde karar geçmişinin korunmasına katkı sağladığı değerlendirilmiştir. Çalışma ayrıca ADR kayıtlarının kaynak kodla birlikte sürümlenmesinin, kararların teknik değişikliklerle ilişkilendirilmesini ve gelecekte yeniden değerlendirilmesini kolaylaştırdığını göstermektedir. Böylece mimari bilgiye erişim ve kararların izlenebilirliği desteklenmektedir.

Anahtar Kelimeler: Architecture Decision Record, Yazılım Mimarisi, Kurumsal Hafıza, Legacy Sistem, Mimari Karar Yönetimi, Sistem Entegrasyonu, Yazılım Dokümantasyonu

Abstract: This study examines the purpose, implementation, and benefits of the Architecture Decision Record (ADR) methodology for transferring software architecture decisions into organizational memory from the perspective of software teams. The aim of the study is to

demonstrate that not only the outcomes of architectural decisions, but also the context in which decisions were made, the alternatives considered, the rationale behind the selected solution, and their technical or organizational consequences can be preserved as a permanent source of knowledge. As a method, the ADR approach was first examined within a conceptual framework, followed by a case study of the transformation of the Passenger Service System (PSS) connection in the Bookingws project from a Message Queue (MQ)-based structure to direct TCP/IP-based communication. The components of the current and target architectures, communication flows, session management, and the needs underlying the transformation were evaluated through the ADR approach. As a result of the application, ADR records were found to preserve the rationale behind architectural decisions, facilitate the understanding of legacy systems, support the comparison of current and target architectures, and facilitate the onboarding of new team members. It was also evaluated that architectural decisions can be made accessible and reusable at the organizational level rather than remaining dependent on individual experience. However, preparing and maintaining ADRs and finalizing decisions within the team introduce additional documentation and coordination costs. Therefore, the use of ADRs is recommended not for every technical change, but for decisions that have long-term effects and architectural significance. The study demonstrates that ADR is not merely a documentation template, but a software engineering approach that supports making architectural decisions understandable, traceable, and reusable in the future. This approach is particularly valuable for preserving decision history in long-lived, multi-team systems containing legacy components. The study also shows that versioning ADR records together with source code facilitates associating decisions with technical changes and reassessing them in the future. Thus, access to architectural knowledge and the traceability of decisions are supported.

Keywords: *Architecture Decision Record, Software Architecture, Organizational Memory, Legacy Systems, Architectural Decision Management, System Integration, Software Documentation*

1. GİRİŞ

Kurumsal yazılım sistemleri, uzun yıllar boyunca farklı ekipler ve geliştiriciler tarafından geliştirilmektedir. Bu süreçte teknoloji seçimi, entegrasyon yöntemi, veri iletişimi, sistem bileşenleri ve geçiş stratejileri gibi birçok mimari karar alınmaktadır.

Ancak bu kararların önemli bir bölümü, kararın alındığı dönemde kullanılan toplantı notları, elektronik postalar, sohbet uygulamaları veya pull request yorumları içerisinde kalmaktadır. Zaman içerisinde bu kayıtların bulunması zorlaşmakta veya kararın hangi gerekçeyle alındığı unutulmaktadır.

Bu durum aşağıdaki soruların cevaplanmasını güçleştirmektedir:

- Belirli bir teknoloji neden seçilmiştir?
- Hangi alternatifler değerlendirilmiştir?
- Kararın alınmasındaki temel gerekçe nedir?
- Karar hâlâ geçerli midir?
- Kararı kim, hangi koşullar altında almıştır?
- Aynı konu neden daha önce tartışılmış olmasına rağmen yeniden gündeme gelmektedir?

Bu soruların cevapsız kalması, kurumsal bilgi kaybına, tekrar eden tartışmalara ve ekiplerin kişilere bağımlı hâle gelmesine neden olabilir.

Architecture Decision Record, yazılım mimarisiyle ilgili önemli kararların ve bu kararların gerekçelerinin yapılandırılmış biçimde kayıt altına alınmasını sağlayan bir yöntemdir [1], [3], [4], [7].

ADR yaklaşımında kararın sonucu kadar kararın alınma süreci, bağlamı, alternatifleri ve

sonuçları da belgelenmektedir [1], [3], [7].

Bu çalışmanın amacı, ADR metodolojisinin yazılım ekiplerine sağladığı faydaları incelemek ve gerçek bir yazılım dönüşüm süreci üzerinden ADR kullanımının nasıl uygulandığını göstermektir.

II. ARCHITECTURE DECISION RECORD YAKLAŞIMI

ADR, belirli bir mimari kararın geçmişini ve geçerlilik koşullarını açıklayan kısa ve odaklanmış bir dokümandır [3], [4].

Tipik bir ADR aşağıdaki bölümlerden oluşmaktadır [1], [3], [7], [9]:

- Başlık ve karar numarası
- Kararın durumu
- Tarih
- Karar alan ekip veya kişiler
- Bağlam
- Problem veya ihtiyaç
- Değerlendirilen alternatifler
- Seçilen karar
- Kararın gerekçesi
- Teknik ve organizasyonel sonuçlar

ADR'nin temel amacı, yalnızca “hangi kararın alındığını” açıklamak değildir. Aynı zamanda kararın neden alındığını ve hangi alternatiflerin neden tercih edilmediğini görünür hâle getirmektir [1], [3], [7].

Bu yönüyle ADR, kaynak kodun nasıl çalıştığını açıklayan teknik dokümantasyondan farklı bir işlev üstlenmektedir. Teknik dokümantasyon sistemin mevcut durumunu açıklarken, ADR belirli bir mimari tercihin arkasındaki düşünce sürecini kayıt altına almaktadır [3], [4], [10].

III. ADR KULLANIMINI ÖNEREN MİMARİ KARAR

Çalışma kapsamında hazırlanan örnek karar kaydı aşağıdaki temel bilgileri içermektedir:

ADR Numarası: ADR-0001

Başlık: Mimari Kararların Kayıt Altına Alınması

Durum: Accepted

Tarih: 19.08.2026

Karar Alanlar: Teknik Takım Liderleri ve Müdürler

A. Bağlam

Projelerde mimari kararlar çoğunlukla toplantılar, ekip içi sohbetler veya pull request tartışmaları sırasında alınmaktadır. Ancak bu iletişim kanalları, uzun vadeli bir mimari bilgi deposu olarak kullanılmaya uygun değildir.

Toplantı kayıtları ve sohbet mesajları zaman içerisinde kaybolabilmekte, pull request yorumları ise belirli bir kod değişikliğiyle sınırlı kalabilmektedir [2], [5], [6]. Ayrıca kararların kişilerle ilişkilendirilmesi, ekip üyeleri değiştiğinde bilgi kaybı yaşanmasına neden olabilmektedir.

Bu nedenle mimari açıdan önemli kararların standart bir formatta kayıt altına alınmasına ihtiyaç duyulmuştur [1], [4], [7].

B. Değerlendirilen Alternatifler

Alternatif 1: Toplantılar veya ekip içi sohbetler

Toplantılar ve sohbet uygulamaları, kararların ekip üyeleriyle birlikte alınmasını kolaylaştırmaktadır. Farklı kişilerin görüşleri aynı ortamda değerlendirilebilmektedir.

Bununla birlikte bu yöntemlerde kararların uzun vadede bulunması zorlaşabilmektedir. Kararların gerekçeleri zamanla unutulabilmekte ve bilgi belirli kişilerin hafızasına bağımlı hâle

gelebilmektedir.

Alternatif 2: Pull request yorumları

Pull request yorumları, alınan kararın kod değişikliğiyle olan ilişkisini göstermektedir. Kararın alındığı teknik bağlam incelenebilmektedir.

Ancak pull request yorumları genellikle belirli bir değişiklikle sınırlıdır. Mimari kararların uzun vadeli ve merkezi bir bilgi deposu olarak aranması zor olabilir.

Alternatif 3: ADR kullanımı

ADR kullanımı, mimari kararların belirli bir formatta ve merkezi bir yapıda saklanmasını sağlamaktadır [1], [4], [5], [7].

ADR yaklaşımının avantajları şunlardır:

- Kararın bağlamı ve gerekçesi kaybolmaz.
- Mimari bilgi kişilere bağımlı olmaktan çıkar.
- Değerlendirilen alternatifler görülebilir.
- Kararların gelecekte yeniden değerlendirilmesi kolaylaşır.
- Benzer projelerde mevcut kararlardan yararlanılabilir.
- Mimari karar alma süreci daha bilinçli ve izlenebilir hâle gelir.

Bu yaklaşımın temel dezavantajı, her önemli karar için ek dokümantasyon hazırlanması ve kararın ekip içinde sonuçlandırılması için zaman ayrılmasıdır.

C. Alınan Karar

Mimari açıdan önemli her karar için Architecture Decision Record oluşturulmasına karar verilmiştir.

ADR'ler aşağıdaki bilgileri içermelidir:

- Başlık
- Karar durumu
- Tarih
- Karar alan kişiler veya ekip
- Bağlam
- Değerlendirilen alternatifler
- Seçilen çözüm
- Kararın gerekçesi
- Teknik ve operasyonel sonuçlar

ADR kayıtlarının kaynak kodla birlikte versiyonlanması ve proje deposunda veya kurumun mimari dokümantasyon alanında saklanması kararlaştırılmıştır. ADR'ler kaynak kodla birlikte sürüm kontrol sisteminde tutulduğunda, karar geçmişinin izlenmesi ve teknik değişikliklerle ilişkilendirilmesi kolaylaşmaktadır [1], [3], [5].

IV. UYGULAMA ÖRNEĞİ: BOOKINGWS VE PSS BAĞLANTI DÖNÜŞÜMÜ

ADR metodolojisinin uygulanmasını göstermek amacıyla Bookingws projesinde gerçekleştirilen PSS bağlantı dönüşümü incelenmiştir.

Bookingws, bu çalışmada PSS ile uygulama katmanı arasındaki iletişimi sağlayan bir orta katman uygulaması olarak ele alınmaktadır. Uygulama, rezervasyon süreçlerinin ihtiyaç duyduğu sistemler arası iletişim akışında görev almakta ve PSS tarafındaki işlemlere erişim için bir entegrasyon noktası oluşturmaktadır. Bu nedenle Bookingws içerisinde alınan mimari kararlar yalnızca uygulamanın kendi kod yapısını değil, bağlandığı dış sistemlerin iletişim biçimini ve oturum yönetimini de etkilemektedir.

Bookingws projesinin uzun süre yaşayan bir yazılım sistemi olması, zaman içinde farklı teknolojilerin ve entegrasyon yaklaşımlarının aynı mimari içerisinde bulunmasına neden olabilmektedir. Çalışmada incelenen PSS bağlantısı da bu durumun bir örneğidir. Önceki yapıda Bookingws ile Troya PSS arasındaki iletişim doğrudan kurulmak yerine mesajlaşma

altyapısı ve listener bileşeni üzerinden gerçekleştirilmiştir. Bu yapı, iletişimin yalnızca iki uç sistem arasındaki bağlantıdan ibaret olmamasına; mesajın kuyruğa bırakılması, alınması ve PSS tarafına aktarılması gibi ek adımların yönetilmesine neden olmuştur.

Bu çalışma açısından Bookingws'in önemi, belirli bir ürün veya teknoloji hakkında genel bir tanıtım yapmak değil, gerçek bir mimari dönüşümün ADR ile nasıl belgelendiğini göstermesidir. Bu nedenle aşağıdaki bölümlerde Bookingws'in PSS entegrasyonu, kullanılan MQ tabanlı iletişim yapısı, bu yapıdaki temel bileşenlerin rolleri ve dönüşüm sonrasında oluşan hedef mimari birlikte açıklanmaktadır.

A. Dönüşümün Arka Planı

Bookingws projesinde Passenger Service System bağlantısı uzun süre Message Queue tabanlı bir yapı üzerinden gerçekleştirilmiştir. Daha sonra MQ altyapısından TCP/IP tabanlı doğrudan iletişime geçilmiştir.

Bu dönüşümün arka planında aşağıdaki ihtiyaçlar bulunmaktadır:

- MQ altyapısının karmaşıklığını azaltmak
- Ara bileşen ve listener bağımlılıklarını azaltmak
- Legacy session yönetimi yaklaşımını yeniden değerlendirmek
- Daha sade bir entegrasyon yapısı oluşturmak
- PSS tarafındaki teknolojik dönüşüme uyum sağlamak
- Mevcut ve hedef mimarinin anlaşılmasını kolaylaştırmak

Bu süreçte yalnızca teknik değişikliğin yapılması değil, değişikliğin neden yapıldığının ve nasıl yönetildiğinin belgelenmesi de önemli hâle gelmiştir.

B. MQ Tabanlı İletişim Yapısına Genel Bakış

Message Queue (MQ), uygulamalar arasında gönderilen mesajların doğrudan aynı anda iletilmesi yerine bir mesajlaşma altyapısı üzerinden taşınmasına olanak veren bir iletişim yaklaşımıdır. Bu yapıda gönderici uygulama mesajı bir kuyruğa bırakabilir; mesajı işleyecek bileşen ise uygun zamanda kuyruğu okuyarak mesajı hedef sisteme aktarabilir. Böylece gönderici ile alıcı arasındaki iletişim akışı belirli ölçüde ayrıştırılmış olur.

Bu çalışmada MQ altyapısı, Bookingws ile Troya PSS arasındaki iletişimde kullanılan ara katman olarak ele alınmaktadır. MQ Queue mesajların beklediği noktayı, MQ Listener ise kuyruktaki mesajları alıp PSS tarafına ileten bileşeni temsil etmektedir. Bu ayrım, iletişim akışının tek bir bağlantıdan ziyade birden fazla bileşenin birlikte çalıştığı bir yapı oluşturmaya neden olmaktadır. Dolayısıyla mimarinin anlaşılması için yalnızca Bookingws ve PSS'nin değil, aradaki MQ bileşenlerinin görevlerinin de açıklanması gerekmektedir.

1) MQ Queue ve MQ Listener

MQ Queue, gönderici tarafından oluşturulan mesajların hedef tüketici tarafından alınmasına kadar tutulduğu mantıksal mesaj kuyruğudur. Bookingws tarafından PSS'ye yönelik bir istek oluşturulduğunda, mevcut mimaride bu istek doğrudan PSS'ye gönderilmek yerine MQ Queue katmanına bırakılmaktadır. Kuyruk, iletişim akışındaki gönderici ve alıcı tarafları birbirinden ayıran ara noktayı oluşturmaktadır.

MQ Listener ise kuyruğu izleyen ve ilgili mesajları alarak hedef sisteme ileten uygulama bileşenidir. Bu nedenle mevcut yapıda Bookingws'in ürettiği mesajın PSS'ye ulaşması için Queue ve Listener birlikte çalışmaktadır. Bu iki bileşen, sistemin işleyişine esneklik sağlayabilse de aynı zamanda yönetilmesi gereken ek bağımlılıkları ve hata senaryolarını beraberinde getirmektedir. Çalışmada timeout, kuyrukta bekleme ve mesajın hedefe aktarılması gibi konuların mimari bağlam içinde değerlendirilmesi bu nedenle önemlidir.

2) CRI ve Session Yönetimi

Mevcut mimaride CRI, session yönetimiyle ilişkili bir yapı olarak kullanılmaktadır. Session yönetimi, iki sistem arasındaki iletişim sırasında bir isteğin hangi bağlantı veya oturum

bağlamında yürütüldüğünün takip edilmesi açısından önem taşımaktadır. Bu nedenle MQ katmanının ortadan kaldırılması yalnızca mesajın hangi kanaldan taşınacağına değıştirilmesi anlamına gelmemekte, session yönetiminin uygulanma biçiminin de yeniden ele alınmasını gerektirmektedir.

Dönüşüm sonrasında CRI yapısının korunması, ancak MQ katmanından bağımsız şekilde ele alınması, mimari değışikliğin yalnızca iletişim protokolü değışimi olarak değerdendirilmemesi gerektiğini göstermektedir. ADR içerisinde bu tür bağımlılıkların açıkça belirtilmesi, gelecekte sistemi inceleyen ekiplerin hangi bileşenin neden korunduğunu veya değıştirildiğini anlayabilmesine yardımcı olmaktadır.

Mevcut iletişim zincirindeki temel roller

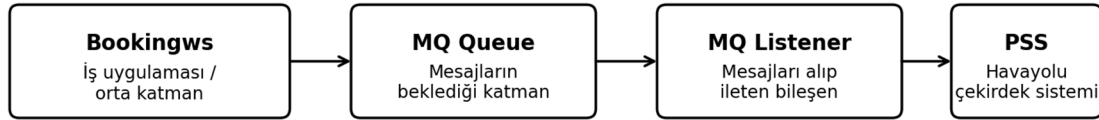


Fig. 1. Mevcut iletişim zincirindeki temel bileşenlerin rolleri.

C. Mevcut Mimarinin Belgelenmesi

Mevcut yapı aşağıdaki temel akış üzerinden çalışmaktadır:

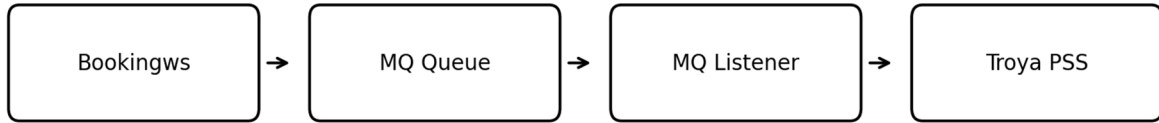


Fig. 2. Bookingws ile Troya PSS arasındaki mevcut MQ tabanlı iletişim akışı.

Bu yapıda:

- İstekler MQ kuyruğuna gönderilmektedir.
- MQ Listener mesajları alarak PSS sistemine iletmektedir.
- CRI, session yönetimi için kullanılmaktadır.
- Kuyrukta bekleme, timeout ve mesaj kaybı gibi hata senaryoları ayrıca ele alınmaktadır.
- İletişim akışı birden fazla bileşenin birlikte çalışmasını gerektirmektedir.

ADR sayesinde bu yapı yalnızca teknik bileşenleriyle değil, mevcut yapının neden karmaşık olduğu ve hangi sorunları doğurduğu ile birlikte kayıt altına alınmıştır.

D. Hedef Mimarinin Belgelenmesi

Dönüşüm sonrasında iletişim akışı aşağıdaki hâle gelmiştir:



Fig. 3. Dönüşüm sonrasında Bookingws ile Troya PSS arasındaki hedef iletişim akışı.

Şekil 2 ve Şekil 3 birlikte değerdendirildiğinde, dönüşümün temel mimari etkisinin Bookingws ile PSS arasındaki iletişim yolundaki ara MQ bileşenlerinin kaldırılması ve iletişim

akışının doğrudan TCP/IP bağlantısına taşınması olduğu görülmektedir. Bu değişiklik ADR içerisinde yalnızca sonuç olarak değil, mevcut yapının bağlamı ve hedef yapının gerekçesiyle birlikte kayıt altına alınmıştır.

Yeni yapıda:

- MQ Queue katmanı kaldırılmıştır.
- MQ Listener katmanı kaldırılmıştır.
- Bookingws ile PSS arasında doğrudan TCP/IP iletişimi kurulmuştur.
- Session yönetiminin uygulanma biçimi değiştirilmiştir.
- CRI yapısı korunmakla birlikte, MQ katmanından bağımsız şekilde ele alınmıştır.
- Mevcut ve hedef mimarinin farkları kayıt altına alınmıştır.

Bu dönüşümün amacı çalışmanın ana konusu olarak MQ ile TCP/IP arasında genel bir teknik üstünlük karşılaştırması yapmak değildir. Dönüşüm, ADR'nin gerçek bir mimari değişiklik sırasında hangi bilgileri görünür ve yeniden kullanılabilir hâle getirdiğini göstermek için örnek olarak kullanılmıştır.

V. ADR'İN SAĞLADIĞI FAYDALAR

A. Mimari Kararların Gerekçelerinin Korunması

ADR, kararın yalnızca sonucunu değil, kararın hangi ihtiyaçtan doğduğunu ve hangi alternatiflerin değerlendirildiğini de saklamaktadır [1], [3], [4], [7].

Bu sayede gelecekte ekip üyeleri “Neden bu teknoloji seçildi?” sorusuna yalnızca kişisel hafızaya veya eski toplantı kayıtlarına başvurmadan cevap bulabilmektedir.

B. Legacy Mimarinin Anlaşılmasının Kolaylaşması

MQ ve CRI session yönetimi gibi karmaşık yapıların mevcut durumunun belgelenmesi, yeni ekip üyelerinin sistemi daha hızlı anlamasına yardımcı olmuştur.

ADR içerisinde mevcut mimarinin akışı, bileşenleri, bağımlılıkları ve sorunları birlikte açıklandığı için sistemin geçmiş durumu daha anlaşılır hâle gelmiştir.

C. Mevcut ve Hedef Mimarinin Karşılaştırılabilmesi

ADR, eski ve yeni mimarinin aynı doküman içerisinde açıklanmasını sağlamıştır. Bu sayede:

- Hangi bileşenlerin kaldırıldığı,
- Hangi sorumlulukların değiştiği,
- Session yönetiminin nasıl etkilendiği,
- Geçişin hangi gerekçelerle yapıldığı

daha kolay görülebilir hâle gelmiştir.

D. Kurumsal Hafızanın Oluşturulması

ADR, mimari bilginin belirli kişilerin hafızasında kalmasını önleyerek kurumsal hafızaya katkı sağlamaktadır [2], [4], [5], [6].

Ekip üyeleri değişse bile kararların bağlamı, gerekçesi ve sonuçları korunmaktadır. Böylece proje belirli kişilerin deneyimine daha az bağımlı hâle gelmektedir.

E. Yeniden Kullanılabilir Bilgi Kaynağı Oluşturulması

Bookingws projesinde hazırlanan mimari dokümantasyon, benzer entegrasyon dönüşümleri gerçekleştirecek başka ekipler için de referans niteliği taşımıştır.

Aynı veya benzer dönüşümü yapacak ekipler:

- Mevcut mimarinin nasıl analiz edildiğini,
- Hangi karar başlıklarının ele alındığını,
- Hangi sorunlarla karşılaşıldığını,
- Geçiş sürecinin nasıl belgelendiğini

inceleyerek çalışmaya başlayabilmektedir [1], [4], [5].

Bu durum “bir kez yaz, tekrar tekrar kullan” etkisi oluşturmaktadır.

F. Onboarding Sürecinin Desteklenmesi

Yeni ekip üyeleri, yalnızca kaynak kodu incelemek yerine mimari kararların arkasındaki gerekçeleri de görebilmektedir [2], [5], [6], [10].

Bu sayede yeni geliştiricilerin:

- Sistemin geçmişini anlaması,
- Mevcut teknolojik tercihleri kavraması,
- Eski ve yeni mimari arasındaki ilişkiyi görmesi,
- Gelecekte benzer kararları daha bilinçli alması

kolaylaşmaktadır.

VI. ADR KULLANIMININ SINIRLILIKLARI

ADR yaklaşımının faydalarının yanında bazı maliyetleri ve sınırlılıkları da bulunmaktadır:

- Her önemli karar için ek dokümantasyon hazırlanması gerekir [2], [3], [5].
- ADR’lerin güncel tutulması için sorumluluk belirlenmelidir ve kararların yaşam döngüsü izlenmelidir [4], [7].
- Kararların ekip içinde tartışılması ve sonuçlandırılması zaman alabilir.
- Çok küçük veya kısa vadeli değişiklikler için ADR hazırlanması gereksiz dokümantasyon oluşturabilir.
- Eski ADR’lerin geçerliliğini kaybetmesi durumunda yeni ADR hazırlanması veya mevcut kaydın güncellenmesi gerekir.

Bu nedenle ADR her teknik değişiklik için değil, uzun vadeli etkisi olan ve mimari açıdan önemli kararlar için kullanılmalıdır [1], [2], [7].

ADR’ler kararın yaşam döngüsünü göstermek amacıyla Proposed, Accepted, Rejected ve Superseded gibi durumlarla takip edilebilir. Bir karar kabul edildikten sonra önemli ölçüde değişmesi gerektiğinde, mevcut kaydın değiştirilmesi yerine yeni bir ADR hazırlanması ve önceki ADR’nin Superseded olarak işaretlenmesi önerilmektedir [3], [4], [7], [10].

VII. TARTIŞMA

Bookingws projesindeki uygulama, ADR’nin yalnızca bir dokümantasyon şablonu olmadığını göstermektedir. ADR, karar verme sürecini daha görünür, izlenebilir ve yeniden değerlendirilebilir hâle getiren bir yazılım mühendisliği aracıdır.

MQ altyapısından TCP/IP tabanlı iletişime geçiş örneğinde ADR’nin temel katkısı, belirli bir iletişim teknolojisini diğerine üstün ilan etmek değil; dönüşümün neden gerekli olduğunu, mevcut sistemin hangi özelliklere sahip olduğunu, hedef yapının nasıl tasarlandığını ve geçiş sırasında hangi kararların alındığını kurumsal bir kayıt hâline getirmektir.

Bu yaklaşım, gelecekte benzer bir mimari karar gündeme geldiğinde ekiplerin aynı analizleri tekrar yapmasını azaltmaktadır. Ayrıca kararların yalnızca deneyimli ekip üyeleri tarafından bilinen örtük bilgiler olmaktan çıkarak erişilebilir bir bilgi kaynağına dönüşmesini sağlamaktadır.

Bununla birlikte ADR’nin etkili olabilmesi için kayıtların yalnızca hazırlanması yeterli değildir. ADR’lerin proje yaşam döngüsüne dâhil edilmesi, kaynak kodla birlikte saklanması, karar durumlarının güncel tutulması ve ekip üyeleri tarafından düzenli biçimde kullanılması gerekmektedir.

VIII. SONUÇ

Bu çalışmada, Architecture Decision Record metodolojisinin yazılım ekiplerine sağladığı faydalar Bookingws projesindeki PSS bağlantı dönüşümü üzerinden incelenmiştir.

Çalışma sonucunda ADR kullanımının:

- Mimari kararların gerekçelerini koruduğu,

- Kurumsal mimari hafızayı güçlendirdiği,
- Legacy sistemlerin anlaşılmasını kolaylaştırdığı,
- Yeni ekip üyelerinin sisteme uyumunu desteklediği,
- Aynı konuların tekrar tekrar tartışılmasını azalttığı,
- Mevcut ve hedef mimarilerin karşılaştırılmasını kolaylaştırdığı,
- Benzer projelerde yeniden kullanılabilir bilgi sağladığı

görülmüştür.

ADR yaklaşımı, mimari bilgiyi kişilere bağımlı olmaktan çıkararak ekip ve kurum düzeyinde erişilebilir hâle getirmektedir [2], [4], [5], [6]. Özellikle uzun ömürlü, çok ekipli ve legacy bileşenler içeren yazılım projelerinde bu yaklaşım önemli bir değer sunmaktadır [1], [4], [7], [10].

Bununla birlikte ADR kullanımı ek dokümantasyon ve koordinasyon maliyeti oluşturmaktadır. Bu nedenle ADR'lerin mimari açıdan önemli kararlar için kullanılması, küçük ve geçici teknik değişiklikler için ise gereksiz dokümantasyondan kaçınılması önerilmektedir.

Sonuç olarak ADR, yazılım mimarisi kararlarının yalnızca kaydedilmesini değil, bu kararların anlaşılabilir, izlenebilir ve gelecekte yeniden kullanılabilir olmasını sağlayan etkili bir yöntemdir.

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Multiscale Intelligent Analysis of Gibbs -Thomson Driven Nanostructure Evolution from STM Data

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Abstract We present a computational framework for intelligent multiscale analysis of STM topographies of indium nanostructures formed on layered A^3B^6 chalcogenide surfaces. The proposed approach combines Flooding (Watershed) segmentation, fractal feature extraction, and statistical morphology analysis for quantitative characterization of growth kinetics and surface evolution.

Keywords: *Intelligent Image Analysis, Scanning Tunneling Microscopy, Flooding Segmentation, Fractal Dimension, Computational Microscopy*

I. INTRODUCTION

Modern scanning probe microscopy techniques, including atomic force microscopy (AFM) and scanning tunneling microscopy (STM), generate large volumes of complex topographical data that require advanced computational interpretation methods. In recent years, the rapid development of intelligent information systems, image-processing algorithms, and data-driven analysis approaches has significantly expanded the capabilities of nanoscale surface characterization [1].

Layered A^3B^6 chalcogenide semiconductors, such as In_4Se_3 , $InSe$, and $InTe$, represent promising materials for nanoelectronic and optoelectronic applications due to strongly anisotropic crystal structure and quasi 2D nature [2-4]. Their surfaces can be prepared in atomically clean state by mechanical cleavage, providing convenient templates for the formation of self-assembled metal nanostructures. The morphology and ordering of such nanostructures strongly influence the electronic and transport properties of metal-semiconductor interfaces and therefore require reliable quantitative characterization methods.

STM enables high-resolution visualization of local surface morphology, electronic inhomogeneity, and nanoscale growth processes. However, STM images often exhibit irregular, multiscale, and partially self-affine patterns that are difficult to characterize using only conventional statistical parameters such as RMS roughness or average grain size [5]. Moreover, the large amount of height-coordinate information contained in STM datasets creates the need for intelligent computational approaches capable of extracting hidden morphological descriptors and identifying characteristic growth regimes.

In this context, methods originating from computer vision, intelligent image analysis, and pattern recognition become increasingly important for nanoscale surface studies. In particular, segmentation algorithms, multiscale feature extraction, fractal analysis [6, 7], and statistical morphology descriptors provide efficient tools for quantitative interpretation of STM topographies [8]. Recent advances in machine learning, computational microscopy, and intelligent image processing have enabled automated extraction of morphology descriptors, segmentation of nanoscale structures, and data-driven interpretation of scanning probe

microscopy datasets [9].

In the present work, we propose a computational framework for intelligent multiscale analysis of STM topographies of indium nanostructures formed on layered A₃B₆ chalcogenide surfaces, namely In₄Se₃ and InTe.

II. RESULTS AND DISCUSSION

A. Computational Workflow

All STM topographies consisted of 400×400 pixels regardless of the physical scan size. STM datasets were acquired for multiple deposition stages and thermal treatment conditions using both large-area ($1 \mu\text{m} \times 1 \mu\text{m}$) and high-resolution nanoscale ($50 \text{ nm} \times 50 \text{ nm}$) scans. In the proposed approach, experimental STM measurements serve as the source of multiscale topographical datasets for subsequent intelligent computational analysis. Each STM image was represented as a height-coordinate matrix preserving full 3D surface morphology information.

The computational workflow consisted of several consecutive stages: (i) preprocessing of STM datasets, (ii) reciprocal-space enhancement using Fast Fourier Transform (FFT) filtering, (iii) Flooding (Water-shed) segmentation, (iv) extraction of morphology descriptors, and (v) multiscale statistical and fractal analysis of nanostructure evolution.

Initial preprocessing of STM topographies was performed using WSxM software (Nanotec Electronica) [10]. This stage included surface flattening, noise suppression, normalization of height distributions, and FFT-assisted filtering in reciprocal space. Such procedures improve visualization of partially ordered surface regions and reduce local tunneling artefacts affecting quantitative morphology characterization. In addition to conventional roughness analysis, including RMS roughness, skewness, and kurtosis [11], the STM datasets were further analyzed using intelligent morphology characterization methods.

Segmentation of nanostructures was performed using the Flooding method implemented in WSxM software [10]. This approach, also referred to as the Watershed method, simulates gradual flooding of the STM topography and tracks the evolution of isolated surface regions above the flooding level. Unlike conventional computer-vision water-shed implementations frequently applied to binarized grayscale images, the WSxM Flooding approach directly operates on the original STM height-coordinate information. During the segmentation procedure, the computational framework automatically evaluated the number of visible nanostructures (hills), nearest-neighbor distances, flooded surface area, volume evolution, and height-distribution statistics as functions of the flooding level.

Comparative multiscale analysis was carried out for STM datasets acquired at different spatial resolutions in order to identify local and global manifestations of nanostructure coalescence, anisotropic ordering, and Gibbs-Thomson driven growth kinetics. As is known, the Gibbs-Thomson effect introduces an exponential dependence between the population of nanostructures (large vs small) and their size due to its impact on the chemical potential and hence on the equilibrium concentration or vapor pressure of atoms near the surface [12, 13].

B. Multiscale STM Dataset Characterization

The proposed computational workflow was applied to multiscale STM datasets acquired during consecutive stages of indium deposition on layered A₃B₆ chalcogenide surfaces. Fig. 1 presents representative STM topographies of the (100) In₄Se₃ surface obtained for large-area ($1 \mu\text{m} \times 1 \mu\text{m}$) and nanoscale high-resolution ($50 \text{ nm} \times 50 \text{ nm}$) scans. The datasets correspond to different deposition times followed by activation of secondary solid-state dewetting (SSD) through thermal treatment.

Since all STM datasets were acquired with identical matrix dimensions of 400×400

pixels, variation of the physical scan area naturally provides multiscale representation of the surface morphology. In large-area scans, one pixel corresponds to approximately ($2.5 \text{ nm} \times 2.5 \text{ nm}$) of the surface, whereas for nanoscale scans the effective pixel size decreases to about ($0.125 \text{ nm} \times 0.125 \text{ nm}$). Such representation enables computational analysis of global nanostructure organization and local coalescence processes within a unified data-processing framework.

Computational analysis of the STM datasets demonstrates gradual evolution of surface morphology during In deposition. At early deposition stages, the surfaces exhibit heterogeneous distributions of small isolated nanostructures, while longer deposition times lead to formation of larger connected regions and partially ordered surface arrangements. After activation of SSD, additional surface reorganization effects become visible, indicating anisotropic redistribution of deposited In governed by the crystallographic structure of the layered substrates.

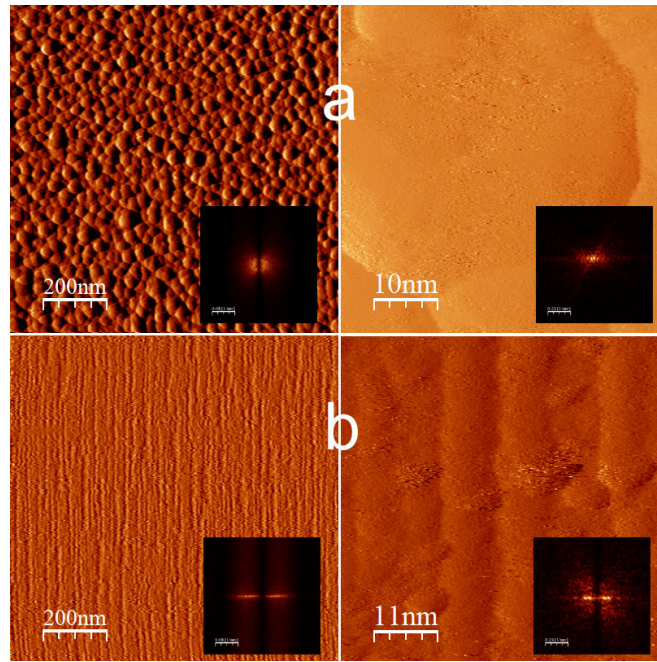


Fig. 1. STM images of (100) In_4Se_3 surface morphology: ($1 \mu\text{m} \times 1 \mu\text{m}$) (left) and ($50 \text{ nm} \times 50 \text{ nm}$) areas (right) acquired in the processes of consistent In deposition with accumulation of deposited amount and final annealing: a) 620 s deposited surface; b) next annealed at 473K. Insets show corresponding images processed by 2D FFT

To improve visualization of hidden ordering effects and enhance subsequent segmentation stability, FFT-assisted preprocessing was applied to the STM datasets. The corresponding reciprocal-space filtered images shown in Fig. 1 reveal partially ordered nanostructure distributions, particularly after activation of SSD processes. For highly heterogeneous deposition stages, reciprocal-space ordering remains blurred, indicating the coexistence of multiple competing growth regimes and local morphology fluctuations.

C. Flooding-Based Segmentation of Nanostructures

To investigate the evolution of indium nanostructures quantitatively, Flooding (Watershed) segmentation was applied to the preprocessed STM datasets. Figs. 2 and 3 present representative segmentation results for the (100) In_4Se_3 surface after 620 s of indium deposition for both large-area and nanoscale STM datasets.

Within the proposed computational framework, the Flooding procedure simulates gradual immersion of the STM topography by an abstract flooding level and dynamically tracks

isolated surface regions remaining above the flooded surface. Since the WSxM implementation directly operates on original height-coordinate matrices rather than binarized grayscale images, the segmentation process preserves the three-dimensional morphology of the investigated nanostructures.

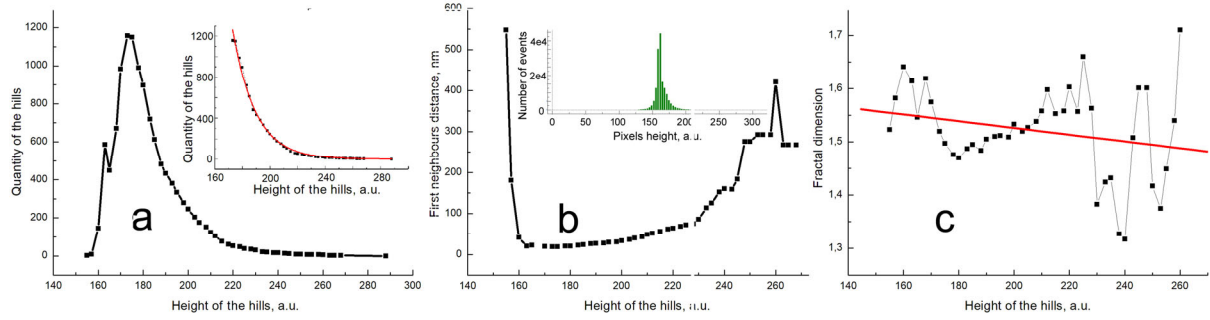


Fig. 2. Flooding analysis result for ($1 \mu\text{m} \times 1 \mu\text{m}$) area on (100) In_4Se_3 surface after 620 s of indium deposition: (a) number of segmented nanostructures (hills) as a function of flooding height (inset: first-order Exponential fit); (b) nearest-neighbour distance versus flooding height (inset: pixel height distribution); (c) fractal dimension evolution during flooding (black squares) with linear approximation (red line)

The extracted segmentation descriptors reveal pronounced scale-dependent behavior of indium nanostructure evolution. The dependencies shown in Figs. 2a and 3a describe the number of segmented nanostructures (hills) detected above the flooding level as a function of relative surface height. At intermediate flooding levels, the number of segmented regions reaches a maximum due to simultaneous coexistence of multiple partially connected islands. Further increase of the flooding level results in progressive disappearance of smaller nanostructures.

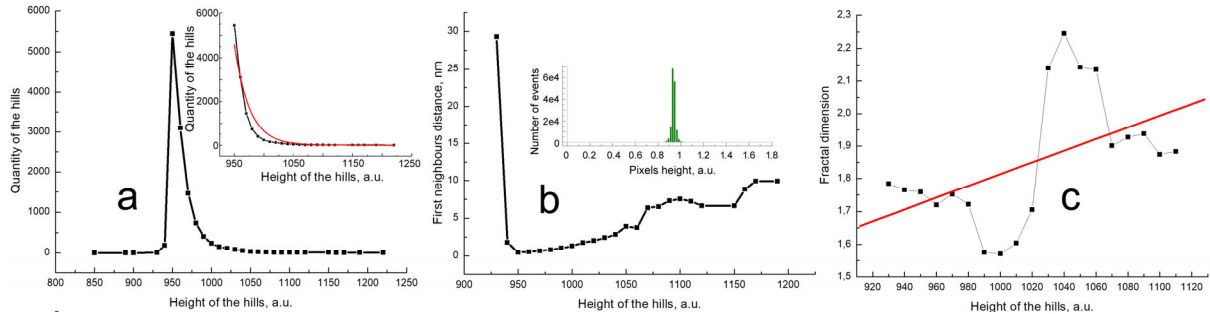


Fig. 3. Flooding analysis result for ($50 \text{ nm} \times 50 \text{ nm}$) area on (100) In_4Se_3 surface after 620 s of indium deposition: with the same (a), (b) and (c) positions as for Fig. 2

For large-area STM datasets, the reduction of segmented regions follows behavior close to first-order exponential decay. In contrast, nanoscale datasets exhibit steeper-than-exponential reduction kinetics. Such scale-sensitive behavior indicates cooperative interactions between neighboring nanostructures and correlated coalescence processes that become detectable only at sufficiently high spatial resolution.

The proposed segmentation framework therefore enables intelligent extraction of hidden morphology evolution patterns directly from STM height-coordinate datasets and provides quantitative characterization of surface coarsening processes associated with Gibbs-Thomson driven nanostructure growth.

D. Feature Extraction and Morphometrics

Based on the segmented STM datasets, quantitative morphology descriptors were extracted

for subsequent statistical analysis of surface evolution. The extracted feature set included fractal dimension values, nearest-neighbor distances, RMS roughness, skewness, kurtosis, flooded surface area, and height-distribution statistics.

The pixel height distributions shown in the insets of Figs. 2b and 3b demonstrate clear differences between large-area and nanoscale STM datasets. Large-area scans exhibit nearly Gaussian height distributions resulting from statistical averaging over multiple heterogeneous nanostructure populations. In contrast, nanoscale STM datasets demonstrate sharper and more localized distributions that reflect local clustering effects and stronger sensitivity to neighboring island interactions.

The extracted nearest-neighbor distance dependencies additionally confirm this interpretation. Minimum nearest-neighbor distances are observed near flooding levels corresponding to maximal coexistence of segmented nanostructures. Such behavior indicates formation of densely packed nanostructure ensembles during intermediate stages of surface evolution. Large-area datasets primarily describe global growth modes and long-range nanostructure distributions, whereas nanoscale datasets reveal local coalescence effects, clustering phenomena, and fine structural details of self-assembled In nanostructures.

E. Fractal Descriptor Evolution and Growth Kinetics

Fractal analysis of the segmented STM datasets was performed to characterize the complexity and self-affine organization of the deposited nanostructures. Besides, the measure of deposited metal nanostructured surface complexity of the topography the fractal dimension analysis could be used to explore the effect of preparation conditions on topographical quality [14] and, e.g., for 2D substrates [15]. The calculated fractal dimension dependencies during flooding analysis are shown in Figs. 2c and 3c. The extracted fractal descriptors demonstrate comparatively stable behavior over broad flooding ranges, indicating partial self-affinity of the experimentally formed nanostructures.

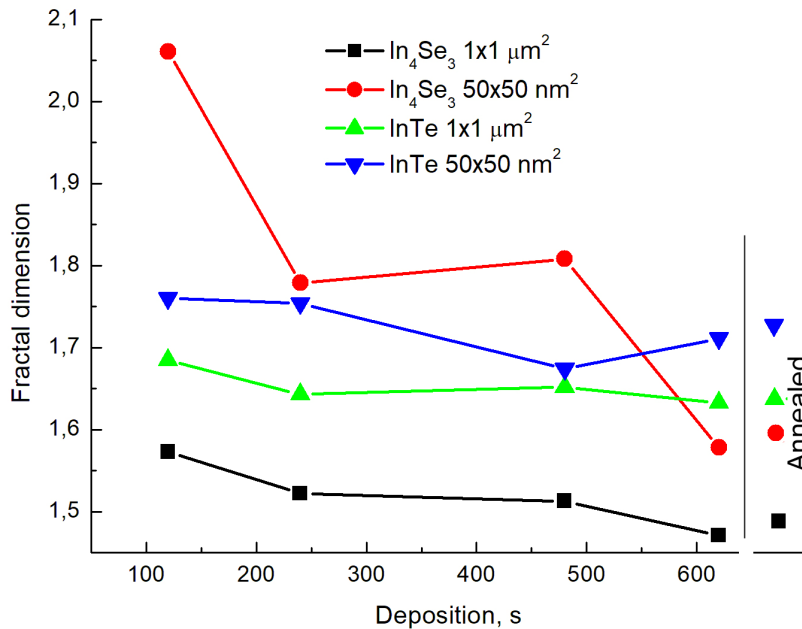


Fig. 4. Fractal dimension evolution extracted from multiscale (1 μm × 1 μm) and (50 nm × 50 nm) STM datasets of In nanostructures formed on (100) In₄Se₃ and (001) InTe surfaces.

The rightmost values correspond to the post-annealing stage after activation of SSD

For large-area STM datasets, the fractal dimension evolution remains relatively smooth and can be approximated linearly. In contrast, nanoscale datasets exhibit stronger local

fluctuations due to increased sensitivity to local morphology heterogeneity and height-coordinate variations. The obtained results reveal strong correlation between fractal descriptors and statistical morphology parameters extracted from the STM datasets. In particular, fractal dimension evolution is closely associated with height-distribution characteristics and segmentation dynamics observed during flooding analysis. Such correlations demonstrate that fractal descriptors effectively capture the characteristic topographical states of deposited indium nanostructures.

Fig. 4 summarizes the kinetics of fractal dimension evolution for In nanostructures formed on (100) In₄Se₃ and (001) InTe surfaces under comparable deposition conditions. For both substrates and for both STM scan sizes, gradual reduction of fractal dimension values is observed with increasing deposition time. Higher fractal dimension values detected during early deposition stages correspond to increased lateral heterogeneity and continuous nucleation of new nanostructures. Progressive decrease of fractal descriptors indicates transition toward more morphologically stable coatings formed through island coalescence and Gibbs-Thomson driven surface energy minimization.

After activation of secondary SSD processes, a slight increase of fractal dimension is observed. Such behavior reflects partial reorganization of the deposited surface and formation of more anisotropic heterogeneous nanostructures influenced by the crystallographic symmetry of the layered substrates. The obtained results demonstrate that fractal descriptors represent sensitive quantitative indicators of nanoscale surface evolution and growth-regime transitions.

III. CONCLUSION

Overall, the obtained results demonstrate that integration of Flooding-based segmentation, multiscale morphology characterization, and fractal feature extraction provides an effective computational framework for automated analysis of nanoscale surface evolution processes. Special attention is devoted to the identification of Gibbs-Thomson driven coarsening effects, anisotropic nanostructure ordering, and scale-dependent manifestations of surface evolution processes. The proposed approach may be further extended toward machine-learning-assisted classification of STM datasets, intelligent identification of growth regimes, and development of autonomous computational microscopy systems for real-time nanoscale surface characterization.

ACKNOWLEDGMENT

The authors are grateful to Dr. Piotr Mazur for providing the STM datasets through the cooperation between Ivan Franko National University of Lviv and the University of Wrocław.

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New York Sarı Taksi Ücreti Tahmini için Bağımsız Hiperparametre Optimizasyonu ile Bileşen Tabanlı Regresyon

Component-Based Regression with Independent Hyperparameter Optimization for NYC Yellow Taxi Fare Forecasting

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Özet: Akıllı ulaşım sistemlerinde dinamik ve doğru ücret tahmini, hizmet sağlayıcıların operasyonel verimliliğinin artırılması ve fiyatlandırma şeffaflığının sağlanması açısından kritik öneme sahiptir. Mevcut tahmin modelleri, taksi ücretlerini çoğunlukla bütüncül bir “toplam tutar” değişkeni üzerinden ele almakta; ana ücret, sabit vergiler ve bahşiş gibi yapısal olarak farklı özelliklere sahip alt bileşenlerin özgün matematiksel dinamiklerini yeterince dikkate almamaktadır. Bu çalışmada, New York City (NYC) Taxi and Limousine Commission (TLC) verileri kullanılarak toplam ücreti oluşturan ana ücret, ek ücretler, vergiler, bahşiş ve otoyol ücretleri dâhil olmak üzere dokuz farklı ücret bileşeninin bağımsız olarak modellendiği bileşen temelli bir tahmin mimarisi önerilmiştir. Araştırma kapsamında 3,6 milyondan fazla yolculuk kaydı, meteorolojik veriler ve resmî tatil takvimi gibi dışsal değişkenlerle bütünleştirilerek kapsamlı bir özellik mühendisliği sürecinden geçirilmiştir. Modelleme aşamasında, her bir ücret bileşeni için Optuna tabanlı bağımsız hiperparametre optimizasyonu gerçekleştirilmiş; ardından Hafif Gradyan Artırma Makinesi (LightGBM), Ekstra Ağaçlar ve Yapay Sinir Ağları (YSA) algoritmalarının performansları karşılaştırmalı olarak değerlendirilmiştir. Elde edilen bulgular, önerilen bileşen temelli yaklaşımın geleneksel toplam ücret tahmin modellerine kıyasla daha yüksek tahmin performansı sağladığını göstermiştir. Önerilen model, 2.6929 ortalama mutlak hata (MAE) ve 0.9134 belirleme katsayısı (R^2) değerlerine ulaşmıştır. Sonuç olarak, karmaşık fiyatlandırma yapılarının alt bileşenlerine ayrıştırılarak modellenmesinin ücret tahmin performansını artırdığı belirlenmiştir.

Anahtar Kelimeler: Ücret Tahmini, Hiperparametre Optimizasyonu, Regresyon, Bileşen Temelli Modelleme

Abstract: In intelligent transportation systems, dynamic and accurate fare prediction is critical for enhancing the operational efficiency of service providers and ensuring pricing transparency. Existing prediction models typically treat taxi fares as a holistic "total amount" variable, often failing to adequately account for the unique mathematical dynamics of sub-components—such as the base fare, fixed taxes, and tips—that possess distinct structural characteristics. This study proposes a component-based forecasting architecture that independently models nine distinct fare components—including base fare, surcharges, taxes, tips, and tolls—using data from the New York City (NYC) Taxi and Limousine Commission (TLC). As part of the research, over 3.6 million trip records underwent a comprehensive feature engineering process, integrating

them with exogenous variables such as meteorological data and the official public holiday calendar. During the modeling phase, independent hyperparameter optimization based on Optuna was performed for each fare component; subsequently, the performances of Light Gradient Boosting Machine (LightGBM), Extra Trees, and Artificial Neural Network (ANN) algorithms were comparatively evaluated. The findings demonstrate that the proposed component-based approach yields superior forecasting performance compared to traditional total fare forecasting models. The proposed model achieved a Mean Absolute Error (MAE) of 2.6929 and a coefficient of determination (R^2) of 0.9134. In conclusion, the study establishes that modeling complex pricing structures by decomposing them into their sub-components enhances fare forecasting performance.

Keywords: *Fare Forecasting, Hyperparameter Optimization, Regression, Component-Based Modeling*

I. GİRİŞ

Kentsel ulaşım sistemleri, özel araçlar, toplu taşıma ve trafik yönetimi gibi farklı bileşenleri bir araya getiren bütünleşik yapılarıyla modern kentlerin sürdürülebilir işleyişinde ve bireylerin yaşam kalitesinin artırılmasında önemli bir rol oynamaktadır [1]. Son yıllarda Uber ve Lyft gibi araç çağırma platformlarının yaygınlaşmasıyla birlikte, İsteğe Bağlı Mobilite hizmetleri kent içi ulaşımın önemli bileşenlerinden biri hâline gelmiştir [2]. Bu dönüşüm, yolculuk ücretlerinin doğru ve güvenilir biçimde tahmin edilmesini hem kullanıcılar hem de hizmet sağlayıcılar açısından önemli bir gereklilik hâline getirmiştir. Doğru ücret tahminleri, kullanıcıların fiyatlandırma süreçlerini daha öngörülebilir ve şeffaf biçimde değerlendirmelerine katkı sağlarken [3]. Hizmet sağlayıcıların operasyonel planlama ve kaynak yönetimi süreçlerini daha etkin yürütmelerine olanak tanımaktadır [4]. Özellikle trafik yoğunluğu, hava koşulları ve talep düzeyindeki değişimler gibi dışsal faktörlerden etkilenen dinamik fiyatlandırma mekanizmalarında, yolculuk ücretlerinin yüksek doğrulukla tahmin edilmesine yönelik güvenilir modellere duyulan gereksinim giderek artmaktadır.

Taksi ücreti tahminine yönelik mevcut çalışmalar incelendiğinde, toplam yolculuk maliyetinin çoğunlukla tek bir hedef değişken olarak ele alındığı ve farklı makine öğrenmesi ile derin öğrenme yöntemlerinin bu hedefin tahmininde kullanıldığı görülmektedir. Örneğin, farklı makine öğrenmesi yöntemlerinin ücret tahminindeki etkinliğini değerlendiren bir çalışmada Rasgele Orman (RO), Lasso Regresyon, Ridge Regresyon ve XGBoost algoritmaları karşılaştırılmıştır. Elde edilen sonuçlar, XGBoost'un diğer modellere kıyasla daha düşük Kök Ortalama Kare Hata (RMSE) ve daha yüksek R^2 değerleri sağladığını göstermiş; doğrusal olmayan ve karmaşık ilişkileri modelleme yeteneği sayesinde XGBoost, $R^2=0,83$ değeriyle karşılaştırılan yöntemler arasında en yüksek tahmin performansına ulaşmıştır [5]. Benzer şekilde, açıklanabilirlik ve model şeffaflığını ön plana çıkaran bir başka araştırmada Karar Ağaçları yönteminin ücret tahminindeki etkinliği incelenmiştir. Geçmiş Uber yolculuk kayıtlarının kullanıldığı çalışmada, yolculuk mesafesi ve yolcu sayısı gibi temel değişkenlerin ücret üzerindeki etkileri değerlendirilmiş ve modelin %90,33 düzeyinde R^2 değerine ulaştığı bildirilmiştir. Ayrıca düşük hesaplama gereksinimi ve yorumlanabilir yapısı nedeniyle bu tür modellerin gerçek zamanlı ücret tahmini uygulamalarında daha karmaşık yöntemlere alternatif oluşturabileceği belirtilmiştir [6].

Tekil makine öğrenmesi modellerinin yanı sıra, farklı algoritmaların güçlü yönlerini bir araya getiren hibrit ve topluluk öğrenme yaklaşımları da ücret tahmininde kullanılmaktadır. Ulaşım sistemlerinde hız, trafik yoğunluğu ve ücret gibi değişkenlerin birlikte değerlendirildiği bir araştırmada, Lineer Regresyon ile Karar Ağacı algoritmalarının birleştirildiği hibrit modelin tekil modellere kıyasla daha yüksek tahmin başarısı sağladığı ve %93 düzeyinde R^2 değerine

ulaştığı raporlanmıştır. Bu sonuçlar, farklı öğrenme algoritmalarının tamamlayıcı özelliklerinin bir araya getirilmesinin kentsel ulaşım verilerindeki karmaşık ilişkilerin modellenmesine katkı sağlayabileceğini göstermiştir [7]. Benzer biçimde, araç çağırma hizmetlerinde derin öğrenme yöntemlerinin performansını inceleyen bir çalışmada Boston bölgesine ait Uber ve Lyft verileri kullanılarak LSTM, BiLSTM ve dikkat mekanizmalı BiLSTM modelleri karşılaştırılmıştır. BiLSTM+Attention modelinin karmaşık zamansal bağımlılıkların modellenmesinde en yüksek tahmin performansını sağladığı, ancak artan hesaplama maliyetinin operasyonel açıdan bir kısıt oluşturabileceği belirlenmiştir. Standart LSTM modelinin ise tahmin başarısı ile hesaplama verimliliği arasında daha dengeli bir yapı sunduğu bildirilmiştir. Ayrıca yolculuk mesafesi, günün saati ve hava durumu gibi değişkenlerin ücret tahminindeki önemine dikkat çekilmiştir [4].

Ücret tahmini yalnızca kullanılan öğrenme algoritmasına değil, fiyatlandırmayı etkileyen farklı veri kaynaklarının modele ne ölçüde yansıtıldığına da bağlıdır. Bu doğrultuda, operasyonel ve finansal göstergelere ek olarak anlamsal bilgilerin fiyatlandırma süreçlerindeki rolünü inceleyen bir çalışmada boylamsal veri analizi Üretken Yapay Zekâ teknikleriyle bütünleştirilmiştir. Kümülatif Bağlantı Karma Modelinin kullanıldığı araştırmada, şirketlerin yıllık faaliyet raporlarından çıkarılan duygu analizi göstergeleri ile teknoloji odaklı ifadelerin fiyat kategorilerinin tahmininde anlamlı değişkenler olduğu belirlenmiştir. Böylece geleneksel nicel değişkenlere ek olarak kurumsal raporlardan elde edilen semantik bilgilerin de fiyatlandırma süreçleriyle ilişkili olabileceği gösterilmiştir [3].

Fiyatlandırma yapısının daha ayrıntılı incelenmesi, toplam ücret içerisinde yer alan bileşenlerin farklı davranış örüntülerine sahip olabileceğini de ortaya koymaktadır. Bu kapsamda, New York City taksi pazarında bahşiş davranışlarını inceleyen bir çalışmada farklı ödeme sistemlerinin yolcuların bahşiş tercihleri ve bu tercihlerin öngörülebilirliği üzerindeki etkileri araştırılmıştır. Yaklaşık 280 milyon yolculuk kaydının analiz edildiği çalışmada, geleneksel sarı taksilerde kullanılan araç içi ödeme ekranlarının bahşiş davranışlarını belirli oranlar etrafında yoğunlaştırdığı ve bahşiş tutarlarının tahmin edilebilirliğini $R^2 \approx 0,72$ düzeyine yükselttiği belirlenmiştir. Buna karşılık, uygulama tabanlı ulaşım hizmetlerinde bahşiş davranışlarının daha değişken ve öngörülmesi güç bir yapı sergilediği ve tahmin performansının $R^2 \approx 0,17$ düzeyinde kaldığı bildirilmiştir. Ayrıca, sıfır değerlerin yoğun olduğu veri yapılarının modellenmesinde CatBoost algoritmasının Tweedie kayıp fonksiyonuyla birlikte kullanılmasının etkili sonuçlar sağladığı rapor edilmiştir [8].

Taksi verilerindeki karmaşık yapı yalnızca ücret bileşenlerinden değil, aynı zamanda mekânsal ve zamansal bağımlılıklardan da kaynaklanmaktadır. Bu ilişkileri ele alan bir çalışmada, NYC Taxi and Limousine Commission tarafından yayımlanan 2015 yılı Sarı Taksi veri kümesinden 6 Ekim 2015 tarihine ait yolculuk kayıtları kullanılmış; veriler Manhattan'daki 39 posta koduna göre mekânsal, 15 dakikalık aralıklara göre ise zamansal olarak ayrıştırılmıştır. Yüksek boyutlu mekânsal-zamansal ilişkilerin modellenmesi amacıyla Genelleştirilmiş Spatio-Temporal Otoregresif model ile Çift Hiyerarşik Grup LASSO düzenleme yöntemi birlikte uygulanmıştır. Bulgular, geliştirilen yaklaşımın geleneksel VAR ve ARMA modellerine kıyasla daha düşük Ortalama Kare Tahmin Hatası sağladığını ve komşu bölgeler arasındaki zamana bağlı ilişkileri daha etkili biçimde modellediğini göstermiştir [9].

Bu yöntemsel çeşitlilik, İsteğe Bağlı Mobilite alanındaki tahmin yaklaşımlarının zaman içerisinde önemli ölçüde geliştiğini göstermektedir. Nitekim 2016–2025 döneminde yayımlanan 291 hakemli çalışmayı inceleyen sistematik bir literatür taraması, ARIMA-GARCH gibi geleneksel istatistiksel yöntemlerin özellikle 2021 sonrasında yerini büyük ölçüde makine öğrenmesi ve derin öğrenme yaklaşımlarına bıraktığını ortaya koymuştur. Bununla birlikte, gradyan artırmalı karar ağaçları, RO ve Destek Vektör Regresyonu gibi

geleneksel makine öğrenmesi yöntemlerinin, sınırlı veri veya yüksek açıklanabilirlik gerektiren uygulamalarda önemini koruduğu belirtilmiştir. Derin öğrenme tarafında, 2017–2020 döneminde yaygın olarak kullanılan RNN ve LSTM tabanlı modellerin günümüzde daha çok hibrit mimarilerin bileşenleri olarak değerlendirildiği; mekânsal-zamansal ilişkilerin modellenmesinde grafik tabanlı ağların, uzun mesafeli ve küresel bağımlılıkların öğrenilmesinde ise TFT ve ADFormer gibi Transformer tabanlı mimarilerin kullanımının arttığı bildirilmiştir. Ayrıca adillik, federatif öğrenme ve olasılıksal belirsizlik modellemesinin güncel araştırma konuları arasında yer aldığı; Büyük Dil Modelleri ve kuantum tabanlı yöntemlerin ise yeni araştırma yönleri olarak dikkat çekmeye başladığı belirtilmiştir [2].

Bununla birlikte, literatürde kullanılan yöntemler gelişmiş olsa da taksi ücreti tahminine yönelik çalışmaların önemli bir bölümünde toplam yolculuk maliyetinin tek bir hedef değişken olarak modellenmesi temel yaklaşım olmayı sürdürmektedir [5,6]. Oysa toplam yolculuk ücreti; ana tarife ücreti, zamana bağlı ek ücretler, Metropolitan Transportation Authority (MTA) vergisi gibi düzenlemeler kapsamında belirlenen sabit kalemler, otoyol geçiş ücretleri ve yolcu tercihlerine bağlı olarak değişen bahşiş tutarı gibi farklı niteliklere sahip bileşenlerden oluşmaktadır. Bu bileşenler gerek oluşum mekanizmaları gerekse istatistiksel özellikleri bakımından birbirinden farklıdır. Örneğin, bazı vergi ve ek ücret kalemleri önceden tanımlanmış kurallara göre belirlenirken, bahşiş tutarı yolcu davranışı ve çeşitli dışsal faktörlerden etkilenmesi nedeniyle daha yüksek belirsizlik içermektedir [8]. Dolayısıyla, farklı özelliklere sahip tüm ücret bileşenlerinin tek bir hedef değişken altında modellenmesi, bileşenlere özgü değişkenliklerin yeterince temsil edilememesine neden olabilir. Ayrıca bu yaklaşım, toplam ücret içerisindeki her bir bileşenin katkısının ayrı ayrı değerlendirilmesini güçleştirerek modelin açıklanabilirliğini sınırlandırabilir.

Bu çalışmada, söz konusu yöntemsel sınırlılığı ele almak amacıyla NYC Taxi and Limousine Commission tarafından sağlanan Sarı Taksi veri kümesine dayalı bileşen temelli bir ücret tahmin mimarisi önerilmektedir. Geleneksel toplam ücret tahmini yaklaşımından farklı olarak, toplam yolculuk ücretini oluşturan dokuz ayrı ücret kalemi birbirinden bağımsız tahmin problemleri olarak ele alınmaktadır. Ayrıca geleneksel mesafe ve zaman değişkenlerine ek olarak sıcaklık, yağış ve görüş mesafesi gibi hava durumu değişkenleri ile resmi tatil bilgileri modele dahil edilmektedir. Her bir ücret bileşeninin kendine özgü veri yapısına uygun model ve hiperparametrelerin belirlenebilmesi amacıyla Optuna kullanılarak bağımsız hiperparametre optimizasyonu gerçekleştirilmektedir. Böylece önerilen yaklaşım, toplam ücretin doğrudan tek bir hedef olarak tahmin edilmesi yerine, farklı oluşum mekanizmalarına sahip ücret bileşenlerinin ayrı ayrı modellenmesi ve elde edilen tahminlerin bütünleştirilmesi esasına dayanmaktadır.

II. VERİ KÜMESİ VE ÖN İŞLEME

Bu bölümde, tahmin modelinde kullanılan veri setinin hazırlanmasına ilişkin süreç ayrıntılı olarak ele alınmaktadır. Bu kapsamda veri toplama ve temizleme işlemleri, verilerin düzenlenmesi, dışsal veri kaynaklarıyla bütünleştirilmesi ve özellik mühendisliği aşamaları, benimsenen metodolojik çerçeve doğrultusunda sistematik olarak açıklanmaktadır.

A. NYC TLC Veri Kümesi

Çalışmada veri kaynağı olarak, NYC Taksi ve TLC tarafından yayımlanan Ocak 2026 dönemine ait Sarı Taksi seyahat kayıtları kullanılmıştır. Ham veri seti toplam 3.724.889 gözlem ve 20 öznitelikten oluşmakta olup, seyahat başlangıç ve bitiş zamanları, yolcu sayısı, seyahat mesafesi ile ücret bileşenlerine ilişkin ayrıntılı bilgileri kapsamaktadır [10].

B. NYC TLC Veri Kümesi

Regresyon tabanlı tahmin modellerinin aykırı gözlemlere ve gürültülü verilere karşı duyarlı olması, modelleme aşamasından önce verilerin kapsamlı bir ön işleme sürecinden geçirilmesini gerekli kılmaktadır [5,11]. Bu doğrultuda, veri kalitesinin artırılması ve tahmin performansını olumsuz etkileyebilecek hatalı veya tutarsız kayıtların giderilmesi amacıyla çeşitli veri temizleme ve düzenleme işlemleri gerçekleştirilmiştir.

İlk olarak, veri setindeki eksik değerler incelenmiş ve yolcu sayısı, tarife kodu, yoğunluk ek ücreti ve havalimanı tarifesine değişkenlerinde toplam 1.088.058 eksik değer tespit edilmiştir. Ücret bileşenlerine ilişkin eksik değerler, ilgili ücret kaleminin bulunmadığını gösterecek şekilde 0 değeriyle doldurulmuştur. Kategorik nitelikteki tarife kodunda bulunan eksik değerler ise -1 değeriyle temsil edilen bilinmeyen sınıfına atanmıştır. Ayrıca, analiz sürecine anlamlı bir katkı sağlamayan çevrimdışı veri iletim bayrağı (store-and-forward flag) değişkeni veri setinden çıkarılmıştır.

Veri bütünlüğünün sağlanması amacıyla, yapıları gereği negatif değer almaması gereken değişkenler de kontrol edilmiştir. Yapılan inceleme sonucunda altyapı iyileştirme ek ücretinde 39.732, toplam ücrette 39.984, ana seyahat ücretinde 39.463, MTA vergisinde 37.730, yoğunluk ek ücretinde 30.448, ilave ücretlerde 20.035, havalimanı tarifesinde 9.225 ve otoyol/köprü geçiş ücretlerinde 3.391 negatif değer içeren kayıt belirlenmiştir. Seyahat mesafesi değişkeninde ise herhangi bir negatif değere rastlanmamıştır. Aynı kaydın birden fazla değişkende tutarsızlık içerebilmesi dikkate alınarak hatalı gözlemler benzersiz satırlar üzerinden değerlendirilmiş ve toplam 40.049 kayıt veri setinden çıkarılmıştır.

Son olarak, yolcu sayısı değişkeninde standardizasyon işlemi gerçekleştirilmiştir. Araç kapasitesini aşacak şekilde 6'dan büyük olarak kaydedilen yolcu sayıları, taksinin azami kapasitesini temsil eden 6 değeriyle sınırlandırılmıştır. Bölgesel ortalamanın hesaplanmasına olanak sağlayacak yeterli geçerli gözlemin bulunmadığı başlangıç bölgelerinde ise hatalı veya eksik yolcu sayılarının düzeltilmesinde veri setinin genel yolcu sayısı ortalamasından yararlanılmıştır.

C. Çok Katmanlı Dış Veri Entegrasyonu

Tahmin modelinin doğruluğunu artırmak amacıyla seyahat kayıtları meteorolojik ve zamansal dışsal verilerle zenginleştirilmiştir. Bu doğrultuda, NYC taksi bölgelerine ait coğrafi sınırları içeren shapefile kullanılarak her bölgenin merkez noktası hesaplanmıştır. Elde edilen bölge koordinatları, EPSG:2263 koordinat referans sisteminden EPSG:4326 coğrafi koordinat sistemine dönüştürülerek enlem ve boylam bilgileri belirlenmiştir. Meteorolojik verilerle zamansal eşleştirmenin sağlanabilmesi amacıyla yolculuk başlangıç zamanları en yakın saate yuvarlanarak referans zaman bilgisi oluşturulmuştur. Daha sonra konum ve zaman bilgileri kullanılarak Open-Meteo API üzerinden ilgili tarih ve saate ait sıcaklık, yağış, kar yağışı ve rüzgâr hızı gibi değişkenleri kapsayan toplam 21 meteorolojik özellik veri setine entegre edilmiştir.

Meteorolojik değişkenlerin yanı sıra, seyahat talebi üzerindeki takvimsel etkilerin modele yansıtılması amacıyla resmi tatil bilgileri de veri setine dahil edilmiştir. Bu amaçla Python'un açık kaynaklı holidays kütüphanesi kullanılarak ilgili döneme ait resmi tatil takvimi oluşturulmuş ve her seyahat kaydı için yolculuk tarihinin resmi tatile denk gelip gelmediğini belirten ikili bir gösterge değişkeni tanımlanmıştır.

Dışsal verilerin entegrasyonunun ardından eşleştirme işlemlerinin tutarlılığı kontrol edilmiştir. Geçersiz veya hatalı taksi bölge kodları olan 264 ve 265 nedeniyle meteorolojik verilerle eşleştirilemeyen 5.800 kayıt ile yalnızca tek bir gözlem içeren bölgelere ait kayıtlar veri setinden çıkarılmıştır. Böylece meteorolojik ve zamansal dışsal verilerle uyumlu, tutarlı ve modelleme sürecinde kullanılmaya hazır nihai analiz veri kümesi elde edilmiştir.

D. Öznitelik Mühendisliği ve Nihai Veri Matrisi

Veri ön işleme sürecinin son aşamasında, ham verilerden tahmin sürecine katkı sağlayabilecek yeni öznitelikler türetilmiş ve model eğitiminde kullanılacak nihai veri matrisi oluşturulmuştur. Bu doğrultuda, öncelikle yolculuk başlangıç ve bitiş zamanları arasındaki fark hesaplanarak seyahat süresi saniye cinsinden elde edilmiş ve ardından saat birimine dönüştürülmüştür. Seyahatlerin zamansal özelliklerini modele yansıtmak amacıyla yolculuk başlangıç saati ve haftanın günü değişkenleri oluşturulmuştur. Bunun yanı sıra, seyahat mesafesinin yolculuk süresine oranlanmasıyla ortalama hız özniteliği hesaplanmıştır. Sıfıra bölme hatalarının önlenmesi amacıyla bu hesaplamada seyahat süresine küçük bir epsilon değeri ($\epsilon = 0,0001$) eklenmiştir.

New York City ulaşım sisteminde özel ücretlendirme uygulamalarının bulunduğu havalimanı yolculuklarının temsil edilebilmesi amacıyla ayrıca ikili bir havalimanı gösterge değişkeni oluşturulmuştur. Bu işlemde Newark (1), JFK (132) ve LaGuardia (138) havalimanı bölgeleri esas alınmış; yolculuğun başlangıç veya varış bölgesinin bu kodlardan herhangi biriyle eşleşmesi durumunda gösterge değişkenine 1, diğer durumlarda ise 0 değeri atanmıştır.

Öznitelik mühendisliğinin ardından, yalnızca ara işlemlerde kullanılan, yinelenen bilgi içeren veya model eğitiminde veri sızıntısına yol açabilecek değişkenler veri setinden çıkarılmıştır. Bu kapsamda toplam ücret, yolculuk başlangıç ve bitiş zaman damgaları ile meteorolojik verilerin eşleştirilmesi amacıyla oluşturulan ara zaman değişkenleri model girdilerinden kaldırılmıştır. Ayrıca, istatistiksel değerlendirme açısından yeterli sayıda gözlem içermeyen ve yalnızca birer kayıt bulunan 99 ve 44 numaralı kalkış bölgelerine ait gözlemler analiz dışında bırakılmıştır.

Veri temizleme, dışsal veri entegrasyonu ve öznitelik mühendisliği aşamalarının tamamlanmasının ardından nihai veri seti 3.679.038 gözlem ve 42 değişkenden oluşmuştur. Bu yapı içerisinde Tablo 1'de verilen 33 bağımsız değişken, çoklu çıktı tahmin yaklaşımı kapsamında dokuz farklı ücret bileşeninin tahmin edilmesinde model girdileri olarak kullanılmıştır.

Table I. Model Eğitiminde Kullanılan Bağımsız ve Bağımlı Değişken Listesi

Değişken	Açıklama
VendorID, payment_type	Sırasıyla veri sağlayıcı (TPEP) ve yolcu ödeme yöntemi (Kredi kartı, nakit vb.) kodları.
passenger_count	Araçtaki yolcu sayısı
trip_distance, trip_duration	Seyahat mesafesi (Mil) ve başlangıç/bitiş zamanlarından hesaplanan seyahat süresi (Saat).
avg_speed	Seyahat mesafesinin süreye oranlanmasıyla hesaplanan ortalama hız
RatecodeID	Yolculuk sonunda uygulanan nihai ücret tarifi oranı kodu.
PULocationID, DOLocationID	Yolculuğun başladığı ve bittiği TLC taksi bölgesi kimlik numaraları (ID).
is_holiday, is_airport	Yolculuk gününün resmi tatil olma durumunu ve bölgenin havalimanı (JFK, LGA, EWR) içerme durumunu belirten ikili (binary) göstergeler.
pickup_hour, pickup_day, is_day	Yolculuğun başladığı saat dilimi (0–23), haftanın günü (0–6) ve gün ışığı durumu (Gündüz: 1, Gece: 0).
temperature_2m, apparent_temperature, relative_humidity_2m, dew_point_2m, precipitation, rain, snowfall, snow_depth, weather_code, surface_pressure, pressure_msl, cloud_cover (total, low, mid, high), visibility, wind_speed_10m, wind_direction_10m, wind_gusts_10m	sıcaklık (°C), hissedilen sıcaklık (°C), bağıl nem (%), çiğ noktası (°C), toplam yağış (mm), yağmur (mm), kar yağışı (cm), kar derinliği (m), WMO hava kodu, yüzey ve deniz seviyesi basınçları (hPa), bulutluluk oranları (%), görüş mesafesi (m), rüzgar hızı (km/s), yönü ve ani rüzgar hamlesi

fare_amount, extra, mta_tax, tip_amount,
tolls_amount, improvement_surcharge,
congestion_surcharge, Airport_fee,
cbd_congestion_fee

Tahmin edilmesi hedeflenen; ana taksimetre ücreti, yoğun saat/gece farkı, MTA vergisi, bahşiş, köprü/otoyol geçişleri, altyapı harcı, trafik sıkışıklığı, havalimanı ve iş merkezi (CBD) yoğunluk kesintilerini içeren maliyet kalemleri (\$).

^a Çalışma kapsamında kullanılan 33 adet bağımsız değişken ve tahmin edilmesi hedeflenen 9 adet bağımlı ücret kalemi.

III. METODOLOJİ

Geleneksel regresyon yaklaşımlarında taksi ücreti genellikle toplam ücret tek bir hedef değişken olarak ele alınmaktadır. Bu çalışmada ise farklı bir yaklaşım benimsenmiş; NYC Sarı Taksi seyahat ücreti, toplam tutar üzerinden modellenmek yerine maliyeti oluşturan her bir ücret bileşeni ayrı bir çıktı değişkeni olarak ele alınmıştır. Böylece, her ücret kaleminin kendine özgü istatistiksel ve matematiksel özellikleri korunarak Bileşen tabanlı bir tahmin çerçevesi oluşturulmuştur. Bu yaklaşımın, farklı ücret bileşenlerinin birbirinden bağımsız dinamiklerini daha etkin biçimde öğrenerek modelin tahmin başarısını artırması hedeflenmiştir.

Modellerin genellenebilirliğini değerlendirmek amacıyla veri kümesi, yolculuk başlangıç bölgelerinin dağılımı korunacak şekilde tabakalı bir ayırıştırma stratejisi kullanılarak %80 eğitim ve %20 test veri kümesi olmak üzere iki alt kümeye ayrılmıştır. Önerilen modelin mimarisi Şekil 1’de verilmiştir.

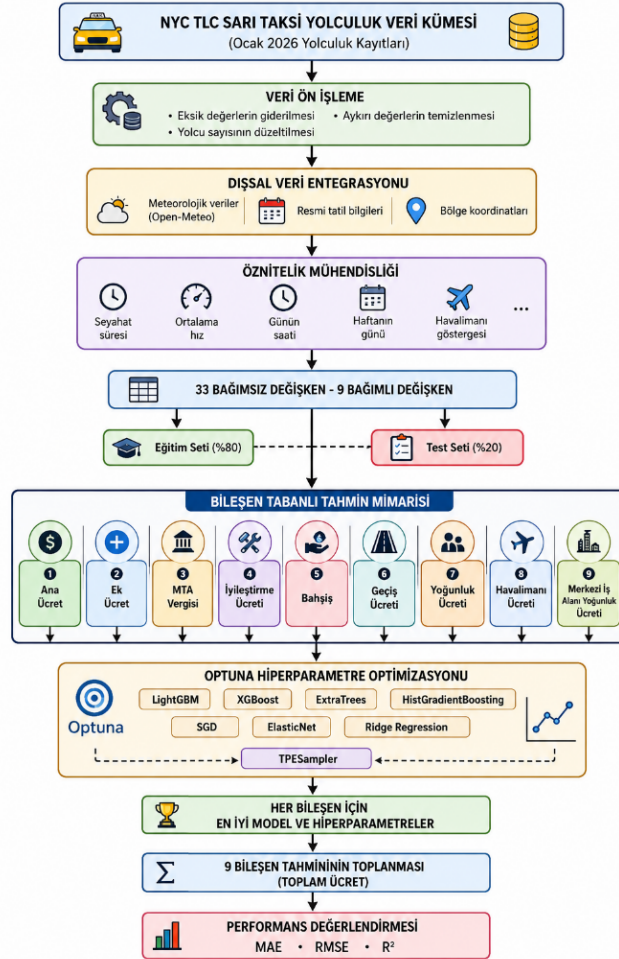


Fig. 1. Önerilen Bileşen Tabanlı Tahmin Modelinin Mimarisi

A. Bileşen tabanlı Modelleme Çerçevesi

Bileşen tabanlı modelleme yaklaşımında, toplam seyahat ücreti tek bir hedef değişken olarak tahmin edilmek yerine, ücret yapısını oluşturan dokuz farklı bileşene ayırıştırılarak her bir bileşen bağımsız olarak modellenmiştir. Bu yaklaşımın temelinde, ücret kalemlerinin oluşum

biçimleri ve istatistiksel özellikleri açısından birbirinden farklı yapılar sergilemesi yer almaktadır. Seyahat mesafesine göre belirlenen ana seyahat ücreti ile yasal düzenlemeler kapsamında sabitlenen MTA vergisi ve altyapı iyileştirme ek ücreti, ücret yapısının daha deterministik bileşenlerini oluşturmaktadır. Buna karşılık ilave ek ücretler, yoğunluk ek ücreti, havalimanı tarifesı, iş merkezi yoğunluk kesintisi ve otoyol/köprü geçiş ücretleri zamansal ve konumsal koşullara bağlı olarak değişkenlik göstermektedir. Bahşış tutarı ise doğrudan yolcu tercihine bağlı olması nedeniyle diğer ücret bileşenlerine kıyasla daha yüksek değışkenlik gösteren stokastik bir yapıya sahiptir.

Ücret bileşenleri arasındaki bu heterojenlik göz önünde bulundurularak, düşük varyansa sahip daha deterministik ücret kalemlerinin, yüksek değışkenlik gösteren bahşış ve geçiş ücretlerinin etkisi altında kalmasının önlenmesi amaçlanmıştır. Bu doğrultuda, dokuz ücret bileşeninin her biri için bağımsız regresyon modelleri oluşturulmuş ve her hedef değışken kendi dağılımsal özellikleri ve dinamikleri doğrultusunda ayrı ayrı modellenmiştir. Böylece, ücret bileşenlerine özgü yapıların tahmin sürecinde korunması ve toplam seyahat ücretinin tahmin doğruluğunun artırılması hedeflenmiştir.

B. Optuna ile Bağımsız Hiperparametre

Her bir ücret bileşeni için en uygun regresyon yönteminin ve ilgili modele ait hiperparametrelerin belirlenmesi amacıyla Optuna tabanlı hiperparametre optimizasyonu gerçekleştirilmiştir. Optimizasyon sürecinde LightGBM, XGBoost, Stochastic Gradient Descent (SGD), ExtraTrees, Histogram Gradient Boosting Regressor (HistGradientBoostingRegressor), ElasticNet ve Ridge Regression algoritmaları aday modeller olarak değerlendirilmiştir. Hiperparametre arama uzayının etkin biçimde taranması için Tree-structured Parzen Estimator (TPE) örnekleme yöntemi tercih edilmiştir. Arama sürecinin başlangıcında geniş bir çözüm uzayının keşfedilmesini sağlamak ve erken aşamada yerel optimumlara yönelme olasılığını azaltmak amacıyla `n_startup_trials` değeri 30 olarak belirlenmiştir. Ayrıca, hiperparametreler arasındaki olası ilişkilerin optimizasyon sürecine yansıtılması amacıyla `multivariate=True` seçeneğı etkinleştirilerek parametrelerin amaç fonksiyonu üzerindeki ortak etkileri dikkate alınmıştır. Farklı model mimarilerine özgü hiperparametre uzaylarının aynı optimizasyon sürecinde yönetilebilmesi için `group=True` ayarı kullanılmıştır. Paralel olarak yürütölen denemelerde aynı veya benzer hiperparametre kombinasyonlarının tekrar değerlendirilmesini sınırlandırmak ve arama uzayının daha etkin biçimde taranmasını sağlamak amacıyla ise `constant_liar=True` stratejisinden yararlanılmıştır.

Optimizasyonun amaç fonksiyonu modelin RMSE performansı temel alınarak tanımlanmıştır. Bu kapsamda, RMSE değeri en aza indirilmesine karşılık gelecek şekilde -RMSE değeri en büyüklenmesi esas alınmıştır. Model geliştirme için ayrılan veri kümesi kendi içerisinde yeniden bölünerek verilerin %75'i eğitim, kalan %25'i doğrulama amacıyla kullanılmıştır. Her Optuna denemesinde önerilen hiperparametre kombinasyonu kullanılarak ilgili regresyon modeli eğitim kümesi üzerinde eğitilmiş ve doğrulama kümesinden elde edilen -RMSE değeri amaç fonksiyonuna geri aktarılmıştır. Optimizasyon sürecinin tamamlanmasının ardından, dokuz ücret bileşeninin her biri için doğrulama performansı en yüksek olan regresyon algoritması ve bu algoritmaya ait optimal hiperparametre kombinasyonu ayrı ayrı belirlenerek nihai modeller oluşturulmuştur.

C. Karşılaştırmalı Analiz Tasarımı

Önerilen bileşen temelli modelleme yaklaşımının tahmin performansı üzerindeki etkisini incelemek amacıyla üç farklı modelleme stratejisi karşılaştırılmıştır. İlk stratejide, Bileşen Temelli Optimizasyon yaklaşımı kullanılarak dokuz ücret bileşeninin her biri için Optuna aracılığıyla en uygun regresyon algoritması ve hiperparametre kombinasyonu ayrı ayrı belirlenmiştir. Her bileşene ait bağımsız modellerden elde edilen tahminler daha sonra birleştirilerek toplam seyahat ücreti hesaplanmıştır. İkinci stratejide, Doğrudan Toplam

Tahmini yaklaşımı uygulanmış ve toplam seyahat ücreti herhangi bir alt bileşene ayrılmadan tek bir hedef değişken olarak modellenmiştir. Bu kapsamda LightGBM ve Yapay Sinir Ağı (YSA) modelleri kullanılmıştır. Üçüncü stratejide ise Çok Çıktılı Regresyon yaklaşımı benimsenmiş ve ExtraTrees ile YSA modelleri, dokuz ücret bileşenini aynı eğitim süreci içerisinde eş zamanlı olarak tahmin edecek şekilde yapılandırılmıştır.

Bu deneysel düzen ile toplam seyahat ücretinin ayrı bileşenlere ayrıştırılarak modellenmesinin, doğrudan toplam ücret tahmini ve çok çıktılı regresyon yaklaşımlarına kıyasla tahmin performansı üzerindeki etkisi karşılaştırmalı olarak değerlendirilmiştir. Tüm modellerin performansları R^2 ve MAE metrikleri kullanılarak ölçülmüş; böylece üç farklı modelleme stratejisinin açıklanan varyans ve tahmin hatası bakımından karşılaştırılması gerçekleştirilmiştir.

IV. DENEYSEL ÇALIŞMA

Bu bölümde, Optuna tabanlı hiperparametre optimizasyonu sonucunda elde edilen deneysel bulgular sunulmaktadır. İlk olarak, regresyon modelleri için oluşturulan hiperparametre arama uzayları tanımlanmakta, ardından optimizasyon süreci sonucunda her bir ücret bileşeni için seçilen en uygun regresyon algoritmaları ve bunlara ait optimal hiperparametre konfigürasyonları incelenmektedir. Son aşamada ise önerilen bileşen temelli modelleme yaklaşımının tahmin performansı karşılaştırma modelleriyle birlikte değerlendirilerek elde edilen sonuçlar ayrıntılı olarak analiz edilmektedir.

Optimizasyon sürecinde değerlendirilen yedi farklı regresyon algoritmasına ait hiperparametreler, arama aralıkları ve dağılım türleri Tablo 2'de sunulmaktadır. Belirlenen arama uzayları, her bir algoritma için uygun hiperparametre kombinasyonlarının sistematik biçimde araştırılmasına ve tahmin performansı açısından en uygun konfigürasyonların belirlenmesine olanak sağlayacak şekilde oluşturulmuştur.

Table II. Optuna Hyperparameter Search Spaces for the Regression Models

Model	Hiperparametre	Arama Aralığı	Dağılım Tipi
LightGBM	Ağaç Sayısı (n_estimators)	[100, 1000]	Tam Sayı (Adım: 100)
	Öğrenme Oranı (learning_rate)	[0.02, 0.2]	Logaritmik
	Maksimum Derinlik (max_depth)	[3, 11]	Tam Sayı (Adım: 1)
	Maksimum Yaprak Sayısı (num_leaves)	[3, 60]	Tam Sayı (Adım: 3)
	Yaprak İçin Min. Veri (min_child_samples)	[10, 100]	Tam Sayı (Adım: 5)
	Alt Örneklem Oranı (subsample)	[0.1, 1.0]	Ondalıklı (Adım: 0.1)
	Ağaç Başına Öznitelik Oranı (colsample_bytree)	[0.1, 1.0]	Ondalıklı (Adım: 0.1)
XGBoost	L1 Düzenleştirme (reg_alpha)	[1e-8, 2.0]	Logaritmik
	L2 Düzenleştirme (reg_lambda)	[1e-8, 2.0]	Logaritmik
	Ağaç Sayısı (n_estimators)	[100, 1000]	Tam Sayı (Adım: 100)
	Öğrenme Oranı (learning_rate)	[0.02, 0.2]	Logaritmik
	Maksimum Derinlik (max_depth)	[3, 7]	Tam Sayı (Adım: 1)
	Min. Çocuk Düğüm Ağırlığı (min_child_weight)	[1, 8]	Tam Sayı (Adım: 1)
	Alt Örneklem Oranı (subsample)	[0.1, 1.0]	Ondalıklı (Adım: 0.1)
	Ağaç Başına Öznitelik Oranı (colsample_bytree)	[0.1, 1.0]	Ondalıklı (Adım: 0.1)

	Düğüm Bölme Eşiği (gamma)	[0.0, 2.0]	Ondalık (Adım: 0.2)
SGD	Ağaç Oluşturma Yöntemi (tree_method)	hist	Sabit
	Düzenleştirme Katsayısı (alpha)	[1e-6, 1e-2]	Logaritmik
	L1 Ceza Oranı (l1_ratio)	[0.0, 1.0]	Ondalık (Adım: 0.1)
	Başlangıç Öğrenme Oranı (eta0)	[1e-3, 1e-1]	Logaritmik
	Kayıp Fonksiyonu (loss)	huber	Sabit
	Ceza Terimi (penalty)	elasticnet	Sabit
	Öğrenme Oranı Stratejisi (learning_rate)	adaptive	Sabit
	Erken Durdurma (early_stopping)	true	Sabit
	Doğrulama Kümesi Oranı (validation_fraction)	0.1	Sabit
	Değişimsiz İterasyon Sınırı (n_iter_no_change)	15	Sabit
ExtraTrees	Maksimum İterasyon (max_iter)	10000	Sabit
	Tolerans (tol)	1e-4	Sabit
	Ağaç Sayısı (n_estimators)	[10, 200]	Tam Sayı (Adım: 10)
	Maksimum Derinlik (max_depth)	[3, 9]	Tam Sayı (Adım: 1)
	Bölünme İçin Min. Örneklem (min_samples_split)	[2, 10]	Tam Sayı (Adım: 1)
	Yaprak İçin Min. Örneklem (min_samples_leaf)	[1, 5]	Tam Sayı (Adım: 1)
	Maksimum Öznitelik Sayısı (max_features)	sqrt, log2	Kategorik
	Öğrenme Oranı (learning_rate)	[0.02, 0.2]	Logaritmik
	Maksimum Derinlik (max_depth)	[3, 60]	Tam Sayı (Adım: 1)
	Maksimum İterasyon (max_iter)	[100, 10000]	Tam Sayı (Adım: 100)
HistGradientBoosting	Yaprak İçin Min. Örneklem (min_samples_leaf)	[10, 100]	Tam Sayı (Adım: 5)
	Düzenleştirme Katsayısı (alpha)	[0.1, 18.9]	Logaritmik
	Düzenleştirme Katsayısı (alpha)	[0.001, 4.901]	Logaritmik
	L1 Ceza Oranı (l1_ratio)	[0.1, 0.9]	Ondalık (Adım: 0.1)
	Maksimum İterasyon (max_iter)	[1000, 10000]	Tam Sayı (Adım: 1000)
Ridge ElasticNet			

Dokuz farklı ücret bileşeni için bağımsız olarak yürütülen Optuna optimizasyon süreçleri sonucunda, her bir hedef değişkenin karakteristik özelliklerine en uygun regresyon algoritması ve optimal hiperparametre konfigürasyonu belirlenmiştir. Optimizasyon sürecinde, her bağımlı değişken için değerlendirilen tüm modeller arasında elde edilen en yüksek amaç fonksiyonu değeri ile bu sonuca ulaşılan iterasyon numarası Tablo 3'de sunulmaktadır. Optimizasyon sonucunda seçilen en başarılı model mimarileri ve bu modellere ait eğitim aşamasında elde edilen performans değerleri ise Tablo 4'de ayrıntılı olarak verilmektedir.

Table III. Ücret Bileşenleri İçin Her Model İle Elde Edilen Uygunluk Değerleri

Ücret Kalemi	Model	Uygunluk Değeri (-RMSE)	İterasyon Numarası
Havalimanı Ücreti (Airport_fee)	hist_gbm	-0,08717	48
	lightgbm	-0,08996	15
	xgboost	-0,09210	199
	extra_trees	-0,19251	168
	Ridge	-0,23105	140
	elasticnet	-0,23106	276
	sgd	-0,24817	69
CBD Yoğunluk Ücreti (cbd_congestion_fee)	hist_gbm	-0,12322	260
	lightgbm	-0,12521	16
	xgboost	-0,15640	22

	extra_trees	-0,30848	151
	ridge	-0,31619	26
	elasticnet	-0,31637	111
	sgd	-0,35616	3
Yoğunluk Ek Ücreti (congestion_surcharge)	hist_gbm	-0,18306	230
	lightgbm	-0,19983	143
	xgboost	-0,21211	109
	extra_trees	-0,68007	118
	ridge	-0,81592	291
	elasticnet	-0,81593	32
	sgd	-1,22275	93
Ek Ücret (extra)	hist_gbm	-0,24448	214
	lightgbm	-0,24693	103
	xgboost	-0,28305	13
	extra_trees	-1,21616	264
	ridge	-1,36202	9
	elasticnet	-1,36247	25
	sgd	-1,55565	12
Tarife Ücreti (fare_amount)	lightgbm	-5,81270	182
	xgboost	-5,91800	61
	hist_gbm	-5,95834	44
	extra_trees	-12,743	148
	ridge	-13,2286	51
	elasticnet	-13,2291	283
	sgd	-14,6410	14
Geliştirme Ek Ücreti (improvement_surcharge)	lightgbm	-0,01426	154
	hist_gbm	-0,01503	271
	xgboost	-0,01549	262
	ridge	-0,02843	72
	elasticnet	-0,02847	63
	sgd	-0,02877	4
	extra_trees	-0,04033	27
MTA Vergisi (mta_tax)	lightgbm	-0,01637	247
	xgboost	-0,01660	21
	hist_gbm	-0,01664	239
	extra_trees	-0,04491	258
	ridge	-0,05388	169
	elasticnet	-0,05389	61
	sgd	-0,05478	117
Bahşiş Tutarı (tip_amount)	lightgbm	-2,24911	127
	hist_gbm	-2,25490	1
	xgboost	-2,28649	3
	extra_trees	-2,85717	89
	ridge	-3,27700	258
	elasticnet	-3,27702	38
	sgd	-3,56536	17
Geçiş Ücretleri (tolls_amount)	lightgbm	-1,21960	215
	hist_gbm	-1,27329	123
	xgboost	-1,30635	288
	extra_trees	-1,73628	73
	ridge	-1,78821	239
	elasticnet	-1,78821	12
	sgd	-1,95303	2

Table IV. Ücret Bileşenleri İçin Optimal Model ve Hiperparametre Setleri

Ücret Kalemi	En İyi Model	Uygunluk Değeri (-RMSE)	Optimal Hiperparametre Seti
Tarife Ücreti (fare_amount)	LightGBM	-5.8127	n_estimators=1000, learning_rate=0.0597, max_depth=9, num_leaves=60, min_child_samples=20, subsample=0.2, colsample_bytree=0.7
Ek Ücret (extra)	HistGBM	-0.2444	learning_rate=0.0807, max_depth=30, max_iter=1800, min_samples_leaf=10
MTA Vergisi (mta_tax)	LightGBM	-0.0163	n_estimators=300, learning_rate=0.0287, max_depth=7, num_leaves=36, min_child_samples=10, subsample=0.6, colsample_bytree=0.9
Geliştirme Ek Ücreti (improvement_surcharge)	LightGBM	-0.0142	n_estimators=100, learning_rate=0.1690, max_depth=4, num_leaves=51, min_child_samples=10, subsample=0.9, colsample_bytree=1.0
Bahşış Tutarı (tip_amount)	LightGBM	-2.2491	n_estimators=400, learning_rate=0.0267, max_depth=11, num_leaves=57, min_child_samples=100, subsample=0.2, colsample_bytree=0.7
Geçiş Ücretleri (tolls_amount)	LightGBM	-1.2196	n_estimators=1000, learning_rate=0.1, max_depth=9, num_leaves=31, min_child_samples=20, subsample=1.0, colsample_bytree=1.0
Yoğunluk Ek Ücreti (congestion_surcharge)	HistGBM	-0.1830	learning_rate=0.05, max_depth=25, max_iter=2000, min_samples_leaf=20
Havalimanı Ücreti (Airport_fee)	HistGBM	-0.0871	learning_rate=0.0350, max_depth=56, max_iter=7600, min_samples_leaf=85
CBD Yoğunluk Ücreti (cbd_congestion_fee)	HistGBM	-0.1232	learning_rate=0.0706, max_depth=55, max_iter=9100, min_samples_leaf=25

Her bir ücret bileşeni için optimizasyon sonucunda belirlenen en uygun modellerin test veri kümesi üzerindeki tahmin başarıları, MAE ve R^2 performans metrikleri kullanılarak değerlendirilmiştir. Modellerin test aşamasında elde ettiği performans sonuçları Tablo 5'te ayrıntılı olarak sunulmuştur.

Table V. Optimal Modellerin Tahmin Performansı

Hedef Değişken	MAE (\$)	R^2
Tarife Ücreti (fare_amount)	1.9763	0.9075
Ek Ücret (extra)	0.0528	0.9819
MTA Vergisi (mta_tax)	0.0011	0.9095
Geliştirme Ek Ücreti (improvement_surcharge)	0.0005	0.9933
Bahşış Tutarı (tip_amount)	0.9615	0.6160
Geçiş Ücretleri (tolls_amount)	0.3197	0.7002
Yoğunluk Ek Ücreti (congestion_surcharge)	0.0352	0.9806
Havalimanı Ücreti (Airport_fee)	0.0064	0.9657
CBD Yoğunluk Ücreti (cbd_congestion_fee)	0.0553	0.8769
TOPLAM (Bütünleşik Model)	2.6929	0.9134

Önerilen bileşen temelli modelleme yaklaşımının etkinliğini değerlendirmek amacıyla, doğrudan toplam ücret tahmini ve çok çıktılı regresyon tabanlı geleneksel yöntemlerle karşılaştırmalı performans analizi gerçekleştirilmiştir. Farklı modelleme stratejilerinin test veri kümesi üzerinde elde ettiği MAE ve R^2 değerleri Tablo 6'da sunulmakta ve yöntemlerin tahmin doğruluğu ile açıklayıcılık performansları sayısal olarak karşılaştırılmaktadır.

Table VI. Optimal Modellerin Tahmin Performansı

Tahmin Stratejisi	Toplam MAE (\$)	Toplam R ²
Önerilen Bileşen tabanlı Optimizasyon	2.6929	0.9134
Doğrudan Toplam Tahmini	2.7896	0.9106
Çok Çıktılı ANN	3.1888	0.8922
Doğrudan Toplam Tahmini	3.2452	0.8910
Çok Çıktılı Ekstra Ağaçlar (9 Alan Eşzamanlı)	9.5667	0.5280

^{a.} Bütünleşik ücret yapısının doğrudan ve çok çıktı modellerle tahmini ile önerilen yöntemin performans farkları.

Bu çalışmada, taksi yolculuklarına ait toplam ücretin doğrudan tek bir hedef değişken olarak tahmin edilmesi yerine, toplam ücreti oluşturan dokuz farklı bileşenin bağımsız regresyon modelleriyle tahmin edilmesine ve elde edilen bileşen tahminlerinin birleştirilmesine dayanan bileşen temelli bir makine öğrenmesi yaklaşımı geliştirilmiştir. Her bir ücret bileşeni için uygun model ve hiperparametrelerin belirlenmesinde Optuna tabanlı optimizasyon uygulanmıştır. Elde edilen deneysel sonuçlar, önerilen yaklaşımın farklı modelleme stratejileri karşısındaki tahmin performansını ortaya koyarken, bileşen bazında gerçekleştirilen değerlendirmeler ücret kalemlerinin farklı karakteristik özelliklerinin model başarısı üzerindeki etkilerinin incelenmesine olanak sağlamıştır.

Genel tahmin performansları karşılaştırıldığında, Tablo 11'de sunulan sonuçlara göre doğrudan toplam ücret tahmini gerçekleştiren modeller arasında en yüksek performans LightGBM tarafından elde edilmiştir. LightGBM modeli 2,7896 \$ MAE ve 0,9106 R² değerlerine ulaşmıştır. YSA tabanlı modeller kendi aralarında değerlendirildiğinde, çok çıktı mimarının 3,1888 \$ MAE değeriyle toplam ücreti tek hedef değişken olarak tahmin eden YSA modeline göre 3,2452 \$ MAE daha düşük tahmin hatası ürettiği görülmüştür. Buna karşılık, Çok Çıktılı ExtraTrees modeli 9,5667 \$ MAE ve 0,5280 R² değerleriyle karşılaştırılan yöntemler arasında en düşük tahmin performansını göstermiştir.

Bu karşılaştırma içerisinde önerilen Bileşen Temelli Optimizasyon yaklaşımı, 2,6929 \$ MAE ve 0,9134 R² değerleriyle değerlendirilen yöntemler arasında en düşük MAE ve en yüksek R² değerlerine ulaşmıştır. Elde edilen bulgular, toplam seyahat ücretinin tek bir hedef değişken olarak ele alınması yerine, farklı oluşum mekanizmalarına ve dağılımsal özelliklere sahip ücret kalemlerinin ayrı ayrı modellenmesinin tahmin performansına katkı sağladığını göstermektedir. Bu sonuç, bileşen temelli yaklaşımın genel performans avantajının hangi ücret kalemlerinden kaynaklandığının ayrıca incelenmesini gerekli kılmaktadır.

Bu doğrultuda, Tablo 10'da verilen bileşen bazlı sonuçlar incelendiğinde ücret kalemlerinin tahmin performansları bakımından iki temel yapı sergilediği görülmektedir. İlk grupta, büyük ölçüde belirli kurallar, yasal düzenlemeler, zaman bilgisi veya biniş ve iniş bölgeleri tarafından belirlenen daha deterministik ücret bileşenleri yer almaktadır. Altyapı iyileştirme ek ücreti (improvement_surcharge) için R²=0,9933, ek ücret (extra) için R²=0,9819, MTA vergisi (mta_tax) için R²=0,9095 ve yoğunluk ek ücreti (congestion_surcharge) için R²=0,9806 değerleri elde edilmiştir. Bu bileşenlerde özellikle HistGradientBoostingRegressor ve LightGBM modellerinin yüksek tahmin performansı sağladığı belirlenmiştir. Bu durum, söz konusu ücret kalemlerinin belirlenmesinde etkili olan kural, zaman ve konum temelli ilişkilerin modeller tarafından yüksek doğrulukla temsil edilebildiğini göstermektedir.

Buna karşılık, davranışsal veya çevresel belirsizliklerden daha fazla etkilenen ücret bileşenlerinde tahmin performansının görece düştüğü görülmektedir. Bu grupta en düşük R² değerleri bahşiş tutarı (tip_amount) için 0,6160, otoyol/köprü geçiş ücretleri (tolls_amount) için ise 0,7002 olarak elde edilmiştir. Bahşiş miktarı; yolcunun bireysel tercihleri, sosyoekonomik özellikleri, algılanan hizmet kalitesi ve yolculuk deneyimi gibi mevcut veri

kümesinde doğrudan temsil edilmeyen faktörlerden etkilenebilmektedir. Benzer şekilde, otoyol ve köprü geçiş ücretleri de kullanılan güzergâh ve anlık rota tercihlerine bağlı olarak değişkenlik gösterebilmektedir. Bu faktörlerin veri setinde doğrudan yer almaması, söz konusu ücret bileşenlerindeki değişkenliğin diğer bileşenlere kıyasla daha sınırlı düzeyde açıklanmasına neden olmuş olabilir.

Bileşen bazındaki farklılıklara rağmen, toplam seyahat ücretinin önemli bir bölümünü oluşturan ana seyahat ücretinde (fare_amount) yüksek bir tahmin performansı elde edilmiştir. Mesafe ve zaman temelli değişkenlerden yararlanan model, ana seyahat ücretindeki varyansın %90,75'ini açıklamıştır. Ana ücret bileşeninde elde edilen bu yüksek R^2 değeri, toplam seyahat ücretinin bileşen bazında tahmin edilerek yeniden oluşturulmasında önerilen yaklaşımın genel performansına önemli bir katkı sağlamaktadır. Böylece bileşen temelli modelleme, yalnızca toplam ücret düzeyinde değil, toplam ücreti meydana getiren farklı kalemlerin tahmin edilebilirlik düzeylerinin ayrı ayrı değerlendirilmesine de olanak vermektedir.

Tahmin doğruluğunun yanı sıra, önerilen yaklaşımın gerçek zamanlı sistemlerde kullanılabilirliğinin değerlendirilmesi amacıyla modellerin çıkarım süreleri de analiz edilmiştir. Dokuz bağımsız regresyon modelinin ardışık olarak çalıştırıldığı ve hesaplama yükünün en yüksek olduğu senaryoda, tek bir yolculuğa ilişkin tüm ücret bileşenlerinin tahmin edilerek toplam ücretin hesaplanması için gereken ortalama süre 119,06 ms olarak ölçülmüştür. Bu toplam süre; ana seyahat ücreti için 1,42 ms, ek ücretler için 21,80 ms, MTA vergisi için 1,23 ms, altyapı iyileştirme ek ücreti için 1,21 ms, bahşiş tutarı için 1,30 ms, otoyol/köprü geçiş ücretleri için 1,44 ms, yoğunluk ek ücreti için 39,21 ms, havalimanı tarifesini için 17,79 ms ve merkezi iş alanı sıklık ücreti için 33,63 ms olarak ölçülen çıkarım sürelerinin toplamından oluşmaktadır.

Bu sonuçlar, bileşen temelli yaklaşımın dokuz ayrı regresyon modelinden oluşmasına rağmen tek bir yolculuk için tahmin işleminin yaklaşık 0,12 saniyede tamamlanabildiğini göstermektedir. Ayrıca, dokuz modelin birbirinden bağımsız olarak tahmin üretmesi, uygun donanım ve yazılım altyapılarında bu işlemlerin paralel olarak yürütülmesine olanak tanımaktadır. Benzer şekilde, birden fazla yolculuğun toplu olarak işlenmesiyle hesaplama kaynaklarının daha etkin kullanılması mümkündür. Dolayısıyla paralel işlem ve toplu çıkarım tekniklerinin uygulanması durumunda mevcut çıkarım süresinin daha da azaltılması beklenebilir.

Genel olarak değerlendirildiğinde, önerilen bileşen temelli yaklaşımın 2,6929 \$ MAE ve 0,9134 R^2 ile doğrudan toplam ücret ve çok çıktılı regresyon yaklaşımlarından daha yüksek tahmin performansı sağladığı görülmektedir. Bileşen düzeyindeki bulgular, özellikle kural, zaman ve konum bilgileriyle belirlenen ücret kalemlerinin yüksek doğrulukla tahmin edilebildiğini, davranışsal ve rota tercihleriyle ilişkili bileşenlerde ise tahmin performansının görece sınırlı kaldığını ortaya koymaktadır. Bununla birlikte, tek bir yolculuk için 119,06 ms düzeyinde ölçülen çıkarım süresi, önerilen mimarinin hesaplama maliyeti açısından gerçek zamanlı uygulamalarda kullanılabilir bir yapıya sahip olduğunu göstermektedir. Bu yönüyle geliştirilen yaklaşım, ücret bileşenlerinin ayrı ayrı incelenmesine olanak sağlarken toplam seyahat ücretinin yüksek doğrulukla tahmin edilmesini de desteklemektedir.

V. SONUÇLAR

Bu çalışmada geliştirilen Optuna destekli bileşen temelli tahmin yaklaşımı, New York TLC yolculuk veri kümesi üzerinde %91,34 R^2 ve 2,69 \$ MAE değerlerine ulaşarak çalışma kapsamında karşılaştırılan doğrudan toplam ücret tahmini ve çok çıktılı regresyon yaklaşımlarına göre daha yüksek tahmin performansı göstermiştir. Elde edilen bulgular, her bir ücret bileşeninin kendine özgü dağılımsal ve karakteristik yapısına uygun regresyon algoritması ile hiperparametre konfigürasyonunun ayrı ayrı belirlenmesinin genel tahmin

başarısına katkı sağladığını ortaya koymuştur. Bu doğrultuda, Optuna tabanlı hiperparametre optimizasyonunun bileşenlere özgü modellerin yapılandırılmasında etkili bir yöntem olduğu görülmüştür.

Gelecek çalışmalarda, mevcut veri yapısının yol ağı bilgileri, gerçek zamanlı trafik yoğunluğu ve güzergâh verileri gibi ek dışsal değişkenlerle genişletilmesi planlanmaktadır. Bu bilgilerin özellikle rota ve davranışsal faktörlere bağlı olarak daha yüksek değişkenlik gösteren bahşiş ve otoyol/köprü geçiş ücretlerinin modellenmesine katkı sağlaması beklenmektedir. Ayrıca, önerilen yaklaşımın modüler yapısı, elde edilen tahmin performansı ve tek bir yolculuk için yaklaşık 0,12 saniyelik çıkarım süresi, yöntemin akıllı ulaşım sistemleri, dijital taksimetreler ve araç çağırma platformları gibi gerçek zamanlı uygulamalarda kullanılabilirliğine yönelik önemli bir potansiyel ortaya koymaktadır.

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Design and Development of a Sustainable Modular Toy and Book Storage Unit with a Rotating Mechanism Using Hemp Composite Panels

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Abstract: With growing environmental awareness and indoor air quality concerns, the modern furniture industry is undergoing a critical transition toward sustainable bio-based materials and ergonomic, multifunctional designs. Children's living and learning spaces demand furniture solutions that are not only structurally sound and durable, but also biologically harmless, emission-free, and developmentally stimulating. This study investigates the design, prototyping, and technical characterization of an innovative, multifunctional 360-degree rotating modular toy and bookcase unit fabricated with sustainable hemp-based composite particleboards (PureBoard YL / Hempboard). The wood-like core of industrial hemp (*Cannabis sativa* L.), derived as a secondary by-product from agricultural and textile processes, was utilized as an eco-friendly core furnish bonded with 100% bio-based, No Added Formaldehyde (NAF) resin systems complying with the TS EN 312 P2 standard for interior furniture. The structural architecture of the unit integrates four distinct multi-functional elevations: an erasable whiteboard with an integrated pen tray, a modular perforated pegboard panel for hanging organizational accessories, an ergonomic open book storage rack positioned at child-accessible height, and dual sliding pull-out storage bins for Montessori-oriented toy organization. Complete circular mobility is achieved through a heavy-duty lazy Susan ball-bearing rotating mechanism mounted on a wide circular base plate equipped with a safety braking mechanism and non-slip floor contact pads. Mechanical and structural evaluations revealed that the hemp composite panel possesses a bending strength of 10 N/mm², an internal bond tensile strength of 0.24 N/mm², an edge screw-holding capacity exceeding 450 N, and a 2-hour thickness swelling rate above 20%. To overcome the raw panel's localized tensile sensitivity and moderate screw-holding values, specialized structural joining techniques combining mechanical fittings with PVAc adhesive reinforcements and constrained shelf spans were implemented. Digital 3D CAD modeling and CNC fabrication workflows successfully verified structural integrity, manufacturing feasibility, and ergonomic safety through extensive edge radiusing. The developed unit successfully reduces VOC emissions to zero, promotes circular economy through agricultural waste valorization, and provides an interactive educational micro-environment that fosters independent reading, motor creativity, and organizational habits in early childhood.

Keywords: Hempboard, Sustainable Furniture, Modular Design, Zero-VOC

I. INTRODUCTION

Indoor air quality and material sustainability have emerged as decisive criteria in the evaluation and procurement of nursery and children's residential furniture. Conventional wood-based composite panels, such as standard medium-density fiberboard (MDF) and urea-

formaldehyde-bonded particleboards, are recognized sources of volatile organic compound (VOC) emissions, predominantly free formaldehyde gases [1]. In pediatric environments, prolonged inhalation of off-gassed formaldehyde represents a documented risk factor for respiratory sensitivities, asthma exacerbation, and contact allergies [2]. Concurrently, global industrial initiatives are accelerating the transition from fossil-reliant polymers and virgin timber harvesting toward renewable, circular agro-industrial residues capable of sequestering carbon [3].

Industrial hemp (*Cannabis sativa* L.) exhibits remarkable ecological and mechanical properties, absorbing significantly greater quantities of atmospheric carbon dioxide per hectare during its brief 4- to 5-month vegetative cultivation cycle compared to mature timber stands requiring 20 to 50 years to mature [3]. The woody core (hurds/shivs) remaining after bast fiber extraction for textile applications represents a high-cellulose lignocellulosic resource ideally suited for composite panel manufacturing [1]. Through the application of bio-based, No Added Formaldehyde (NAF) resin formulations, bio-composite boards such as Hempboard (PureBoard YL) achieve rigorous non-hazardous emission classifications while delivering acoustic damping, thermal insulation, and natural antimicrobial properties [4-6].

In addition to ecological material requirements, modern children's furniture design increasingly incorporates Montessori-aligned developmental philosophies. These pedagogical concepts emphasize child autonomy, self-directed exploration, tactile interaction, and spatial order [7]. Single-purpose storage modules frequently fail to accommodate constrained residential spatial footprints and fail to engage children dynamically. To address these multidisciplinary challenges, this paper presents the complete engineering design, technical characterization, and prototype fabrication of a four-sided 360-degree rotating modular toy and book storage station developed by the Almila Mobilya Design Center. By integrating sustainable NAF hemp particleboards with multifaceted ergonomic surfaces, including a drawing board, modular pegboard, and dual storage systems, this study establishes a practical manufacturing framework bridging bio-composite material science with child-centered industrial product design.

II. MANUSCRIPT CONTENT

A. Material Characterization and Properties

The primary structural substrate utilized for the carcass and interior partition elements was PureBoard YL (Hempboard), developed by the Kastamonu Entegre R&D Center. The panel complies with the TS EN 312 - Type P2 technical standard for interior furniture panels intended for use in dry ambient conditions. The furnish comprises woody hemp hurds bonded via a 100% bio-based adhesive matrix formulated without added formaldehyde (NAF), thereby achieving verified zero-VOC operational ratings.

Table I summarizes the baseline mechanical and physical parameters determined for the 18 mm hemp-based particleboard substrate in comparison with conventional commercial particleboard (suntalam).

Table I. Physical and Mechanical Properties of Hempboard vs. Standard Particleboard

PROPERTY PARAMETER	TEST STANDARD / CONDITION	HEMPBOARD (PUREBOARD YL)	STANDARD PARTICLEBOARD
BENDING STRENGTH (MOR)	TS EN 310	10.0 N/mm ²	11.0 – 13.0 N/mm ²
INTERNAL BOND TENSILE STRENGTH	TS EN 319	0.24 N/mm ²	0.35 – 0.40 N/mm ²
EDGE SCREW-HOLDING CAPACITY	TS EN 320	> 450 N	700 – 800 N

THICKNESS SWELLING (2 HOURS)	TS EN 317	> 20 %	8 – 14 %
FORMALDEHYDE EMISSION RATING	EN 717-1 / NAF	Zero-VOC (NAF)	Class E1 (≤ 0.1 ppm)

Values based on technical test datasets from Kastamonu Entegre A.Ş. and Almila Mobilya Design Center laboratory evaluations [8].

B. Design Methodology and Functional Integration

The conceptualization of the rotating activity station was guided by spatial compactness, multi-sensory stimulation, and ergonomic accessibility. Anthropometric standards for early childhood (ages 3 to 8) established an overall unit height envelope under 1150 mm, ensuring all functional tiers remain within arm's reach. The four vertical facades are configured as follows:

Front Elevation (Creative Drawing Station): Houses a high-gloss, magnetic dry-erase whiteboard flanked by an integrated lower storage trough designed for markers, erasers, and drawing implements.

Rear Elevation (Modular Pegboard Station): Features an engineered perforated pegboard panel equipped with modular repositionable hanging pegs and accessories, accommodating variable craft tool arrangements and tactile play items.

Lateral Elevation A (Ergonomic Display Shelf): Comprises front-facing book display ledges that present book covers outwardly, lowering cognitive barriers for pre-literate children and encouraging independent reading selection.

Lateral Elevation B (Montessori Toy Storage): Contains internal horizontal routing slots supporting two removable, heavy-duty lightweight storage bins alongside dedicated open shelving compartments [7].

Mobility and stability are governed by an internal rotating assembly located between the primary vertical carcass and the broad circular base platter. To prevent tipping and unintended movement during vigorous whiteboard usage, the base platter incorporates non-slip elastomer ground pads and an integrated manual mechanical locking brake mechanism.

C. Structural Engineering and Joinery Optimization

Because the experimental Hempboard material exhibits lower internal bonding (0.24 N/mm^2) and edge screw-holding capability ($> 450 \text{ N}$) relative to standard commercial particleboard, structural joinery required proactive engineering interventions. Mechanical fast-assembly cam-lock connectors (minifix pins and housings) were supplemented systematically with wooden dowels and cross-linked polyvinyl acetate (PVAc) structural adhesives. This dual-fastener approach disperses localized shear stresses across a larger contact area, safeguarding against core delamination. Furthermore, horizontal shelf spans were structurally restricted to a maximum unsupported length of 360 mm to completely eliminate mid-span flexural deflection (creep sag) under cumulative book loads.

D. Digital Modeling and Prototype Manufacturing Workflow

Digital solid modeling was conducted using SolidWorks parametric software to analyze volumetric balance, clearance geometry during 360-degree rotation, and center-of-gravity trajectories. Following kinematic verification, 2D production documentation and nesting layouts were generated in AutoCAD (Fig. 1).

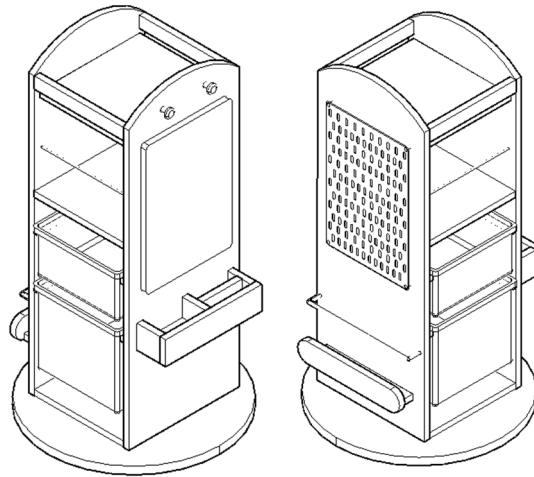


Fig. 1. 3D Modeling Image Created in AutoCAD

Panel cutting, edge grooving, perimeter radiusing, and pegboard perforation arrays were executed on multi-axis computer numerical control (CNC) machining centers. All exposed exterior edges and perimeter corner vertices were machined with a generous 12 mm radius to comply fully with juvenile impact safety guidelines (Fig. 2).



Fig. 2. Project Prototype Images

III. RESULTS AND DISCUSSION

Physical assembly and operational validation of the prototype confirmed the functional viability of integrating agricultural hemp composites into high-interaction juvenile furniture. The total product weight was approximately 14% lighter than an identical carcass built from standard industrial MDF, significantly reducing rotational inertia on the mechanical turntable bearing and facilitating smooth, child-actuated rotation.

Rotational dynamics operated smoothly across repeated 360-degree cycles. The incorporated foot-accessible braking wedge effectively immobilized the turntable assembly, ensuring absolute rigidity during whiteboard writing and drawing exercises. In physical load

testing, individual shelves supported continuous static loads of 25 kg for 120 hours without measurable mid-span deflection or joint separation.

Environmental and hygienic evaluations demonstrated critical competitive advantages over petroleum-based resin panels. PureBoard YL emits zero detectable formaldehyde vapors (NAF), ensuring pristine ambient nursery air quality. Furthermore, the inherent bioactive lignocellulosic profile of industrial hemp fibers provides natural resistance against mold, fungal proliferation, and bacteria, rendering the surface hygienic for early childhood environments. Moisture sensitivity evaluations (2-hour thickness swelling > 20%) demonstrated that raw hempboard edges require impervious surface sealing. High-pressure laminate facing and moisture-barrier edge banding were applied across all perimeter interfaces, completely isolating the core matrix from spilled liquids or humidity variations.

Beyond functional and mechanical validation, the project delivers substantial economic value, domestic competitiveness, and international market viability. In modern, shrinking urban living spaces, the 360-degree rotating vertical storage architecture captures prominent market attention by maximizing spatial efficiency on a minimal footprint. In the domestic nursery and youth furniture sector, positioning the product within the non-toxic (zero-VOC) category drives robust sales momentum and elevated consumer satisfaction among health-conscious parents. From a raw material supply chain perspective, the official decree published in the Official Gazette on January 31, 2026, authorized industrial hemp cultivation across 21 provinces—including Samsun, Konya, and Kayseri. This regulatory development enables domestic agricultural by-products to be directly converted into high-value engineered furniture, drastically reducing logistics costs and reliance on imported materials. Furthermore, full alignment with the European Green Deal positions this bio-composite furniture line with strong export potential toward European Union (EU) eco-conscious markets [9].

Finally, the broad societal impact and industry leadership established by this project open new technological frontiers. The unique combination of material lightweighting and natural acoustic insulation properties creates a fertile foundation for subsequent R&D initiatives across infant, children, and youth furniture sectors. Through strategic inter-industry collaboration with the Kastamonu Entegre R&D Center, the initiative presents an exemplary circular economy product development model. This collaborative framework establishes a pioneering benchmark and authoritative reference for the broader furniture manufacturing ecosystem, catalyzing the wider adoption of sustainable bio-composite materials.

A. Abbreviations and Acronyms

Standard technical acronyms and domain-specific terminology employed throughout this paper are defined as follows upon their primary textual occurrence:

VOC: Volatile Organic Compound

NAF: No Added Formaldehyde

MDF: Medium-Density Fiberboard

MOR: Modulus of Rupture (bending strength)

MOE: Modulus of Elasticity (flexural modulus)

IB: Internal Bond (tensile strength perpendicular to panel plane)

TS: Thickness Swelling

CNC: Computer Numerical Control

CAD: Computer-Aided Design

PVAc: Polyvinyl Acetate

HPL: High-Pressure Laminate

EN: European Norm (European Standard)

TS EN: Turkish Standard adopted from European Norm

B. Equations

The mechanical characterization of the hemp composite panel and the structural deflection response of the storage shelves under transverse loading were evaluated using standardized analytical formulations. Symbols are defined prior to or immediately following each equation in accordance with SI unit conventions.

The bending strength, or modulus of rupture (MOR, denoted as f_m), of the test specimens was determined in accordance with TS EN 310 via three-point static bending loading as

$$f_m = \frac{3.F_{max}.l_1}{2.b_1.t_1^2} \quad (1)$$

where f_m is the bending strength (N/mm^2), F_{max} is the maximum breaking force (N), l_1 is the distance between the centers of the test supports (mm), b_1 is the specimen width (mm), and t_1 is the specimen thickness (mm).

The internal bond tensile strength (IB, denoted as f_t) perpendicular to the plane of the hemp particleboard was calculated according to TS EN 319 by

$$f_t = \frac{F_{max}}{a_2.b_2} \quad (2)$$

where f_t represents the tensile strength perpendicular to the face (N/mm^2), F_{max} is the breaking load at failure (N), and a_2 and b_2 denote the length and width of the test specimen (mm), respectively.

The physical dimensional stability across short-term exposure to liquid immersion was quantified via the percentage thickness swelling (TS) according to TS EN 317 as

$$f_m = \left(\frac{t_2 - t_0}{t_0} \right) \cdot 100 \quad (3)$$

where TS is the relative thickness swelling (%), t_0 is the initial thickness measured prior to immersion (mm), and t_2 is the thickness measured following 2 hours of complete water immersion (mm).

To prevent unsightly sag and avoid structural overloading of the lower-strength hemp composite substrate, the maximum mid-span flexural deflection (δ_{max}) of the simply supported horizontal book shelves under a uniformly distributed load was governed using the Euler-Bernoulli beam formulation:

$$\delta_{max} = \frac{5.q.L^4}{384.E.I} \quad (4)$$

In (4), δ_{max} denotes the maximum deflection at mid-span (mm), q is the uniform linear design load resulting from stacked books (N/mm), L is the unsupported shelf span length (mm), E is the flexural modulus of elasticity of the hempboard panel (N/mm), and I is the second

moment of area of the shelf cross-section defined by $I = (b.t^3) / 12$, where b is shelf depth and t is panel thickness. As demonstrated by (4), deflection scales with the fourth power of span length (L^4) consequently, restricting the unsupported span to 360 mm successfully maintained δ_{max} within strict serviceability tolerances $\delta_{max} \leq L/400$.

IV. CONCLUSION

This study successfully developed, manufactured, and evaluated an innovative 360-degree rotating modular children's storage and activity center constructed from sustainable, bio-based Hempboard composite panels. By combining agricultural hemp residues with zero-emission NAF adhesives, the design achieved full compliance with TS EN 312 P2 criteria while eliminating hazardous VOC emissions from children's living spaces. The engineering integration of hybrid dowel-minifix adhesive joinery effectively resolved the lower screw-retention capacity of the hemp substrate, ensuring robust structural integrity. The unit consolidates reading, drawing, play storage, and hanging organization into an ultra-compact footprint, demonstrably fostering child independence and spatial order. Future research will focus on long-term cyclical fatigue testing of the rotating hardware and industrial upscaling for serial furniture manufacturing.

ACKNOWLEDGMENT

The author thanks the Almila Mobilya Design Center team, the prototyping technical workshop personnel, and the Kastamonu Entegre A.Ş. R&D Center for supplying the Hempboard raw material panels and technical test datasets under R&D Project ALM.TSRM.25.03.

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An Algorithmic Framework for Generating 3D Periodic Concrete Meso-structures for Monte Carlo Radiation Transport

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Abstract: The use of ionizing radiation sources continues to grow across medical imaging, radiotherapy, industrial radiography, and nuclear applications. These developments drive the need for improved radiation safety and concrete formulations that provide effective biological shielding against gamma and neutron radiation. Most existing research relies on physical experiments and Monte Carlo-based particle transport simulations to identify appropriate concrete mixtures. In this study, we present a stochastic algorithmic framework to generate 3D periodic concrete meso-structures for ionizing radiation transport modeling. The algorithm uses Random Sequential Adsorption (RSA) coupled with a template pool that produces random polyhedral and spherical aggregate shapes. Particle size distributions are controlled using Inverse Transform Sampling based on Fuller or Andreasen gradations. Collision detection is handled by a two-stage hybrid engine using Feret diameter filtering alongside ccKdTree and python-fcl libraries, followed by a five-stage periodic boundary condition (PBC) clipping protocol. The continuous geometry converts into 3D voxel arrays compatible with lattice and cell inputs in Monte Carlo codes such as MCNP6, OpenMC and Geant4. Material IDs, mass densities, and elemental mass fractions are mapped directly into individual voxels. The spatial definition enables simulation of micro-scale photon and neutron scattering and absorption within the heterogeneous concrete matrix. Furthermore, the proposed framework enables systematic investigation of aggregate morphology, and spatial distribution, providing a flexible computational platform for evaluating shielding performance under different radiation fields and concrete mixture designs. Although resolving these detailed geometries requires substantial computational resources and high-performance computing (HPC), the framework bridges concrete meso-scale modeling and nuclear safety analysis.

Keywords: Radiation Shielding, Concrete Meso-structure, Random Sequential Adsorption (RSA), Monte Carlo Transport

I. INTRODUCTION

Primary and secondary containment structures in nuclear power plants (NPPs), spent fuel storage installations, medical linear accelerator (LINAC) rooms, and industrial irradiation facilities require biological shielding that meets regulatory standards to protect personnel and surrounding areas [1, 2]. Concrete remains the primary choice for these facilities because it can be cast into structural geometries on site, uses accessible materials, and carries structural loads while attenuating radiation [3, 4].

Its attenuation capacity depends on bulk density, elemental composition, hydration level, porosity, and aggregate mineralogy [5, 6]. For heavy gamma shielding, mixes incorporate high-

density, high-atomic-number (high-Z) aggregates like barite (BaSO_4), magnetite (Fe_3O_4), and hematite (Fe_2O_3). To moderate fast neutrons and capture thermal neutrons, high-hydrogen cement paste is combined with boron additives, including boron carbide (B_4C), colemanite, and boric acid [3, 7]. Radiation transport through these heterogeneities, including scattering, absorption, and secondary particle yield, is commonly evaluated using Monte Carlo (MC) simulations [8, 9].

This study presents a Python framework designed to generate 3D meso-structure for concrete computational modelling. The framework produces synthetic geometries under periodic boundary conditions, yielding spatial data structures formatted directly into Monte Carlo codes.

II. LITERATURE REVIEW AND THEORETICAL BACKGROUND

A. Mesoscale Modeling Approaches to Concrete

The literature relies on two main approaches to generate synthetic concrete meso-scale models:

1. Laguerre Tessellation Methods: These approaches generate Voronoi or Laguerre cells from spatial seed points, which are then converted into polyhedral aggregates [10]. While effective for achieving high volume fractions, they offer limited control over realistic particle size distributions and complex convex geometric forms.

2. 3D Grid Partitioning and Random Placement Methods: These techniques place aggregates into a defined matrix volume according to target statistical distributions while checking for geometric overlap [11]. Random Sequential Adsorption (RSA) provides the operational basis for such placement schemes [12, 13]. Under RSA, particles are introduced sequentially, and any placement that overlaps an existing aggregate is rejected [12]. However, packing non-spherical particles at high volume fractions without intersections becomes computationally demanding.

B. Voxelized Geometry in Radiation Shielding Simulations

Monte Carlo particle transport codes, including MCNP, OpenMC, Geant4, FLUKA, PHITS, define complex geometries through analytical surface combinations or voxel lattices [8, 9]. For microstructural transport, defining the domain as an array 3D volumetric pixel (voxels) improves particle tracking performance [4, 14]. Each voxel is assigned the mass density and elemental composition of its corresponding phase, allowing calculation of bulk shielding metrics such as particle flux, absorbed dose, linear attenuation coefficients (μ), and half-value layers (HVL) [14].

III. METHODOLOGY AND ALGORITHMIC FRAMEWORK

The algorithmic framework is implemented in Python and consists of five core components:

1. Template pool generating `scipy.spatial.ConvexHull` and `feret_diameter` filtering.
2. Particle size sampling from Fuller or Andreasen distributions via inverse transform sampling.
3. Two-stage hybrid collision detection pairing a `cKDTree` broad phase with a `python-fcl` narrow phase.
4. Periodic boundary condition enforcement through a five-stage clipping and repair protocol (`safe_boolean_clip`).
5. Matrix and interfacial transition zone (ITZ) spacing control using a `fine_void_offset_factor` of 1.05.

A. Stochastic Geometry and Template Pool Architecture

Rather than generating an individual mesh for every aggregate, the framework builds a normalized template pool to limit runtime:

- Polyhedral aggregates: Points are sampled randomly on a sphere with controlled radial noise to obtain angular, non-spherical shapes. The corresponding convex surface mesh (Trimesh) is built using `'scipy.spatial.ConvexHull'`.
- Spherical elements: Ideal sphere are generated and cached for fine aggregates and void phases.
- Shape constraints: Geometries are filtered by minimum and maximum projected Feret diameters (`'feret_diameters'`). Overly elongated or flat particles that fall outside target aspect ratios are discarded before populating the pool.

B. Size Distribution and Scaling Abstraction

Inverse transform sampling scales template particles to match target grading curves, such as Fuller or Andreasen distributions. Given the lower and upper sieve size limits (S_{min} , S_{max}) and distribution exponent (n), the `sample_scale` function computes a dimensionless scale factor for each sampled particle. Multiplying a selected base template by this scalar yields its final physical dimensions.

C. Two-Stage Hybrid Collision Detection Engine

Collision checking is the primary computational bottleneck when packing thousands of discrete inclusions. The framework divides this check into broad and narrow phases:

- Broad phase filtering: The centers of mass and bounding sphere radii (`bounding_radius`) of all placed particles are tracked in memory. When a new candidate particle arrives, spatial partitioning is performed using the `'scipy.spatial.cKDTree'` architecture to query only potential collisions in the candidate's immediate vicinity (`'query_ball_point'`). At this stage, a safe search radius is determined by applying a dynamic `'global_max_radius'` filter that encompasses all groups.
- Narrow phase verification: For candidates detected in the immediate vicinity, an Axis-Aligned Bounding Box (AABB) overlap test is performed first. If the candidates are polyhedra, the hierarchical bounding volume trees (`'BVHModel'`) from the `'python-fcl'` library are utilized to complete the exact surface-to-surface (Exact Mesh Collision) analysis within the order of microseconds.
- BatchOptimization: To avoid rebuilding the spatial tree (`cKDTree`) after every insertion, new candidates are held in a pending list with a `'batch_size=100'` parameter. Particles are first rapidly collided with the elements in this list (using sphere-sphere analytical distance equations); once the list reaches capacity, the `cKDTree` is updated in a single operation.
- Matrix Cache: Homogeneous transformation matrices based on `'quaternion_matrix'` (for rotational transformations) are precomputed and stored in a pool (`'ROTATION_POOL'`), to minimize redundant trigonometric operations.

D. Periodic Boundary Conditions and Boolean Clipping

The domain enforces periodic boundary conditions (PBC) along all coordinate axes for representative volume element (RVE). To ensure homogeneity in radiation transport (MCNP/OpenMC) and periodic finite element analysis (FEA), the model is generated to be fully compatible with PBCs.

- When a particle is detected touching or extending (boundary crossings) beyond the cube boundaries (`domain_size_mm`), `'get_periodic_translations'` function calculates the required periodic shifts and the volume of the particle lying outside the boundary. It also places corresponding periodic copies (shifts) across opposing boundaries.

- A staged Boolean clipping algorithm (using `trimesh.boolean.intersection`` backed by `manifold3d`` engine) is executed to trim the model to its physical boundaries. If the solid model cannot be clipped due to geometric singularities, the engine initiates a five-step repair protocol (`safe_boolean_clip``) comprising mesh cleaning, convex hull enforcement, micro-perturbation, and tolerance-based cube expansion.

E. Void Check and Microstructural Realism

To enhance microstructural realism in the simulation, fine aggregates and void phases are placed using a spacing parameter, `fine_void_offset_factor=1.05``. This offset prevents fine elements and voids within the matrix phase from adhering to surrounding polyhedral aggregates, accounting for a theoretical interfacial transition zone (ITZ) boundary layer while avoiding geometric overlap errors that could otherwise occur during numerical mesh generation.

Figure 1 illustrates a representative mesoscale geometry produced by this pipeline.

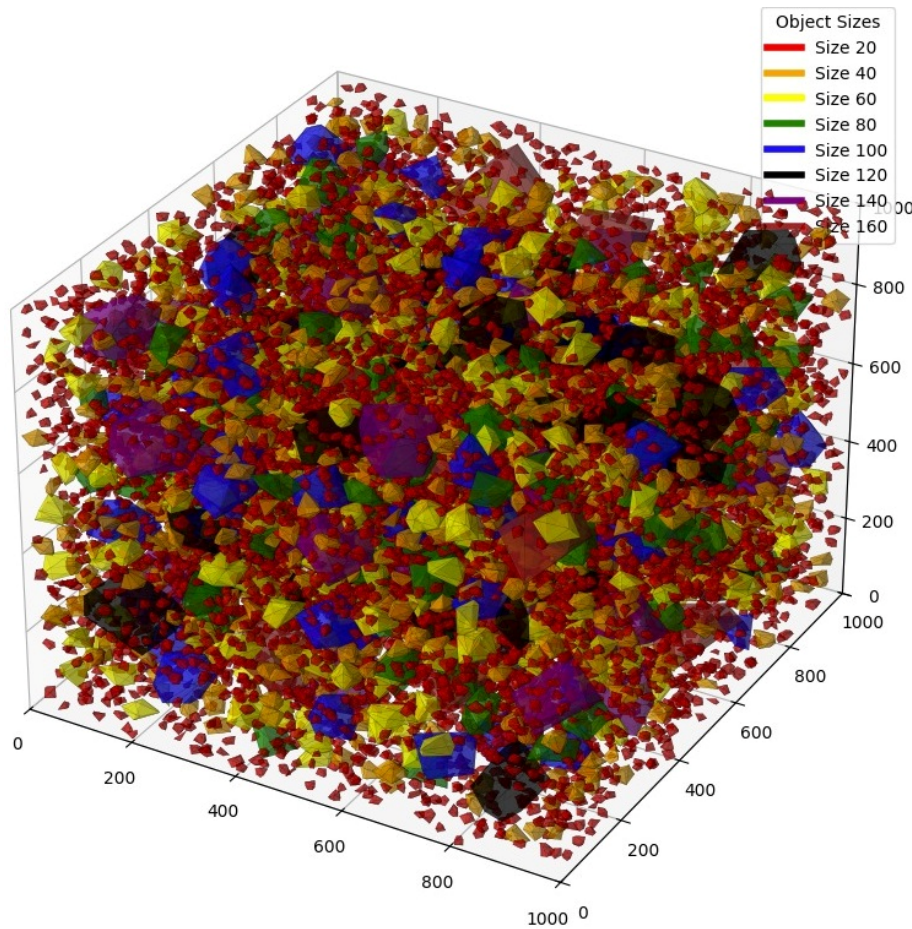


Fig. 1. Image of a synthetic concrete model.

IV. CONCLUSION

In this study, an algorithmic framework was developed to generate 3D periodic concrete meso-structures for Monte Carlo radiation transport simulations.

Key outcomes include:

1. Target polyhedral aggregate degradations and non-spherical shapes were generated using a template pool architecture, Feret diameter filtering, and inverse transform sampling.
2. Particle overlap was eliminated at high volume fractions by combining `cKDTree`` spatial

partitioning with `python-fcl` narrow-phase mesh collision checks.

3. Periodic boundary conditions were enforced, and non-manifold boundary cut errors were resolved, through a five-stage safe Boolean clipping protocol.

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A Comparative Study on the Effect of Porosity on the Yield Strength and Compressive Toughness of Aluminum Foams

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Abstract: In this study, the effect of porosity on the yield strength and compressive toughness of aluminum foams was experimentally investigated. Aluminum foam specimens with nominal porosities of 50%, 60%, and 70% were fabricated using a powder metallurgy route combined with the space-holder technique. Pure aluminum powder with a grain size ranging from 7 to 15 μm and carbamide particles with a size range of 1 to 2 mm were used as the matrix and temporary space-holder materials, respectively. The powder-carbamide mixtures were compacted at 250 MPa using a uniaxial hydraulic press. The resulting green specimens were immersed in demineralized water at 80 °C for at least 3 h to remove the carbamide, dried at 50 °C for at least 6 h, and subsequently sintered at 645 °C for 3 h under an argon atmosphere. At least three specimens were tested for each nominal porosity level, and compression tests were conducted at a compression speed of 1 mm/min. The measured average porosity values of the specimens with nominal porosities of 50%, 60% and 70% were 54.29%, 61.9%, and 71.83%, respectively. Yield strength was determined using the 0.2% offset method, while compressive toughness was calculated as the entire area under each recorded stress-strain curve. The specimens with 50% nominal porosity exhibited an average yield strength of 16.3 MPa and an average compressive toughness of 19.2 MJ/m³. For the 60% nominal-porosity specimens, the corresponding values decreased to 8.7 MPa and 12.4 MJ/m³, respectively. The 70% nominal-porosity specimens exhibited the lowest average yield strength and compressive toughness values, at 5.6 MPa and 5.4 MJ/m³, respectively. These results demonstrate a clear decrease in both yield strength and compressive toughness with increasing porosity, confirming the strong influence of pore volume on the compressive mechanical performance of aluminum foams produced by the powder metallurgy space-holder method.

Keywords: Lightweight, Aluminum, Yield Strength, Porosity, Compressive Toughness

I. INTRODUCTION

Metallic foams are lightweight materials that combine low density and relatively high mechanical properties [1], [2]. Due to its low density (2.7 g/cm³), low melting temperature (660°C), high electrical and thermal conductivity, ductility, high strength and high corrosion resistance, aluminum is one of the most widely researched metals for metallic foam applications [3], [4]. Because of its properties aluminum foams excel in various industrial applications such as automotive, aerospace and aviation, rail system vehicles, construction industry, defense industry [5], [6].

The standout mechanical property of aluminum foams is their high mechanical load absorption capacity and yield strength [7], [8]. Pore morphology of aluminum foams significantly affects their mechanical properties. Within the context of pore morphology,

overall porosity and cell diameter are among the standout features. Thus, modifying pore morphology can lead to major changes in mechanical properties of the foam structure [9], [10]. For this reason, experimentally demonstrating the impact of pore morphology variations of aluminum foams on compressive toughness and yield strength can help to understand which pore morphology would be optimal for further studies. Thus, in this study, pure aluminum foam specimens with three different porosity levels (samples with nominal porosities of 50%, 60% and 70% by volume) have been obtained by powder metallurgy method and subjected to compression tests. Stress-strain diagrams were obtained from compression tests and yield strength and compressive toughness parameters were analyzed based on the resulting diagrams.

II. EXPERIMENTAL PROCEDURE

A. Material

In this study, aluminum powder with 99% purity and grain sizes ranging from 7 to 15 μm and carbamide with 98.5% purity and grain size ranging from 1 to 2 mm as a temporary space holder material were used.

B. Method

To fabricate the aluminum foam specimens, a conventional powder metallurgy route was combined with the space-holder technique. Aluminum powder was mixed with carbamide at nominal volume fractions of 50%, 60%, and 70%. The mixtures were compacted at 250 MPa using a uniaxial hydraulic press. The resulting green samples were immersed in demineralized water at 80 °C for at least 3 h to dissolve the carbamide and were subsequently dried in an oven at 50 °C for at least 6 h. After removal of the carbamide, the dried green samples were sintered at 645 °C for 3 h in an argon atmosphere. The resulting specimens were then subjected to compression testing for mechanical characterization. For each nominal porosity level at least three specimens were subjected to compression testing and the speed of the compression was set to 1 mm per minute.

III. RESULTS AND DISCUSSION

A. Determination of Porosity

In this section, the porosity (ϕ) of the fabricated specimens was evaluated. Equation (1) was used to calculate the porosity (ϕ), where “ ρ ” is the calculated density of the specimen and “ ρ_{Al} ” is the theoretical density of aluminum (2.7 g/cm³).

$$\phi = \left[1 - \frac{\rho}{\rho_{Al}} \right] \cdot 100 \quad (1)$$

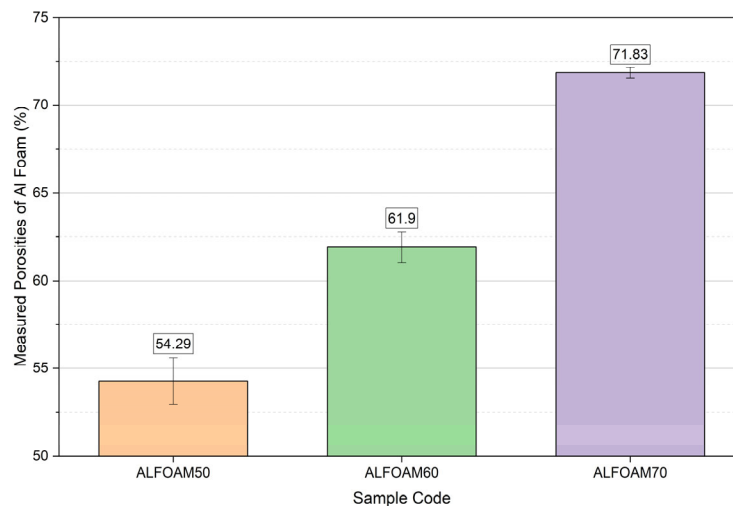


Fig. 1. The porosity of Al foam samples. ALFOAM50, ALFOAM60 and ALFOAM70 refer to the samples obtained with nominal porosities of 50%, 60% and 70% by volume, respectively.

B. Compression Test

In this section, yield strength and compressive toughness results were evaluated. The 0.2% offset method was applied to each stress-strain curve to determine the yield strength. Compressive toughness was calculated as the entire area under each recorded stress-strain curve.

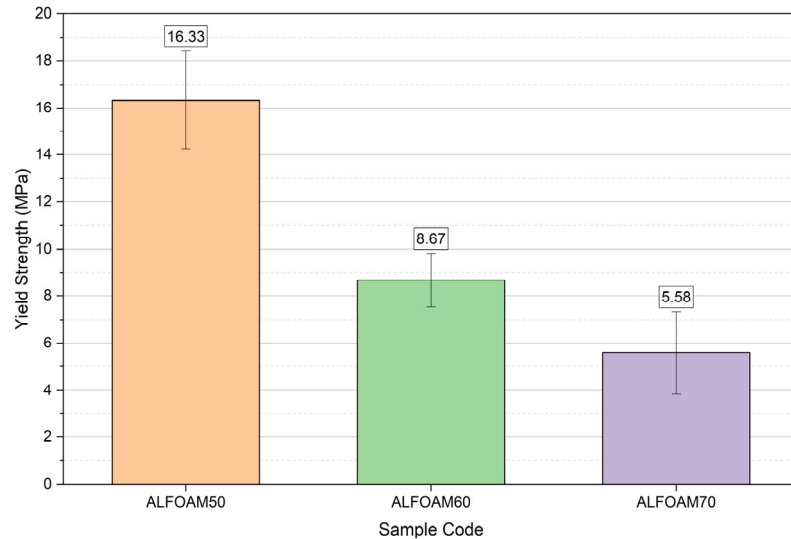


Fig. 2. Effect of porosity on the yield strength of the aluminum foam specimens. ALFOAM50, ALFOAM60 and ALFOAM70 refer to the samples obtained with nominal porosities of 50%, 60% and 70% by volume, respectively.

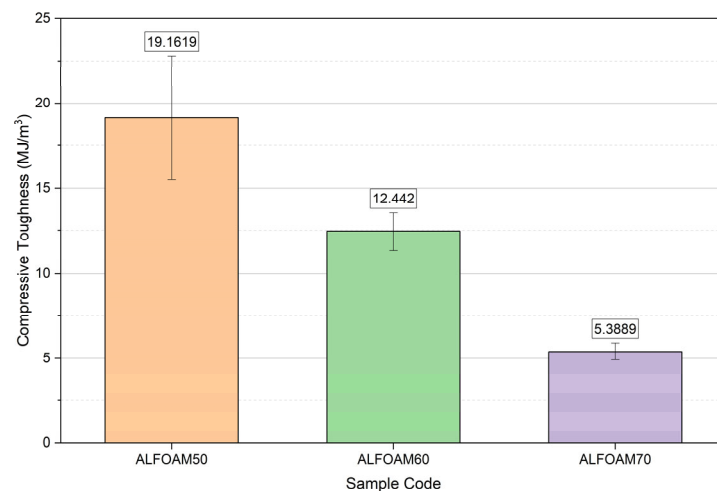


Fig. 3. Effect of porosity on the compressive toughness of the aluminum foam specimens. ALFOAM50, ALFOAM60 and ALFOAM70 refer to the samples obtained with nominal porosities of 50%, 60% and 70% by volume, respectively.

Fig. 2 and Fig. 3 display the relationship of the porosity with yield strength and compressive toughness. As the porosity increases, the ratio of the solid profile within the structure decreases which is why yield strength and compressive toughness decrease. The decrease of mechanical properties with the increase of porosity in this study is a consistent trend seen in other studies on aluminum foams fabricated by powder metallurgy and space holder method [9], [11], [12]. Yang et al. investigated aluminum foams with porosities of 50%, 60%, and 70% and similarly reported decreasing mechanical performance and energy absorption with increasing porosity [12]. A similar trend was reported by Alizadeh et al. for aluminum foams with the same porosity levels [11]. Gölbaşı et al. also observed a decrease in compressive stress with increasing porosity in open-cell aluminum foams produced by powder metallurgy [9].

IV. CONCLUSION

The aim of this study was to experimentally investigate and to demonstrate the relationship between porosity and mechanical properties (yield strength and compressive toughness). Aluminum foam specimens with three nominal porosity levels were fabricated using a powder metallurgy route combined with a space-holder technique and were subsequently subjected to compression testing. The results showed that both yield strength and compressive toughness decreased with increasing porosity. These findings demonstrate the trade-off between porosity and mechanical performance and may provide a basis for designing lightweight aluminum foam structures with application-specific mechanical properties.

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Impact of Hybrid Reinforcement of Mg and B₄C on the Yield Strength and Compressive Toughness of Aluminum Foams

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Abstract: In this study, the effect of simultaneous magnesium (Mg) and boron carbide (B₄C) reinforcement on the porosity, yield strength, and compressive toughness of aluminum foams was experimentally investigated. Pure Al foam and Al-1 wt.% Mg-5 wt.% B₄C hybrid composite foam specimens were fabricated under identical processing conditions using a powder metallurgy route combined with the space-holder technique. Pure Al powder with a grain size of 7-15 μm , Mg powder with an average grain size of 40 μm , B₄C powder with an average grain size of 3.5 μm , and carbamide particles with a size range of 1-2 mm were used. For the hybrid composition, Al and 5 wt.% B₄C powders were first mixed in ethanol by ball milling, after which 1 wt.% Mg was introduced and the mixture was further homogenized by magnetic stirring. Pure Al and hybrid composite powders were separately mixed with 70 vol.% carbamide, compacted at 250 MPa, immersed in demineralized water at 80 °C for at least 3 h to remove the space holder, dried at 50 °C for at least 6 h, and sintered at 645 °C for 3 h under an argon atmosphere. At least three specimens from each composition were subjected to compression testing at a compression speed of 1 mm/min. Yield strength was determined using the 0.2% offset method, while compressive toughness was calculated as the entire area under each recorded stress-strain curve. The average porosity values of the pure Al and hybrid composite foams were 71.83% and 70.57%, respectively. The hybrid reinforcement increased the average yield strength from 5.58 to 7.61 MPa and the average compressive toughness from 5.39 to 6.25 MJ/m³, corresponding to increases of approximately 36% and 16%, respectively. However, these values remained below the results previously obtained for separately reinforced 1 wt.% Mg and 5 wt.% B₄C aluminum foams fabricated under comparable processing conditions. Therefore, although the combined Mg-B₄C reinforcement improved the mechanical performance relative to pure Al foam, it did not produce an additive or synergistic strengthening effect under the investigated conditions.

Keywords: Magnesium, Boron Carbide, Aluminum Foam, Composite, Compression Test

I. INTRODUCTION

Metallic foams are lightweight, porous materials with relatively low density and relatively high yield strength and compressive toughness [1], [2]. Aluminum is one of the most examined metals because of its low density (2.7 g/cm³), low melting temperature (660°C), high electrical and thermal conductivity, ductility, high strength and high corrosion resistance [3], [4]. Because of its physical and mechanical properties, aluminum foams are used in industries where weight reduction and mechanical strength are required [2], [5]. Therefore, research for optimizing mechanical properties and weight of aluminum foams has been ongoing for various industrial applications [5], [6]. Due to the physical form of the metallic foams, their mechanical

properties are strongly affected by pore morphology, porosity, matrix composition, and the type and amount of reinforcement [7]. With the addition of other materials such as metals or ceramics, it could be possible to obtain improved mechanical properties while maintaining the porous and lightweight structure [8].

Magnesium is widely used in many sectors, just like aluminum, both in matrix form and as a reinforcement material, due to its physical and mechanical properties, such as ductility, low density (1.74 g/cm^3), good impact absorption capability, and low melting point [9]. On the other hand, B₄C is a very popular ceramic material because of its high Young's modulus (450 GPa), low density (2.52 g/cm^3) and exceptionally high hardness (3000 HV) [10].

Reinforcing aluminum with magnesium and B₄C particles and fabricating a hybrid composite foam may provide a route for preserving the pore morphology and lightweight structure while increasing the yield strength and compressive toughness of the foam. In our previous studies, the effects of Mg and B₄C additions on aluminum foams were investigated separately [11], [12]. Mg addition improved the compressive properties up to a certain reinforcement level, while B₄C reinforcement also resulted in changes in the compressive response depending on its content.

In the present study, Mg and B₄C were used as dual powder reinforcement elements of the aluminum matrix foam to investigate the mechanical response of the hybrid composite foam under compression testing. Pure aluminum foam specimens and Al-1%Mg-5%B₄C composite foam specimens were fabricated under the same conditions and evaluated in terms of yield strength and compressive toughness (obtained from stress-strain diagrams) and porosity.

Based on an expanded dataset obtained after our previous B₄C reinforced Al foam study, the 5 wt.% B₄C composition exhibited the highest yield strength among the investigated compositions. Therefore, 5 wt.% B₄C was selected for the present hybrid reinforcement study. For magnesium reinforcement, 1 wt.% Mg was selected based on the previous study, in which this composition exhibited the highest yield strength among the investigated Mg contents.

Although Al-Mg/B₄C composites and B₄C-reinforced aluminum alloy foams have previously been investigated, studies concerning the simultaneous addition of Mg and B₄C to highly porous aluminum foams produced by the powder metallurgy space-holder route appear to be limited [13], [14], [15], [16], [17]. Therefore, in the present study, 1 wt.% Mg and 5 wt.% B₄C were simultaneously incorporated into an aluminum foam fabricated by the powder metallurgy space-holder method and the resulting porosity, yield strength, and compressive toughness were compared with those of pure aluminum foam.

II. EXPERIMENTAL PROCEDURE

A. Material

In this study, pure Al was used as the matrix material, while boron carbide (B₄C) and magnesium (Mg) served as reinforcement materials.

The space holder method was used to obtain the foam structure and carbamide (CH₄N₂O) was used as the space holder material. The physical properties of the materials used in this study are displayed in Table I.

Table I. The materials used in this study and their physical properties

Material	Grain size	Purity (%)	Density (g/cm^3)
Al	7-15 μm	99	2.7
Mg	40 μm	99.8	1.74
B ₄ C	3.5 μm	99	2.52
Carbamide	1-2 mm	98.5	1.32

B. Method

For fabricating the aluminum foam samples, a conventional powder metallurgy route was combined with the space-holder technique. For fabricating hybrid composite foam, Al and wt. 5% B4C powders were mixed with ethanol by a ball mill for 15 minutes at 800 rpm. After that, wt. 1% Mg powder was introduced to the mixture of composite powder and ethanol. Subsequently, the final mixture of Al-5% B4C-1% Mg was stirred for 15 minutes by a magnetic stirrer. After that, the mixture of powder and ethanol was filtered. Next, the mixture of powder was sieved to resolve the clumping caused by filtering and drying which resulted in obtaining the composite powder mixture. At the next step of the process, for fabrication of the pure Al foam samples and hybrid composite samples, pure Al powder and composite powder were separately mixed with carbamide at the ratio of 70% by volume. Then, the mixtures were formed under 250 MPa by a uniaxial hydraulic press. The obtained green samples were immersed in demineralized water at 80 °C for at least 3 h to dissolve the carbamide and were subsequently dried in an oven at 50 °C for at least 6 h. After removal of the carbamide, the dried green samples were sintered at 645 °C for 3 h in an argon atmosphere. The sintered specimens were then subjected to compression testing for mechanical characterization. For each chemical composition at least three specimens were subjected to compression testing and the speed of the compression was set to 1 mm per minute.

III. RESULTS AND DISCUSSION

A. Determination of Porosity

In this section, the porosity (ϕ) of the fabricated specimens was evaluated. Equation (1) was used to calculate the porosity (ϕ), where “ ρ ” is the calculated density of the specimen and “ ρ_{Al} ” is the theoretical density of aluminum (2.7 g/cm³). The density of Al (2.7 g/cm³) was used as the reference theoretical density for both compositions.

$$\phi = \left[1 - \frac{\rho}{\rho_{Al}}\right] \cdot 100 \quad (1)$$

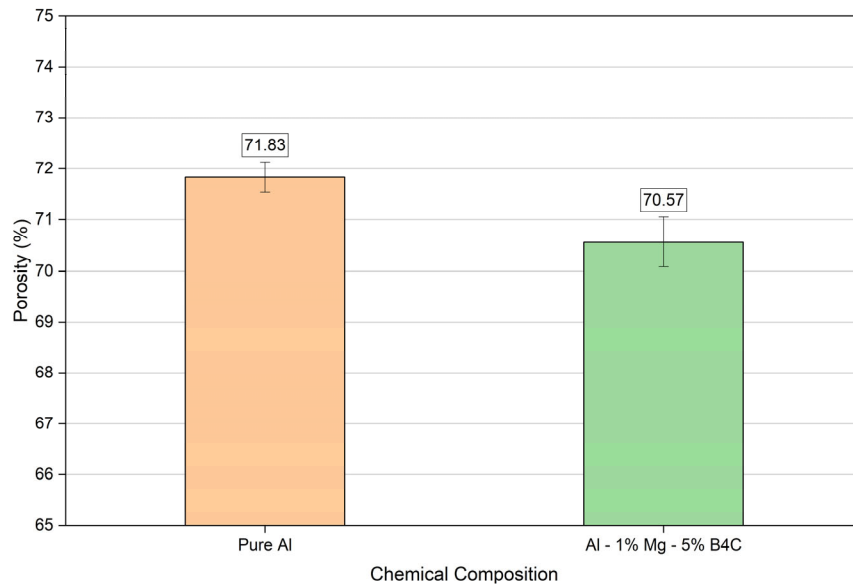


Fig. 1. Porosity of Pure Al foam and Hybrid composite foam (Al-1% Mg -5% B4C)

B. Compression Test

In this section, yield strength and compressive toughness results were evaluated. The 0.2% offset method was applied to each stress-strain curve to determine the yield strength.

Compressive toughness was calculated as the entire area under each recorded stress-strain curve.

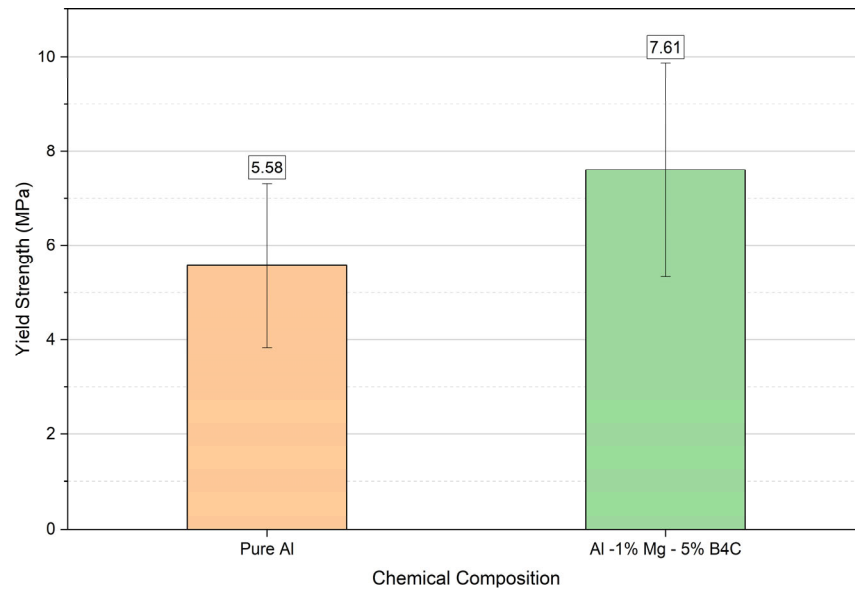


Fig. 2. Yield Strength of Pure Al foam and Hybrid composite foam (Al-%1 Mg -5% B4C)

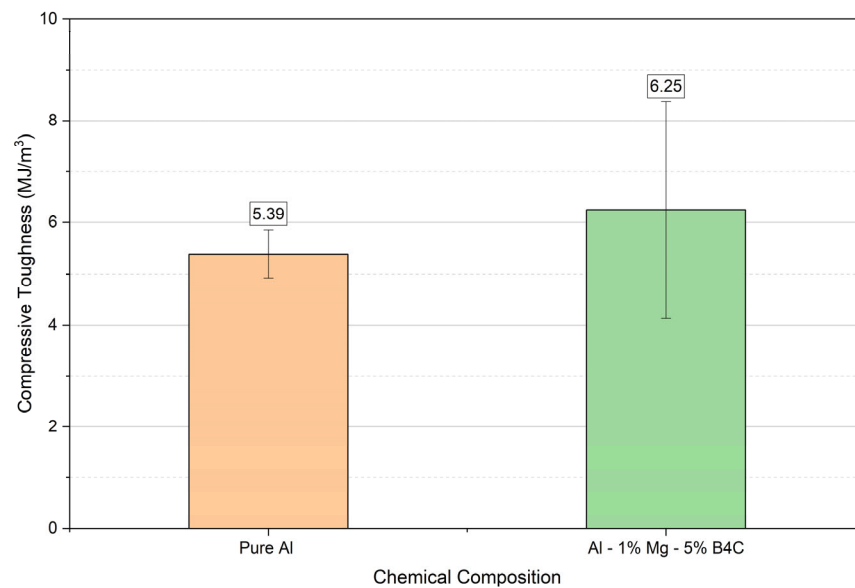


Fig. 3. Compressive Toughness of Pure Al foam and Hybrid composite foam (Al-%1 Mg -5% B4C)

Fig. 2 and Fig. 3 display the yield strength and the compressive toughness results of the two chemical compositions of the study. The pure Al foam exhibited an average yield strength of 5.58 MPa and an average compressive toughness of 5.39 MJ/m³. The Al - 1 wt.% Mg - 5 wt.% B₄C foam exhibited average yield strength and compressive toughness values of 7.61 MPa and 6.25 MJ/m³, respectively. Following our previous B₄C-reinforcement study, the experimental dataset was subsequently expanded with additional specimens. Based on this expanded and previously unpublished dataset, the wt. 5% B₄C reinforced Al foams exhibit 11.3 MPa yield strength on average and 7.9 MJ/m³ compressive toughness on average. On the other hand, in our previous study on Mg addition to Al foams, wt. 1% Mg reinforced Al foams exhibit 9.1 MPa yield strength on average and 7.2 MJ/m³ compressive toughness on average [11]. Based on the data obtained for this study and from our previous studies, separate addition of B₄C and

Mg to Al foams displayed better yield strength and compressive toughness performance than combined reinforcement.

Although both yield strength and compressive toughness increased in comparison to pure Al foam, the values remained below those previously obtained with the individual additions of 1 wt.% Mg and 5 wt.% B₄C. Therefore, since the previous and present specimens were fabricated under comparable compaction, space-holder removal, sintering and compression testing conditions, the combined reinforcement did not exhibit an additive or synergistic strengthening effect under the investigated conditions.

IV. CONCLUSION

The purpose of this study was to experimentally investigate and to demonstrate the impact of simultaneous addition of 1 wt.% Mg and 5 wt.% B₄C on yield strength and compressive toughness of pure Al foam. The reinforcement of pure Al foams with 1 wt.% Mg and 5 wt.% B₄C improved both yield strength and compressive toughness compared to pure Al foam. However, the mechanical performance remained below the values previously obtained with the individual Mg and B₄C additions. Under the comparable processing conditions, the combined reinforcement did not produce an additive or synergistic improvement in mechanical performance.

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Numerical Investigation of Smooth Trailing-Edge Morphing on the NACA 2412 Airfoil

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Abstract: This study investigates the effect of smooth trailing-edge morphing on the aerodynamic response of a NACA 2412 airfoil at a chord Reynolds number of 2.2×10^6 . A two-dimensional, steady, incompressible Reynolds-averaged Navier–Stokes solver was implemented in MATLAB using a cell-centred finite-volume method, with turbulence closure provided by the Spalart–Allmaras model. The baseline geometry was reconstructed from published NACA 2412 coordinates. Calculated lift, drag, surface pressure and skin friction were compared with the experimental measurements, along with the upper-surface separation location. Three structured grids were examined, and the finest grid, containing 98,304 cells, was used for all subsequent comparisons. At the highest validation angle of 12.4° , the fine-grid discretization uncertainty was 0.43% for lift and 1.60% for drag. The calculated lift coefficient was 1.40, compared with a measured value of 1.33; this difference exceeds the estimated grid uncertainty. The predicted upper-surface separation location was $x/c = 0.915$, compared with $x/c = 0.925$ in the experiment. The numerical model assumed fully turbulent flow, whereas the experimental model used transition strips. Smooth trailing-edge morphing was then applied from $x/c = 0.75$ to the trailing edge, with deflection angles of $\delta = -2^\circ, +2^\circ, +4^\circ$ and $+6^\circ$; positive δ denotes downward deformation. Downward morphing increased lift at all investigated angles of attack. At $\alpha = 0.2^\circ$, the $\delta = +6^\circ$ configuration increased the lift coefficient by 0.44 relative to the baseline; at $\alpha = 12.4^\circ$, the increase was 0.34. Drag increased with downward morphing at a fixed angle of attack. When the configurations were compared at equal lift instead, the lowest-drag configuration reduced drag by up to 10% relative to the baseline at $C_L = 1.3$. The results show that the aerodynamic assessment of trailing-edge morphing depends on whether angle of attack or lift is held constant.

Keywords: NACA 2412, Trailing-Edge Morphing, Aerodynamic Performance, Reynolds-Averaged Navier–Stokes, Computational Fluid Dynamics

I. INTRODUCTION

An airfoil with fixed geometry cannot maintain the same aerodynamic response across all operating conditions. Changes in angle of attack alter the pressure distribution, boundary-layer development and eventually the extent of flow separation. Reliable assessment of a geometry modification therefore requires a well-characterized reference airfoil. The NACA 2412 is suitable for this purpose because Seetharam et al. [1] measured aerodynamic forces, surface pressure, skin friction, and separation locations. A later experimental report also documents separated flows over the NACA 2412 and two other airfoils [2]. Numerical comparisons using this profile have further demonstrated the importance of checking computational results against measured data [3].

Morphing offers a means of changing the airfoil contour to suit different aerodynamic requirements. Wind-tunnel tests of a continuous camber-changing trailing edge [4] and

subsequent studies of morphed airfoils [5,6] show that the deformation profile can influence lift, drag and flow development. Research directly involving the NACA 2412 has examined the aerodynamic effect of a step associated with a morphing skin [7], alternative morphed geometries [8], compliant trailing-edge structures [9], and coordinated leading- and trailing-edge camber changes [10]. These studies address different geometries and operating conditions; their performance results should therefore be interpreted within the conditions of each investigation.

Further NACA 2412 studies have examined baseline predictions and other geometric modifications. Matsson et al. [11] compared wind-tunnel pressure measurements with CFD results, while Sarkar and Mughal [12] studied the effect of angle of attack using an SST turbulence model. Mohamed et al. [13] investigated a bio-inspired leading edge for separation control. Venkatesan et al. [14] examined surface dimples, Faadihillah et al. [15] studied riblets on a flap, and Khanna et al. [16] compared different camber configurations. These investigations establish useful context for the present work, although their modifications and operating conditions differ from the smooth trailing-edge deformation examined here.

The studies reviewed above use different deformation shapes or operating conditions and therefore do not directly quantify the effect of a smooth trailing-edge deflection under the reference conditions of [1]. To address this, the present study first assesses a two-dimensional RANS solver implemented in MATLAB with the Spalart–Allmaras turbulence model [17] against the measured lift, drag, surface pressure, skin friction, and separation data at a chord Reynolds number of 2.2×10^6 . Grid convergence is evaluated following Celik et al. [18]. The assessed baseline is then compared with four configurations featuring smooth trailing-edge morphing beginning at $x/c = 0.75$, with deflection angles of $\delta = -2^\circ, +2^\circ, +4^\circ$ and $+6^\circ$; the undeformed airfoil corresponds to $\delta = 0^\circ$. The baseline airfoil was assessed against experimental data over angles of attack from -4° to 12.4° . The trailing-edge morphing configurations were compared at four angles of attack, approximately $0.2^\circ, 4.2^\circ, 8.25^\circ$, and 12.4° , both at fixed angle of attack and, where their lift ranges overlapped, at equal lift.

II. MATERIALS AND METHODS

A. Geometry

The baseline geometry was the NACA 2412 airfoil. Its upper- and lower-surface coordinates were taken from the experimental report of [1]. These points were interpolated to generate the airfoil surface used for grid generation, as shown in Fig. 1; symbols indicate the reported coordinates, and the solid line indicates the interpolated surface. The trailing edge was closed in the numerical geometry. The experimental model had a chord of 0.6096 m and a span of 0.9144 m, and it used 80-grit transition strips at approximately $x/c = 0.05$ on both surfaces. The reference Reynolds number was $Re_c = 2.2 \times 10^6$, and the free-stream Mach number was 0.13. The numerical model was fully turbulent from the leading edge and did not explicitly represent the transition strips or their roughness.

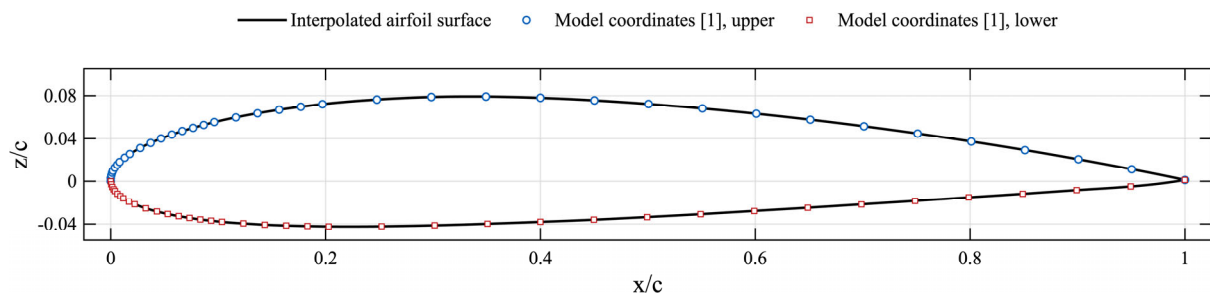


Fig. 1. NACA 2412 model coordinates from [1] and the interpolated airfoil surface used for grid generation.

Trailing-edge morphing was applied to the NACA 2412 airfoil profile beginning at $x/c =$

0.75. The profile upstream of this position remained unchanged, while the trailing-edge region was smoothly deflected. Four deflection angles, $\delta = -2^\circ$, $+2^\circ$, $+4^\circ$, and $+6^\circ$, were examined alongside the baseline profile ($\delta = 0^\circ$). Positive δ denotes downward deflection. The baseline and morphing configurations are shown in Fig. 2.

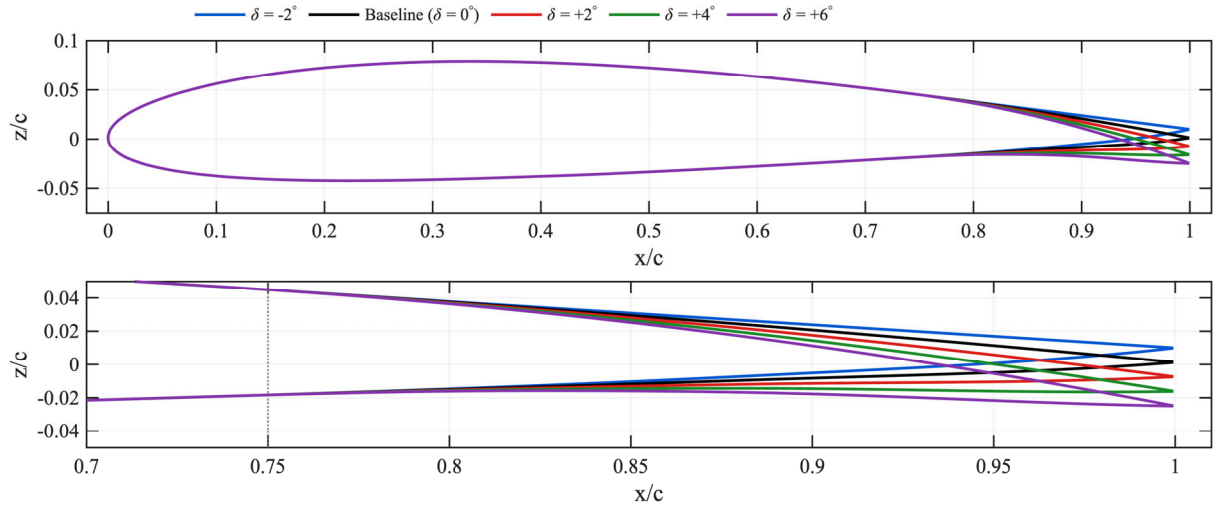


Fig. 2. NACA 2412 baseline and trailing-edge morphing configurations: complete profiles (top) and enlarged trailing-edge region (bottom). Morphing begins at $x/c = 0.75$.

B. Computational Domain and Boundary Conditions

Fig. 3 shows the C-type computational domain and an enlarged view of the airfoil. The outer circular arc has a radius of $20c$ about $x/c = 0.25$; its upper and lower branches meet the downstream boundary at $z/c = \pm 20$. The downstream boundary is located $20c$ behind the trailing edge, at approximately $x/c = 21$. Thus, the displayed outlet is a numerical boundary of the C-grid, not a separate pressure-outlet condition.

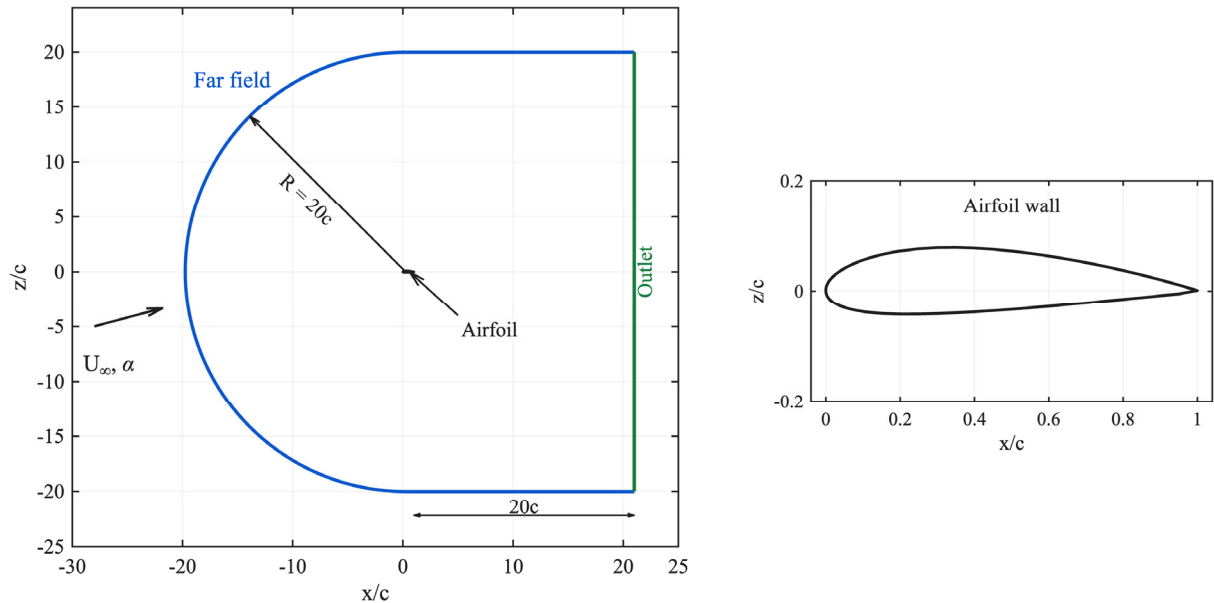


Fig. 3. Boundary-condition schematic for the NACA 2412.

At the airfoil surface, the no-slip and Spalart-Allmaras (SA) wall conditions are

$$u_w = w_w = 0, \quad \tilde{v}_w = 0 \quad (1)$$

At the far field and downstream boundaries, the velocity is prescribed with a circulation correction:

$$(u_b, w_b) = (\cos\alpha, \sin\alpha) + [\Gamma/(2\pi r^2)](z, -(x - 0.25)) \quad (2)$$

Here, $r^2 = (x - 0.25)^2 + z^2$ and $\Gamma = C_L/2$ is updated from the current lift coefficient. The boundary pressure is $p_b = (1 - u_b^2 - w_b^2)/2$, and the SA variable is prescribed as $\tilde{v}_b = 3Re_c^{-1}$. Coordinates and velocities are normalized by the chord and free-stream velocity, respectively.

C. Governing Equations and Turbulence Closure

The two-dimensional, steady, incompressible Reynolds-averaged Navier–Stokes (RANS) equations were solved. Length, velocity and pressure were nondimensionalized by the chord c , free-stream velocity U_∞ and ρU_∞^2 , respectively. The governing equations are

$$\nabla \cdot \mathbf{u} = 0 \quad (3)$$

$$\nabla \cdot (\mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot [(\text{Re}_c^{-1} + \nu_t)(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] \quad (4)$$

Here, $\mathbf{u} = (u, w)$ and ν_t is the eddy viscosity obtained from the one-equation Spalart–Allmaras (SA-noft2) model. The incompressible equations were advanced to a steady solution using artificial compressibility with $\beta = 1$.

D. Mesh Generation and Grid Convergence

A structured C-grid was generated in MATLAB from the reference NACA 2412 coordinates. Grid points were clustered near the airfoil surface as well as the leading and trailing edges. Fig. 4 (a)–(d) shows the complete computational domain, the near-wall mesh, and the leading- and trailing-edge regions. Three systematically refined grids containing 6,144, 24,576, and 98,304 cells were examined. The finest grid was selected for the validation calculations.

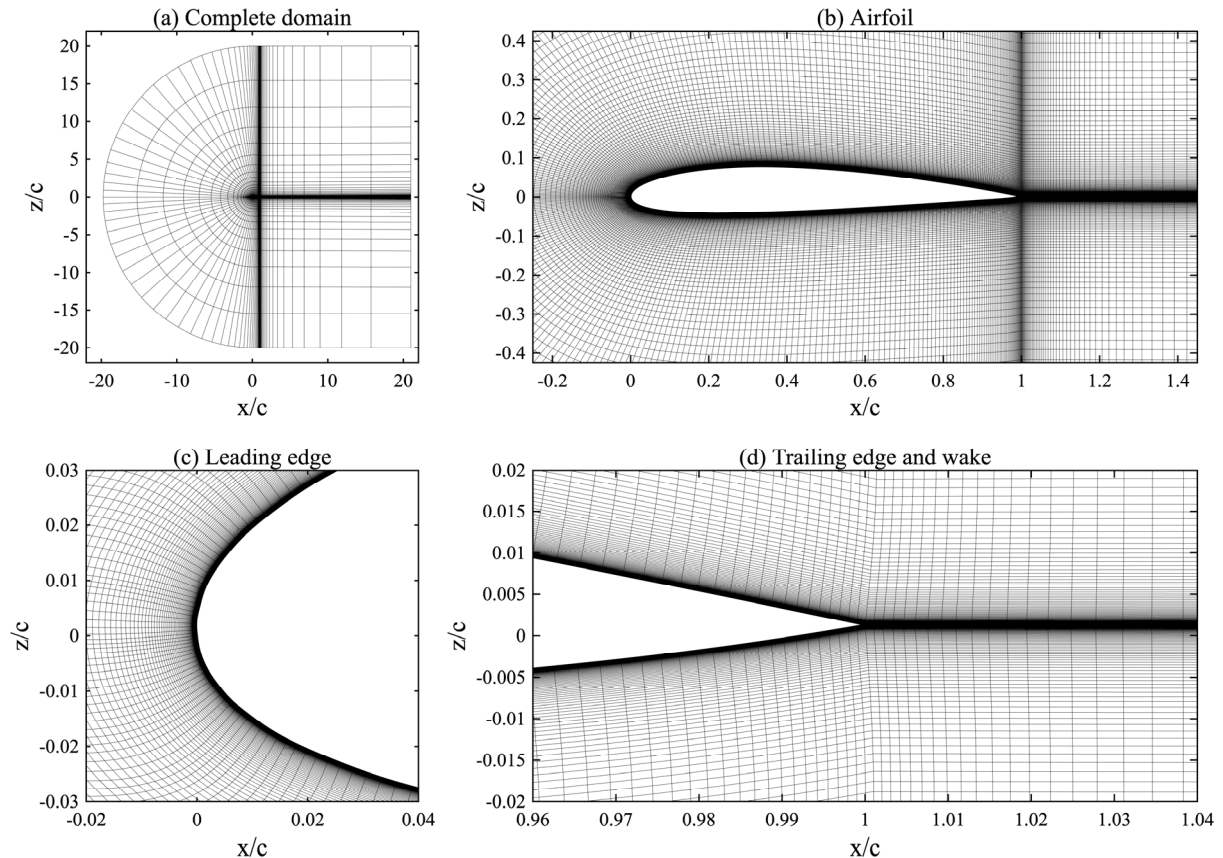


Fig. 4. Structured C-grid around the NACA 2412 airfoil: (a) complete computational domain, (b) airfoil and near-wall mesh, (c) leading-edge region, and (d) trailing-edge and wake region.

Grid convergence was assessed using the lift and drag coefficients at $\alpha = 12.4^\circ$ (Fig. 5). The Grid Convergence Index (GCI) was calculated following the procedure of Celik et al. [18]. Both coefficients changed monotonically towards their Richardson-extrapolated values,

indicated by red stars in Fig. 5. The fine-grid GCI was 0.43% for C_L and 1.60% for C_D . These results supported the selection of the fine grid for the experimental comparisons and subsequent morphing calculations.

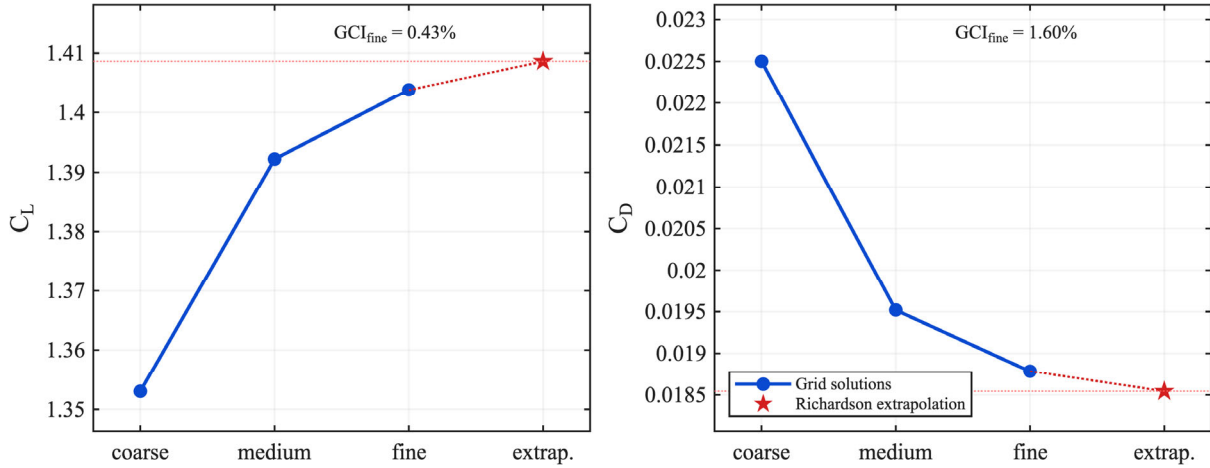


Fig. 5. Grid convergence of the lift and drag coefficients for the NACA 2412 airfoil at $\alpha=12.4^\circ$.

E. MATLAB-Based Numerical Solution

The flow equations were solved using a purpose-written, cell-centred finite-volume MATLAB solver. Mean-flow convective fluxes were evaluated using an artificial-compressibility Roe scheme. First-order reconstruction was used for the initial 50 iterations, followed by MUSCL reconstruction with $\kappa = 1/3$. Viscous gradients were evaluated using a corrected Green-Gauss method. The Spalart-Allmaras equation was solved separately, with first-order upwind convection and an implicit update.

Local pseudo-time stepping was applied, with maximum CFL numbers of 500 for the mean flow and 10 for the turbulence equation. Each case was allowed up to 2,000 iterations. The solver stopped when either the relative continuity residual fell below 10^{-7} or the ranges of C_L and C_D over the preceding 50 iterations fell below 5×10^{-5} and 10^{-5} , respectively. The computed solutions were post-processed to obtain C_L , C_D , surface C_p , surface C_f , and wall y^+ .

III. RESULTS AND DISCUSSION

Figure 6(a) compares the calculated lift coefficient with the experimental measurements [1]. The numerical solution follows the measured variation closely at low and moderate angles of attack. At the highest investigated angle ($\alpha = 12.4^\circ$), the calculated lift coefficient is 1.40, compared with the measured value of 1.33. The relative lift difference is approximately 5.3%, exceeding the 0.43% fine-grid GCI estimated for the baseline airfoil at this angle. Grid discretization alone therefore does not account for the discrepancy. The drag polar in Fig. 6(b) captures the experimental increase in drag with lift, although the calculated drag is generally slightly lower than the measurements at intermediate and high lift coefficients. Thus, the overall trends are reproduced, while the agreement depends on the operating point.

Fig. 7 compares the surface pressure coefficient distributions at $\alpha = 12.4^\circ$. The numerical solution captures the strong upper-surface suction near the leading edge and the subsequent pressure recovery. It follows the experimental upper-surface pressures over most of the chord and represents the forward-chord measurements more closely than the theoretical curve given in [1]. The calculated suction peak is, however, stronger than indicated by the nearest experimental points. The lower-surface distributions show the same overall trend, with smaller local differences along the chord.

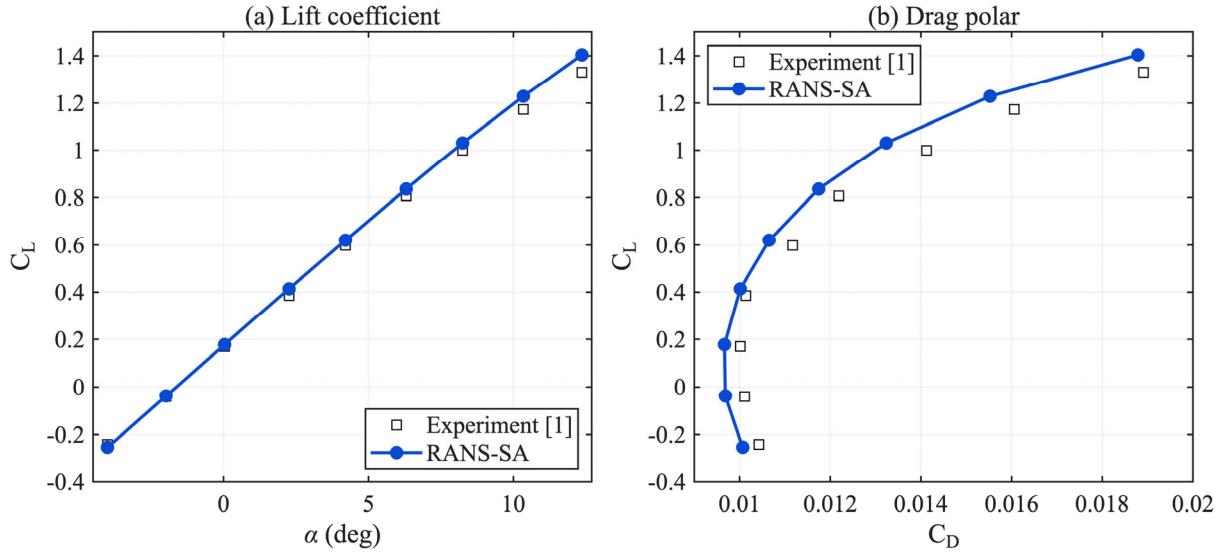


Fig. 6. Comparison of experimental data [1] and RANS-SA solution for the NACA 2412 airfoil: (a) lift coefficient versus angle of attack and (b) drag polar.

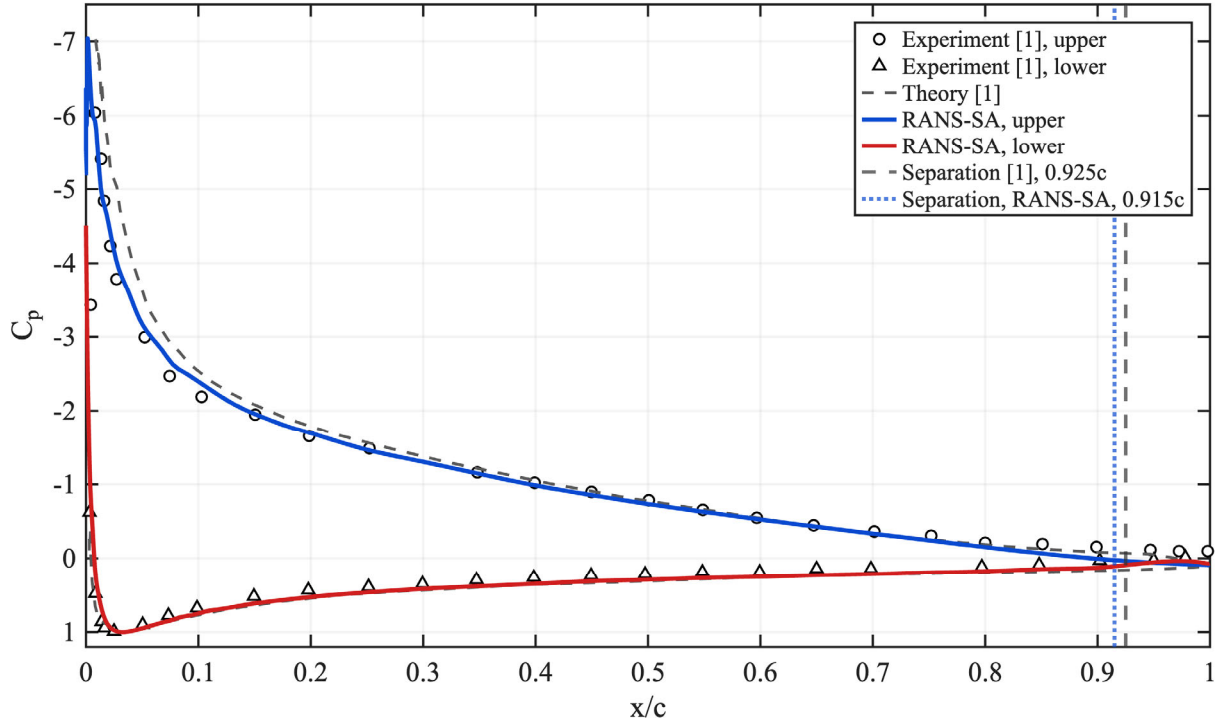


Fig. 7. Comparison of the surface pressure coefficient distribution at $\alpha = 12.4^\circ$ from the experimental data and theory of [1] and the RANS-SA solution.

The skin-friction distributions in Fig. 8 provide a more demanding local comparison. At $\alpha = 0.2^\circ$, the calculated friction generally decreases towards the trailing edge on both surfaces, although individual experimental points differ from the numerical curves. At $\alpha = 12.4^\circ$, the upper-surface friction approaches zero near the trailing edge. The calculated separation location is approximately $x/c = 0.915$, close to the experimental value of $x/c = 0.925$. Differences in skin-friction magnitude remain, particularly near the leading edge and on the lower surface. The experiment used transition strips, whereas the numerical model assumed fully turbulent flow from the leading edge; this distinction should be considered when comparing the near-wall results.

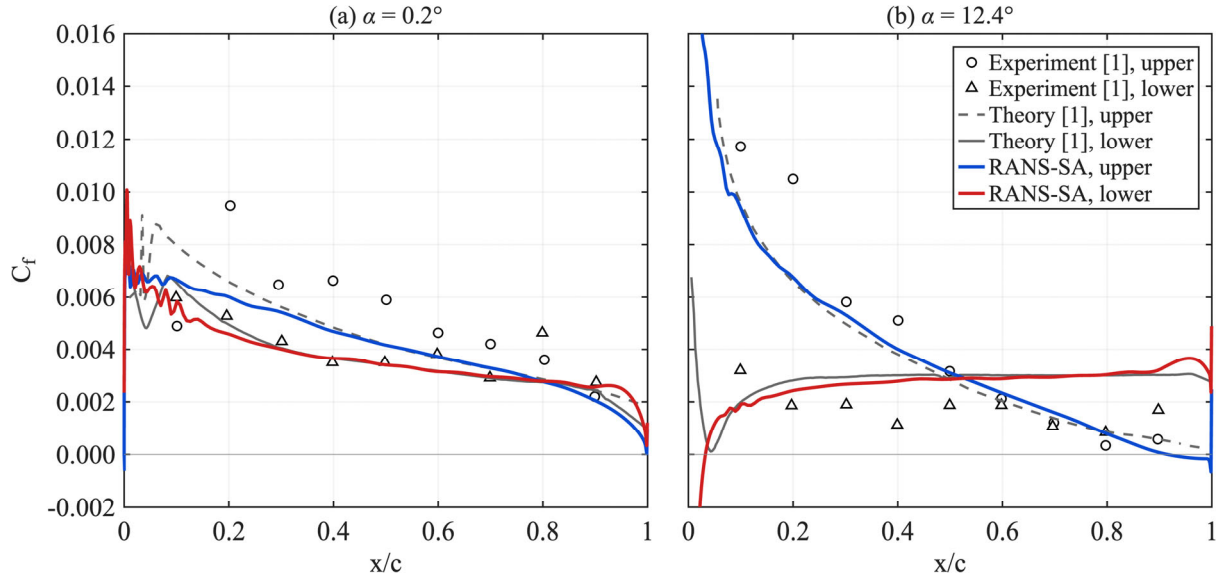


Fig. 8. Comparison of the upper- and lower-surface skin-friction coefficient distributions from the experimental data and theory of [1] and the RANS-SA solution: (a) $\alpha = 0.2^\circ$ and (b) $\alpha = 12.4^\circ$.

Fig. 9(a) shows the effect of trailing-edge morphing on lift. Downward deflection increases C_L at all investigated angles of attack, whereas $\delta = -2^\circ$ reduces it relative to the baseline airfoil. The effect is more pronounced at lower angles: at $\alpha = 0.2^\circ$, $\delta = +6^\circ$ increases C_L by approximately 0.44, compared with approximately 0.34 at $\alpha = 12.4^\circ$. The drag polar in Figure 9(b) shows that drag generally increases with lift. At a fixed angle of attack, downward trailing-edge morphing produces both higher lift and higher drag. For example, at $\alpha = 8.25^\circ$, C_D increases from approximately 0.013 for the baseline to 0.017 for $\delta = +6^\circ$. At a similar lift coefficient, however, a downward-morphed configuration can have lower drag than the baseline in the higher-lift portion of their overlapping ranges. The drag comparison therefore depends on whether angle of attack or lift is held constant.

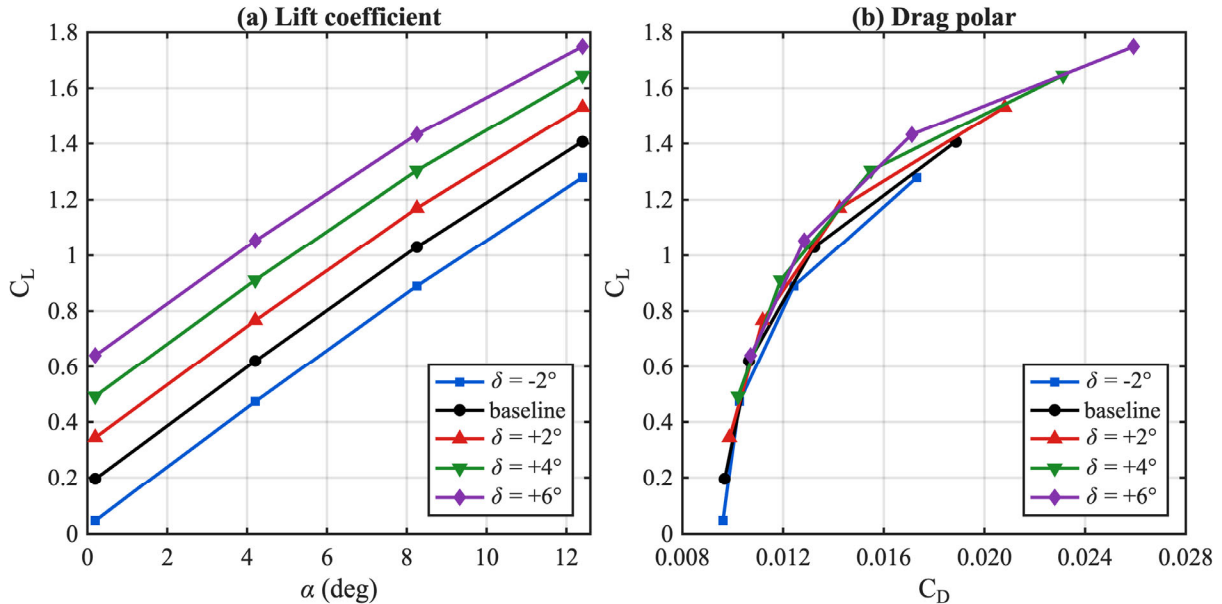


Fig. 9. Aerodynamic coefficients of the baseline and trailing-edge-morphing NACA 2412 airfoils: (a) lift coefficient versus angle of attack and (b) drag polar, with C_D on the horizontal axis and C_L on the vertical axis.

Fig. 10 quantifies the drag reduction at equal lift relative to the baseline airfoil. At each selected C_L , the drag coefficients were interpolated from the computed polars, and the lowest value among the tested morphing angles was identified. The baseline gives the lowest drag at

$C_L = 0.3$. Among the morphed configurations, $\delta = +2^\circ$ gives the lowest drag at $C_L = 0.4$ – 0.5 , $\delta = +4^\circ$ at $C_L = 0.6$ – 0.7 , and $\delta = +6^\circ$ at $C_L = 0.8$ – 1.3 . The reduction increases with C_L and reaches approximately 10% at $C_L = 1.3$.

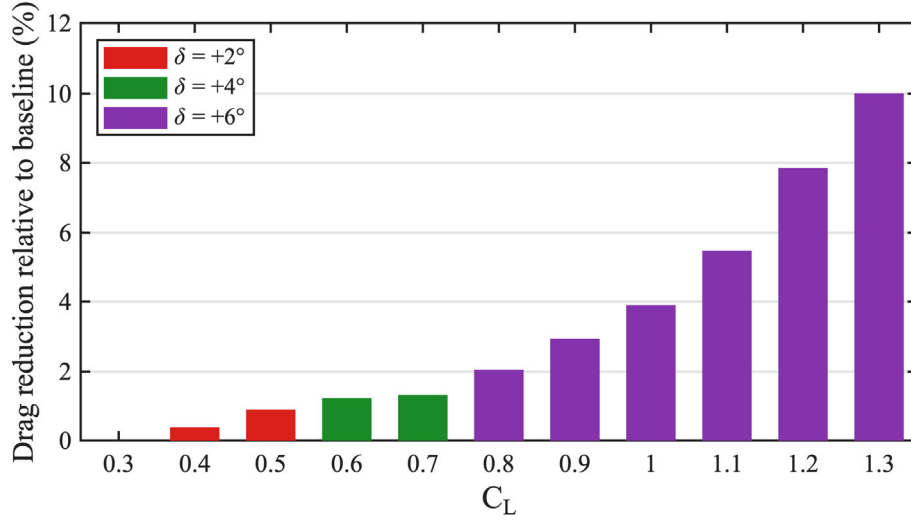


Fig. 10. Drag reduction at equal lift relative to the baseline. Bar colours indicate the lowest-drag tested deflection.

Fig. 11 compares the surface pressure distributions at the same angle of attack, $\alpha = 8.25^\circ$. Increasing downward trailing-edge deflection makes C_p more negative on the upper surface and more positive on the lower surface. The $\delta = -2^\circ$ configuration shows the opposite trend. These pressure changes are consistent with the lift differences shown in Fig. 9(a). The inset makes the effect in the aft region easier to see. The pressure distributions separate around the start of morphing at $x/c = 0.75$ and approach one another near the trailing edge. Differences also appear upstream of $x/c = 0.75$, although the geometry there is unchanged, suggesting that trailing-edge morphing alters the pressure field over the full airfoil.

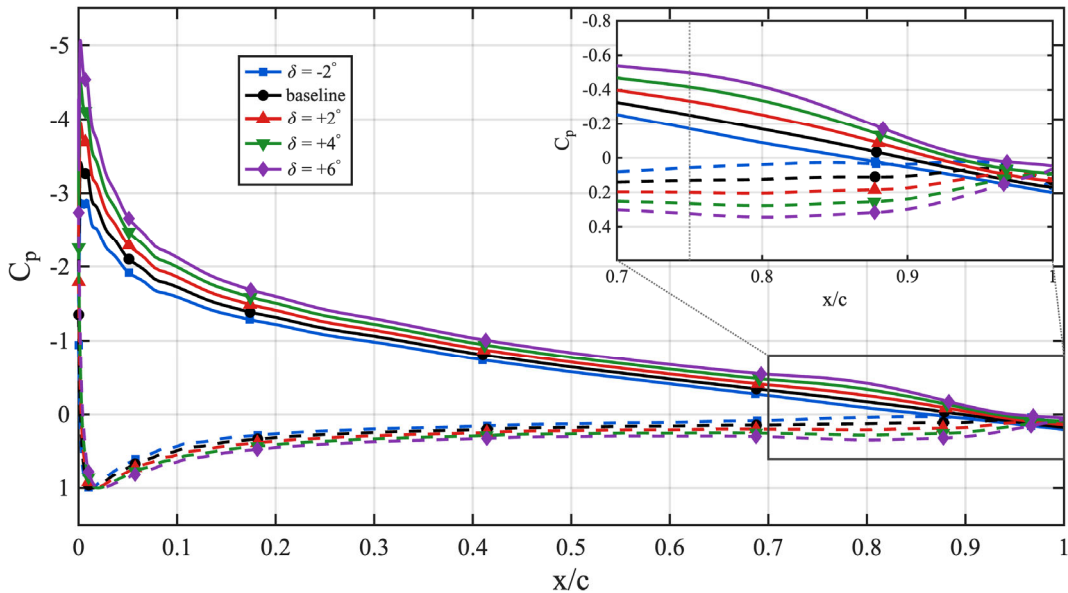


Fig. 11. Surface pressure coefficient distributions of the baseline and trailing-edge-morphed NACA 2412 airfoils at $\alpha = 8.25^\circ$. The inset enlarges the boxed region, $x/c = 0.70$ – 1.00 . Solid and dashed lines represent the upper and lower surfaces, respectively; the vertical dotted line marks $x/c = 0.75$.

IV. CONCLUSION

A two-dimensional MATLAB-based RANS solver was applied to the NACA 2412 airfoil and compared with experimental lift, drag, pressure, skin-friction and separation data. The fine-grid solution reproduced the main aerodynamic trends and predicted the upper-surface

separation position at $x/c = 0.915$, compared with $x/c = 0.925$ in the experiment. At the highest validation angle, however, the calculated lift coefficient exceeded the measured value by approximately 0.07. This difference was larger than the estimated grid uncertainty and indicates a limitation in predictive accuracy at that operating condition.

Smooth trailing-edge deflection beginning at $x/c = 0.75$ produced a consistent change in lift across the reported morphing cases. Downward deflection increased both lift and drag at a fixed angle of attack. At equal lift, interpolation of the computed drag polars showed a different result: among the tested deflections, the lowest-drag configuration reduced drag relative to the baseline by up to approximately 10% at a lift coefficient of 1.3. Thus, the preferred configuration depends on the required operating lift. These findings apply to the investigated angles and deflections within a two-dimensional, fully turbulent model. The experimental transition strips and possible three-dimensional effects were not represented in the calculations.

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Forecast-Aware Energy Management for a Grid-Connected Photovoltaic–Battery Microgrid: A Reproducible Simulation Study

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Abstract—This paper examines forecast-aware energy management for a grid-connected photovoltaic (PV)–battery microgrid and specifies a protocol for reproducible controller comparison. A constrained rolling-horizon linear optimizer schedules charging, discharging, grid import, and export with converter limits, state-of-charge (SOC) bounds, and asymmetric energy-conversion efficiencies. The controller is compared with a self-consumption rule over seven days at 15-min resolution, using a 42-kW PV array and a 100-kWh battery. The simulation results give electricity costs of 299.82 USD for the rule-based controller and 263.96 USD for the predictive controller, a reduction of 11.96%. This economic improvement accompanies higher grid imports (2184.2 versus 1999.9 kWh), a higher peak import (49.9 versus 33.0 kW), and greater battery throughput (925.8 versus 382.3 kWh). Including the stated throughput penalty in the accounting reduces the apparent saving to 7.38%. An energy-management schematic explains the forecast, optimization, actuation, and feedback sequence. The analysis shows that price anticipation supports electricity-cost reduction while autonomy and peak reduction require additional objectives. The benchmark uses synthetic profiles and perfect forecasts; exact independent reconstruction requires complete profile-generation equations or the original time series, together with executable code and solver settings.

Keywords—Battery energy storage, energy management system, microgrid, model predictive control, photovoltaic generation, reproducibility.

I. INTRODUCTION

Microgrids coordinate local generation, storage, and demand through a controllable interface with the utility network [1]. Renewable intermittency and the interaction of operating constraints make their control and energy management challenging [2]. In a grid-connected PV–battery microgrid, the battery can shift energy to expensive periods and absorb PV surplus, but these services can compete: maximizing self-consumption may consume stored energy before an evening price peak, whereas tariff arbitrage may increase grid dependence and battery use. The supervisory EMS therefore needs an explicit objective and a clear account of the resulting trade-offs. Recent research reviews the evolution of centralized, decentralized, and hierarchical microgrid control architectures [3].

Energy scheduling must be distinguished from fast converter control. Hierarchical architectures separate primary regulation, secondary restoration, and the management of power exchange with the external grid [4]. Rule-based scheduling is transparent and inexpensive, but a policy that charges on PV surplus and discharges on demand deficit does not anticipate future conditions. Rolling-horizon EMS formulations incorporate updated forecasts [5], while MPC treats operational constraints within a repeated optimization [6].

Only the first decision is applied before the state is measured and the problem is solved again. A more recent review examines MPC across microgrid functionalities and identifies remaining design and implementation challenges [7].

A recent review relates microgrid sizing and EMS choices to economic and energy-performance objectives [8]. The present work focuses on a compact case study rather than proposing a new MPC algorithm. Its objectives are to formulate an interpretable forecast-aware schedule, quantify its economic benefit against a matched rule-based baseline, verify the reported operating bounds, and expose changes in energy autonomy, peak import, and battery use. A common simulation protocol is essential for attributing differences to the controller rather than to input data, initial energy, or metric definitions [5], [6]. Ensemble nonlinear MPC has also been investigated for residential solar–battery energy management with forecast uncertainty and battery degradation [9]. PV–battery profit optimization in short-term electricity markets further emphasizes the importance of accounting for battery losses, degradation, and power-related charges [10]. These studies motivate assessing several performance indicators alongside the electricity bill.

The study addresses supervisory active-power scheduling at 15-min intervals. It assumes that local inverter controls can track feasible references and that the battery management system (BMS) and protection retain independent authority [4]. Consequently, the results do not establish transient stability, synchronization performance, or fault ride-through capability. The mathematical EMS can be reconstructed from its equations and parameters; exact numerical reproduction additionally requires complete input-profile definitions and implementation settings, as discussed in Section VI and the Appendix.

Section II describes the microgrid, energy-management schematic, component models, and inputs. Section III defines the two controllers and evaluation indicators. Section IV interprets the energy, economic, SOC, peak, and throughput results. Section V discusses horizon sensitivity and implementation. Section VI defines the validity and reproducibility limits, and Section VII concludes the study.

II. MICROGRID ARCHITECTURE AND MODELS

A. System Architecture

The AC-coupled microgrid contains a PV array and its inverter, a bidirectional battery converter, local demand, and a point of common coupling with the utility. Figure 1 distinguishes electrical power paths from information and control paths. The supervisory EMS receives predicted PV generation, predicted demand, tariff information, and measured battery SOC. It computes feasible active-power commands, while local voltage, current, and synchronization loops operate below the scheduling layer [4].

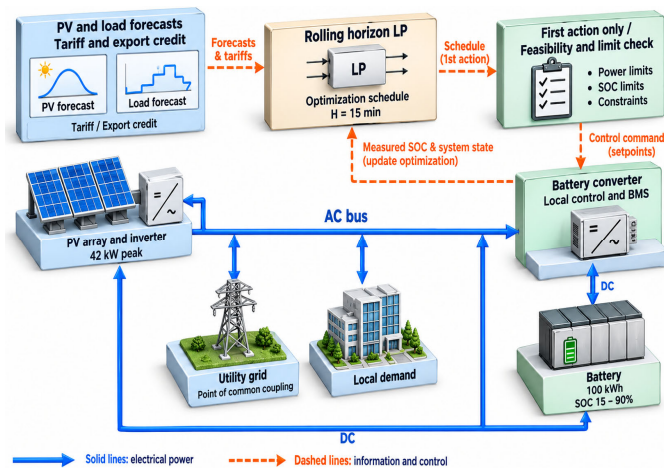


Fig. 1. Forecast-aware supervisory energy management for the grid-connected PV–battery microgrid.

At each sampling instant, the EMS forms a 24-step prediction window, sets the current measured SOC as its initial condition, and minimizes the predicted electricity bill plus a throughput penalty. Feasibility and command limits are checked before the first action is sent to the converter. The grid balances the remaining demand or receives surplus energy; it is not directly controlled as an independent energy source. After 15 min, the SOC is updated and the window advances. This feedback sequence follows the rolling-horizon principle [5], [6]. Grid charging is allowed in the predictive case, which explains why economic optimization can increase total imports.

The battery converter and BMS enforce equipment limits independently of the EMS. Forecast availability and solver status should be checked before dispatch; a failure should trigger the feasible rule-based policy. These are implementation provisions in the architecture, rather than demonstrated communication or hardware tests [4].

Table I. Base-case microgrid parameters

Subsystem	Rated value / model
PV array	42 kW peak, unity-power-factor inverter
Battery	100 kWh energy-capacity parameter; 15–90% SOC; 75 kWh operating window
Converter	±30 kW; $\eta_c = \eta_d = 0.95$
Grid	Unlimited import/export in base case
Sampling	15 min; seven days (672 intervals)
Tariff	0.075/0.115/0.245 USD kWh ⁻¹ ; export 0.045

B. Power Balance and Battery Dynamics

At interval k , the active-power balance is

$$P_{grid,k} + P_{disk,k} + P_{PV,k} = P_{load,k} + P_{ch,k} + P_{exp,k} \quad (1)$$

Charging and discharging powers are nonnegative and limited by the bidirectional converter. The battery state evolves according to

$$S_{k+1} = S_k + \frac{\Delta t}{E_b} \left(\eta_c P_{ch,k} - \frac{P_{disk,k}}{\eta_d} \right) \quad (2)$$

$$S_{min} \leq S_k \leq S_{max}, \quad 0 \leq P_{ch,k}, P_{dis,k} \leq P_{max} \quad (3)$$

Here, E_b is the 100-kWh energy-capacity parameter, $\Delta t = 0.25$ h, and $\eta_c = \eta_d = 0.95$. Charging and discharging are measured on the AC side. Both powers are nonnegative and bounded by 30 kW; SOC remains between 0.15 and 0.90. The accessible energy window is therefore 75 kWh, rather than 100 kWh. Grid import and export are nonnegative with no imposed capacity bound. The constant-efficiency energy model is appropriate for supervisory scheduling, but it does not represent converter transients [4], [6].

The LP does not explicitly impose charge–discharge or import–export complementarity. Under the stated positive import prices, lower export credit, unrestricted grid exchange, and positive throughput penalty, simultaneous opposing flows offer no economic benefit. This property should still be checked in the dispatch outputs. Negative prices, forced terminal targets, or altered constraints can invalidate that argument and may require a mixed-integer formulation [6].

C. Synthetic Input Profiles

The sample index is $k = 0, \dots, 671$ and the position within a day is $h = (k\Delta t \bmod 24)$. The synthetic PV description uses a clipped daylight sinusoid raised to 1.65, a seven-day cloud-

factor vector [0.92, 0.78, 0.88, 0.61, 0.84, 0.95, 0.72], and a small deterministic modulation. Demand combines a 17.5-kW base, a daily sinusoid, Gaussian morning and evening peaks, a weekend multiplier of 0.90, and a bounded periodic perturbation. The stated numerical seed is 26. These profiles define a synthetic scenario and do not represent measured operation at a named site. Figure 2 illustrates two days of the simulated inputs.

For a reproducible benchmark, all amplitudes, phase shifts, Gaussian widths and centers, clipping rules, and day indexing must be specified, together with the exact modulation and perturbation functions. A seed is sufficient only when the random-number generator and distributions are also stated. These details are not fully specified here; the original 672-sample series or their complete generator must therefore accompany any independent replication. A future site-specific study could use measured meteorological inputs and an open PV modeling tool such as pvlib [11], which was not used to validate the present synthetic profiles. The 2023 pvlib project update provides a recent reference for this open modeling framework [12].

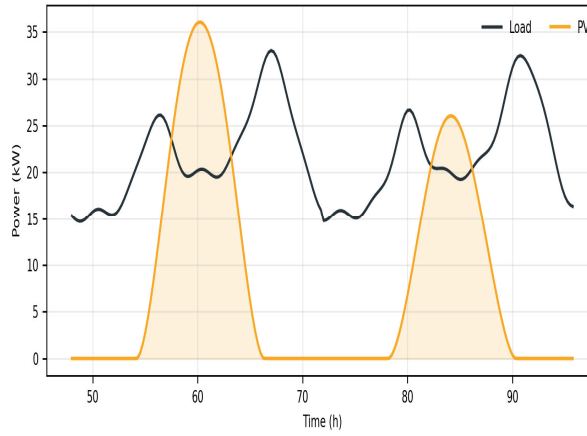


Fig. 2. Simulated load and PV profiles for representative days 3–4.

III. ENERGY MANAGEMENT STRATEGIES

A. Rule-Based Baseline

The baseline first supplies demand from PV. Surplus PV charges the battery subject to the converter rating and upper SOC bound; remaining surplus is exported. During a deficit, the battery discharges subject to its rating and lower SOC bound, and the grid supplies the remainder. The baseline does not charge from the grid or reserve energy for a later tariff peak. It provides a transparent self-consumption comparison; it is not a tariff-aware competitor or a globally optimal reference [2], [8].

B. Forecast-Aware Rolling-Horizon Controller

Every 15 min, the predictive EMS minimizes electricity purchases minus export revenue plus a charge–discharge throughput penalty over the next $H = 24$ available samples, corresponding to six hours [5], [6]:

$$\min J = \sum_k \left[C_{buy,k} P_{grid,k} - C_{sell} P_{exp,k} + C_{deg} (P_{ch,k} + P_{disk,k}) \right] \Delta_t \quad (4)$$

The coefficient $c_{deg} = 0.012$ USD kWh⁻¹ is applied to each directional AC energy flow. It is a scheduling penalty, not a measured cell-aging cost. Equations (1)–(3) hold at every prediction step. A linear programming solver with dual-simplex or interior-point capability can solve this formulation; SciPy’s HiGHS interfaces provide one documented implementation route [13]. The software version, method, tolerances, and presolve settings should be recorded for replication. Perfect within-horizon PV and load forecasts isolate scheduling behavior from prediction errors. Only the first action is applied, and the

optimization is rebuilt from the updated SOC. The horizon is truncated near the end of the record.

The time-of-use import tariff is 0.075 USD kWh⁻¹ from 00:00 to 06:00, 0.115 USD kWh⁻¹ from 06:00 to 17:00 and 22:00 to 24:00, and 0.245 USD kWh⁻¹ from 17:00 to 22:00. Export earns 0.045 USD kWh⁻¹. The controller can charge before an expensive period when avoided purchases exceed efficiency losses and throughput penalties. This tariff-dependent behavior is consistent with economic scheduling formulations [5], [6]. No demand charge or peak-import penalty is included.

C. Evaluation Indicators

The reported electricity cost is import expenditure minus export revenue; it excludes the throughput penalty. The export-based self-consumption indicator is $SC = 1 - E_{\text{export}}/E_{PV}$, and the import-based self-sufficiency indicator is $SS = 1 - E_{\text{import}}/E_{\text{load}}$, as in (5). The figures express these indicators as percentages. With grid charging, SS is an energy-accounting proxy rather than a traced fraction of demand supplied by PV; SC likewise assumes exports can be attributed to PV. Source-resolved battery accounting would be required to quantify actual renewable supply. These definitions must be held fixed across controller comparisons [8].

$$SC = \frac{E_{PV} - E_{\text{export}}}{E_{PV}}, \quad SS = \frac{E_{\text{load}} - E_{\text{import}}}{E_{\text{load}}} \quad (5)$$

Equivalent battery throughput is $T = (E_{\text{charge}} + E_{\text{discharge}})/2$, measured in kWh of AC energy; it is not a count of equivalent full cycles. Peak import is the maximum quarter-hour import power. To assess the implemented optimization criterion, the augmented cost is $C_{\text{aug}} = C_{\text{electricity}} + 2c_{\text{deg}}T$. This distinction prevents an electricity-bill saving from being mistaken for an equal reduction in the complete objective [6].

Both controllers use identical physical inputs, the same sampling interval, and initial SOC = 0.55. Their reported terminal SOC is 0.15, so they receive the same 40-kWh reduction in stored energy across the week. The principal comparison imposes no terminal equality or salvage value. Equal final states improve comparability but do not eliminate end-of-record effects; a replication should also test equal initial and final SOC or a justified terminal value [6].

Table II. Forecast-aware EMS algorithm

Step	Rolling-horizon operation
1	Acquire SOC and the next H samples of PV, load, and tariff
2	Build the linear objective and constraints (1)–(4)
3	Solve the linear program and check feasibility
4	Apply only the first charge/discharge set-point
5	Update SOC using (2), advance one interval, and repeat

IV. SIMULATION RESULTS

A. Energy and Cost Performance

Table III. Seven-day energy and electricity-cost results

Strategy	Import (kWh)	Export (kWh)	Cost (USD)	SC (%)	SS (%)
Rule-based	1999.9	11.3	299.82	99.3	43.6
Predictive	2184.2	139.9	263.96	91.0	38.4

The simulated week has 3546.8 kWh of demand and 1557.4 kWh of PV production. The electricity bill decreases by 35.86 USD, from 299.82 to 263.96 USD, corresponding to 11.96% (approximately 12.0%). This meets the study's electricity-cost objective under the specified tariff and perfect forecasts. The mechanism is consistent with predictive scheduling [5], [6]: stored energy can be reserved for the high-price evening period, and low-price imports can charge the battery before future demand. The aggregate results support an economic advantage for this case, but do not establish a universal saving across tariffs or sites. Import rises by 184.3 kWh (9.22%), while export increases by 128.6 kWh, from 11.3 to 139.9 kWh. SC falls from 99.3% to 91.0% and SS from 43.6% to 38.4%. Cost minimization therefore does not achieve higher energy autonomy in this experiment. With limited storage capacity and charge power, a tariff-oriented schedule can leave less room for later PV surplus or reserve energy instead of immediately serving a deficit. The results identify this trade-off, although interval-level source tracing would be needed to allocate every export and battery flow to PV or grid energy [8].

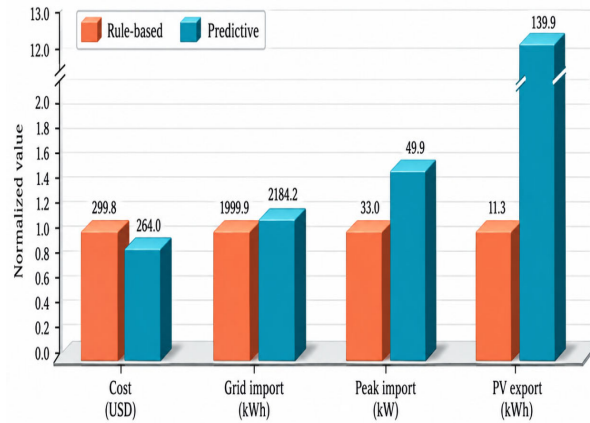


Fig. 3. Performance comparison for the rule-based and predictive strategies; labels show the reported physical values.

B. State-of-Charge and Peak Behavior

Both reported SOC trajectories remain within 15–90%, using the same full operating range. Figure 4 illustrates their different timing over two representative days. The predictive controller changes when energy is charged or released because it anticipates net load and tariff transitions, whereas the baseline reacts to the current deficit or surplus [6]. Identical SOC extrema do not imply identical battery utilization. Bounds on the aggregate trajectories support the feasibility claim at the scheduling level; they do not demonstrate local converter or electrochemical safety [4].

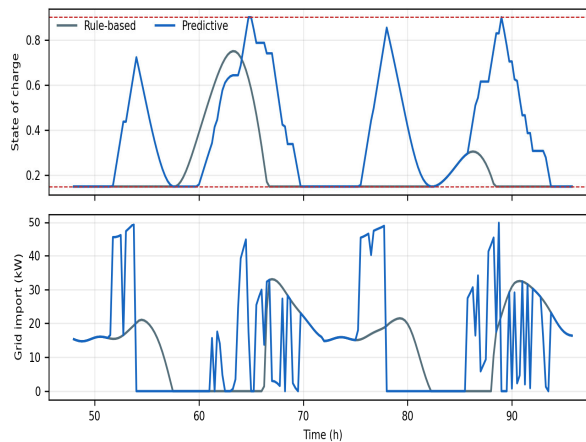


Fig. 4. SOC and grid-import trajectories for the two energy-management strategies.

Peak import increases from 33.0 to 49.9 kW, a rise of 16.9 kW (51.21%). Thus, peak shaving is not achieved by the proposed base-case objective. The larger peak is compatible with scheduled grid charging in addition to local demand. Equation (4) prices imported energy but contains no peak penalty or grid-capacity constraint. An import cap or a linear epigraph variable for maximum import could address this service, but its effects on cost and feasibility require a separate simulation [6], [8].

C. Battery Utilization and Interpretation

Equivalent AC battery throughput rises from 382.3 to 925.8 kWh, an increase of 142.17%. For the stated penalty, the implied cycling charges are 9.18 USD and 22.22 USD, respectively. The augmented weekly costs are consequently 309.00 USD and 286.18 USD; their difference is 22.82 USD, or 7.38%, calculated from the rounded reported results. The predictive strategy remains favorable under this proxy, but its gain is smaller than the 11.96% electricity-bill reduction. Actual battery aging also depends on temperature, SOC, depth of discharge, and operating history [14], so these penalty charges cannot be interpreted as validated replacement costs.

An aggregate energy check provides additional context. Import plus PV minus export and demand equals approximately -0.8 kWh for the baseline and 54.9 kWh for the predictive controller. Given the common 40-kWh fall in stored energy, equation (2) implies battery conversion losses of approximately 39.2 and 94.9 kWh, respectively. These values are derived accounting checks, not additional simulations. Their increase is consistent with the higher throughput and 90.25% round-trip efficiency, which supports the interpretation that additional cycling contributes to the larger total import [6].

The objectives are therefore met to different extents. Electricity-cost reduction and the reported SOC limits are achieved. The case also quantifies the influence of the forecast horizon and exposes battery-use trade-offs. Improved autonomy and lower peak import are not achieved. Independent numerical reproducibility remains conditional on releasing the complete input series or generator and implementation settings. A transparent benchmark matters precisely because it makes these distinctions testable [5], [8].

V. SENSITIVITY AND IMPLEMENTATION DISCUSSION

A. Prediction-Horizon Sensitivity

Table IV. Sensitivity to prediction-horizon length

Steps	Hours	Cost (USD)	Import (kWh)	Peak (kW)	Throughput (kWh)
1	0.25	353.46	2362.5	33.0	19.0
4	1.00	341.45	2360.3	49.9	169.0
12	3.00	293.48	2304.0	49.9	663.3
24	6.00	263.96	2184.2	49.9	925.8
48	12.00	252.82	2038.3	49.4	756.4

The horizon study shows the value of anticipation under perfect forecasts [5], [6]. At one step (15 min), the predictive formulation costs 353.46 USD, exceeding the rule-based bill by 17.89%; with only the current interval visible and a cycling penalty, it uses little storage (19.0 kWh equivalent throughput). Four steps still cost 341.45 USD, 13.88% above the baseline. Twelve steps reduce cost to 293.48 USD, only 2.12% below the baseline. The six-hour horizon reaches 263.96 USD. Optimization alone is therefore insufficient: the prediction window must expose useful future price and net-load conditions.

Extending the horizon from six to twelve hours lowers the bill by a further 11.14 USD (4.22%), to 252.82 USD, while throughput falls from 925.8 to 756.4 kWh (18.30%). Better

foresight can therefore improve timing without necessarily increasing battery use. Peak import nevertheless remains high at 49.4 kW. Six hours is retained as the comparison base case, but the supplied deterministic results do not establish it as the optimal practical compromise. Selecting a field horizon requires forecast-error tests and measured solve times; neither is available here [6].

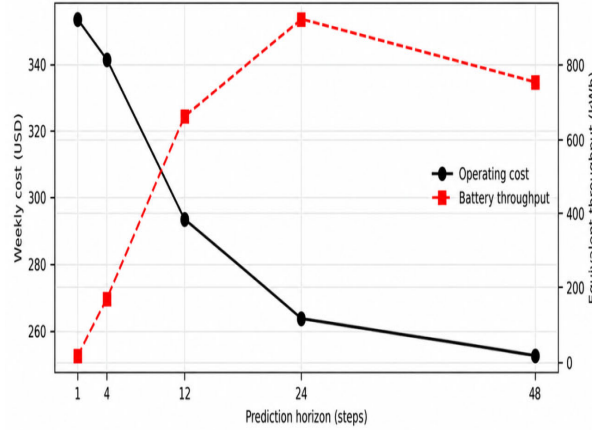


Fig. 5. Prediction-horizon effects on electricity cost and equivalent battery throughput.

B. Computational and Control-Layer Considerations

The supervisory architecture can accommodate forecast uncertainty through robust uncertainty sets or scenario-based scheduling. Robust rolling-horizon microgrid optimization has been investigated explicitly in the literature [15]. Linear import bounds, flexible-load variables, and a maximum-import epigraph can extend the present model. Reactive-power capability, AC network voltages, and converter dynamics require an expanded network model and coordination with local controls [4]. These are proposed extensions rather than results of this experiment. Ensemble nonlinear MPC offers another approach to uncertain residential PV–battery scheduling [9], although it is more complex than the linear deterministic benchmark used here.

A formulation that eliminates SOC states by cumulative substitution has four nonnegative flow variables per prediction step (charge, discharge, import, export), hence 96 continuous variables at $H = 24$. Retaining explicit future SOC states adds 24 variables. This distinction should be stated when reporting problem size. The LP is small, but no execution-time measurements are provided; real-time suitability must be verified on the target hardware using documented solver settings [13]. Forecast-quality checks, state validation, and a feasible rule-based fallback should accompany deployment.

Setpoints should be checked against local converter and BMS limits, time-stamped, and rejected when stale. Ramp limits should be imposed if required by the equipment. The local BMS retains authority over current, voltage, temperature, and battery protection. An infeasible or failed solve should trigger the baseline policy and a diagnostic event rather than silently relax physical constraints. This division of authority follows the separation between supervisory management and local regulation [4].

C. Economic Interpretation

The numerical gain is an operating comparison for one tariff. It does not establish a favorable investment return because capital and replacement costs, auxiliary consumption, taxes, and demand charges are excluded. The throughput term is a transparent scheduling proxy; a planning study should couple the EMS to a battery-aging model validated for the relevant chemistry and operating conditions [14]. Using both electricity cost and augmented cost avoids conflating a bill reduction with lifetime economic benefit. Recent PV–battery

market studies similarly account for degradation, energy losses, and contracted-power penalties when evaluating economic operation [10].

Higher total imports alongside a lower bill are consistent with time-of-use arbitrage: inexpensive purchases can replace costly later imports despite round-trip losses. For the present case, that choice also lowers the import-based autonomy indicator and increases peak demand. Cost, autonomy, peak power, and throughput should therefore be assessed jointly, as EMS and sizing objectives are coupled [8]. A different tariff or explicit peak constraint may change the ranking, so annual or site-wide savings cannot be inferred from the synthetic week.

VI. LIMITATIONS AND VALIDITY

The numerical findings apply to a synthetic seven-day scenario with perfect within-horizon forecasts. Real forecasting errors change charging opportunities and reserve decisions; robust scheduling offers a relevant comparison for future work [15]. The battery has one energy state, fixed efficiency, and a linear throughput penalty. The model excludes thermal behavior, aging feedback, AC network constraints, reactive power, converter transients, and protection coordination. These limitations prevent claims about field reliability, battery lifetime, or hardware stability [4], [14].

Reproducibility is important for this 42-kW PV/100-kWh battery case because controller comparisons are sensitive to the input profiles, initial and terminal energy, tariff timing, horizon, and cost definition [5], [6]. A shared executable benchmark would allow others to distinguish forecast value from changed constraints or favorable initial energy. The EMS equations, parameter table, cloud factors, seed, and summary results establish a comparison protocol, but do not by themselves reconstruct the exact 672 input samples. Complete profile formulas or the original data, solver settings, and code are required before independent numerical agreement can be claimed. Summary accounting checks cannot substitute for rerunning the simulation.

VII. CONCLUSION

For the stated synthetic week, forecast-aware scheduling lowers the electricity bill by 11.96% relative to the self-consumption baseline and respects the reported 15–90% SOC limits. Including the stated throughput penalty gives a 7.38% saving in the augmented cost. The economic gain accompanies higher imports, higher peak demand, lower accounting-based autonomy, and greater battery use. The study therefore supports the value of anticipation for tariff-oriented scheduling [5], [6], while identifying objectives that require additional constraints or penalties. The schematic and reproduction protocol provide a basis for a common benchmark; exact replication requires the complete profiles and executable implementation. Future work should test measured forecasts, peak constraints, a validated aging model [14], and hardware behavior before deployment.

APPENDIX REPRODUCTION PROTOCOL

Use 672 intervals at $\Delta t = 0.25$ h, $E_b = 100$ kWh, initial SOC = 0.55, the bounds in Table I, and the tariff periods in Section III. Release the exact PV and demand series or their full generation equations, including weekend indexing, periodic terms, clipping, and any random-number procedure associated with seed 26. Run the same data through both controllers. At each step, solve (4) for the next $\min(H, 672 - k)$ samples, apply the first action, and update (2). Archive the four flow series, SOC trajectory, solver status, objective value, and physical residuals. Record software versions, solver method, tolerances, and any fallback actions [13]. Check the power balance, SOC evolution, converter bounds, opposing simultaneous flows, and initial and final stored energy. Calculate the electricity bill separately from the augmented cost and report SC, SS, peak import, and equivalent AC throughput using the

definitions in Section III. Compare horizon lengths of 1, 4, 12, 24, and 48 steps. Input identity must be verified before interpreting differences as solver effects. Numerical tolerances may be agreed after code and data are released; no fixed 0.1-kWh or 0.01-USD replication guarantee can be made from an incomplete profile specification [6], [13].

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Agroclimatic Assessment Of Compound Hot-Dry Conditions During The Growing Season In Çanakkale, Türkiye

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Abstract: Compound hot-dry conditions can create agricultural impacts that are not adequately represented by temperature or precipitation considered separately, particularly in Mediterranean environments where crop development and irrigation demand coincide with the warm and dry season. This study quantified the co-occurrence, temporal distribution, and recent-period amplification of compound hot-dry conditions in Çanakkale, northwestern Türkiye, using monthly observations from Turkish State Meteorological Service station 17112 for 1929-2025. The April-October agricultural season was evaluated. For each calendar month, a hot condition was defined as monthly maximum temperature (T_{max}) at or above its long-term 90th percentile (P_{90}), while a dry condition was defined as monthly precipitation at or below its 20th percentile (P_{20}); compound months satisfied both criteria simultaneously. Only observed T_{max} -precipitation pairs were classified, and missing precipitation was never interpreted as zero. Across 601 valid agricultural-season months, 23 compound events were detected. Their frequency increased from 2.25% in 1929-1995 to 6.97% in 1996-2025, corresponding to a risk ratio of 3.10 (95% CI: 1.36-7.03; Fisher $p = 0.0064$). An equal-length comparison produced the same conclusion: 2.09% in 1966-1995 versus 6.97% in 1996-2025 ($RR = 3.33$, $p = 0.0281$). Observed co-occurrence over the full record was 1.57 times the frequency expected if hot and dry conditions were independent ($p = 0.0124$). The four-class agroclimatic composition (neither, hot only, dry only, compound) also differed between the historical and recent periods (chi-square = 16.47, $p = 0.0009$). The latest 20-year window (2006-2025) reached a compound-event frequency of 9.29%. A fixed 1961-1990 threshold sensitivity analysis similarly showed a rise from 4.25% to 11.94% ($RR = 2.81$, $p < 0.001$). These results indicate a robust recent amplification of simultaneous heat and precipitation deficiency and support compound-event screening as a complementary tool for agricultural climate-risk and irrigation planning.

Keywords: Compound Events, Agroclimatology, Heat Stress, Precipitation Deficit, Mediterranean Climate, Irrigation Planning

I. INTRODUCTION

Agricultural climate risk is frequently produced by combinations of meteorological drivers rather than by isolated extremes. Compound weather and climate events describe situations in which multiple hazards or drivers occur simultaneously, sequentially, or in spatially connected regions and jointly increase the probability or severity of impacts [1]-[4]. Compound hot-dry conditions are a particularly relevant multivariate hazard because high temperature can enhance atmospheric evaporative demand and crop water loss at the same

time that low precipitation limits natural water supply. Such interactions can create impacts that are not captured when heat and water availability are monitored independently [3], [8].

Evidence from multiple regions shows that concurrent heat and drought have become an increasingly important component of climate risk. In the United States, the concurrence of drought and heatwaves increased markedly during the twentieth century [5]. Across the Mediterranean Basin, compound warm spells and droughts increased during 1979-2018, with warming identified as a major driver of the change [6]. Compound warm-dry events are also a recognized feature of Mediterranean climate variability [7], and recent European-scale work identifies the Mediterranean and western Türkiye among the principal hotspots of compound hot-dry risk [9]. These findings are especially important for agriculture because heat and moisture extremes interact through crop physiology, soil-plant-atmosphere processes, and management responses [8].

Çanakkale, located in northwestern Türkiye, experiences a Mediterranean-influenced climate characterized by cool and relatively wet winters and warm, dry summers. Agricultural production from late spring through early autumn therefore occurs during the period in which high thermal load and limited rainfall can overlap. Previous analyses of the same station record have demonstrated strong recent warming and substantial seasonal water constraints; however, conventional single-variable analyses do not directly quantify the joint occurrence of unusual heat and unusual rainfall deficiency. A compound-event framework can add this missing dimension without requiring the assumption that each driver acts independently.

The objective of this study was to characterize compound hot-dry conditions during the April-October agricultural season in Çanakkale using a 97-year monthly station record. The study addressed four questions: (i) how frequently do locally unusual hot and dry conditions co-occur; (ii) is their recent-period frequency different from the historical record; (iii) is the observed co-occurrence greater than expected under independence; and (iv) are the conclusions robust to equal-length period comparison and an alternative fixed climatological reference period? The analysis deliberately emphasizes event co-occurrence, relative risk, moving-window behavior, and sensitivity analysis rather than repeating monotonic trend tests used in previous work.

II. MATERIALS AND METHODS

A. Data and quality control

Monthly maximum temperature ($T_{\max}$), minimum temperature ($T_{\min}$), mean temperature, and total precipitation observations from Turkish State Meteorological Service station 17112 in Çanakkale were used for 1929-2025. Annual summary rows (month code 13) were excluded. The precipitation series was assembled by prioritizing the manual station record and using the automatic-station observation only where the manual value was unavailable. Genuine observed 0.0 mm precipitation values were retained. Months with no observed precipitation in either source remained missing and were not converted to zero. This decision is important for compound-event analysis because assigning zero to an unobserved month would artificially create dry events. Diurnal temperature range (DTR) was calculated as $T_{\max}$ minus $T_{\min}$.

The final event classification used only months for which both $T_{\max}$ and precipitation were observed. This produced 601 valid April-October month pairs over the study period. Sample sizes therefore vary by calendar month, with 94 valid pairs in April and May and fewer observations in the historically drier summer months where early precipitation records were less complete. All frequency calculations explicitly use the number of valid observed pairs as the denominator.

B. Compound hot-dry definition

To remove the dominant seasonal cycle, thresholds were estimated separately for each calendar month over the full 1929-2025 record. A month was considered hot when $T_{\max}$ was

at or above the 90th percentile (P90) of Tmax for that calendar month. A month was considered dry when total precipitation was at or below the 20th percentile (P20) for that calendar month. The use of percentile-based thresholds is consistent with compound-event frameworks that define anomalies relative to local climatology [2], [4], [9]. Because this study uses monthly rather than daily data, the identified events should be interpreted as monthly agroclimatic anomalies rather than short-duration heatwave-drought episodes.

$$Hot_m = 1 [Tmax_m \geq P90_m] \quad (1)$$

$$Dry_m = 1 [P_m \leq P20_m] \quad (2)$$

$$Compound_m = Hot_m \times Dry_m \quad (3)$$

where m denotes a specific calendar month, P is monthly precipitation, and the indicator function equals 1 when the condition is satisfied. The main agricultural analysis window was April-October, which spans late spring, summer, and early autumn crop-water-management conditions in the study area. Each valid month was additionally assigned to one of four mutually exclusive classes: neither extreme, hot only, dry only, or compound hot-dry.

C. Period comparison, dependence, and sensitivity analyses

The primary comparison contrasted 1996-2025 with the preceding historical record, 1929-1995. Event/non-event proportions were compared with Fisher's exact test, and risk ratios (RR) with 95% confidence intervals were calculated. Because the historical interval is longer, an equal-length sensitivity analysis compared 1966-1995 with 1996-2025. The full four-class stress composition was compared between historical and recent periods with a chi-square test and summarized with Cramer's V.

To evaluate whether hot and dry conditions co-occurred more often than expected under statistical independence, the expected compound frequency was calculated as the product of the marginal hot and dry frequencies. A 2 x 2 contingency table of hot/non-hot and dry/non-dry conditions was evaluated with Fisher's exact test. A 20-year moving compound frequency was also calculated to visualize multidecadal changes in event prevalence without fitting a monotonic trend model. Windows were retained when at least 70% of the nominal 140 April-October months had valid pairs.

Robustness to threshold-reference choice was examined by fixing monthly P90 Tmax and P20 precipitation thresholds to the 1961-1990 climatological period and reclassifying the complete record. This sensitivity analysis tests whether the recent-period contrast persists when thresholds are not estimated from the full record, which contains the recent warm decades. Meteorological characteristics of compound and non-compound months were compared descriptively and with the Mann-Whitney U test.

Table I. Calendar-month thresholds and compound-event frequency during April-October.

Month	Valid n	Tmax P90 (°C)	Rain P20 (mm)	Compound n	Compound (%)
Apr	94	26.58	19.06	5	5.32
May	94	31.80	8.72	5	5.32
Jun	90	35.97	4.74	2	2.22
Jul	75	38.00	0.60	4	5.33
Aug	70	37.20	0.10	4	5.71
Sep	87	34.28	2.88	1	1.15
Oct	91	29.25	18.00	2	2.20

III. RESULTS

A. Event frequency and hot-dry dependence

Across April-October, 23 compound hot-dry months were detected among 601 valid observed Tmax-precipitation pairs, corresponding to an overall occurrence of 3.83%. Monthly compound frequency ranged from 1.15% in September to 5.71% in August (Table I). The P20 rainfall thresholds were especially low in midsummer (0.60 mm in July and 0.10 mm in August), so a midsummer compound classification represents the concurrence of very high monthly Tmax with rainfall at the extreme low end of an already dry seasonal distribution.

The joint behavior of the two drivers was not equivalent to simple chance overlap. Across the full agricultural-season record, 70 valid months met the hot criterion and 126 met the dry criterion. If the two conditions were independent, their marginal frequencies imply an expected compound occurrence of 2.44%; the observed occurrence was 3.83%, an enhancement factor of 1.57. The hot-dry contingency table produced an odds ratio of 2.03 and Fisher's exact $p = 0.0124$ (chi-square $p = 0.0093$). The strongest calendar-month enhancement was observed in April, where compound occurrence was 2.47 times the independence expectation. Month-specific tests were treated as exploratory because event counts were small.

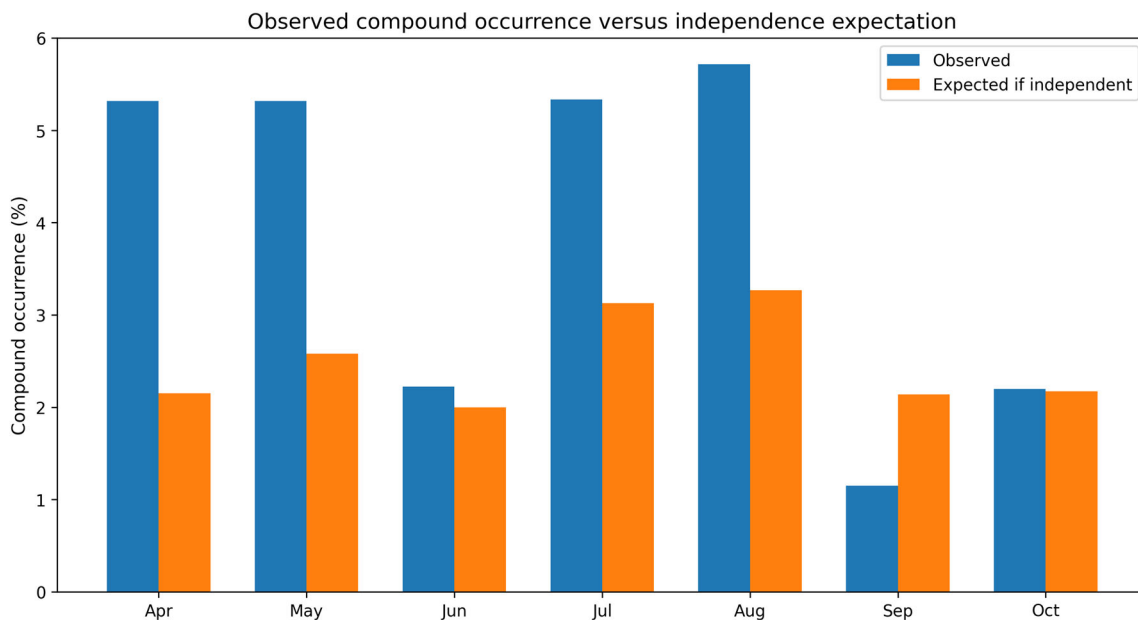


Fig. 1. Observed compound hot-dry occurrence by calendar month compared with the frequency expected if hot and dry conditions were statistically independent.

B. Historical-to-recent amplification

The clearest change was the contrast between the recent 30-year period and the preceding historical record. During 1929-1995, 9 compound events occurred among 400 valid agricultural-season months (2.25%). During 1996-2025, 14 events occurred among 201 valid months (6.97%). The recent-period risk was therefore 3.10 times the historical rate (95% CI: 1.36-7.03), and Fisher's exact test indicated a significant difference ($p = 0.0064$). Fourteen of the 23 total events occurred after 1995 even though the recent period represented only about one-third of the valid observations.

The equal-length sensitivity analysis supported the same interpretation. In 1966-1995, 4 compound events occurred among 191 valid months (2.09%), compared with 14 among 201 valid months (6.97%) during 1996-2025. The corresponding RR was 3.33 (95% CI: 1.11-9.93; $p = 0.0281$). Month-level changes were particularly conspicuous in June and July: no compound months were detected in the historical comparison period for either month, whereas the recent period contained two June events and four July events. Because of zero

and small cell counts, these monthly contrasts are presented as descriptive evidence rather than independent confirmatory tests.

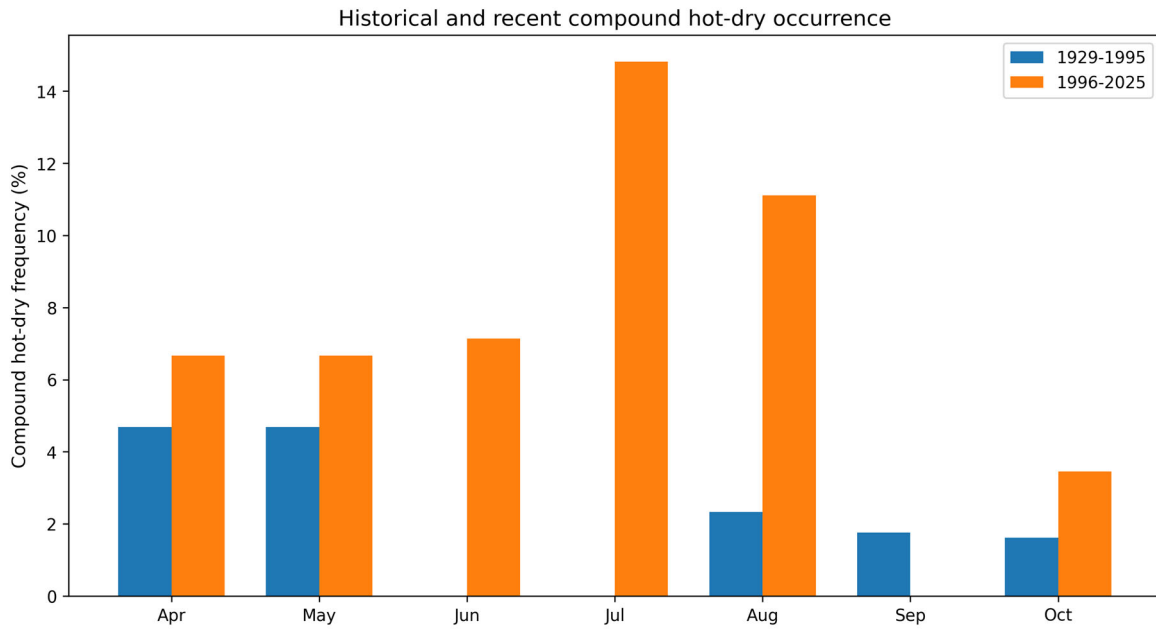


Fig. 2. Calendar-month compound hot-dry frequency in the historical record (1929-1995) and the recent period (1996-2025). Frequencies use only months with observed Tmax and precipitation.

Table II. Primary and sensitivity comparisons of compound hot-dry occurrence.

Analysis	Period 1	Events/N	%	Period 2	Events/N	%	RR (95% CI)	Fisher p
Historical vs recent	1929-1995	9/400	2.25	1996-2025	14/201	6.97	3.10 (1.36-7.03)	0.0064
Equal 30-year sensitivity	1966-1995	4/191	2.09	1996-2025	14/201	6.97	3.33 (1.11-9.93)	0.0281
1961-1990 fixed thresholds	1929-1995	17/400	4.25	1996-2025	24/201	11.94	2.81 (1.55-5.11)	0.0009

C. Temporal clustering and moving-window behavior

The event chronology further shows that compound months became increasingly concentrated in the recent portion of the record. Historical events were sparse and separated by long intervals, whereas the post-2000 period contains repeated clusters, including July-August 2007, August 2021, June-July 2024, and June-July 2025. The year-month heatmap highlights this transition and also shows that recent events span multiple parts of the agricultural season rather than being confined to a single calendar month.

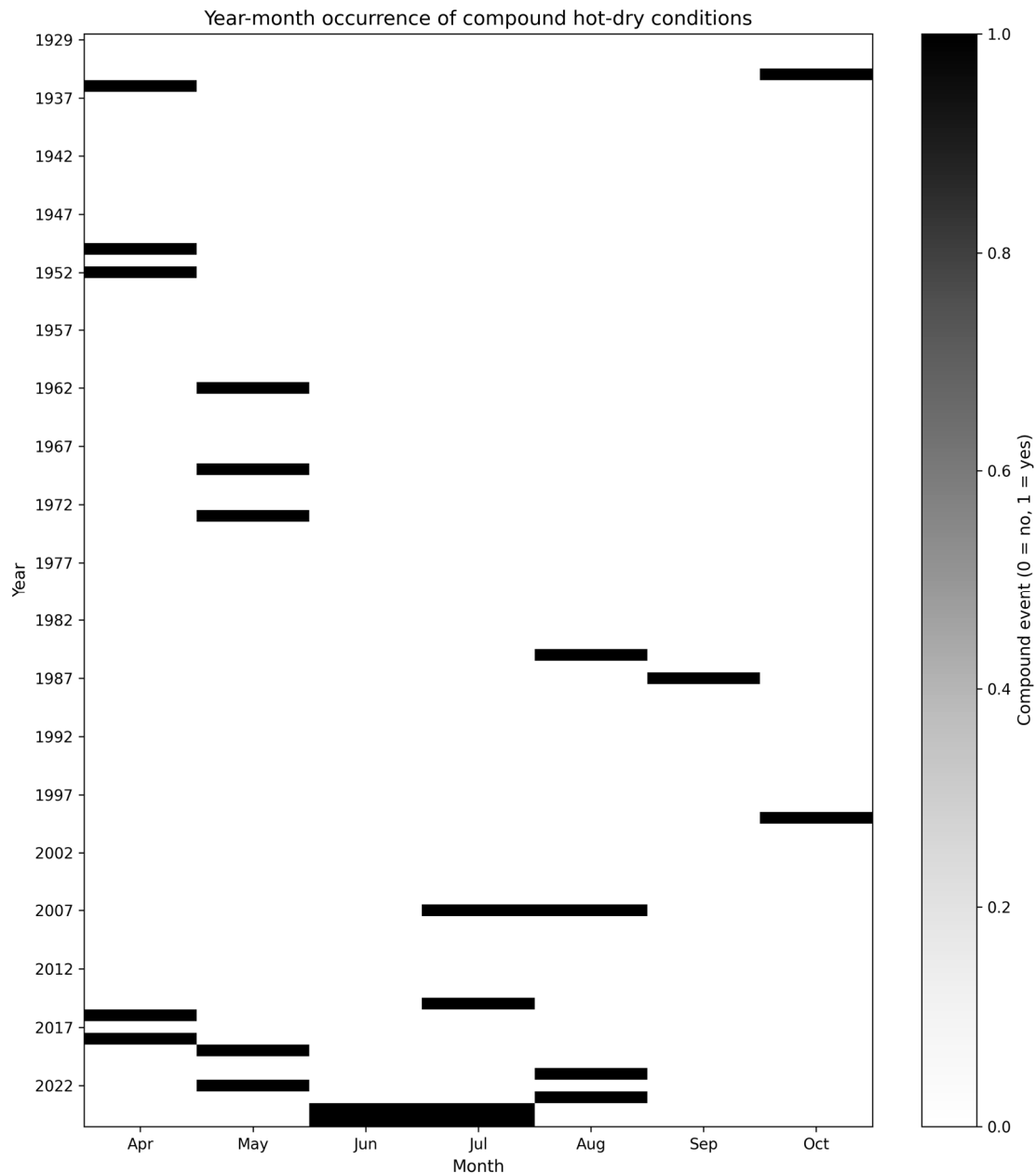


Fig. 3. Year-month occurrence of compound hot-dry conditions during April-October. Black cells indicate detected compound events; blank cells represent non-compound valid months or missing observations as masked in the plotted matrix.

The 20-year moving frequency remained mostly between approximately 1.5% and 3.3% through much of the twentieth century, but rose sharply in the most recent windows. The 2006-2025 window contained 13 compound events among 140 valid observations, yielding a frequency of 9.29%. For comparison, the earliest retained window (1929-1948) had a frequency of 1.94%. This moving-window diagnostic is descriptive rather than a formal trend test, but it illustrates the increasing concentration of events in the recent record.

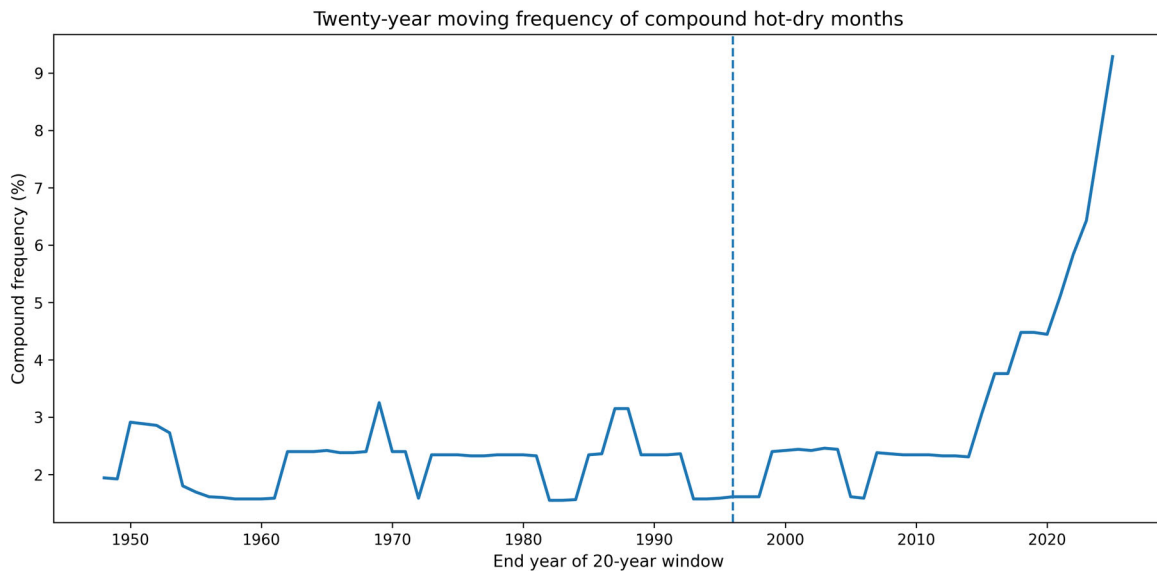


Fig. 4. Twenty-year moving frequency of compound hot-dry months. The dashed vertical line marks 1996, the start of the recent comparison period.

D. Shift in agroclimatic stress composition and event intensity

The recent period was characterized by a broader redistribution of agroclimatic stress classes, not only by an increase in the compound category. In 1929-1995, 75.50% of valid months were classified as neither hot nor dry, 6.00% as hot only, 16.25% as dry only, and 2.25% as compound. In 1996-2025, the neither category decreased to 62.69%, while hot-only months increased to 11.44%, dry-only months to 18.91%, and compound months to 6.97%. The four-class distribution differed significantly between periods (chi-square = 16.47, df = 3, $p = 0.0009$; Cramer's $V = 0.166$), indicating a small-to-moderate restructuring of warm-season agroclimatic conditions.

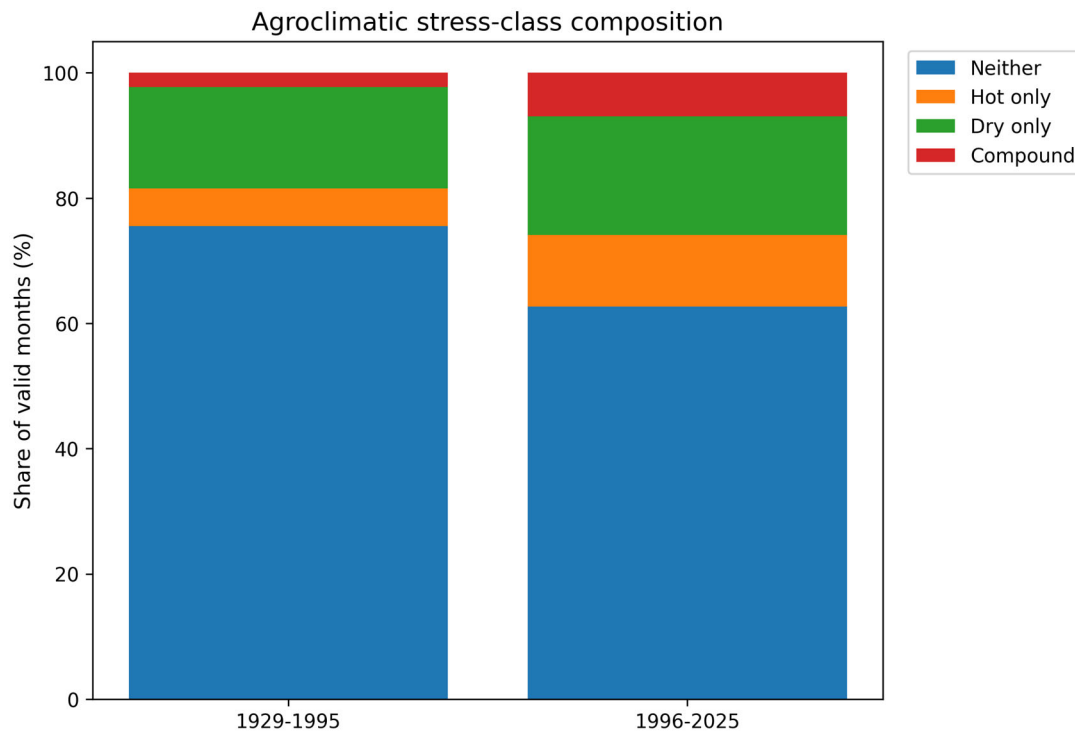


Fig. 5. Composition of valid April-October months classified as neither, hot only, dry only, or compound hot-dry in the historical and recent periods.

Compound months also had a distinct meteorological signature (Table III). Mean Tmax was 34.18 °C during compound months compared with 30.08 °C during other valid agricultural-season months ($p < 0.001$). Mean DTR was 22.51 °C versus 20.67 °C ($p = 0.0069$). Mean precipitation was only 4.26 mm during compound months compared with 31.01 mm otherwise ($p < 0.001$). Differences in Tmin and mean temperature were not statistically significant at the 0.05 level, suggesting that the classification primarily isolates unusually high daytime maxima occurring together with very low rainfall.

Table III. Meteorological characteristics of compound and non-compound April-October months.

Variable	Compound n	Compound mean	Other n	Other mean	Difference	Mann-Whitney p
Tmax (°C)	23	34.18	578	30.08	4.11	<0.001
Tmin (°C)	23	11.67	578	9.40	2.27	0.0983
Tmean (°C)	23	21.48	574	19.61	1.86	0.0815
DTR (°C)	23	22.51	578	20.67	1.84	0.0069
Precipitation (mm)	23	4.26	578	31.01	-26.75	<0.001

Event intensity varied substantially. Some recent midsummer events had precipitation essentially at zero with only modest exceedance above the monthly Tmax P90, while several spring events combined larger rainfall deficits with stronger thermal exceedance. July 2025 reached 40.5 °C with 0.0 mm precipitation; June 2025 reached 37.7 °C with 0.0 mm precipitation. The two-dimensional intensity view therefore adds information that is lost when all compound months are treated as equally severe.

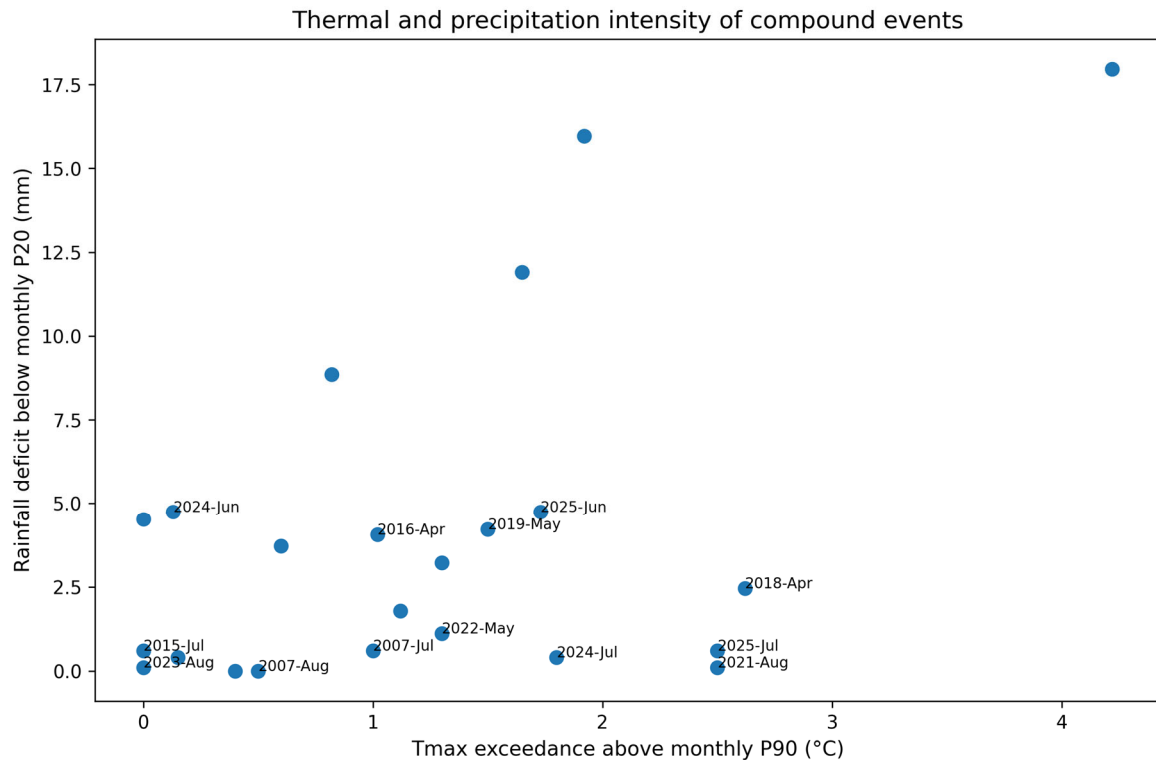


Fig. 6. Thermal exceedance above the monthly Tmax P90 threshold versus precipitation deficit below the monthly P20 threshold for detected compound events. Recent events are labeled where space permits.

E. Sensitivity to the percentile-reference period

The recent-period amplification was not an artifact of estimating percentile thresholds from the full record. When monthly thresholds were fixed to the 1961-1990 reference climate, compound frequency was 4.25% in 1929-1995 and 11.94% in 1996-2025. The recent-period risk remained 2.81 times higher (95% CI: 1.55-5.11; Fisher $p = 0.0009$). The absolute frequencies are higher under the fixed baseline because recent warming shifts more months above a historical $T_{\max}$ P90 threshold, but the direction and statistical strength of the period contrast remain consistent with the primary full-record threshold analysis.

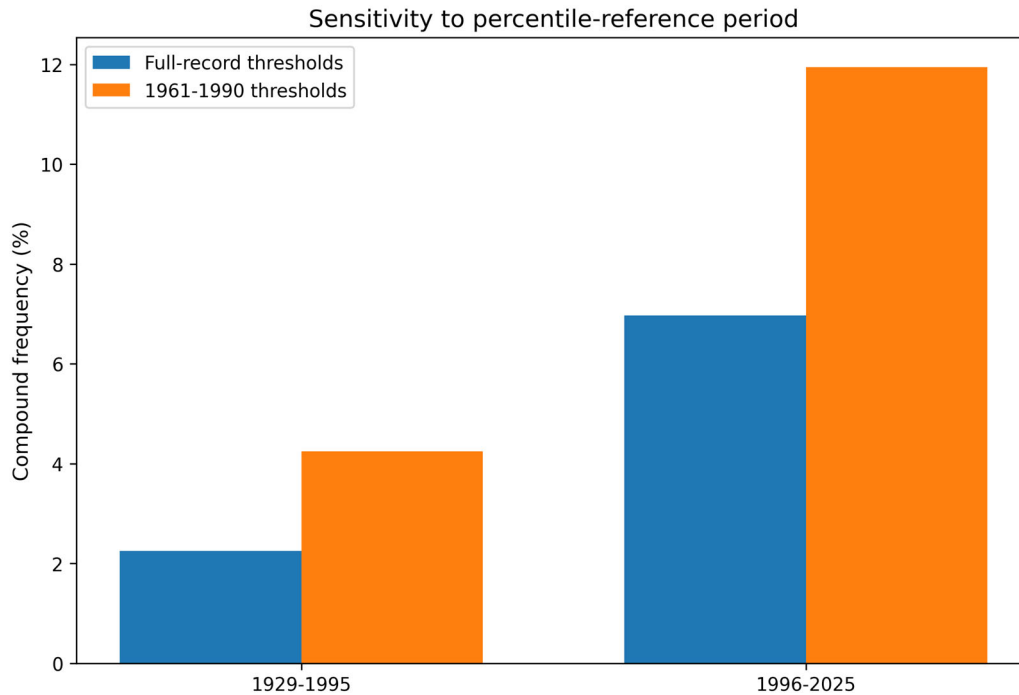


Fig. 7. Sensitivity of historical and recent compound-event frequency to threshold reference. Full-record thresholds use 1929-2025; the alternative analysis fixes monthly thresholds to 1961-1990.

IV. DISCUSSION

The analysis provides several independent lines of evidence that compound heat and precipitation deficiency have become more prominent in the recent climate record of Çanakkale. The primary period comparison indicates a threefold increase in risk, the equal-length 30-year comparison yields a similar RR, the fixed 1961-1990 threshold analysis also shows a strong recent-period increase, and the 20-year moving frequency rises sharply in the latest windows. Agreement among these diagnostics is important because each addresses a different potential source of methodological sensitivity: unequal period length, threshold nonstationarity, and dependence on a single binary comparison.

The results are directionally consistent with the broader compound-event literature. Zscheischler et al. [1], [2] and AghaKouchak et al. [3] emphasize that multivariate extremes require joint analysis because marginal behavior alone can underestimate risk. Global hotspot analysis also identifies compound hazards as geographically structured rather than random combinations of independent drivers [4]. For the Mediterranean, Vogel et al. [6] reported increasing compound warm spells and droughts, and De Luca et al. [7] demonstrated the importance of warm-dry event dependence in the basin. More recent European evidence similarly identifies the Mediterranean and western Türkiye as areas of elevated and intensifying compound hot-dry risk [9].

The independence analysis is particularly informative for the present study. The observed full-record compound frequency was 1.57 times the marginal expectation under

independence. This indicates that high Tmax and low precipitation do not simply overlap at the rate expected from their separate frequencies. Physical mechanisms that can promote such dependence include persistent anticyclonic circulation, reduced cloudiness, soil-moisture limitation, and land-atmosphere feedbacks that enhance sensible heating during dry conditions [3], [7]. The monthly station data used here cannot attribute events to those mechanisms, but the significant positive association supports treating the hazard as a joint process rather than as two unrelated extremes.

Agriculturally, the shift in stress-class composition is as relevant as the change in the compound category itself. The proportion of neither-hot-nor-dry months decreased by nearly 13 percentage points, while hot-only and compound classes both expanded. Such changes can affect crop development through several pathways: high daytime temperatures increase canopy and atmospheric demand, rainfall deficits reduce direct soil-water replenishment, and the concurrence of both stresses can restrict physiological recovery and increase irrigation sensitivity. Reviews of crop responses indicate that compound heat-moisture extremes can produce yield effects that differ from the sum of single-stress responses, which motivates multi-stress adaptation rather than separate heat and drought management [8].

The monthly resolution also defines the scope of inference. A month classified as compound hot-dry is not equivalent to a meteorological heatwave or a daily drought episode; it represents a monthly-scale agroclimatic state. Short hot spells embedded in otherwise moderate months can therefore be missed, and a monthly rainfall total does not describe event timing or soil infiltration. Conversely, monthly screening is useful for long historical station records because it provides a stable, transparent framework that can be applied when daily data are incomplete. The method is therefore best viewed as a first-level agricultural climate-risk indicator rather than a crop-damage model.

Data completeness is another limitation. Historical precipitation observations are less complete than recent observations, particularly in summer, so frequency denominators differ among months and periods. This was handled by retaining only observed Tmax-precipitation pairs, explicitly reporting sample sizes, and avoiding any conversion of missing precipitation to zero. The equal 30-year comparison and fixed-baseline sensitivity analysis further reduce concern that the main conclusion is produced by historical record length or threshold construction. Nevertheless, future work should repeat the analysis with homogenized daily observations, soil-moisture or evapotranspiration indicators, crop-specific heat thresholds, and additional stations across northwestern Türkiye.

V. CONCLUSION

Using a 97-year monthly station record, this study identified 23 compound hot-dry months during the April-October agricultural season in Çanakkale. The primary event frequency increased from 2.25% in 1929-1995 to 6.97% in 1996-2025, corresponding to a recent-period RR of 3.10 ($p = 0.0064$). An equal-length 30-year comparison produced a comparable RR of 3.33, while a fixed 1961-1990 threshold analysis yielded an RR of 2.81 ($p < 0.001$). Observed compound occurrence was 1.57 times the frequency expected under independence, and the overall four-class agroclimatic composition shifted significantly toward greater hot and compound exposure. The latest 20-year window reached a compound-event frequency of 9.29%.

These convergent results show that the recent climate record contains a substantially greater share of agricultural-season months in which exceptional daytime heat and precipitation deficiency coincide. The framework does not quantify crop yield loss or irrigation requirement directly, but it identifies climatic situations in which agricultural water-management stress is more likely. Integrating compound-event screening with crop calendars, soil-water observations, and irrigation scheduling could therefore improve local climate-risk assessment and support adaptation planning in Mediterranean agricultural systems.

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Impact of Different Observation Weighting Models on PPP Positioning Accuracy and Convergence Time

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Abstract: Precise Point Positioning (PPP) performance depends not only on the functional model and the accuracy of precise products, but also on the appropriate stochastic modeling of GNSS observations. In particular, observations at low elevation angles may be more affected by multipath, atmospheric effects, and unmodeled residual errors. Therefore, elevation-dependent weighting approaches are commonly used to reduce the contribution of such observations to the solution. In this study, the effects of different observation weighting approaches on the positioning accuracy and convergence performance of GPS-based static PPP solutions were investigated. Six weighting approaches, namely Equal, Sin², Sine, Cosine, Exponential, and Sine-Piecewise, were evaluated at six IGS stations using 24 h of GPS observation data recorded at a 30 s sampling interval on day of year 001 of 2026. The same observation data, precise orbit, clock, and bias products, and PPP processing parameters were used in all solution scenarios so that the observed performance differences could primarily be attributed to the weighting approach. The solutions were evaluated in terms of 2D and 3D RMS values and 2D and 3D convergence times. The mean 2D RMS values ranged from 2.063 to 2.361 cm, while the mean 3D RMS values ranged from 3.026 to 3.328 cm. The lowest mean 2D RMS value was obtained with the Sine-Piecewise approach, whereas the lowest mean 3D RMS value was achieved with the Sine approach. Compared with equal weighting, the mean 2D RMS decreased by approximately 12.6% with the Sine-Piecewise approach, while the mean 3D RMS decreased by approximately 9.1% with the Sine approach. The shortest mean 2D convergence time was 8.25 min for both the Sin² and Sine approaches, while the shortest mean 3D convergence time was 8.33 min for the Sine approach. The Sine approach reduced the mean 3D convergence time by approximately 35.9% compared with equal weighting. The results indicate that elevation-dependent observation weighting can improve PPP positioning accuracy and convergence performance; however, the best-performing weighting approach may vary depending on the station and the evaluation metric used.

Keywords: *Precise Point Positioning (PPP), Observation Weighting, Stochastic Model, Positioning Accuracy, Convergence Time*

I. INTRODUCTION

Precise Point Positioning (PPP) is an absolute positioning technique that jointly utilizes undifferenced GNSS pseudorange and carrier-phase observations [1], [2]. Unlike conventional double-difference-based relative positioning methods, PPP enables high-accuracy positioning with a single GNSS receiver without requiring a simultaneously operating reference station. In this respect, PPP differs from Single Point Positioning (SPP), which is primarily based on code

observations, through the use of precise satellite orbit and clock products, the inclusion of carrier-phase observations in addition to code measurements, and the detailed modeling of major error sources [3].

The performance of a PPP solution depends not only on the adopted functional model and the accuracy of the precise products, but also on the appropriate characterization of the stochastic properties of the observations. Realistic modeling of observation variances directly affects the weighting of the observations in the Kalman filter and, consequently, the accuracy of the estimated parameters.

The error characteristics of GNSS observations may vary depending on the satellite elevation angle. In particular, observation quality may degrade at low elevation angles due to increased multipath effects, atmospheric influences, and unmodeled residual errors. Therefore, instead of assigning constant standard deviations to the observations, modeling the standard deviations as a function of satellite elevation angle is a commonly adopted approach in PPP applications.

Kiliszek et al. [4] investigated the effect of elevation-dependent observation weighting on GPS PPP solutions obtained using different precise orbit and clock products. Their results showed that the impact of weighting on positioning accuracy and convergence time varied depending on the precise product used. In most solutions, positioning accuracy was improved and convergence time was reduced for some products; however, a slight degradation in performance was observed for solutions based on Ultra-Rapid products. Liu et al. [5] examined the effects of four different elevation-dependent stochastic models on positioning accuracy and convergence performance in GPS/BDS PPP solutions. The study showed that the different stochastic models produced similar results in terms of positioning accuracy and precision, with differences remaining at the sub-millimeter level. In contrast, more pronounced differences were observed in convergence time and convergence stability. Among the investigated models, the stochastic model based on an exponential function was reported to provide the shortest convergence time and the highest convergence stability. Liu et al. [6] evaluated the performance of four different elevation-dependent stochastic models in real-time GPS/Galileo/BDS PPP solutions. Although the models yielded similar positioning accuracy, they had different effects on convergence time and convergence stability. Under the investigated conditions, the sine-based weighting model was found to provide shorter convergence times and more stable solutions.

Previous studies indicate that the observation weighting model can influence PPP positioning accuracy and, in particular, convergence performance. However, the performance of different weighting models may vary depending on the GNSS constellation used, the data set, the processing strategy, and the adopted evaluation criteria. In this study, the effects of different observation weighting models on GPS-based static PPP solutions were compared using the same observation data from the same stations and identical processing parameters. In this way, the analysis was designed so that the observed performance differences among the models would primarily reflect the applied weighting approach rather than changes in the data set or processing strategy. The models were evaluated in terms of 2D and 3D RMS (Root Mean Square) values and convergence times.

II. DATA AND METHODOLOGY

A. Data Set and PPP Processing Strategy

Within the scope of this study, GNSS observation data from six IGS stations selected to represent different geographical regions were used. The spatial distribution of the stations is shown in Fig. 1. The analyses were performed using 24 h of GPS observation data recorded at a 30 s sampling interval on day of year (DOY) 001 of 2026. The precise satellite orbit, clock, and bias products required for the PPP solutions were obtained from the CODE MGEX Final products for the same day. To evaluate the effects of different stochastic models on solution performance under comparable conditions, consistent processing conditions were maintained

across all stations and solution scenarios by using the same observation duration, sampling interval, and precise products.

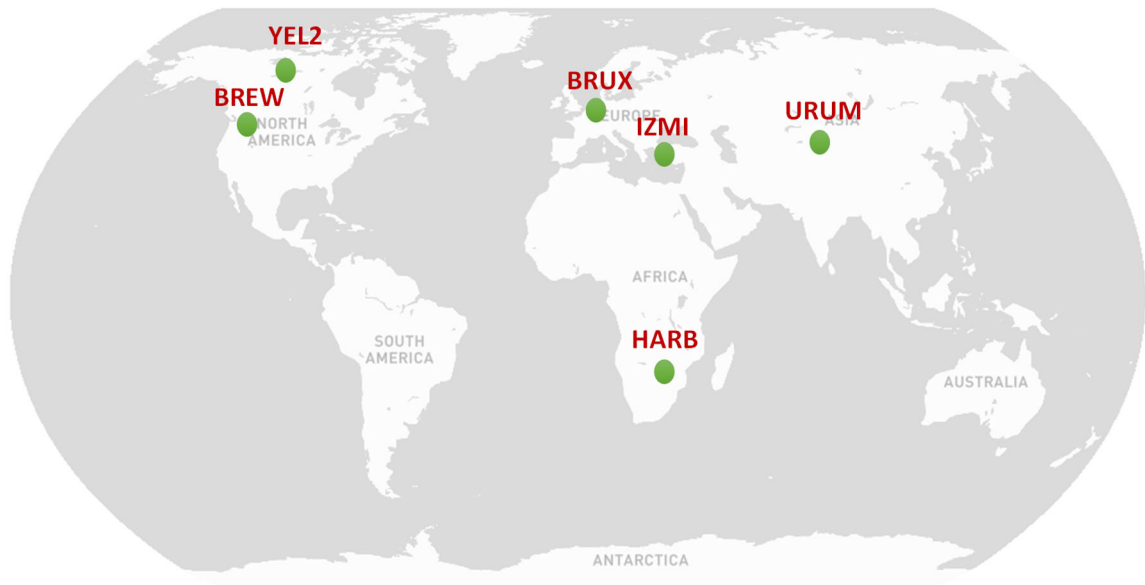


Fig. 1. Geographical distribution of the IGS stations used in the PPP analyses

To evaluate the effects of different stochastic models on PPP solution performance under comparable conditions, all data-processing strategies and modeling options other than the stochastic model were kept identical across all solution scenarios. Accordingly, the same observation duration, sampling interval, precise products, and PPP processing parameters were used for all stations. The PPP processing strategy and the main processing parameters applied to all stations are presented in Table I.

Table I. PPP processing strategy adopted in the study

Parameters	Models, Strategies and Data
Software	In-house PPP software
Processing method	Static PPP, post-processing mode
Observations	GPS dual-frequency code and carrier-phase observations
Observation combination	Dual-frequency ionosphere-free linear combination
Signal selection	Code: P1/C1, P2; Phase: L1, L2
Precise products	CODE MGEX final orbit and clock products
Estimation method	Extended Kalman Filter (EKF)
Raw observation std	Code: 0.30 m, Phase: 0.002 m
Observation weighting	Equal and five elevation-dependent weighting models (see Section II. B)
Elevation cut-off	5°
Observation interval	30 s
Troposphere	Saastamoinen ZHD, VMF3 mapping functions, GPT3 gradients
Antenna corrections	IGS ANTEX PCO/PCV corrections

Parameters	Models, Strategies and Data
Cycle slip detection	Geometry-Free and Melbourne–Wübbena combinations
Other corrections	Phase wind-up [7], relativistic effects [8], solid Earth tides, phase-code alignment, receiver clock-jump correction
Estimated state parameters	Receiver coordinates, receiver clock offset, tropospheric zenith wet delay, float carrier-phase ambiguities
Performance metrics	2D and 3D RMS , 2D and 3D convergence time (CT)

B. Observation Weighting Models

In this study, six different observation weighting models were evaluated to investigate the effect of stochastic model selection on PPP solution performance. In the investigated models, the nominal standard deviation values defined for code and carrier-phase observations were used directly in the reference model, whereas in the other models these values were scaled using different functions of the satellite elevation angle. Accordingly, the variances of the code and carrier-phase observations as a function of elevation angle were generally expressed by (1) and (2), respectively,

$$\sigma_P^2(e) = \sigma_{P,0}^2 q(e) \quad (1)$$

$$\sigma_L^2(e) = \sigma_{L,0}^2 q(e) \quad (2)$$

where $\sigma_{P,0}^2$ ve $\sigma_{L,0}^2$, denote the nominal standard deviations assigned to the code and carrier-phase observations, respectively, (e) is the satellite elevation angle, and $q(e)$ represents the variance scaling function of the corresponding model. The nominal standard deviations were set to 0.30 m for code observations and 0.002 m for carrier-phase observations. Based on the general formulation given in (1) and (2), the weighting models considered in this study are described below.

Equal weighting represents the reference case in which no elevation-dependent scaling is applied. In this case, the nominal standard deviations assigned to the code and carrier-phase observations are used directly. Accordingly, the variance scaling function is defined by (3) as

$$q(e) = 1 \quad (3)$$

For the Sin² model, the observation variance is scaled inversely with the square of the sine of the satellite elevation angle [9, 10]. In this approach, the variance increases rapidly at low elevation angles, whereas the scaling factor approaches unity as the satellite approaches the zenith. Consequently, observations at low elevation angles are assigned lower weights in the PPP solution. The variance scaling function of the model is defined by (4).

$$q(e) = \frac{1}{\sin^2 e} \quad (4)$$

In the Sine model, the observation variance is scaled as a function of the sine of the satellite elevation angle. The variance scaling function of the model is defined by (5). In this study, the parameters (a) and (b) were both set to 1, resulting in the scaling function $q(e) = 1 + 1/\sin^2(e)$ [11].

$$q(e) = a^2 + \frac{b^2}{\sin^2(e)} \quad (5)$$

In the Cosine model, the observation variance is scaled as a function of the cosine of the satellite elevation angle. The variance scaling function of the model is defined by (6) [9, 12]. In this study, $a = b = 1$ was adopted, resulting in the scaling function $q(e) = 1 + \cos^2(e)$.

$$q(e) = a^2 + b^2 \cos^2(e) \quad (6)$$

In the Exponential model, the observation variance is scaled as a function of the satellite elevation angle using an exponential function. The variance scaling function of the model is defined by (7). In this study, $a = 0.43$, $b = 1.77$, and $e_0 = 10^\circ$ were used [4].

$$q(e) = a^2 + b^2 \exp\left(-\frac{2e}{e_0}\right) \quad (7)$$

The Sine-Piecewise model, proposed by Withchayangkoon [13], defines different variance scaling behaviors for observations at low and high elevation angles. In the Sine-Piecewise model, a threshold elevation angle of 30° is used, and the observation variances at low elevation angles are scaled more strongly, thereby assigning lower weights to these observations. The variance scaling function used in this study is defined by (8).

$$q(e) = \begin{cases} \frac{1}{\sin^2(e)}, & e \leq 30^\circ \\ \frac{1}{\sin(e)}, & e > 30^\circ \end{cases} \quad (8)$$

The six weighting approaches evaluated in this study and their corresponding $q(e)$ functions are presented in Table II.

Table II. Observation weighting models evaluated in the study

Model No.	Model	Variance scaling function $q(e)$
Model 1	Equal	Eq. (3)
Model 2	Sin ²	Eq. (4)
Model 3	Sine	Eq. (5)
Model 4	Cosine	Eq. (6)
Model 5	Exponential	Eq. (7)
Model 6	Sine-Piecewise	Eq. (8)

C. Performance Assessment

For the accuracy assessment of the PPP solutions, precise coordinates derived from the weekly SINEX solutions of the analyzed IGS stations were used as reference coordinates. The coordinates estimated from PPP were transformed into the local topocentric system with respect to the reference coordinates, and the position differences in the east (ΔE), north (ΔN), and up (ΔU) directions were obtained for each epoch [14]. The horizontal (2D) and three-dimensional (3D) accuracies of the solutions were computed using only the post-convergence epochs according to (9) and (10), respectively. In the equations, n denotes the total number of epochs included in the evaluation after convergence.

$$RMS_{2D} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\Delta E_i^2 + \Delta N_i^2)} \quad (9)$$

$$RMS_{3D} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\Delta E_i^2 + \Delta N_i^2 + \Delta U_i^2)} \quad (10)$$

Convergence time was determined as the elapsed time from the beginning of the solution to the first epoch at which the positioning errors fell below the predefined threshold values and remained continuously below these thresholds for 10 consecutive epochs. The convergence criteria were set to 10 cm and 15 cm for the 2D and 3D positioning errors, respectively. The post-convergence positioning accuracy of the PPP solutions was evaluated using the 2D and 3D RMS values calculated from the position differences obtained from the first epoch satisfying the corresponding convergence criterion to the end of the solution.

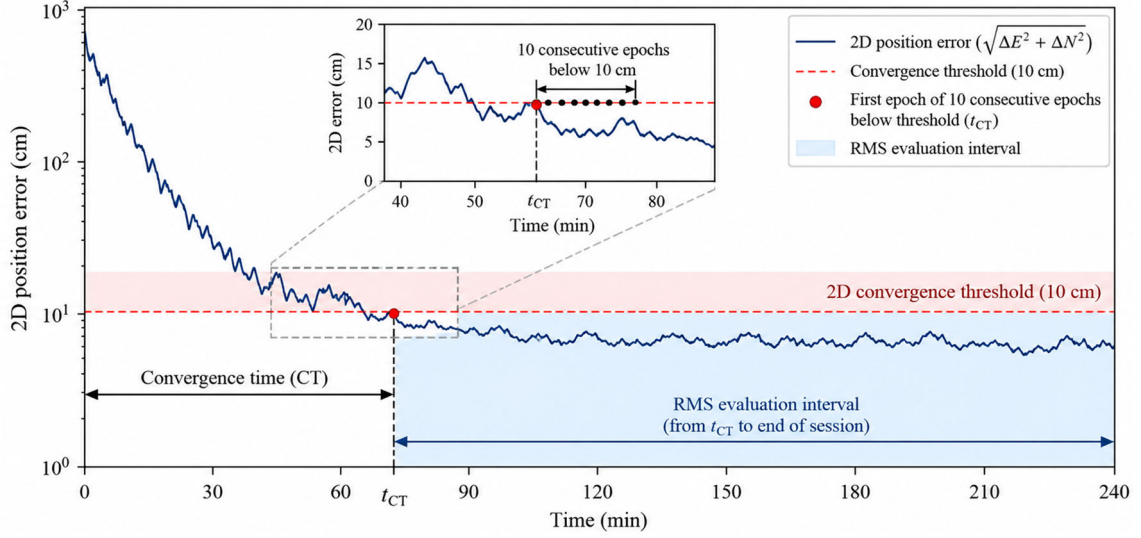


Fig. 2. Illustration of the convergence time determination criterion

III. RESULT AND DISCUSSION

This section comparatively examines the effects of six different observation weighting approaches on PPP positioning accuracy and convergence performance. The evaluations were carried out using the 2D and 3D RMS values and the 2D and 3D convergence times obtained from six IGS stations. Differences among the weighting approaches were analyzed both on a station-by-station basis and in terms of overall mean performance, and the dependence of PPP solution performance on the weighting strategy, station, and performance metric was discussed.

A. Positioning Accuracy

Table III presents the station-based 2D and 3D RMS values obtained using the six different observation weighting approaches, together with the mean results for the six stations. The mean 2D RMS values ranged from 2.063 to 2.361 cm, while the mean 3D RMS values ranged from 3.026 to 3.328 cm. Among the investigated approaches, the lowest mean 2D RMS value, 2.063 cm, was obtained with the Sine-Piecewise approach, whereas the lowest mean 3D RMS value, 3.026 cm, was achieved with the Sine approach. Compared with equal weighting, the mean 2D RMS decreased by approximately 12.6% with the Sine-Piecewise approach, while the mean 3D RMS decreased by approximately 9.1% with the Sine approach.

The differences among the weighting approaches became more pronounced for the 3D RMS values at some stations. However, the weighting approach yielding the lowest RMS values varied from station to station. For example, at the YEL2 station, the lowest 2D RMS value was obtained with equal weighting, whereas the lowest 3D RMS value was achieved with the

Exponential model. Similarly, at the IZMI station, the Sine-Piecewise approach produced the lowest 2D RMS value, while the Exponential model yielded the lowest 3D RMS value.

Overall, the results indicate that elevation-dependent weighting can improve PPP positioning accuracy, although the magnitude of the improvement varies depending on the station and weighting approach. Considering the mean results for the six stations, the Sine-Piecewise approach provided the lowest 2D RMS, while the Sine approach produced the lowest 3D RMS. Nevertheless, no single weighting approach showed consistently superior performance across all stations.

Table III. Station-based 2D/3D RMS values obtained using different observation weighting approaches (cm)

Station	Equal	Sin ²	Sine	Cosine	Exponential	Sine-Piecewise
YEL2	1.657 / 3.062	2.550 / 3.075	2.260 / 2.928	1.749 / 3.014	1.805 / 2.787	2.524 / 2.960
BRUX	1.726 / 2.116	1.621 / 2.167	1.601 / 2.118	1.661 / 2.103	1.673 / 2.150	1.645 / 2.208
IZMI	2.278 / 2.854	1.949 / 3.445	1.928 / 3.115	2.166 / 2.861	2.114 / 2.844	1.890 / 3.484
BREW	1.685 / 2.576	1.417 / 2.028	1.390 / 2.023	1.605 / 2.465	1.426 / 2.190	1.431 / 2.015
HARB	5.058 / 6.162	3.473 / 4.166	3.653 / 4.364	4.750 / 5.802	4.576 / 5.495	3.253 / 3.809
URUM	1.762 / 3.198	1.663 / 3.720	1.630 / 3.605	1.728 / 3.191	1.646 / 3.424	1.635 / 3.806
Mean	2.361 / 3.328	2.112 / 3.100	2.077 / 3.026	2.277 / 3.239	2.207 / 3.148	2.063 / 3.047

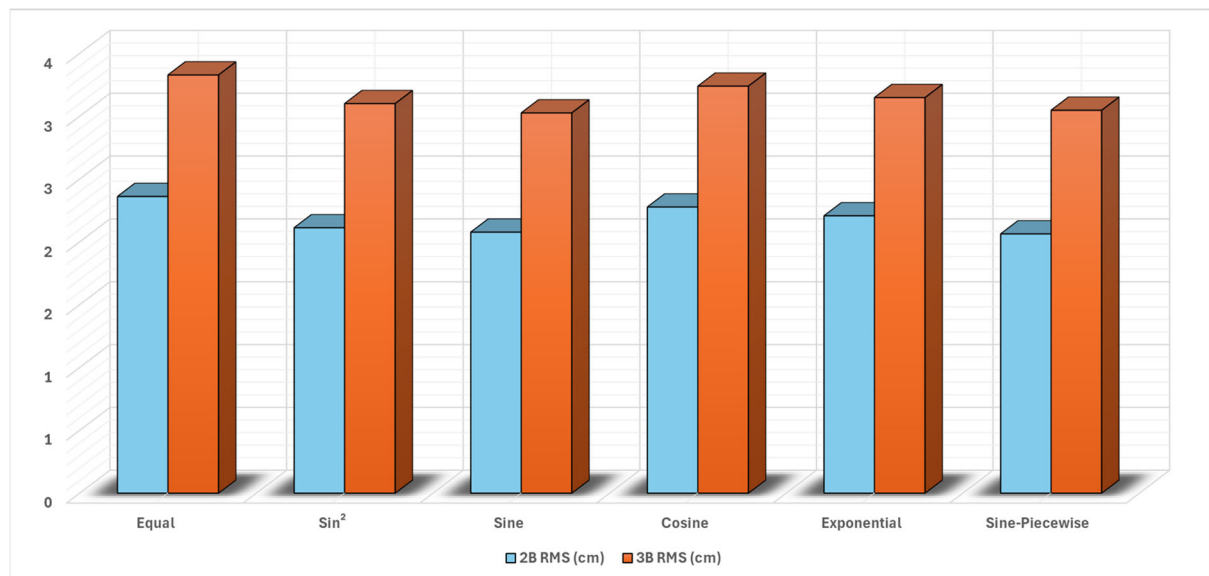


Fig. 3. Comparison of the mean 2D and 3D RMS values obtained using different observation weighting approaches

B. Convergence Performance

Table IV presents the station-based 2D and 3D convergence times obtained for the six different observation weighting approaches, together with the mean values for the six stations. The mean 2D convergence times ranged from 8.25 to 11.50 min, while the mean 3D convergence times ranged from 8.33 to 13.00 min. The shortest mean 2D convergence time, 8.25 min, was obtained with the Sin² and Sine approaches, whereas the shortest mean 3D convergence time, 8.33 min, was achieved with the Sine approach. Compared with equal weighting, the mean 2D convergence time decreased by approximately 28.3% for both the Sin² and Sine approaches, while the mean 3D convergence time decreased by approximately 35.9% for the Sine approach.

However, as observed for positioning accuracy, the convergence performance also varied

among the stations, and no single weighting approach exhibited the same behavior across all cases. In particular, at the HARB station, the 3D convergence time decreased from 34.0 min with equal weighting to 15.0 min with the Sin^2 , Sine, and Sine-Piecewise approaches. In contrast, at some stations, the differences among the weighting approaches were more limited, or different approaches produced similar convergence times.

Overall, elevation-dependent observation weighting appears to have the potential to improve PPP convergence performance. Considering the mean results of the six stations, the Sin^2 and Sine approaches yielded relatively low average convergence times for both 2D and 3D solutions; in particular, the Sine approach provided a pronounced reduction in 3D convergence time compared with equal weighting.

Table IV. Station-based 2D/3D CT values obtained using different observation weighting approaches (min)

Station	Equal	Sin^2	Sine	Cosine	Exponential	Sine-Piecewise
YEL2	2.5 / 9.0	2.5 / 2.5	2.5 / 2.5	2.5 / 9.0	2.5 / 9.0	8.5 / 9.0
BRUX	5.0 / 7.5	4.0 / 3.0	4.0 / 3.0	4.5 / 6.0	3.0 / 2.5	4.5 / 4.0
IZMI	12.0 / 11.0	7.0 / 10.5	7.5 / 10.5	12.0 / 11.0	12.0 / 9.5	7.5 / 10.5
BREW	11.0 / 5.5	10.5 / 7.5	10.5 / 7.5	10.5 / 6.0	11.0 / 7.5	10.0 / 7.5
HARB	33.5 / 34.0	14.0 / 15.0	13.5 / 15.0	33.0 / 33.0	12.0 / 25.0	14.0 / 15.0
URUM	5.0 / 11.0	11.5 / 12.5	11.5 / 11.5	4.5 / 11.0	9.5 / 4.0	11.0 / 11.5
Mean	11.50 / 13.00	8.25 / 8.50	8.25 / 8.33	11.17 / 12.67	8.33 / 9.58	9.25 / 9.58

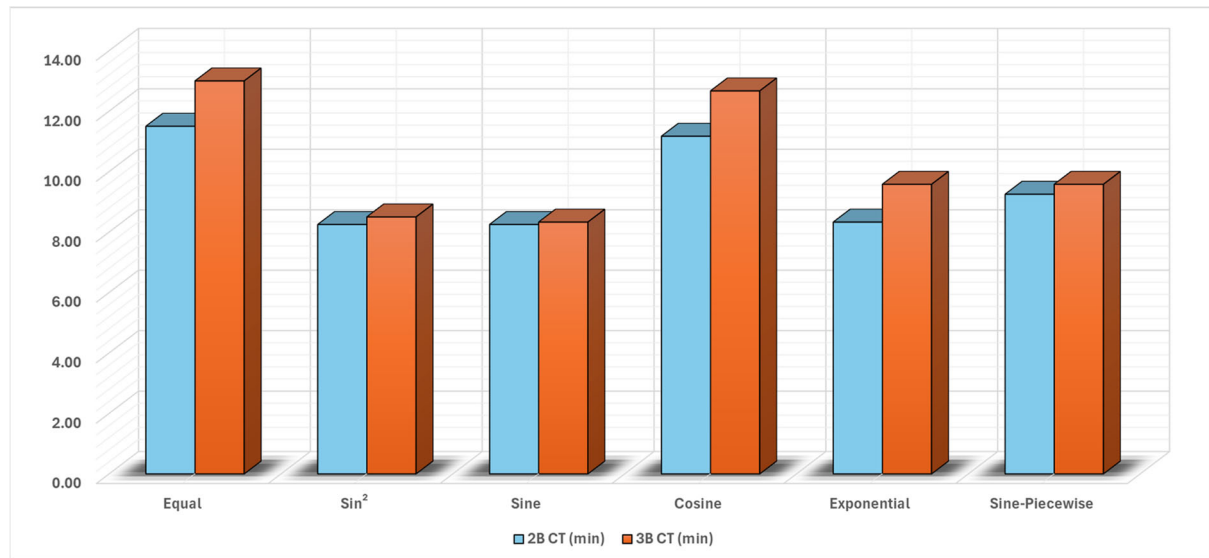


Fig. 3. Comparison of the mean 2D and 3D CT values obtained using different observation weighting approaches

IV. CONCLUSION

This study investigated the effects of different observation weighting approaches on PPP positioning accuracy and convergence performance. Six weighting approaches, namely Equal, Sin^2 , Sine, Cosine, Exponential, and Sine-Piecewise, were compared at six IGS stations using the same PPP processing strategy. The evaluations were conducted based on 2D and 3D RMS values and 2D and 3D convergence times.

The results showed that the observation weighting approach can have a noticeable effect on PPP performance. Considering the mean results of the six stations, the lowest 2D RMS value

was obtained with the Sine-Piecewise approach at 2.063 cm, followed by the Sine approach at 2.077 cm. For 3D RMS, the lowest mean value of 3.026 cm was achieved with the Sine approach. Compared with equal weighting, the mean 2D RMS decreased by approximately 12.6% with the Sine-Piecewise approach, while the mean 3D RMS decreased by approximately 9.1% with the Sine approach. In terms of convergence performance, the Sin² and Sine approaches provided the shortest mean 2D convergence time of 8.25 min, whereas the shortest mean 3D convergence time of 8.33 min was obtained with the Sine approach. The Sine approach reduced the mean 3D convergence time by approximately 35.9% compared with equal weighting.

However, the station-based results showed that no single weighting approach provided the best performance across all stations and all performance metrics. Nevertheless, when the mean results of the six stations were considered, all elevation-dependent weighting approaches yielded lower 2D and 3D RMS values and shorter 2D and 3D convergence times than equal weighting. The findings of this study are limited to the six stations and the one-day data set analyzed herein. Therefore, further investigations using different data sets and observation conditions are required to more comprehensively assess the performance of the weighting approaches.

ACKNOWLEDGMENT

This study is derived from the first author's ongoing doctoral thesis conducted at the Department of Geomatics Engineering, Graduate Education, Training and Research Institute, Konya Technical University.

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Determination of Hydrokinetic Energy Generation Sites in Data-Scarce Semi-Arid Urban Waterways for Sustainable Urbanization: A Synthetic Demonstration

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Abstract: Additive site-selection scores let a strong resource value compensate for an unsafe, prohibited or seasonally inoperable reach. This matters in semi-arid urban waterways, where low flow, rapid floods, debris and sparse observation govern whether a turbine can run at all. This paper sets out a screening sequence with four components. Physical, legal and ecological gates are applied before any weighting. Net energy is integrated only inside the device operating envelope. Preference comparison is bounded by veto thresholds, and evidence confidence is reported beside each criterion rather than multiplied into it. The sequence is run end to end on a synthetic five-reach example whose device envelope, velocity generator, probability distributions, decision thresholds and random seed are all reported, so that the calculation can be repeated. Three results follow. An additive score computed on the same inputs ranks an ecologically excluded reach second of five, above two reaches that pass every gate. Within the feasible set, the reach with the largest annual net electricity is not the reach the sequence recommends, because its debris outages cross the veto threshold. Loss accounting shows that differences between reaches come from producible hours and outage frequency rather than from peak velocity, the lowest-velocity feasible reach losing 109 days to velocities below cut-in. Over 20,000 draws the recommended reach is selected in 80 percent of cases against 76 percent for the highest score, and that gap is the veto operating. The contribution is a screening-to-validation protocol with a reproducible worked example, not a universal score or a verified generation forecast.

Keywords: *Decision Support, Evidence Confidence, Hydrokinetic Energy, Operational Availability, Sustainable Urbanization, Urban Waterways*

I. INTRODUCTION

Hydrokinetic turbines extract energy from the velocity of moving water without a large hydraulic head or a storage reservoir. River currents, artificial channels, irrigation canals and some wastewater conveyance systems can therefore support distributed generation where conventional hydropower is unsuitable [1]–[3]. The technology suits urban waterways because electricity is generated near demand, but urban settings also concentrate infrastructure, public access, flood hazard and ecological pressure.

Resource assessment cannot stop at the fastest cross-section. A feasible installation must stay submerged, limit blockage, survive floods, pass debris, allow maintenance access, protect habitat and connect safely to a load. Spatial multi-criteria analysis can combine these conflicting factors, but only when fatal constraints, uncertainty and preference remain visible

in the output, and seasonal streams sharpen the problem because high instantaneous power can coexist with few annual operating hours. This paper therefore asks how fatal constraints should be separated from compensable preferences, and how operating time and evidence quality should modify a first-pass ranking. The answer offered is a decision sequence for screening, with a worked example that runs every component of that sequence on inputs a reader can regenerate.

I. LITERATURE REVIEW

Successive technology reviews have catalogued device configurations, conversion systems and micro-scale rural applications [4], [5]. The applied literature has since moved toward integrated spatial decisions. Fouz et al. [6], [7] combined exploitable resource, installation cost and socioeconomic-environmental effects in an integrated index and then extended it toward cost-effective siting, while Carballo et al. [8] proposed an integrated framework for sustainable exploitation. Bnoussaad [9] applied weighted overlay to the Hudson River, Brown et al. [10] compared Alaskan communities across resource, demand, grid, economic and climate-risk factors, and Salinas-León and Ochoa-Correa [11] applied a spatial multi-criteria approach with analytic hierarchy weights to Ecuadorian rivers. A recent review reinforces the need to match device geometry to site characteristics [12].

Spatial multi-criteria analysis and integrated indices are therefore established, and three things these studies leave open define the gap addressed here. Constraints that cannot be traded away are handled inside the same weighted sum as preferences, so a fatal condition can be outweighed. A velocity statistic is used in place of producible hours, although power depends on the cube of a time-varying velocity and floods lie outside the device envelope rather than inside the resource. The quality of the evidence behind a criterion is either ignored or multiplied into the score, which has no physical interpretation.

II. MATERIALS AND METHODS

A. Resource and Site Conditions

Kinetic power scales with the cube of the representative velocity, and the extractable fraction depends on the power-coefficient curve and on electrical losses, so annual energy must be computed from a time-varying velocity rather than from an annual mean [13]. Device and site are screened together: depth and clearance constrain rotor size, narrow geometries require explicit blockage assessment [14], and sediment response matters for foundations [15]. Fish responses depend on species, confinement, visibility and turbulence, so ecological gates must be set case by case [16], [17].

B. Gates Before Weighting

The waterway is divided into hydraulically coherent reaches, inputs and provenance are inventoried, flow regimes are characterized, gates are applied, surviving reaches are ranked using performance and availability indicators while evidence confidence is reported separately and used in the advancement rule, and robust candidates proceed to measurement. A reach fails before any weighting if a single gate returns zero, so feasibility is the Boolean product

$$F_i = \prod_k g_{ik} \quad g_{ik} \in \{0,1\} \quad (1)$$

which prevents a high velocity or a short grid distance from compensating for inadequate submergence, prohibited use or unacceptable flood and safety conditions.

C. Operating States and Net Energy

Let i denote a reach, d a device and t a time step. The operating indicator o_{idt} equals one only when velocity lies inside the device envelope, depth and clearance suffice, blockage stays

below the project limit, and no flood, debris, curtailment or maintenance flag is active. This keeps flood peaks out of the production total. Net annual electricity is

$$E_{id} = \sum_t \left[1/2 \rho A_d C_{p,d} (V_{it}) V_{it}^3 \eta_d o_{idt} - P_{aux,d,t} \right] \Delta t \quad (2)$$

where ρ is water density, A_d the swept area, $C_{p,d}$ the power-coefficient curve, η_d drivetrain and electrical efficiency, and P_{aux} auxiliary demand. Substituting an average velocity into a cubic relation is not equivalent.

D. Preference Comparison Bounded by Veto

For feasible pairs, benefit criteria are normalized as

$$r_{ij} = \frac{x_{ij} - x_{j,\min}}{x_{j,\max} - x_{j,\min}} \quad (3)$$

with the direction reversed for cost criteria, and a diagnostic score summarizes the trade-offs,

$$S_i = \sum_j w_j r_{ij} \quad \sum_j w_j = 1. \quad (4)$$

Equation (4) is compensatory by construction. Non-compensation comes from the gates that precede it and the veto thresholds applied after it, and analytic hierarchy weighting is used only to elicit the weights, never to declare a site feasible. Because the normalization range is taken from the alternatives that survive the gates, adding or removing a candidate can change the order of the rest; normalizing against the device envelope or a regulatory limit removes that dependence. Final comparison combines two rules. An outranking relation records which alternatives are strictly preferred: alternative a outranks b only when the weighted concordance index reaches a predeclared level and no criterion vetoes the comparison,

$$C(a, b) = \sum_j w_j c_j(a, b), \quad a \succ b \Leftrightarrow C(a, b) \geq c^* \quad \text{and} \quad v_j(a, b) = 0 \quad \forall j \quad (5)$$

where $c_j(a, b)$ equals one when a is at least as good as b on criterion j and zero otherwise, c^* is the concordance level, set to 0.60 here, and v_j is the veto indicator for criterion j . The relation is partial: pairs that reach neither direction are incomparable, and incomparability is a legitimate output rather than a failure. Because a partial relation need not identify a single candidate, the recommendation itself follows a veto-bounded ranking rule, which selects the highest-scoring alternative that carries no active veto. Results are then assigned to action classes: A for field verification, B for targeted data collection, C for redesign or deferral, D for rejection. Table 1 gives the criterion groups, the illustrative weights and the indicator carrying each group.

Debris enters the sequence twice, and the two roles are distinct. Debris-related downtime modifies annual energy and operational availability, whereas the veto represents a separate project-level maintainability constraint. The veto is triggered only when the outage burden exceeds the maximum operationally acceptable level, so the criterion is not penalized twice for the same reason.

Table 1. Criterion groups, illustrative weights and the indicator carrying each group.

Criterion group	Weight	Indicator
Hydraulic resource	0.30	Annual net electricity, (2)
Technical feasibility	0.20	Depth and blockage margin
Hazard and operability	0.20	Operational availability
Environmental compatibility	0.15	Habitat sensitivity index
Spatial and economic integration	0.15	Access and connection index

E. Evidence Confidence

Evidence confidence is reported beside every criterion on an ordinal provenance scale: E1 multi-season field measurement, E2 calibrated model, E3 short campaign, E4 spatial proxy, E5 expert assumption. Confidence is deliberately not multiplied into suitability or energy, because such a product has no physical interpretation and can reverse preferences arbitrarily. A predeclared rule instead moves any class-A candidate carrying a decision-critical E4 or E5 input into class B until the uncertainty is reduced, and missing values never receive a neutral score. The effect is easiest to see on the example below. If the velocity input of R3 rested on an E4 spatial proxy rather than on measurement, the advancement rule would move R3 from class A to class B despite its leading score, and it could return to class A only after targeted measurement removed the evidence limitation.

F. Specification of the Synthetic Example

Table 2 gives the specification. Every entry is a declared assumption of this demonstration, and none of it describes a real device or a real reach. Five hypothetical reaches represent regulated canal flow, shallow intermittent flow, stable treated-effluent contribution, high-resource debris exposure and an ecologically protected reach.

The power coefficient follows a smooth ramp between cut-in and rated velocity and is then reduced so that shaft power is held at its rated value up to cut-out,

$$C_p(V) = \begin{cases} 0 & V < V_{in} \text{ or } V > V_{out} \\ C_{p,max}(3x^2 - 2x^3), \quad x = \frac{V-V_{in}}{V_{rated}-V_{in}} & V_{in} \leq V < V_{rated} \\ C_{p,max}(V_{rated}/V)^3 & V_{rated} \leq V \leq V_{out} \end{cases} \quad (6)$$

Daily velocity is the product of a seasonal shape and lognormal variability: the shape is $1 + a\cos(2\pi(t - t_0)/365)$ with amplitude $a = 0.55$ and peak on day $t_0 = 75$, and the multiplier is lognormal with median one and log standard deviation 0.35. A flood event drawn on day t is retained with probability equal to the seasonal shape at t divided by $1 + a$, which concentrates floods in the wet season. Where outages coincide, precedence runs flood, then debris, then maintenance, so each non-operating day is attributed to one cause only and the day counts in Table 3 sum with the operating days to 365.

Table 2. Specification of the synthetic demonstration.

Setting	Value
Rotor diameter; swept area	1.50 m; 1.77 m ²
Cut-in; rated; cut-out velocity	0.70; 2.00; 3.00 m/s
Peak power coefficient; efficiency	0.40; 0.85
Auxiliary demand; clearance each side	40 W; 0.25 m
Minimum depth; blockage limit	2.00 m; 0.15
Seasonal amplitude; peak day	0.55; day 75
Day-to-day variability, log SD	0.35
Floods per year; duration; multiplier	4; 2 to 4 d; 2.5 to 4.0
Debris outages, low / moderate / high	2 / 6 / 14 per year; 1 to 3 d each
Scheduled maintenance	5 d, low-flow season
Draw: velocity scale	Lognormal, median 1.00, log SD 0.15
Draw: peak power coefficient	Normal(0.40, 0.03), truncated to [0.30, 0.48]
Draw: drivetrain efficiency	Normal(0.85, 0.03), truncated to [0.75, 0.93]

Setting	Value
Draw: debris outage rate	Gamma, shape 4, scale = class rate / 4
Draw: weights; veto threshold	Dirichlet(40 w); Uniform(0.03, 0.06)
Concordance level c^*	0.60
Number of draws; random seed	20,000; 20260922

III. RESULTS AND DISCUSSION

A. Gate Outcome and Operating States

Table 3 reports the reach inputs, the gate result and the operating quantities computed from (2). Blockage ratios are 0.10, 0.14, 0.09, 0.12 and 0.10 for R1 to R5, the debris classes are moderate, low, low, high and moderate, the habitat sensitivity indices are 0.35, 0.30, 0.40, 0.55 and 0.90, and the access indices are 0.55, 0.60, 0.70, 0.45 and 0.65. Availability is the operating share of the year: 0.63, 0.50, 0.70, 0.72 and 0.73. Two reaches are removed before any weighting: the shallow reach fails the submergence gate because its depth is below the 2.00 m required by the device envelope, and the protected reach fails the ecological gate. Neither exclusion depends on how favourable the remaining criteria are.

Table 3. Synthetic reach inputs, gate result and computed operating quantities. Days lost are attributed to one cause each and sum with operating days to 365.

Reach	V (m/s)	Depth (m)	Gate	Operating d	Below cut-in d	Flood d	Debris d	Maintenance d	Net energy (kWh/yr)
R1	1.10	2.2	Pass	229	109	11	11	5	3472
R2	0.75	0.8	Fail: submergence	181	177	0	4	3	1132
R3	1.25	2.8	Pass	256	90	10	4	5	4877
R4	1.45	2.4	Pass	264	58	21	17	5	5854
R5	1.30	2.6	Fail: legally protected habitat	267	80	9	4	5	5082

Five maintenance days are scheduled on every reach. R2 records three, because two of them coincide with debris outages and the precedence rule counts each day once, under the higher-precedence cause.

The totals show why a velocity statistic is a weak proxy for deliverable energy. R4 records the largest annual net energy at 5854 kWh but loses the most days to hazard: 21 to flood or above-envelope velocity and 17 to debris clearance, against 10 and 4 for R3. The lowest-velocity feasible reach, R1, loses 109 days to velocities below cut-in, the dominant loss mechanism in a seasonal regime and one invisible in any annual mean (Fig. 1).

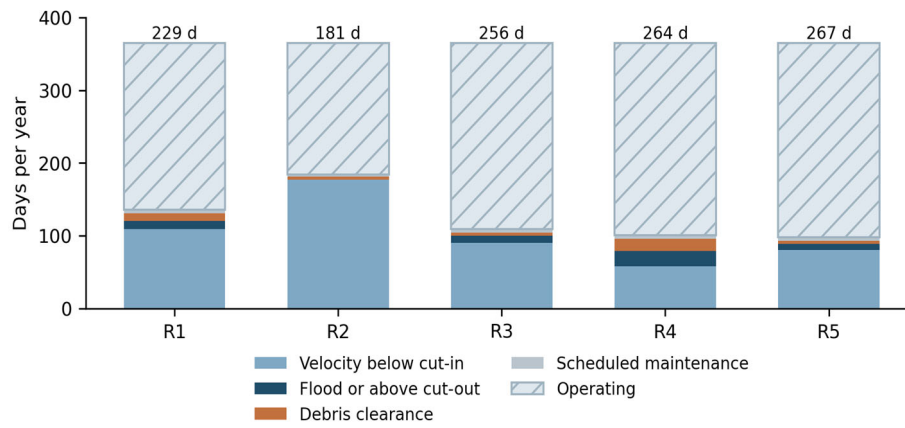


Figure 1. Days lost per year by cause for each reach.

B. What an Additive Score Does with The Same Inputs

Table 4 reports the diagnostic score of (4) computed on all five reaches with the gates and the veto switched off. The ecologically protected reach R5 ranks second of five and outscores two reaches that pass every gate. Its high velocity, adequate depth, low blockage and high availability are enough to carry a habitat sensitivity of 0.90 through the weighted sum. On these inputs an additive map would place an ecologically excluded reach above feasible alternatives, and the exclusion would have to be remembered by the analyst rather than enforced by the method.

Table 4. Additive score with gates and veto switched off.

Reach	Additive score	Passes every gate
R3	0.887	Yes
R5	0.741	No: protected habitat
R4	0.701	Yes
R1	0.608	Yes
R2	0.240	No: submergence

C. Gated Ranking, Veto and Recommendation

Within the feasible set the diagnostic scores are 0.794 for R3, 0.533 for R4 and 0.277 for R1. With the debris veto threshold at 4 percent of the year, R4 loses 4.7 percent to debris clearance and is vetoed, so it cannot outrank another alternative regardless of its score. Table 5 gives the pairwise concordance indices for the three feasible reaches. Only one pair reaches the level of 0.60: R3 outranks R1 with a concordance of 0.85. R3 and R4 reach 0.50 in both directions and are therefore incomparable under the relation, and R4 cannot outrank anything because its veto is active. Because the relation does not single out a candidate, the recommendation comes from the veto-bounded ranking rule.

Table 5. Weighted concordance index $C(a,b)$ for the feasible reaches. The concordance level is 0.60.

$C(a,b)$	R1	R3	R4
R1	.	0.15	0.50
R3	0.85	.	0.50
R4	0.50	0.50	.

Table 6 compares the three decision models on the same inputs. A gate-only mask, which is standard practice in spatial screening, already removes the two infeasible reaches, but it leaves

the ranking of the survivors to the weighted sum alone. Adding the veto changes the output from a ranking into an assignment, and it is that step, not the mask, that separates the best score from the recommended action.

Table 6. Output of three decision models on the same inputs.

Decision model	Output
Additive score only	R3 > R5 > R4 > R1 > R2
Gates, then additive score	R3 > R4 > R1
Gates, score, then veto	R3 to field verification; R4 to targeted data collection; R1 retained as a lower-priority feasible alternative

The outcome separates three quantities that an additive map would merge: R4 has the largest annual net energy, R3 has the highest diagnostic score, and R3 is also the reach recommended for field verification because it is the highest-scoring alternative carrying no active veto. R4 is assigned to targeted data collection, since a debris-frequency campaign would establish whether its outage rate is genuinely above the project limit, and R1 is retained as a lower-priority feasible alternative, since it passes every gate and carries no veto but has the weakest resource persistence of the three.

D. Uncertainty

Table 7 reports the probabilities and score intervals for the three feasible reaches under the distributions of Table 2. R3 holds the highest score in 76 percent of draws and is recommended in 80 percent. That gap is the veto operating: R4 occasionally achieves the highest score, but its debris outage rate crosses the threshold often enough that it is recommended in only 7 percent of draws. The Monte Carlo standard error of a probability near one half is 0.4 percentage points at this sample size, so probabilities are reported to the nearest percentage point.

Table 7. Robustness over 20,000 draws.

Reach	P(highest score)	P(recommended)	5th to 95th percentile
R1	13%	13%	0.20 to 0.75
R3	76%	80%	0.41 to 0.98
R4	11%	7%	0.04 to 0.63

E. Interpretation and Limits

Gates and vetoes changed the selected reach on inputs where a weighted sum did not, and the difference came from producible hours and outage frequency rather than from peak velocity. This has a direct consequence for semi-arid cities: intermittent streams can show high velocities during short storms and still deliver little dependable annual energy, which is what the 109 days below cut-in at R1 represent. Treated wastewater discharges and regulated canals may offer more persistent flow, but water quality, corrosion, fouling and operational control then become more important. The appropriate unit of comparison is not peak theoretical power; net annual energy, producible hours, capacity factor, shutdown frequency and maintenance burden belong in the same table.

The limits should be read with the results. The example is synthetic, so it shows that the sequence behaves as intended on known inputs and says nothing about any real river. The velocity generator is a stylized seasonal process rather than a calibrated hydrological model. The device envelope is a declared specification to be replaced by a certificate in any application. Absolute energy values therefore carry no external meaning, while the relative ordering is the object of interest. The weights stand in for elicitation and must not be reused as design defaults, and because normalization is taken over the surviving set the scores would

shift if a sixth reach were added. The confidence rule was not activated in the base-case calculation, because the only reach carrying a low-confidence critical input was removed by a gate first; its operation is instead illustrated by the hypothetical R3 scenario in Section III.E. Debris probability and rapid-flood shutdown dominated the availability differences here and are poorly reported in a record that favors successful demonstrations.

IV. CONCLUSION

Hydrokinetic siting in urban waterways cannot be reduced to finding the highest current velocity. Velocity controls resource magnitude, but dependable deployment also requires adequate depth and clearance, persistent flow, manageable blockage, flood survival, debris tolerance, ecological compatibility and a feasible connection. Four steps follow. Physical, legal, safety and ecological exclusions are applied before weighted ranking. Energy is integrated only inside the operating envelope. Vetoes bound the weighted comparison. Evidence confidence is reported beside each criterion instead of being multiplied into the score. On the synthetic example this changed the recommended reach, and the published specification allows the calculation to be repeated. Final decisions still require field verification, calibrated hydraulics, turbine-specific performance data and lifecycle assessment, so the approach lets limited desk-stage data direct investigation while preventing a screening map from being read as a verified generation forecast.

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In Silico Investigation of *Origanum onites* Essential Oil Constituents against Cancer- and Inflammation-Associated Molecular Targets

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ABSTRACT

Origanum onites L. essential oil is well known for its rich and diverse blend of volatile compounds, several of which have been associated with notable biological activities. Building on this background, the present study used molecular docking to investigate how the oil's major constituents interact with three protein targets closely linked to cancer biology: epidermal growth factor receptor (EGFR), matrix metalloproteinase-9 (MMP-9), and cyclooxygenase-2 (COX-2).

For this purpose, the main constituents identified in the essential oil were docked into the crystal structures of EGFR (PDB ID: 1M17), MMP-9 (PDB ID: 4XCT), and COX-2 (PDB ID: 3LN1). Prior to the docking runs, the protocol was validated by redocking each protein's native co-crystallized ligand into its own binding site, confirming that the method could reliably reproduce the experimentally observed binding poses. The predicted binding affinities, orientations, and key residue interactions were then analyzed in detail for each compound.

Across the three targets, the constituents showed clearly distinct binding profiles. Several stood out with favorable predicted binding affinities and formed meaningful interactions with residues known to be involved in ligand recognition. Taken together, these results provide a molecular-level picture of how *O. onites* constituents may engage with proteins implicated in cell proliferation, extracellular matrix remodeling, and inflammatory processes.

Although these findings are purely computational, they highlight specific compounds and interactions that merit further investigation, providing a useful foundation for future biochemical and cell-based studies aimed at validating their actual biological relevance.

Keywords: *Origanum onites* L.; essential oil; molecular docking; EGFR; MMP-9; COX-2; molecular interactions; natural products

Development of A Mobile Application Calculating Natural Gas Energy

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ABSTRACT

Accurate and reliable energy calculation of natural gas is of great importance for measurement, billing, operation, energy management and technical evaluation processes. Since the energy content of natural gas varies depending on its composition and various thermodynamic parameters, the accurate evaluation of these parameters is essential for reliable energy calculations. In this study, a mobile application was developed to calculate the energy content of natural gas at natural gas stations using gas composition and relevant thermodynamic parameters according to ISO 6976:1995. The developed application aims to provide a fast, reliable, repeatable and user-friendly method for calculating energy quantities.

Within the scope of the study, gas composition data and other relevant parameters required for energy calculations were obtained from 11 different natural gas stations operated by BOTAŞ. Real field data collected from these stations were used in the developed mobile application to perform the necessary calculations and determine the energy values of natural gas. The calculation algorithm of the application was designed to automatically perform energy calculations based on the entered gas composition and thermodynamic parameters. This approach enables the calculation process to be carried out more rapidly and consistently.

To evaluate the accuracy and reliability of the developed mobile application, the obtained results were compared with those calculated using Kelton Flocalc, which was used as the reference application in natural gas and oil industry. The results demonstrated that the energy values calculated by the developed mobile application were exactly identical to those obtained from Kelton Flocalc. This finding confirms that the calculation algorithm implemented in the mobile application is fully consistent with the reference application.

The results indicate that the developed mobile application can be effectively used to perform fast, reliable and practical energy calculations at natural gas stations. Its mobile platform provides a significant operational advantage by enabling calculations to be performed under field conditions without requiring a computer or fixed system. This study presents a validated, user-oriented digital solution that can support field operations and improve the efficiency of energy calculation processes in the natural gas industry.

Keywords—Energy Calculation; ISO 6976:1995; Kelton Flocalc; Natural Gas; Mobile Application

Urban Density Redistribution Based on The Fresnel Diagram: A Morphological Comparison at Equal Total Floor Area

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ABSTRACT

Urban density is often associated with building height. However, for a given total building floor area, different distributions of building footprint can result in substantially different building heights and open-space configurations. This study revisits the Fresnel Diagram as used by Leslie Martin and Lionel March to explore how the same amount of floor space can be accommodated in different ways on a given site, particularly through the comparison of centralised pavilion and perimeter-based courtyard forms. Building on this theoretical approach, the present study compares a reference layout composed of detached building blocks with four alternative courtyard-based configurations derived from the geometric logic of the Fresnel Diagram. Across all cases, site area and total building floor area are held constant, while the spatial distribution of building footprint is varied. In the courtyard-based alternatives, the footprint is redistributed from small detached blocks to larger perimeter blocks enclosing more continuous central open spaces. The comparison considers total building footprint, equivalent average number of storeys, and open-space organisation. Changes relative to the reference configuration are expressed as the percentage reduction in equivalent average number of storeys and the percentage increase in total building footprint. The calculations reveal a clear trade-off between building footprint and building height. In the reference model, a footprint of 38,400 square metres requires eight storeys to accommodate the total building floor area. In the courtyard-based alternatives, the footprint increases to between 71,520 and 82,080 square metres, representing an increase of approximately 86 to 114 percent. This allows the same total building floor area to be accommodated with an equivalent average of 3.74 to 4.30 storeys. This corresponds to a reduction in the equivalent average number of storeys of approximately 46 to 53 percent. The results show that the same total building floor area can be accommodated through substantially different combinations of building footprint and building height. More importantly, the findings suggest that redistributing building footprint according to the geometric logic of the Fresnel Diagram can support lower-rise urban development without reducing total building floor area. The study therefore presents the Fresnel Diagram as a simple geometric framework for testing alternative density distributions and for examining the relationships between building footprint, equivalent average number of storeys, and open-space organisation.

Keywords—Fresnel Diagram; Urban Density; Urban Morphology; Floor Area; Building Height; Open Space

Reuse of Treated Municipal Wastewater for Agricultural Irrigation: Opportunities, Environmental Risks, and Requirements for Safe Use

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ABSTRACT

Freshwater scarcity and increasing competition among agricultural, urban, and industrial water users are strengthening interest in the reuse of treated municipal wastewater for irrigation. Treated wastewater can provide a relatively reliable supplementary water source while also supplying nitrogen, phosphorus, potassium, and other nutrients that may partially reduce mineral fertilizer requirements. However, these benefits are accompanied by environmental and health related concerns that require appropriate management. This focused narrative review synthesizes recent peer reviewed evidence, field studies, meta analyses, regulatory documents, and international guidance on the opportunities, risks, and management requirements of treated municipal wastewater reuse for agricultural irrigation. The main benefits are freshwater substitution, improved irrigation supply reliability, and nutrient contribution. Field evidence indicates that treated wastewater can maintain acceptable crop productivity under suitable conditions, although yield enhancement is not universal and nutrient inputs do not necessarily replace conventional fertilization. Salinity and sodicity are among the most important environmental constraints. Repeated irrigation may increase soil electrical conductivity and sodium adsorption ratio, with consequences that depend on soil texture, drainage, irrigation history, and wastewater characteristics. Elevated sodicity should therefore be interpreted as a degradation pressure requiring monitoring rather than automatic evidence of structural soil failure. Microbiological safety is determined by the entire reuse pathway rather than treatment status alone. Treatment performance, crop type, irrigation method, and contact between irrigation water and edible plant tissues strongly influence exposure. Microbial contamination of irrigation water does not necessarily result in contamination of harvested crops, but appropriate treatment, disinfection, and verification monitoring remain necessary. Residual pharmaceuticals, other contaminants of emerging concern, and antimicrobial resistance determinants introduce additional uncertainty. Their occurrence in treated water should not be equated directly with crop accumulation, meaningful exposure, or demonstrated health effects because risk is contaminant, pathway, and receptor specific. Safe agricultural reuse therefore requires a fit for purpose, multi barrier approach that combines treatment, monitoring, crop selection, irrigation practice, soil characteristics, and exposure pathways. Current risk based regulatory frameworks reinforce this system level perspective by extending management beyond the reclamation facility to distribution, storage, field application, and environmental monitoring. Overall, sustainable reuse depends on matching water quality with crop, soil, and irrigation conditions and maintaining effective monitoring and risk management throughout the complete reuse system.

Keywords: Treated Municipal Wastewater; Agricultural Irrigation; Water Reuse; Salinity; Sodicity; Emerging Contaminants; Risk Management

Analysis of Global Research Trends in Food Sustainability Education Using Scientific Mapping and Fuzzy Logic Approaches: Thematic Evolution and Future Perspectives

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ABSTRACT

The sustainability of food systems is a multidisciplinary field encompassing food safety, environmental conservation, economic accessibility, healthy nutrition, and social well-being. Global population growth, climate change, increasing pressure on natural resources, food waste, changing consumption patterns, and economic inequalities have intensified the need for sustainable food systems. However, transforming production and supply chains alone is insufficient. Enhancing individuals' knowledge and awareness of food safety, healthy nutrition, environmental sustainability, and responsible consumption is equally important. In this context, education plays a critical role in transforming knowledge and attitudes into sustainable behaviors and promoting safe and responsible food practices throughout society. This study aims to examine the global scientific development of food sustainability education through bibliometric and scientific mapping techniques and to explore the potential contribution of Fuzzy Logic to the assessment of food safety awareness, consumer attitudes, perceptions, and sustainable food behaviors. The conceptual framework focuses on the relationship between sustainable food systems and consumer education, with particular emphasis on food safety awareness, sustainable nutrition, responsible consumption, and behavioral transformation. The consumer-oriented component of the study is planned to use online survey data collected from individuals residing in different provinces of Türkiye and Turkish consumers living in France, Germany, the United Kingdom, North Macedonia, Kosovo, and Bulgaria. The survey addresses food purchasing practices, sources of food safety information, general food safety awareness, knowledge of risky foods, and awareness of foodborne illnesses. Fuzzy Logic is proposed as an analytical approach for modeling consumer awareness, attitudes, and perceptions through graded membership functions rather than rigid categorical classifications. Linguistic variables such as “low,” “medium,” and “high” can thus be represented mathematically, allowing uncertainty and gradual differences in consumer awareness to be incorporated into the analysis. The international sample is intended to facilitate comparisons of how educational, economic, and socio-cultural conditions may influence food safety awareness among consumers with similar cultural backgrounds. The bibliometric component examines thematic evolution, keyword co-occurrences, co-citation relationships, research clusters, and changes in research themes over time within the international literature on food sustainability and education. Scientific mapping is used to identify the conceptual structure of the field and the major research directions shaping its development. Existing literature indicates the prominence of themes including sustainability, education for sustainable development, nutrition, food systems, and sustainability-oriented curriculum development. Emerging areas include student engagement

with food systems, digital technologies, big data, artificial intelligence, university-community collaboration, and innovative educational models focused on sustainability. Overall, the study conceptualizes food sustainability education as an integrated field connecting consumer awareness, food safety, sustainable consumption, education, digital transformation, and data-driven analytical approaches. Bibliometric and thematic analyses provide insight into the global development and research priorities of the field, while Fuzzy Logic offers a complementary framework for addressing uncertainty and gradual variation in consumer perceptions and awareness. The study is expected to contribute to identifying knowledge gaps, clarifying emerging research directions, and developing a scientific basis for future educational programs and sustainable food policies. It also highlights the importance of international collaboration, sustainability-oriented curricula, and individual awareness in supporting safe and sustainable food choices and contributing to the achievement of the United Nations Sustainable Development Goals.

Keywords— *Food sustainability; Food safety awareness; Consumer education; Sustainable food systems; Fuzzy Logic; Bibliometric analysis; Scientific mapping; Sustainable consumption*

A Component-Wise Ablation Study of Real-Time Audio-Visual Emotion Recognition

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ABSTRACT

Real-time audio-visual emotion recognition must predict from past observations. However, published recognizers mostly rely on pre-recorded clips, and they share a common design of pretrained encoders fused by a learned head. Each publication ablates only the module it introduces, so the accuracy of any shared component remains underexplored, as is the cost of the causality constraint that a real-time system requires. This study presents a component-wise ablation of a causal, real-time audio-visual emotion recognition system constructed from pretrained components, over 303 training runs across CREMA-D and RAVDESS datasets. The protocol uses eleven speaker-disjoint folds with three seeds per fold. Each ablation compares two configurations that differ in a single component. One configuration has the component present, and one excludes the component while keeping the remaining components of the system same. System accuracy depends primarily on the pretrained encoders. On one CREMA-D fold, frozen pretrained features achieve 69.3 percent test accuracy, and the full system achieves 78.5 percent, whereas a smaller model trained from scratch achieves only 42.1 percent on the same CREMA-D fold. Removing the causality constraint, so that the model may also use later frames of a clip, changes accuracy by less than one point on CREMA-D and RAVDESS datasets. Weight averaging contributes 2.6 points to the system accuracy on RAVDESS dataset, and a stronger causal temporal layer increases the system accuracy by 1.8 points on CREMA-D dataset. The selected system runs at 6.0 milliseconds per streaming step on Graphics Processing Unit (GPU) and 21.0 milliseconds on Central Processing Unit (CPU) and reaches 75.9 percent on CREMA-D and 70.0 percent on RAVDESS. The larger offline teacher model used to train the selected system, which takes each clip in full as input, reaches 79.8 percent on CREMA-D. To conclude, quality of audio and visual encoders contributes more to the accuracy of the audio-visual emotion recognition system rather than the fusion head design merging the audio and visual channels. An emotion recognizer restricted to past observations achieves similar accuracy to the identical recognizer that takes the whole clip as input.

Keywords—*Real-time Emotion Recognition, Knowledge Distillation, Weight Averaging, Audio-Visual Emotion Recognition.*

Real-Time Markerless Estimation of 3-DoF Instantaneous Head Angular Position Using RGB-D Vision for Human–Robot Motion Mapping

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ABSTRACT

Accurate and responsive estimation of human head orientation is essential for intuitive human-robot interaction, motion analysis, and vision-based robotic control. This work presents a real-time, markerless framework for estimating three-dimensional head orientation using synchronized RGB and depth data acquired from an Intel RealSense D455f camera and MediaPipe facial landmark detection. The system measures the three rotational degrees of freedom of the head using the conventional roll, pitch, and yaw representation, corresponding to lateral flexion, flexion-extension, and axial rotation, respectively.

Rather than relying on a single pose estimation method, the proposed framework integrates complementary orientation information derived from facial transformation data, RGB-D facial landmark reconstruction, and Perspective-n-Point (PnP) pose estimation. Head orientation is represented internally using rotation matrices and quaternions, while neutral-relative angular displacement is computed with respect to an automatically or manually calibrated reference pose. An adaptive filtering strategy is employed to reduce measurement noise while maintaining a target update rate of 30 Hz and low control latency.

The framework also evaluates landmark availability, depth quality, estimator agreement, and pose-estimation residuals to generate a real-time confidence metric without suppressing measurements under low-confidence conditions. The developed system can be used as a vision-based motion-reference interface for controlling a three-degree-of-freedom soft robotic head capable of bending and twisting motions. Experimental validation against a reference 3-DoF angular measurement system is used to characterize the accuracy, precision, repeatability, effective sampling rate, latency, cross-axis coupling, and reliability of the proposed method across the functional range of human head motion. The proposed approach provides a foundation for real-time, non-contact mapping of human head orientation to multi-degree-of-freedom robotic or game systems.

Keywords: Head pose estimation, RGB-D vision, Human–Robot interaction, MediaPipe, RealSense, roll–pitch–yaw, motion tracking, continuum robotics..

Maliyet Kısıtı Altında Regresyon Test Seti Oluşturmada İnsan ve Yapay Zekâ Seçimlerinin Karşılaştırılması

Comparing Human and AI Selection for Regression Test Suite Construction Under a Cost Constraint

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ÖZET

Regresyon testleri, yazılım değişikliklerinin daha önce doğrulanan işlevlerde istenmeyen etkiler oluşturup oluşturmadığını değerlendirmek amacıyla yürütülür. Yeni özellikler, hata düzeltmeleri ve bileşen güncellemeleri mevcut davranışları etkileyebildiğinden bu testler yazılım kalitesinin korunmasında önemlidir. Bununla birlikte, test havuzunun büyümesi tüm senaryoların her sürümde çalıştırılmasını güçleştirir. Bu nedenle regresyon seti oluşturulurken gereksinim kapsamı ile koşum maliyeti arasında denge kurulması gerekir. Büyük dil modellerinin bu kararlarda kullanılması, uzmanlarla seçim benzerliğinin ve değerlendirme süresinin birlikte incelenmesini gerekli kılmaktadır.

Bu çalışmada, Turkish Technology bünyesinde görev yapan yedi yazılım testi uzmanının oluşturduğu regresyon setleri tek bir yapay zekâ çıktısıyla karşılaştırılmıştır. Kurgusal bir e-ticaret sisteminde kupon geliştirmesi için 30 mevcut regresyon ve 20 yeni fonksiyonel test senaryosundan oluşan aday havuzu kullanılmıştır. Koşum süreleri eşit kabul edilmiş, seçim bütçesi en fazla 35 senaryoyla sınırlandırılmıştır. Senaryolar; değişiklik ilişkisi, iş etkisi, geçmiş hata bilgisi, son koşum yaşı ve gereksinim kapsamıyla tanımlanmıştır. Seçim benzerliği, ortak seçilen senaryoların setlerin birleşimindeki benzersiz senaryolara oranını gösteren Jaccard katsayısıyla; kapsam ise temsil edilen gereksinim gruplarının toplam 14 gruba oranıyla değerlendirilmiştir.

Yapay zekâ 35, uzmanlar 19–35 senaryo seçmiştir. Yapay zekâ–uzman ortalama Jaccard benzerliği %75,74, uzmanlar arasındaki 21 karşılaştırmanın ortalaması %71,46 bulunmuştur. Daha dar set seçen katılımcı dışlandığında bu değerler sırasıyla %79,32 ve %79,08 olmuştur. Böylece benzerliğin set büyüklüğüne duyarlılığı da gösterilmiştir. Yapay zekâ bütün gereksinim gruplarını kapsarken uzmanların ortalama kapsamı %94,90'dır. Aynı gün içinde kaydedilen beş oturumun ortalama süresi 40,2 dakika, medyanı 41 dakikadır. İki katılımcının ertesi güne uzanan kayıtları, aktif çalışma süresi doğrulanamadığından süre özetine alınmamıştır. Yapay zekâ seçimi 1 dakika 20 saniyede tamamlamış; beş uzman oturumunun ortalamasına göre sürede %96,7 azalma sağlanmıştır.

Bulgular, incelenen vakada yapay zekâ seçimlerinin uzman tercihleriyle örtüştüğünü ve insan karar çeşitliliğine yakın bir örüntü sergilediğini göstermektedir. Ancak tek vaka ve tek model çıktısı, genelleme ve tekrarlanabilirlik değerlendirmesini sınırlar. Gereksinim kapsamı gerçek hata bulma başarısı olarak yorumlanmamalı; zaman kazancı eşdeğer ölçüm koşullarında ayrıca doğrulanmalıdır.

Anahtar Kelimeler—Regresyon Testi; Yapay Zeka

ABSTRACT

Regression testing assesses whether software changes introduce unintended effects on previously verified functionality. Because new features, bug fixes, and component updates may affect existing behavior, regression testing plays an important role in maintaining software quality. However, as the test pool grows, executing all test scenarios in every release becomes increasingly difficult. Constructing a regression test suite therefore requires a balance between requirements coverage and test execution cost. The use of large language models for these decisions calls for examining both the similarity of their selections to those of experts and the time required to make those selections.

This study compared regression test suites constructed by seven software testing experts at Turkish Technology with a single AI-generated selection. The candidate pool consisted of 30 existing regression test scenarios and 20 new functional test scenarios for the addition of a coupon feature to a fictional e-commerce system. All scenarios were assumed to have equal execution times, and the selection budget was capped at 35 scenarios. Each scenario was characterized by its relationship to the software change, business impact, historical test failure information, number of releases since its last execution, and requirements coverage. Selection similarity was evaluated using the Jaccard coefficient, calculated as the number of scenarios selected in common divided by the number of distinct scenarios in the union of the two sets. Coverage was measured as the proportion of the 14 requirements groups represented by the selected scenarios.

The AI selected 35 scenarios, while the experts selected between 19 and 35. The mean AI-expert Jaccard similarity was 75.74%, compared with a mean of 71.46% across the 21 pairwise comparisons among experts. When the participant who selected a smaller set was excluded, these values were 79.32% and 79.08%, respectively, demonstrating the sensitivity of the similarity measure to set size. The AI selection covered all requirements groups, whereas the experts' mean coverage was 94.90%. The five sessions with start and end times recorded on the same day had a mean duration of 40.2 minutes and a median of 41 minutes. Records for two participants extended into the following day and were excluded from the duration summary because their active working time could not be verified. The AI completed its selection in 1 minute and 20 seconds, representing a 96.7% reduction in elapsed time relative to the mean duration of the five expert sessions.

The findings indicate that, in the case examined, AI selections overlap with expert preferences and exhibit a pattern comparable to the variation in human decisions. However, the use of a single case and a single model output limits generalizability and the assessment of reproducibility. Requirements coverage should not be interpreted as evidence of actual fault detection effectiveness, and time savings should be further validated under equivalent measurement conditions.

Keywords—Regression Testing; Artificial Intelligence

Comparative Evaluation of Collective Level Density Effects On Nuclear Reaction Cross Sections

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ABSTRACT

Reliable nuclear reaction cross section predictions depend on both the nuclear level density and the dominant reaction mechanism. This study evaluates the reaction dependence of collective level density effects through four representative cases: deuteron induced scandium 47 production from titanium 47, photon induced two neutron emission from germanium 74, proton induced indium 111 production from cadmium 111, and neutron capture on gadolinium 160. Calculations using the Collective Semi-Classical Fermi Gas Model, abbreviated as CSCFGM, were performed within TALYS 2.0 and compared with EXFOR measurements, the default constant temperature plus Fermi gas option, and TENDL-2025 evaluated residual production data. The collective model combines a constant temperature description at low excitation energies with a Fermi gas formulation at higher energies, incorporating collective contributions into the energy dependent level density parameter. Experimental agreement was assessed using excitation function shapes and relative deviation indicators. Because experimental uncertainties were incomplete for some datasets, these indicators were interpreted as measures of model discrepancy rather than universal uncertainty weighted goodness of fit tests.

The results demonstrate that the influence of collective enhancement depends on the reaction mechanism. For the germanium photonuclear reaction, the mean absolute relative deviation decreases from 14.63 percent with default TALYS to 9.06 percent with CSCFGM. For gadolinium neutron capture, the corresponding deviation decreases from 150.46 to 93.66 percent, although substantial discrepancies remain. The collective model reproduces the main excitation function features, including the peak regions of the germanium and cadmium reactions. However, default TALYS yields lower global relative deviations for the titanium and cadmium cases. An additional comparison of five gamma strength prescriptions for germanium confirms that photonuclear cross sections cannot be interpreted from the level density input alone. These findings identify both the predictive value and the limitations of collective enhancement. Reliable modeling of reactions with important breakup, pre-equilibrium, or resonance contributions requires complementary assessment of optical model potentials, gamma strength functions, and competing reaction mechanisms.

Keywords: Nuclear Level Density; Collective Effects; Reaction Cross Sections; CSCFGM; TALYS; EXFOR

Eye- Blink Detection Using EEG Time-Amplitude Images And Transfer Learning

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ABSTRACT

Electroencephalography (EEG)-based Brain-Computer Interface (BCI) systems have significant potential to enable individuals with severe motor impairments to communicate with their environment. In conditions such as advanced-stage Amyotrophic Lateral Sclerosis (ALS) and locked-in syndrome, voluntary eye blinking may serve as an alternative control signal in BCI systems, as it is one of the limited motor functions that can remain preserved. In this study, a transfer learning-based approach using EEG time-amplitude images was developed for EEG-based eye-blink detection. The publicly available BLINK dataset, which includes voluntary eye blinking (EEG-IO), spontaneous eye blinking during video viewing (EEG-VV), and spontaneous eye blinking during reading (EEG-VR), was used. EEG signals recorded from the Fp1 and Fp2 channels at a sampling frequency of 250 Hz were filtered using a 0.5–45 Hz Butterworth band-pass filter. For the classification of blink and non-blink conditions, 1-second epochs were generated using the midpoints of blink events as reference points. The resulting EEG epochs were converted into time-amplitude images, which were subsequently classified using a transfer learning-based ResNet-50 model. The ResNet-50 model achieved cross validation-based classification accuracies of 95.45%, 96.18%, and 94.60% for the EEG-IO, EEG-VR, and EEG-VV datasets, respectively, with AUC values ranging from 0.982 to 0.990. The results demonstrate that transforming EEG signals into time-amplitude images and analyzing them using transfer learning methods is an effective approach for detecting eye-blink events with high accuracy. This approach may serve as an alternative control method in EEG-based BCI systems, particularly for individuals with limited voluntary motor function.

Keywords— EEG, Brain-Computer Interface, Eye-Blink Detection, Transfer Learning, ResNet-50

Neotetis'in Kaybolan Denizel Bağlantılarının İzinde: Doğu Anadolu Evaporitlerinden Havza Karşılaştırmalı Bulgular

Tracing the Disintegration of Neotethyan Seaways: A Comparative Evaporite Record from Eastern Anatolia

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ÖZET

Neotetis Okyanusu'nun Doğu Anadolu'daki kapanımı, yalnızca bir okyanusal alanın ortadan kalkmasıyla sınırlı olmayan, havzaların su bütçesini, bağlantılılığını ve çökeltme ortamlarını köklü biçimde değiştiren karmaşık bir paleocoğrafik süreçtir. Bu süreç boyunca denizel bağlantının giderek zayıflaması; sığ deniz, lagün, kıyı sabkhası, evaporitik havza, playa ve gölssel sistemler gibi birbirini izleyen çökeltme ortamlarının gelişmesine neden olmuştur. Bu çalışmada, söz konusu dönüşümün Doğu Anadolu'daki evaporitik istiflerde nasıl kaydedildiği, farklı havzalardan elde edilen sedimantolojik, mineralojik, jeokimyasal ve izotopik verilerin karşılaştırılması yoluyla araştırılmaktadır.

Çalışma kapsamında Muş, Van-Çatak, Van-Başkale (Köprüağzı), KD Van (Koluz) ve Kağızman-Tuzluca havzalarına ait evaporit kayıtları ortak bir paleocoğrafik çerçevede değerlendirilmiştir. Karşılaştırmada özellikle üç temel unsur dikkate alınmıştır: evaporitlerin sülfat kaynağı, havzaların denizel bağlantı derecesi ve çökeltme sisteminin giderek karasal bir karakter kazanması.

Kuzeydoğu Muş evaporitleri, bu dönüşümün erken aşamalarından birini temsil etmektedir. Rupeliyen yaşlı istif içerisinde sığ deniz ve lagün koşullarından kıyı sabkhası ve tuzlu çamur düzlüklerine kadar uzanan fasiyesler birlikte bulunmaktadır. Sr, S ve O izotop verileri ise havzanın tamamen denizel veya tamamen karasal bir sistemden ziyade, denizel ve karasal etkilerin birlikte bulunduğu oldukça sığ ve kısıtlanmış bir ortam olduğunu göstermektedir. Bu özellikler, çalışma alanında Neotetis'in güney kolunun Rupeliyen sırasında son derece sıkıştığını ve denizel bağlantının ileri derecede sınırlandığını düşündürmektedir.

Van-Başkale ve Van-Çatak evaporitleri ise denizel etkinin daha belirgin biçimde korunduğu kısıtlanmış havza sistemlerini temsil etmektedir. Köprüağzı evaporitlerinde lagünden hinterlanda uzanan çökeltme koşulları belirlenmiş ve Sr-S-O izotopları sülfatın Miyosen denizel kökenini desteklemiştir. Bununla birlikte yüksek detritik katkı, tatlısu etkisi, tuzluluk ve pH değişimleri ile hidrotermal ve diyajenetik süreçler evaporit oluşumunu önemli ölçüde etkilemiştir. Van-Çatak istifinde ise denizel kökenli sülfat, yoğun buharlaşmanın egemen olduğu kısıtlanmış marjinal denizel-lagüner ve sabkha koşullarında çökelmiştir. İzotopik veriler denizel sülfat kaynağını desteklerken, oksijen izotopları ve element dağılımları havzaya dönemsel karasal su girişlerini ve ilerleyen tuzlaşmayı ortaya koymaktadır. Buna karşılık KD Van'daki Koluz ve Kağızman-Tuzluca havzaları, denizel etkinin belirgin biçimde zayıfladığı daha ileri bir dönüşüm aşamasını yansıtmaktadır. Koluz evaporitleri, yoğun karasal detritik katkının ve yeraltısuyu destekli buharlaşmanın etkili olduğu geçici playa sisteminde gelişmiş olup, denizel çökeltmenin sona ermesiyle birlikte karasal koşulların egemen hale geldiğini

göstermektedir. Kağızman–Tuzluca havzasında ise izotopik ve jeokimyasal veriler ağırlıklı olarak karasal su koşullarına işaret etmekte; bazı evaporitlerin ise daha eski denizel evaporitlerin çözünmesi ve yeniden çökmesiyle ilişkili olabileceği değerlendirilmektedir.

Bu karşılaştırma, Doğu Anadolu evaporitlerinin yalnızca farklı yaşlardaki jips oluşumlarını temsil etmediğini, aynı zamanda giderek parçalanmış bir Neotetis denizel sisteminin hidrolojik evrimini kaydettiğini ortaya koymaktadır. Denizel sülfatın hâkim olduğu kısıtlanmış havzalardan, tatlısu ve karasal detritik girdilerin arttığı sistemlere; oradan da playa ve tamamen karasal havzalara uzanan bu değişim, denizel bağlantının kaybının havzalar arasında farklı derecelerde gerçekleştiğini düşündürmektedir. Bu nedenle Neotetis'in kapanımı, yalnızca belirli bir stratigrafik seviyeye veya tek bir tektonik olaya indirgenmek yerine, denizel bağlantıların aşamalı olarak zayıfladığı, havza hidrolojisinin yeniden düzenlendiği ve denizel ortamların karasal sistemlere dönüştüğü bölgesel bir paleocoğrafik süreç olarak ele alınabilir. Farklı havzalardan elde edilen evaporit kayıtlarının aynı çerçevede karşılaştırılması, bu dönüşümün mekânsal ve zamansal boyutlarının test edilmesine ve Doğu Anadolu'nun günümüzdeki karasal havza düzenine geçişinin daha bütüncül biçimde anlaşılmasına olanak sağlamaktadır. Böylece evaporitler, yalnızca çökme ortamlarının göstergeleri değil, Neotetis'in parçalanmasından Doğu Anadolu'nun karasal havza sistemlerinin oluşumuna kadar uzanan paleocoğrafik dönüşümün birbirini tamamlayan arşivleri olarak değerlendirilebilir.

Anahtar Kelimeler— *Neotetis; Doğu Anadolu; Evaporit; Paleocoğrafya; İzotop jeokimyası*

ABSTRACT

The closure of the Neotethys Ocean in Eastern Anatolia was not merely the disappearance of an oceanic domain, but a complex paleogeographic process that profoundly altered basin hydrology, connectivity, and depositional environments. During this process, progressive weakening of marine connectivity led to the development of a succession of depositional settings, ranging from shallow-marine and lagoonal environments to coastal sabkhas, evaporitic basins, playas, and lacustrine systems. This study investigates how this transformation is recorded in the evaporitic successions of Eastern Anatolia through a comparative evaluation of sedimentological, mineralogical, geochemical, and isotopic data from different basins.

Evaporite records from the Muş, Van–Çatak, Van–Başkale (Köprübaşı), northeastern Van (Kölçü), and Kağızman–Tuzluca basins are evaluated within a common paleogeographic framework. The comparison focuses particularly on three key aspects: the source of sulfate, the degree of marine connectivity, and the progressive transition of depositional systems toward continental conditions.

The northeastern Muş evaporites represent one of the early stages of this transformation. The Rupelian succession comprises facies ranging from shallow-marine and lagoonal settings to coastal sabkhas and saline mudflats. Sr, S, and O isotope data indicate that the basin was neither entirely marine nor entirely continental, but rather a highly shallow and restricted system influenced by both marine and continental inputs. These characteristics suggest that the southern branch of the Neotethys became extremely shallow and that marine connectivity was strongly restricted in the study area during the Rupelian. The Van–Başkale and Van–Çatak evaporites represent restricted basin systems in which marine influence is more clearly preserved. In the Köprübaşı evaporites, depositional conditions ranged from lagoonal settings to the hinterland, while Sr–S–O isotope data support a Miocene marine origin for the sulfate. Nevertheless, substantial detrital input, freshwater influence, fluctuations in salinity and pH, as well as hydrothermal and diagenetic processes significantly affected evaporite formation. In the Van–Çatak succession, marine-derived sulfate precipitated under restricted marginal-marine, lagoonal, and sabkha conditions dominated by intense evaporation. Isotopic data support a marine sulfate source, whereas oxygen isotopes and elemental distributions indicate episodic input of continental waters and progressive salinization of the basin.

In contrast, the Koluz and Kağızman–Tuzluca basins in northeastern Anatolia represent a more advanced stage of the transition, characterized by a pronounced reduction in marine influence. The Koluz evaporites developed within a transient playa system dominated by intense terrestrial detrital input and groundwater-supported evaporation, indicating the establishment of continental conditions following the termination of marine sedimentation. In the Kağızman–Tuzluca Basin, isotopic and geochemical data predominantly indicate non-marine water conditions, while some evaporites may be related to the dissolution and reprecipitation of older marine evaporites.

This comparison demonstrates that the evaporites of Eastern Anatolia do not merely represent gypsum deposits of different ages, but also record the hydrological evolution of a progressively fragmented Neotethyan marine system. The transition from restricted basins dominated by marine sulfate, through systems increasingly affected by freshwater and terrestrial detrital input, to playa and fully continental environments suggests that the loss of marine connectivity occurred to different degrees among the basins.

Accordingly, the closure of the Neotethys should not be regarded solely in terms of a specific stratigraphic level or a single tectonic event, but rather as a regional paleogeographic process involving progressive weakening of marine connections, reorganization of basin hydrology, and transformation of marine environments into continental systems. Integrating evaporite records from different basins within a common framework provides an opportunity to test the spatial and temporal dimensions of this transformation and to develop a more comprehensive understanding of the transition toward the continental basin configuration of Eastern Anatolia. Thus, evaporites can be regarded not merely as indicators of depositional environments, but as interconnected archives of the paleogeographic transformation extending from the fragmentation of the Neotethys to the development of continental basin systems in Eastern Anatolia.

Keywords— *Neotethys; Eastern Anatolia; Evaporites; Paleogeography, Isotope geochemistry*

Nonlinear Performance Assessment of Special Truss Moment Frames with Different Special Segment Configurations

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ABSTRACT

This study is primarily based on the performance-based design methodology developed by Subhash C. Goel and Shih-Ho Chao. Three Special Truss Moment Frames (STMFs), incorporating Vierendeel, Intermediate Vertical Member (IVM), and X-Diagonal special segment configurations, were designed using three MATLAB-based design procedures. These procedures were developed to determine the required member sections and sizes for the yielding members within the special segments, while also determining the design forces governing the sizing of the non-yielding members outside the special segments. The resulting design parameters were subsequently implemented in a finite element model for strength-based structural design and analysis. Nonlinear pushover and cyclic hysteresis analyses were then conducted to evaluate and compare the structural performance of the three STMF configurations.

Nonlinear static pushover analyses were conducted to compare the lateral responses of three Special Truss Moment Frame (STMF) configurations incorporating Vierendeel, Intermediate Vertical Member (IVM), and X-diagonal special segments. The results revealed distinct differences in initial lateral stiffness and base-shear resistance, with the X-diagonal configuration exhibiting the highest values, followed by IVM and Vierendeel. At the code-based target displacement corresponding to 3% of the total building height, this ranking remained consistent. The load–displacement responses also demonstrated configuration-dependent patterns of strength development, with the rate of increase in base shear diminishing at larger displacements. Overall, the findings highlight the significant influence of special-segment configuration on the lateral stiffness and strength characteristics of STMF systems.

Nonlinear dynamic analyses evaluated three STMF configurations (Vierendeel, IVM, X-Diag) under the Northridge earthquake using a Steel02 material model. The X-Diag system exhibited the highest lateral stiffness and peak base shear, resulting in the lowest relative displacement demands. However, this high stiffness attracted larger seismic forces, resulting in pinched hysteresis loops and limited ductility. Conversely, the more flexible Vierendeel system, despite lower peak strength, achieved larger displacements while maintaining stable, wide loops, demonstrating superior energy dissipation. IVM displayed intermediate behavior. These findings highlight the configuration-dependent trade-off between peak lateral strength/stiffness and cyclic energy dissipation capacity in STMF systems.

Keywords—Special Truss Moment Frames, Nonlinear Pushover Analysis, Dynamic Analysis

2500 kVA 10,5/0,71-0,71 kV Dd0d0 Bağlantı Gruplu Güneş Enerji Santrallerine Uygun 3 Sargılı Transformatör Tasarım Üretim Ve Testi

Design, Manufacturing, And Testing Of A 2500 kVA, 10.5/0.71–0.71 kV, Dd0d0 Three-Winding Transformer For Solar Power Plant Applications

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ÖZET

Güneş enerjisi santrallerinin şebeke entegrasyonunda kullanılan transformatörler; yüksek verimlilik, harmonik dayanımı ve kararlı bir faz yönetimi gerektirir. Bu doğrultuda, iki ayrı evirici (inverter) çıkışını tek bir manyetik gövdede birleştiren üç sargılı transformatörler, sistem entegrasyonunu kolaylaştırırken yatırım maliyetlerini düşürmektedir. Bu çalışma kapsamında, GES uygulamalarına uygun eşit gerilimde çift sekonder gerilim seviyelerine sahip ve primer ve sekonder çıkışları arasında faz farkı oluşmasını engelleyen Dd0d0 bağlantı grubuna sahip üç sargılı bir transformatörün tasarımı, prototip üretimi ve testleri gerçekleştirilmiştir.

Tasarım sürecinde IEC 60076 standartları referans alınmış; elektriksel, termal ve mekanik parametreler optimize edilmiştir. Sistemin kalbini oluşturan Dd0d0 bağlantı yapısı, yüksek gerilim sargısının üçgen (D), iki bağımsız alçak gerilim sargısının ise sıfır derece faz açısına sahip üçgen (d0, d0) olarak yapılandırılmasını sağlamıştır. Bu bağlantı mimarisi, eviricilerden gelen akımların şebekeye simetrik ve kayıpsız aktarılmasına olanak tanımaktadır. Üç kolonlu yönlendirilmiş silisli sacdan imal edilen nüve ve yüksek harmonik akımları ile kısa devre mekanik kuvvetlerine dayanıklı silindirik sargılar bu yapıya göre optimize edilmiştir.

Soğutma sistemi olarak ONAN (Oil Natural Air Natural) yöntemi uygulanmış ve yük altında sargı sıcaklık artışlarının standart limitlerinde kaldığı doğrulanmıştır. Prototip üretimi sonrası yapılan kısa devre testi, dielektrik dayanım ve özellikle Dd0d0 faz ilişkisini doğrulayan gerilim çevirme oranı ile vektör grubu testleri başarıyla tamamlanmıştır. Elde edilen çıktılar, yenilenebilir enerji altyapısı için yüksek verimli ve yerli bir mühendislik çözümü sunmaktadır.

Keywords—*Transformatör, üç sargılı tasarım, güneş enerjisi santrali, ONAN soğutma, harmonik, bağlantı grubu, Dd0d0*

ABSTRACT

Transformers used for the grid integration of solar power plants require high efficiency, harmonic tolerance, and stable phase management. In this context, three-winding transformers that combine the outputs of two separate inverters within a single magnetic core facilitate system integration while reducing investment costs. In this study, the design, prototype

manufacturing, and testing of a three-winding transformer suitable for solar power plant applications, featuring dual secondary voltage levels with equal voltage ratings and a Dd0d0 vector group that prevents phase displacement between the primary and secondary outputs, were carried out.

During the design process, the IEC 60076 series of standards was taken as a reference, and the electrical, thermal, and mechanical parameters were optimized. The Dd0d0 connection configuration, which constitutes the core of the system, consists of a delta-connected high-voltage winding (D) and two independent delta-connected low-voltage windings (d0, d0) with zero-degree phase displacement. This connection architecture enables the symmetrical and efficient transfer of currents from the inverters to the grid. The three-limb core, manufactured from grain-oriented electrical steel, and the cylindrical windings designed to withstand high harmonic currents and short-circuit mechanical forces were optimized according to this configuration.

An ONAN (Oil Natural Air Natural) cooling system was employed, and it was verified that the winding temperature rise under load remained within the limits specified by the relevant standards. Following prototype manufacturing, the short-circuit test, dielectric withstand tests, and, in particular, the ratio and vector group tests verifying the Dd0d0 phase relationship were successfully completed. The results demonstrate a high-efficiency, locally engineered solution for renewable energy infrastructure.

Keywords— *Transformer, three-winding design, solar power plant, ONAN cooling, harmonics, vector group, Dd0d0*

Geleneksel Tahıl Ürünlerin Sürdürülebilir Beslenmedeki Rolü

The Role Of Traditional Cereal Products In Sustainable Diets

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ÖZET

Tahıllar, dünya genelinde enerji ve besin öğelerinin önemli kaynaklarından biri olup geleneksel beslenme örüntülerinin temel bileşenleri arasında yer almaktadır. Bulgur, tam tahıllı ürünler ve farklı yörelere özgü tahıl temelli gıdalar; karbonhidratların yanı sıra protein, diyet lifi, vitamin, mineral ve biyoaktif bileşenlerin diyet katkısı sağlaması açısından önem taşımaktadır. Son yıllarda sürdürülebilir beslenme yaklaşımı, yalnızca çevresel etkileri değil, beslenme yeterliliği, kültürel uygunluk ve gıda çeşitliliğini de birlikte değerlendirmektedir. Bu çalışmanın amacı, geleneksel tahıl ürünlerinin besinsel özellikleri ve sürdürülebilir beslenme ile ilişkisini güncel literatür doğrultusunda değerlendirmektir. Çalışma, kapsamlı bir literatür derlemesi olarak yürütülmüştür. Geleneksel ve tam tahıl ürünlerinin besin bileşimi, diyet lifi ve biyoaktif bileşenleri, sağlıkla ilişkili özellikleri ve sürdürülebilir beslenmedeki rolünü inceleyen hakemli çalışmalar ve derlemeler bu doğrultuda analiz edilmiştir. Bulgurumuz, tahıl temelli gıdaların başlıca karbonhidrat kaynağı olmasının yanında protein, diyet lifi, vitamin, mineral ve biyoaktif bileşenler sağlayabildiğini göstermektedir. Tam tahıl tüketimi, rafine tahıllara kıyasla daha yüksek lif ve biyoaktif bileşen alımıyla ilişkilendirilmektedir. Bulgurun ise dirençli nişasta, diyet lifi ve fenolik bileşikler bakımından önemli bir geleneksel tahıl ürünü olduğu belirlenmiştir. Ayrıca tahıllar, bitkisel protein kaynaklarının diyet içindeki payını artırarak hayvansal protein tüketiminin azaltılmasına yönelik beslenme modellerini desteklemektedir. Sonuç olarak, geleneksel tahıl ürünleri, besin ögesi katkıları ile kültürel olarak kabul görmüş tüketim biçimleri sayesinde sürdürülebilir beslenme modellerinin desteklenmesinde yüksek potansiyel taşımaktadır. Ancak sürdürülebilir beslenme açısından nihai değerlendirme, ürünün besin değeriyle birlikte tüketim miktarı, diyetin bütünü ve gıda sisteminin çevresel ve sosyal boyutları dikkate alınarak yapılmalıdır.

Anahtar Kelimeler—Geleneksel Tahıl Ürünleri; Sürdürülebilir Beslenme; Tam Tahıl; Bulgur; Diyet Lifi

ABSTRACT

Cereals are major contributors to energy and nutrient intake worldwide and are fundamental components of many traditional dietary patterns. Bulgur, wholegrain foods, and region-specific cereal products can contribute carbohydrates as well as protein, dietary fibre, vitamins, minerals, and bioactive compounds to the diet. Sustainable diet approaches

increasingly consider nutritional adequacy together with environmental, cultural, and food-system dimensions. This review aimed to evaluate the nutritional characteristics of traditional cereal products and their potential role in sustainable diets based on current literature. The study was conducted as a comprehensive literature review. Peer-reviewed studies and reviews addressing the nutritional composition of traditional and wholegrain cereal products, dietary fibre, bioactive compounds, health-related properties, and the role of cereals in healthy and sustainable dietary patterns were evaluated. Our findings indicate that cereal-based foods provide protein, dietary fibre, vitamins, minerals, and bioactive compounds in addition to being the primary carbohydrate source. Wholegrain consumption is associated with higher intakes of fibre and bioactive components compared with refined grains. Furthermore, bulgur has been identified as a significant traditional cereal product in terms of resistant starch, dietary fibre, and phenolic compounds. Cereals may also support dietary strategies that increase plant-derived protein and reduce reliance on animal protein. In conclusion, traditional cereal products have great potential to support sustainable dietary patterns through their nutrient contributions, cultural acceptance, and established consumption practices. Nevertheless, their overall contribution to sustainable diets should be assessed by considering nutritional value together with consumption patterns, total dietary composition, and the environmental and social dimensions of the food system.

Keywords—*Traditional Cereal Products; Sustainable Diets; Whole Grains; Bulgur; Dietary Fibre*Kaynakça

Geleneksel Fermente Gıdaların Bağırsak Mikrobiyotası Üzerine Potansiyel Etkileri

Potential Effects Of Traditional Fermented Foods On The Gut Microbiota

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ÖZET

Geleneksel fermente gıdalar, üretim sırasında oluşan mikrobiyal topluluklar ve metabolitler nedeniyle yalnızca duyu ve teknolojik özellikleriyle değil, potansiyel sağlık etkileriyle de dikkat çekmektedir. Son yıllarda fermente gıdaların bağırsak mikrobiyotası ile etkileşimi, beslenme ve gıda mikrobiyolojisinin kesişiminde önemli bir araştırma alanı hâline gelmiştir. Bununla birlikte, fermente gıdalarda bulunan mikroorganizmaların bağırsakta kalıcı olarak kolonize olup olmadığı ve düzenli tüketimin mikrobiyota bileşimini ne ölçüde değiştirdiği henüz tam olarak açıklığa kavuşmamıştır. Bu çalışmanın amacı, geleneksel fermente gıdaların bağırsak mikrobiyotası üzerine potansiyel etkilerini güncel literatür doğrultusunda değerlendirmektir. Çalışma kapsamında geleneksel fermente gıdaların mikrobiyal bileşimi, fermantasyon sırasında oluşan biyoaktif metabolitler ve fermente gıda tüketiminin bağırsak mikrobiyotasıyla ilişkisini inceleyen güncel literatür verileri değerlendirilmiştir. Literatür, fermente gıdaların canlı mikroorganizmalar, organik asitler, peptitler ve diğer mikrobiyal metabolitler aracılığıyla bağırsak mikrobiyotasını etkileyebilecek potansiyele sahip olduğunu göstermektedir. Bununla birlikte, fermente gıdalardan kaynaklanan mikroorganizmaların bağırsakta kalıcı kolonizasyonuna ilişkin kanıtların sınırlı ve heterojen olduğu bildirilmektedir. Bazı insan çalışmalarında fermente gıda tüketimi ile mikrobiyota çeşitliliği ve sağlıkla ilişkili mikroorganizmaların zenginleşmesi arasında ilişkiler gözlenmiş olsa da sonuçlar tüm ürünler için genellenebilir değildir. Ürünün hammaddesi, fermantasyon koşulları, mikrobiyal topluluk yapısı ve tüketim miktarı olası etkileri belirleyen önemli değişkenlerdir. Sonuç olarak, geleneksel fermente gıdalar bağırsak mikrobiyotasıyla etkileşim açısından umut vadeden bir besin grubu olmakla birlikte mevcut kanıtlar kesin nedensel sonuçlar oluşturmak için yeterli değildir. Gelecekte standartlaştırılmış ürünlerle gerçekleştirilecek uzun süreli ve kontrollü insan çalışmalarının, ürün özellikleri ile mikrobiyota yanıtı arasındaki ilişkinin daha net ortaya konmasına katkı sağlayacağı düşünülmektedir.

Anahtar Kelimeler: geleneksel fermente gıdalar, bağırsak mikrobiyotası, fermantasyon, probiyotik, mikrobiyal metabolitler

ABSTRACT

Traditional fermented foods have attracted increasing scientific interest because of their microbial communities and metabolites formed during fermentation. Their interaction with the gut microbiota has become an important research area at the interface of nutrition and

food microbiology. However, the persistence of food-derived microorganisms in the gut and the extent to which regular consumption alters microbiota composition remain incompletely understood. This review aimed to evaluate the potential effects of traditional fermented foods on the gut microbiota based on current literature. A literature review was conducted addressing the microbial composition of traditional fermented foods, bioactive metabolites produced during fermentation, and associations between fermented food consumption and the gut microbiota. Findings related to microbiota composition, microbial diversity, potentially probiotic microorganisms and health-associated microbial metabolites were considered, with particular attention to human studies. The literature indicates that fermented foods may influence the gut microbiota through live microorganisms, organic acids, peptides and other microbial metabolites. Evidence for persistent colonization of the human gut by microorganisms originating from fermented foods remains limited and heterogeneous. Some human studies have reported associations between fermented food consumption, microbiota diversity and enrichment of health-associated microorganisms, but these findings cannot be generalized to all fermented products. Raw materials, fermentation conditions, microbial community structure and intake level may determine the observed effects. In conclusion, traditional fermented foods represent a promising food group in terms of interactions with the gut microbiota; however, current evidence is insufficient to establish definitive causal effects. Long-term, controlled human studies using well-characterized products are needed to clarify relationships between product characteristics and microbiota responses.

Keywords: *traditional fermented foods, gut microbiota, fermentation, probiotics, microbial metabolites*

Beton Köşk Kalıp Isıtıcı Projesi

Concrete Substation Formwork Heating Project

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ÖZET

Elektrik şebekelerinde trafo merkezi olarak kullanılan monoblok beton köşkler, yüksek dayanım ve güvenilirlik gerektiren kritik prefabrik yapı elemanlarıdır. Geleneksel üretim yöntemlerinde beton döküm işleminin tamamlanmasının ardından köşk gövdesi ve çatısının kalıptan çıkarılabilmesi için gereken kürlenme süresi ortalama on iki ila on dört saat sürmektedir. Kalıpların yeniden kullanıma hazır hale gelmesinde yaşanan bu uzun bekleme süresi, tesis içi üretim kapasitesinde zaman kullanımından kaynaklı belirgin düşüslere yol açmaktadır. Bu çalışmada, beton köşk üretiminde kalıp döngü sürelerini kısaltmak, erken yaş basınç dayanımını hızlandırmak ve fabrika üretim kapasitesini iki katına çıkarmak amacıyla geliştirilen yenilikçi bir kalıp içi ısıtma sistemi ele alınmıştır.

Araştırma kapsamında öncelikle hızlandırılmış termal küre uygun C35/45 dayanım sınıfında beton reçetesi optimize edilmiştir. Kalıp kuyularının ortam sıcaklığını ve döküm kalıplarının yüzey sıcaklığını yetmiş santigrat derece seviyesine hassas şekilde ulaştırmak ve sabit tutmak amacıyla özel rezistans düzenekleri ve kontrol panolarından oluşan entegre bir ısıtma sistemi tasarlanmıştır. Betonun yüksek sıcaklık altındaki kimyasal ve termal davranışları incelenerek çimento hidratasyon reaksiyonlarının optimum düzeyde ilerlemesi sağlanmıştır. Isının doğrudan kalıp yüzeylerinden iletildiği bu sistem, konvansiyonel ısıtmalara kıyasla termal kayıpları asgariye indirmiştir.

Elde edilen deneysel ve endüstriyel bulgular, kalıp ve kuyu sıcaklığının yetmiş santigrat derecede kontrollü tutulması sayesinde ürünlerin kalıptan çıkarılma süresinin on iki ila on dört saatten dört saate kadar başarıyla düşürüldüğünü göstermiştir. Bu süre optimizasyonu, beton kalitesinden ödün vermeksizin mevcut kalıplarla üretim hızını ve tesis kapasitesini iki katına çıkarmıştır. Proje, yüksek enerji verimliliği ve düşük döngü süreleriyle sektörde standartları yükselten, rekabetçi ve sürdürülebilir bir model ortaya koymaktadır.

Anahtar Kelimeler— Beton Köşk, Kalıp Isıtma, Hızlandırılmış Kürleme, C35/45 Beton, Kalıp Verimliliği, Kapasite Artışı

ABSTRACT

Prefabricated monolithic concrete transformer substation enclosures represent critical infrastructure components that demand high structural integrity, low water permeability, and rapid demolding cycles to maintain industrial efficiency. In conventional manufacturing environments, demolding cycles for enclosure bodies and roofs typically require twelve to fourteen hours post-pouring before achieving sufficient handling strength. This extended curing latency creates severe bottlenecks in daily plant throughput and significantly restricts overall manufacturing capacity. To resolve these limitations, this project presents an integrated thermal

curing architecture engineered to accelerate early-age concrete hydration, reduce demolding times, and enhance production capacity without compromising structural integrity.

The technical methodology centers on formulating an optimized C35/45 strength class concrete mix tailored for thermal activation, accompanied by the design and deployment of an integrated electrical resistance heating system incorporated directly into the casting pits and steel formwork surfaces. Thermal sensors and specialized distribution panels regulate both the formwork surface temperatures and casting pit ambient conditions to maintain a targeted thermal plateau of seventy degrees Celsius. The study investigated the coupled chemical and thermodynamic response of concrete subjected to rapid elevated curing temperatures, focusing on accelerated cement hydration, microstructural formation, and internal thermal equilibrium.

Experimental findings demonstrate that maintaining mold surface and pit ambient temperatures at seventy degrees Celsius accelerated hydration kinetics dramatically, successfully reducing the critical demolding threshold from twelve to fourteen hours down to just four hours. This notable reduction in curing duration effectively doubles total factory manufacturing capacity while maintaining required compressive strength and structural performance metrics. Furthermore, targeted thermal management significantly optimized electrical energy consumption, providing a sustainable and cost-effective production model for heavy precast concrete operations.

Keywords—*Concrete Substation, Formwork Heating, Accelerated Curing, C35/45 Concrete, Demolding Strength, Productivity Optimization*

Buharlı Fırınlr İin Yeniliki Silikon Buhar İletim Contasının Tasarımı, Malzeme Geliştirilmesi Ve Prototip Üretimi

Design, Material Development, And Prototyping Of An Innovative Silicone Steam Transmission Gasket For Steam Ovens

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ÖZET

Endüstriyel ve ticari buharlı fırınlarda kullanılan buhar iletim contaları, yüksek sıcaklıktaki buharı fırın kabineine güvenli bir şekilde yönlendirmede kritik bir rol oynamaktadır. Geleneksel conta tasarımları; profil kesimi, silikon hortum ve harici plastik adaptör-kelepe montaj gruplarına dayanmaktadır. Sürekli yüksek sıcaklık ve nem maruziyeti altında bu geleneksel montaj grupları sıklıkla mekanik deformasyona, malzeme sertleşmesine, montaj zorluklarına ve operasyonel buhar sızıntısı risklerine yol açmaktadır. Bu teknik kısıtlamaların üstesinden gelmek amacıyla, bu alışmada seri üretime uygun, uluslararası gıda teması yönetmeliklerine tam uyumlu ve yeniliki tek para (monolitik) silikon buhar iletim contasının mühendislik tasarımı, özel silikon malzeme formülasyonu geliştirilmesi, proses kalıp imalatı ve prototip doğrulaması sunulmaktadır.

Geliştirilen conta iki farklı üretim prosesini içeren ift bileşenli bir mimariye sahiptir: ekstrüzyon ile üretilen silikon hortum (makaron) kesiti ve transfer-kompresyon kalıplama yöntemiyle üretilen T-şekilli bağlantı bileşeni. Prosese özgü vulkanizasyon gereksinimlerini karşılamak üzere, iki merdaneli hamur karıştırma sisteminde peroksit ile kürlenene iki özel silikon hamuru (1436 ve C865 kodlu) formüle edilmiştir. İşlenebilirliği optimize etmek amacıyla reometrik kürlenme profilleri (minimum/maksimum tork, pişme başlangıcı ts1/ts2, yarı pişme süresi t50 ve optimum pişme süresi t90) değerlendirilmiştir. Uluslararası standartlara (ISO 48-4 Shore A sertlik, DIN 53504-S2 çekme mukavemeti ve kopma uzaması, ASTM D 624 B yırtılma mukavemeti) uygun olarak mekanik özellikleri belirlemek amacıyla sıcak hidrolik preslerde vulkanize test plakaları (2 mm kalınlık) hazırlanmıştır. Ayrıca, tek gözlü prototip doğrulamasının ardından seri üretim için 8 gözlü transfer-kompresyon birleştirme kalıbı ve özel malafalar tasarlanmış ve imal edilmiştir.

Reometrik analizler, her iki formülasyon için de optimum vulkanizasyon kinetiğini ve mükemmel işlenebilirliği doğrulamıştır. 1436 ve C865 hamurlarının mekanik testleri sırasıyla 8,45 N/mm² ve 8,88 N/mm² çekme mukavemetleri, %317 ve %302 kopma uzaması değerleri ile 24,6 N ve 23,6 N yırtılma mukavemetleri elde etmiştir. Termogravimetrik Analiz (TGA) sonuçları operasyonel koşullar altında yüksek termal kararlılık sergilendiğini göstermiştir. Akredite laboratuvar testleri, gıda teması yönetmeliklerine tam uyumu doğrulamıştır. Prototip numuneler üzerinde gerçekleştirilen fonksiyonel, termal yaşlandırma ve boyut doğrulama testleri tüm müşteri spesifikasyonlarını karşılamış ve İlk Ürün Onayı (FPA) alınmıştır. Monolitik entegre tasarım, harici kelepe adaptörlerine olan ihtiyacı ortadan kaldırarak buhar

sızıntısı risklerini tamamen çözmüş, montaj işçilik maliyetlerini düşürmüş ve başarılı bir ticarileşme sağlamıştır.

Keywords— *Silikon Elastomer; Buhar İletim Contası; Gıda Teması Yönetmelikleri; Transfer-Kompresyon Kalıplama; Reometri; Termal Kararlılık*

ABSTRACT

Steam transmission gaskets utilized in commercial and industrial steam ovens play a critical role in directing high-temperature steam safely into the oven cavity. Conventional gasket designs rely on profile cutting, silicone tubing, and external plastic adapter-clamp assemblies. Under continuous high temperature and moisture exposure, these conventional assemblies frequently suffer from mechanical degradation, material hardening, assembly difficulties, and operational steam leakage risks. To overcome these technical limitations, this study presents the engineering design, custom silicone material formulation development, process mold manufacturing, and prototype verification of an innovative, integrated silicone steam transmission gasket suitable for mass production and fully compliant with international food contact regulations.

The developed gasket comprises a dual-component architecture involving two distinct manufacturing processes: an extruded silicone hose (macaron) section and a T-shaped connection component produced via transfer-compression molding. To meet process-specific vulcanization requirements, two custom peroxide-cured silicone compounds (coded 1436 and C865) were formulated using a two-roll mill mixing system. Rheometric curing profiles (minimum/maximum torque, scorch time ts_1/ts_2 , half cure time t_{50} , and optimum cure time t_{90}) were evaluated to optimize processability. Vulcanized test sheets (2 mm thickness) were prepared on hot hydraulic presses to determine mechanical properties in accordance with international standards (ISO 48-4 Shore A hardness, DIN 53504-S2 tensile strength and elongation at break, ASTM D 624 B tear strength). Furthermore, an 8-cavity transfer-compression assembly mold and custom mandrels were designed and manufactured for mass production following single-cavity prototype validation.

Rheometrical analysis confirmed optimal vulcanization kinetics and excellent processability for both formulations. Mechanical testing of 1436 and C865 compounds yielded Shore A hardness values of 67.2 and 64.5 Shore A, tensile strengths of 8.45 N/mm² and 8.88 N/mm², elongation at break values of 317% and 302%, and tear strengths of 24.6 N and 23.6 N, respectively. Thermogravimetric Analysis (TGA) demonstrated high thermal stability under operational conditions. Accredited laboratory testing verified full compliance with food contact regulations. Functional, thermal aging, and dimensional verification tests conducted on prototype samples met all customer specifications, leading to First Product Approval (FPA). The monolithic integrated design eliminated the need for external clamp adapters, completely resolving steam leakage risks, reducing assembly labor costs, and enabling successful commercialization.

Keywords— *Silicone Elastomer; Steam Transmission Gasket; Food Contact Regulations; Transfer-Compression Molding; Rheometry; Thermal Stability*

Özel Üretim Süreçlerine Yönelik Mikro Servis Mimarili Ve Gerçek Zamanlı Veri Analitiği Destekli Özgün Üretim Yönetim Sistemi Tasarımı Ve Uygulaması: Opm Projesi

Design And Implementation Of A Novel Manufacturing Execution System Supported By Microservice Architecture And Real-Time Data Analytics For Custom Manufacturing Processes: The Opm Project

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ÖZET

Günümüz imalat sanayisinde rekabet gücünü korumak ve operasyonel mükemmelliğe ulaşmak, üretim süreçlerinin anlık ve veriye dayalı yönetilmesini zorunlu kılmaktadır. Ancak özel hammadde gereksinimlerine, hassas tolerans speklerine ve heterojen makine parkuruna sahip işletmelerde piyasada hazır bulunan ticari Üretim Yönetim Sistemi (MES) çözümleri yetersiz kalmakta; entegrasyon zorlukları ve veri kayıpları yaşanmaktadır. Bu çalışmanın amacı, söz konusu kısıtları aşmak üzere Orsav bünyesinde geliştirilen ve "sezgisel yönetimden kanıta dayalı yönetime" geçişi hedefleyen özgün, esnek ve ölçeklenebilir OPM (Orsav Süreç İyileştirme ve Yönetim Sistemi) projesinin tasarımını ve saha uygulamalarını sunmaktır.

Çalışmada, farklı marka ve nesildeki PLC sistemlerinden Modbus ve OPC-UA haberleşme protokolleri aracılığıyla milisaniye düzeyinde zaman damgalı gerçek zamanlı veri toplayan, gürültü arındırma ve veri temizleme kuralları barındıran katmanlı bir veri mimarisi kurgulanmıştır. Sistem, Node.js, TypeScript ve React.js teknolojileriyle esnek bir mikro servis mimarisinde tasarlanmış ve kurumsal ERP sistemiyle çift yönlü API entegrasyonu sağlanmıştır. Analitik katmanda, tesise özgü kısıtlarla ağırlıklandırılmış OEE (Toplam Ekipman Verimliliği) hesaplamaları, Pareto Analizi, İstatistiki Süreç Kontrolü (SPC) ve zaman serisi analizine dayalı Lineer Regresyon ile Hareketli Ortalama algoritmaları kullanılmıştır. Ayrıca fabrika sahasındaki zorlu ergonomik koşullar dikkate alınarak Gestalt ilkelerine uygun, kullanıcı odaklı (UI/UX) ve kapsayıcı tasarım prensiplerini esas alan interaktif gösterge panelleri geliştirilmiştir.

Çalışmanın doğrulama aşamasında, birim ve stres testlerinin ardından üç farklı üretim hattında pilot saha uygulamaları gerçekleştirilmiştir. Elde edilen bulgular; gerçek zamanlı izleme ve anlık kesinti analizleri sayesinde Toplam Ekipman Verimliliği'nde (OEE) %20 artış sağlandığını, dijital kalite kontrol modülü ile kalite onay süreçlerinin %15 hızlandığını ve stand-by/enerji takibi ile enerji maliyetlerinde %10 tasarruf elde edildiğini göstermiştir. Teknoloji Hazırlık Seviyesi 4'ten THS 8 seviyesine başarıyla ulaştırılan bu sistem, işletmede teknik bilgi birikimini kalıcı kılmış, dışa bağımlılığı ortadan kaldırmış ve gelecekteki yapay zeka tabanlı öngörüsül bakım modülleri için sürdürülebilir bir ürün platformu oluşturmuştur.

Anahtar Kelimeler— Üretim Yönetim Sistemi; Mikro Servis Mimarisi; Toplam Ekipman Verimliliği; İstatistiki Süreç Kontrolü; Veri Analitiği; Dijital Dönüşüm

ABSTRACT

In the contemporary manufacturing industry, maintaining competitiveness and achieving operational excellence require real-time, data-driven management of production processes. However, in enterprises with custom raw material requirements, tight tolerance specifications, and heterogeneous machinery, off-the-shelf commercial Manufacturing Execution System (MES) solutions prove inadequate, leading to integration challenges and data losses. The purpose of this study is to present the design and field applications of the novel, flexible, and scalable OPM (Orsav Process Improvement and Management System) project, developed within Orsav to overcome these constraints and facilitate a transition from "intuitive management to evidence-based management".

In this study, a layered data architecture featuring noise reduction and data cleaning rules was developed to gather time-stamped real-time data at the millisecond level from multi-brand and multi-generation PLC systems via Modbus and OPC-UA communication protocols. The system was designed using Node.js, TypeScript, and React.js within a flexible microservice architecture, enabling bidirectional API integration with the enterprise ERP system. In the analytics layer, facility-wide weighted Overall Equipment Effectiveness (OEE) calculations, Pareto Analysis, Statistical Process Control (SPC), and Linear Regression alongside Moving Average algorithms based on time-series analysis were utilized. Furthermore, taking into account the demanding ergonomic conditions of the factory floor, interactive dashboards adhering to Gestalt principles, user-centered (UI/UX) practices, and inclusive design guidelines were developed.

In the validation stage of the study, unit and stress testing was followed by pilot field implementations on three distinct production lines. The findings demonstrated that real-time monitoring and instant downtime analysis achieved a 20% increase in Overall Equipment Effectiveness (OEE), the digital quality control module accelerated quality approval processes by 15%, and standby/energy tracking yielded a 10% saving in energy costs. Successfully elevated from Technology Readiness Level 4 to TRL 8, this system solidified technical know-how within the enterprise, eliminated external dependencies, and created a sustainable product platform for future AI-based predictive maintenance modules.

Keywords— *Manufacturing Execution System; Microservice Architecture; Overall Equipment Effectiveness; Statistical Process Control; Data Analytics; Digital Transformation*

Development of a Green Transformation Compliant Automated Acid Etching System for Dental Implant Surfaces to Improve Microroughness, Cleanliness, Acid Vapor Control, and Waste Reduction

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ABSTRACT

The surface morphology, microroughness, and chemical cleanliness of dental implants play a critical role in long-term clinical success. SLA (Sandblasted, Large-grit, Acid-etched) surface technology is a widely used surface modification method that promotes bone–implant integration (osseointegration) by generating controlled microroughness on the implant surface. However, the semi-automated application of this process during manufacturing presents several challenges regarding surface uniformity, removal of chemical residues, process repeatability, and occupational health and safety.

The semi-automated acid etching system currently used by Proimtech Sağlık Ürünleri A.Ş. relies on operator experience for the adjustment of process parameters such as temperature, processing time, and acid concentration, which may result in variations in surface quality. Furthermore, in processes involving hydrochloric acid (HCl) and sulfuric acid (H₂SO₄), the limited control of chemical vapors and liquid waste in the existing system creates a need for improvement in terms of operator exposure and environmental sustainability. Accordingly, the development of a fully automated, closed-loop, and digitally traceable system has become necessary.

Within the scope of this project, the development of an automated acid etching system compatible with green transformation principles is targeted to achieve homogeneous microroughness, a high level of surface cleanliness, and precisely controlled chemical processing conditions on dental implant surfaces. The project aims to establish an integrated, safe, and reproducible manufacturing infrastructure for dental implant surface treatment processes. The project has been supported and is being carried out under the TÜBİTAK 1832 Industrial Green Transformation call.

Within the project, the mechanical design of the closed-loop acid etching system was initially completed and implemented. The chemical reaction parameters of the system, including temperature, processing time, and acid ratios, were optimized. To ensure operator safety, a sealed processing chamber, an automated lid, and emergency stop mechanisms were developed. Subsequently, a PLC-based automation infrastructure and sensor integration were implemented to enable real-time monitoring, control, and recording of process parameters. System integration studies were also carried out for the filtration of chemical acid vapors, pH-controlled neutralization of liquid waste, and reduction of chemical consumption. The performance of the developed system will be evaluated through pilot production studies, while the morphological and chemical characteristics of the implant surfaces will be verified by SEM and EDS analyses.

At the end of the project, the fully automated acid etching system is intended to achieve a surface microroughness within the range of 1.5–2.5 micrometers, reduce acid consumption by 40 percent, decrease the evaporation rate from 20 percent to 2 percent, reduce the amount of non-recyclable waste by 10 percent, minimize operator exposure to chemicals, and reduce operator dependency by 90 percent. Consequently, the project is expected to contribute to the simultaneous improvement of quality standardization, process safety, and environmental sustainability in dental implant manufacturing.

Keywords— *Dental Implants; Acid Etching; Surface Modification; Microroughness; Green Transformation*

Dikey ve Yatay Enjeksiyon Makineleri İçin Çift Katlı (Asansör) Kalıp Teknolojilerinin Geliştirilmesi ve Proses Doğrulaması

Development and Process Validation of Double-Layer (Elevator) Mold Technologies for Vertical and Horizontal Injection Molding Machines

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ÖZET

Sızdırmazlık elemanlarının seri üretimi; yüksek boyutsal hassasiyet, güvenilir sızdırmazlık performansı ve artan pazar taleplerini karşılayabilecek üretim kapasitesi gerektirmektedir. Geleneksel tek katlı enjeksiyon kalıpları, makine plaka ölçüleriyle sınırlı olması nedeniyle belirli bir alana yerleştirilebilecek kalıp gözü sayısını kısıtlamakta ve üretim kapasitesinde darboğaz oluşturmaktadır. Bununla birlikte, özellikle yatay enjeksiyon makinelerinde çift katlı kalıpların kullanılması, ürünlerin farklı kalıp katlarından alınması ve katlar arasındaki yolluk bağlantılarının ayrılması açısından otomasyon gerektiren ilave proses ihtiyaçları ortaya çıkarmaktadır. Bu çalışma kapsamında, farklı makine konfigürasyonlarına uyarlanabilecek çift katlı kalıp teknolojisinin geliştirilmesi amacıyla dikey ve yatay enjeksiyon makineleri için iki ayrı kalıp ve otomasyon uygulaması tasarlanmış, üretilmiş ve proses koşullarında doğrulanmıştır.

Dikey enjeksiyon makinesi için geliştirilen birinci uygulamada, mevcut makine plaka alanı değiştirilmeden kalıp göz sayısının artırılması amacıyla çift katlı asansör kalıp mimarisi kullanılmıştır. Geleneksel tek katlı kalıpta dört ürün gözü bulunan alana, alt ve üst katlarda toplam sekiz aktif kalıp gözü yerleştirilmiştir. Her iki kalıp katına homojen hammadde iletiminin sağlanması amacıyla dengeli bir yolluk sistemi tasarlanmış, katlar arasında oluşabilecek akış farklılıklarının kontrol edilebilmesi için yolluk kanallarına setskurlu ayar mekanizması entegre edilmiştir. Enjeksiyon hacmi, kalıp izdüşüm alanı, makine kapama kuvveti ve enjeksiyon kapasitesi birlikte değerlendirilerek uygun makine ve proses parametreleri belirlenmiştir. Gerçekleştirilen deneme üretimleri sonucunda, optimize edilen enjeksiyon parametreleriyle sekiz kalıp gözünde dengeli dolum sağlanmış ve üretim sırasında ilave setskur ayarına ihtiyaç duyulmamıştır.

Yatay enjeksiyon makinesi için geliştirilen ikinci uygulamada ise çift katlı kalıp yapısının otomatik çevrimde çalıştırılabilmesi hedeflenmiştir. Enjeksiyon ve vulkanizasyon işlemi tamamlandıktan sonra kalıp yatay doğrultuda açılmakta ve iki ayrı kalıp katı ürün alma pozisyonuna gelmektedir. Kalıp üzerine yerleştirilen iki bağımsız fırça, yukarıdan aşağıya doğru dikey hareket edecek şekilde tasarlanmıştır. Her fırça kendi kalıp katına girerek kalıp yüzeyinde bulunan ürünleri ve yolluk sistemini sıyırmakta, ürünlerin kalıptan ayrılarak toplama alanına düşmesini sağlamaktadır.

Yatay kalıptaki katlar arası malzeme geçişlerinin otomatik ürün alma işlemini engellememesi amacıyla bağlantı bölgelerinde kontrollü et kalınlığı azaltımı uygulanmıştır. Bu inceltirilmiş kopma bölgeleri, enjeksiyon sırasında malzemenin iki kalıp katına sağlıklı biçimde

iletilmesine olanak verirken fırçalama işlemi sırasında bağlantıların kontrollü kuvvet altında ayrılmasını sağlamaktadır. Böylece ürünlerin aşırı çekme kuvvetine maruz kalması, deformasyona uğraması veya kalıp üzerinde kalması önlenmiştir. Fırçalama işleminin tamamlanmasının ardından fırçalar başlangıç pozisyonuna geri çekilmekte, kalıp kapanmakta ve bir sonraki enjeksiyon çevrimi operatör müdahalesine ihtiyaç duyulmadan başlatılmaktadır.

Dikey enjeksiyon uygulamasında gerçekleştirilen karşılaştırmalı performans testlerinde, tek katlı çalışma düzeninde sekiz saatlik vardiyada 480 adet ürün elde edilirken çift katlı kalıbın aktif kullanımıyla vardiya başına 800 adet üretim seviyesine ulaşılmıştır. Böylece üretim kapasitesinde %66 artış sağlanmıştır. Üretilen prototip sızdırmazlık elemanları üzerinde gerçekleştirilen boyutsal doğrulama, fonksiyonel montaj ve sızdırmazlık testlerinde müşteri teknik gereklilikleri karşılanmıştır. Yatay enjeksiyon uygulamasında ise dikey çalışan çift fırça sistemi ve kontrollü kopma bölgeleri sayesinde ürün alma operasyonu otomatik hâle getirilmiş, manuel müdahale azaltılmış ve çevrim sürekliliği sağlanmıştır.

Geliştirilen iki ayrı uygulama, çift katlı kalıp teknolojisinin yalnızca üretim kapasitesini artıran bir kalıp yaklaşımı olmadığını; makine yerleşimi, kalıp açılma yönü, yolluk dengesi ve ürün alma yöntemi birlikte değerlendirilerek farklı enjeksiyon makinesi konfigürasyonlarına uyarlanabilen bütünsel bir üretim çözümü olduğunu göstermiştir. Elde edilen sonuçlar, çift katlı kalıp teknolojisinin yüksek hacimli silikon ve kauçuk parça üretiminde kapasite artışı, proses standardizasyonu, işçilik azaltma ve otomasyon açısından önemli bir uygulama potansiyeline sahip olduğunu ortaya koymaktadır.

Keywords— *Asansör Kalıplama Teknolojisi; Çift Katlı Kalıp; Enjeksiyon Kalıplama Teknolojileri; Üretim Kapasitesi Optimizasyonu; Yolluk Tasarımı; Sızdırmazlık Doğrulaması*

ABSTRACT

The mass production of sealing components requires high dimensional accuracy, reliable sealing performance, and sufficient production capacity to meet increasing market demand. Conventional single-layer injection molds are constrained by the platen dimensions of the injection molding machine, limiting the number of mold cavities that can be accommodated within a given area and consequently creating production capacity bottlenecks. Furthermore, particularly in horizontal injection molding machines, the use of double-layer molds introduces additional process requirements related to the removal of products from different mold layers and the separation of runner connections between the layers, thereby creating a need for automated handling solutions. Within the scope of this study, two separate mold and automation systems were designed, manufactured, and validated under actual process conditions for vertical and horizontal injection molding machines in order to develop a double-layer mold technology adaptable to different machine configurations.

In the first application, developed for a vertical injection molding machine, a double-layer elevator mold architecture was implemented to increase the number of mold cavities without modifying the existing machine platen area. Within the same area where a conventional single-layer mold accommodated four product cavities, a total of eight active cavities were positioned across the lower and upper mold layers. A balanced runner system was designed to ensure uniform material distribution to both mold layers, and a set-screw adjustment mechanism was integrated into the runner channels to enable control of potential flow differences between the layers. Injection volume, projected mold area, machine clamping force, and injection capacity were evaluated together to determine the appropriate machine configuration and process parameters. As a result of the production trials, balanced filling was achieved across all eight cavities using the optimized injection parameters, without requiring any additional set-screw adjustment during production.

In the second application, developed for a horizontal injection molding machine, the objective was to enable the double-layer mold structure to operate in a fully automatic cycle. Following completion of the injection and vulcanization processes, the mold opens in the horizontal direction, bringing both mold layers into the product removal position. Two independent brushes installed on the mold system were designed to move vertically from top to bottom. Each brush enters its corresponding mold layer and sweeps the products and runner system from the mold surface, allowing the molded parts to separate from the mold and fall into the designated collection area.

To prevent the interlayer material connections in the horizontal mold from interfering with the automatic product removal operation, a controlled reduction in wall thickness was incorporated into the connection regions. These predefined breakaway sections allow the material to flow properly between the two mold layers during injection while enabling the connections to separate under a controlled force during the brushing operation. This approach prevents the products from being subjected to excessive tensile forces, deformation, or remaining attached to the mold surface. Once the brushing operation is completed, the brushes return to their initial positions, the mold closes, and the next injection cycle begins without requiring operator intervention.

In comparative performance tests conducted for the vertical injection molding application, 480 parts were produced during an eight-hour shift using the single-layer configuration, whereas the active use of the double-layer mold increased production output to 800 parts per shift. This corresponds to a 66% increase in production capacity. Dimensional validation, functional assembly, and sealing tests performed on the prototype sealing components confirmed compliance with customer technical requirements. In the horizontal injection molding application, the vertically operating dual-brush system combined with the controlled breakaway sections enabled the product removal operation to be automated, reduced manual intervention, and ensured continuous production cycles.

The two developed applications demonstrate that double-layer mold technology is not merely a mold concept for increasing production capacity, but rather an integrated manufacturing solution that can be adapted to different injection molding machine configurations through the combined consideration of machine layout, mold opening direction, runner balance, and product removal methodology. The results indicate that double-layer mold technology offers significant application potential in high-volume silicone and rubber component manufacturing in terms of increased production capacity, process standardization, reduced labor requirements, and automation.

Keywords— *Elevator Mold Technology; Double-Layer Mold; Injection Molding Technologies; Production Capacity Optimization; Runner Design; Sealing Validation*

Wear Behavior and Microstructural Evolution of α/β and β -SiAlON Ceramics Under Different Water-Based Lubrication Conditions

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ABSTRACT

SiAlON ceramics are promising materials for tribological applications due to their high hardness, chemical stability, and mechanical reliability. In this study, the wear behavior and worn-surface microstructural evolution of β -SiAlON and mixed phase α/β -SiAlON ceramics was investigated under various water-lubricated ball-on-disc conditions using 100Cr6 steel and Si₃N₄ counterbodies. The microstructural features of the worn surfaces were examined by scanning electron microscopy to elucidate the dominant wear and tribolayer formation mechanisms.

In the first stage, the effect of SiAlON phase composition was examined in water. The α/β -SiAlON exhibited substantially higher friction coefficients than β -SiAlON against both counterbodies. However, this was not accompanied by higher material loss. The specific wear rate of α/β -SiAlON was approximately 73% lower than that of β -SiAlON against 100Cr6 and approximately 22% lower against Si₃N₄. This behavior was attributed to the combined effects of higher hardness, tribolayer formation, and counterbody interaction. Microstructural examination of the worn surfaces revealed distinct surface evolution depending on both phase composition and counterbody material. A relatively continuous tribolayer on α/β -SiAlON against Si₃N₄, whereas β -SiAlON exhibited a more fragmented surface with fine wear debris. Against 100Cr6, more pronounced steel transfer was observed on the α/β -SiAlON surface.

In the second stage, α/β -SiAlON was tested under three aqueous lubrication conditions: pure water, water containing graphene nanoplatelets, and water containing semi-synthetic metalworking fluid. Graphene reduced friction by approximately 67% against Si₃N₄ but had almost no effect against 100Cr6, while its influence on specific wear rate was limited. In contrast, the semi-synthetic fluid reduced friction by approximately 83% against Si₃N₄ and 93% against 100Cr6, together with wear-rate reductions of approximately 48% and 67%, respectively. Microstructural characterizations further demonstrated that the lubricant additives altered the worn-surface morphology and interfacial tribolayer characteristics. Graphene modified the ceramic–ceramic interface, whereas the semi-synthetic fluid effectively suppressed steel transfer.

Overall, the results demonstrate that SiAlON tribological behavior and worn-surface microstructural evolution are strongly governed by phase composition, counterbody material, tribolayer development, and lubricant chemistry.

Keywords—SiAlON; Ceramic; Microstructural Characterization; Wear

Analysis of Bottlenecks in New Product Launch Processes and the Impact of Agile Methodologies on Process Performance

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ABSTRACT

The global competitive landscape, shortening product life cycles, and the dynamics of electrification necessitate faster, more flexible, and more precise management of New Product Introduction (NPI) processes within the manufacturing sector. In the automotive industry, new product launch represents a critical phase bridging product design and mass production where manufacturability is validated and compliance with rigorous quality standards is ensured. While the traditional "Stage-Gate" model fosters a discipline of shared objectives and traceability, its rigid, linear structure can lead to bottlenecks, delays, and high rework costs when faced with dynamic market conditions. This study aims to analyze the operational and managerial obstacles inherent in automotive new product launch processes and to examine the impact of a hybrid "Agile-Stage-Gate" management model designed to introduce flexibility into the traditional structure on the performance of these processes.

A comprehensive literature review was conducted, and the theoretical feasibility of adapting agile methodologies to physical manufacturing environments was evaluated. It was determined that software-centric agile methods could not be directly transferred to production due to physical time constraints associated with factors such as mold making, prototype validation, and regulatory compliance. To overcome these limitations, a hybrid approach was developed that integrates short-cycle iterations and rapid feedback loops at lower operational levels while maintaining the comprehensive control points of the Stage-Gate model.

The proposed model was implemented in a real-world case study focusing on the market launch of an optical lighting component manufactured via plastic injection molding in the automotive sector. Although the customer had approved the technical documentation during the line audit, the initial inspection yielded an unfavorable result due to operator training gaps regarding work practices and visual inspection, as well as the presence of cracks on the optical surfaces of parts defects that were found to propagate a few days after production. Agile follow-up cycles were implemented to address these issues; the Process Failure Mode and Effects Analysis (PFMEA), control plan, and injection parameters were revised based on risks identified on the production floor. Subsequently, the operator competency matrix (multiskilling list) was updated, and visual inspection standards were established at the workstation.

By bridging the gap between documentation and operational reality, this hybrid approach ensured the success of the new customer audit and the subsequent approval process for serial production. The study highlights that procedural documentation alone is insufficient to guarantee effective new product introduction management in the manufacturing sector, underscoring the critical importance of hybrid models that combine on-site verification with agile flexibility.

Keywords—New Product Introduction; Agile-Stage-Gate; Automotive Industry; Bottleneck Analysis; Plastic Injection; Process Performance; Quality Management)

Alloy Design and Quenching & Partitioning (Q&P) Heat Treatment of Medium-Carbon Round-Bar Steels with High Strength and Enhanced Low-Temperature Toughness

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ABSTRACT

Meeting ISO 898-1 property class 12.9 requirements (yield strength ≥ 1100 MPa, tensile strength ≥ 1220 MPa) while ensuring strict low temperature impact toughness (min. 27 J at -40 °C) is challenging in relatively thin round bars (e.g., $\varnothing 25$ mm) using conventional quenching and tempering (Q&T). Standard grades like 42CrMo4 exhibit high distortion and quench-cracking risks during severe quenching and require expensive alloying (e.g., 34CrNiMo6) to achieve this strength–toughness balance.

To address these challenges, Quenching and Partitioning (Q&P) heat treatment was adapted for round bars, combined with optimized alloy design. Initial trials on standard medium-carbon grades confirmed that suppressing cementite precipitation and stabilizing retained austenite require elevated silicon. A medium-carbon base composition (Fe-0.29C-1.20Si-1.45Mn-1.00Cr-0.08V in wt.%) was established using thermodynamic simulations (JMatPro v10.2). To satisfy the demanding -40 °C impact toughness, the effect of molybdenum additions (0.20 wt.% and 0.40 wt.%) to the vanadium-containing base alloy (0.01 wt.% Mo) was systematically investigated.

Laboratory heats produced via vacuum induction melting and hot rolling to $\varnothing 25$ mm were austenitized at 880 °C (35 min), quenched to the Ms–Mf range (265 – 285 °C), and partitioned at 420 °C for 15 min. All experimental alloys surpassed class 12.9 tensile criteria (yield strength: 1139 – 1187 MPa; tensile strength: 1415 – 1452 MPa). Charpy impact tests at -40 °C showed that while the baseline alloy achieved 15.7 J, additions of 0.20 wt.% Mo and 0.40 wt.% Mo increased the impact energy to 21.3 J and 32.0 J, respectively, successfully exceeding the min. 27 J target without a significant increase in alloying cost compared to 42CrMo4. This work demonstrates the industrial feasibility of producing high-strength, crack-resistant round bars via Q&P heat treatment and Mo alloying.

Keywords— *Quenching and Partitioning (Q&P), Medium-Carbon Round Bars, Molybdenum Addition, Low-Temperature Impact Toughness, Retained Austenite, ISO 898-1 Class 12.9*

Antimicrobial and Mechanical Properties of Biocomposite Films with Cu-Based Metal Organic Frameworks for Packaging Materials

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ABSTRACT

The growing focus on seeking raw materials from renewable sources and efforts to reduce the environmental impact of plastic has created a greater demand for the development of biodegradable food packaging because they are recyclable, non-toxic, and derived from natural resources. The present study focuses on the preparation of PBAT/PLA/PCL, PHA/PBS, and PHA/PHBV blended biocomposite films with Cu-based metal organic frameworks (CuMOF) for food packaging applications. Biocomposite film blends based on PBAT/PLA/PCL (wt.%, 80/10/10), PHA/PBS (wt.%, 80/20), and PHA/PHBV (wt.%, 80/20) with the adding CuMOF nanoparticles (0.1, 0.5, 1.0 wt.%) as antimicrobial agent were evaluated towards their potential application in food packaging materials. The films containing with different concentrations of CuMOF were prepared by solvent-casting method. Biocomposite blended films have been investigated to develop them as an environmentally friendly material with improved mechanical and barrier properties, enabling their usage as replacements for conventional petroleum based food packaging materials. Mechanical properties, water vapor permeability (VWP), oxygen transmission rate (OTR), morphology, thermal stability, and antimicrobial activity are utilized to determine the effect of CuMOF nanocrystals concentration. The chemical and molecular structures were analyzed with ATR-FTIR spectroscopy and X-ray diffraction. The tensile strength, storage modulus and T_g were improved owing to the reinforcement of CuMOF nanocrystals in the blended polymers/MOFs biocomposites. All the films prepared with MOFs gain the increase the resistance to oxygen and water vapor permeabilities. The overall conclusion of the results indicates that the incorporation of antimicrobial nanoparticles is decisive in this prepared films appropriate for bioactive food packaging applications.

Acknowledgement: This work was supported by The Scientific Research Projects Coordination of the Yıldız Technical University (Project Number: YTÜ-BAP-FYL-2023-5692).

Keywords—Biocomposites; Biopolymers; CuMOF; Barrier films; Packaging materials

Reçine 3B Baskı ile Üretilen Üç Delikli Bir Probun Üretilirliğin ve Kullanılabilirliğin İncelenmesi

Investigation of the Manufacturability and Usability of a Three-Hole Probe Produced by Resin 3D Printing

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ÖZET

Çok delikli basınç problemleri, aerodinamik araştırmalarda ve turbomakine testlerinde akış yönünü, toplam basıncı ve statik basıncı ölçmek için yaygın olarak kullanılır. Geleneksel problemler küçük metal tüplerin işlenmesi ve birleştirilmesiyle üretilir ve bu durum problemleri pahalı, teslim süresi uzun ve özel uygulamalara uyarlanması zor hâle getirir. Eklemeli imalat ise prob ucunun, iç kanalların ve gövdenin tek parça olarak üretilmesine imkân verir. Böylelikle tasarım değişiklikleri birkaç gün içinde ve çok daha düşük maliyetle denenebilir. Buna karşın basılı parçaların boyutsal doğruluğu, yüzey kalitesi ve iç kanal bütünlüğü sınırlıdır ve bu tür problemlerin uygun bir kalibrasyon olmadan güvenilir veri verip veremeyeceği açık değildir. Bu çalışmada, reçine esaslı eklemeli imalatla üretilen düşük maliyetli üç delikli bir probun üretilirliği ve iki boyutlu akış ölçümlerindeki kullanılabilirliği, serbest jet düzeneğinde yapılan kalibrasyon yoluyla incelenmiştir. 6 mm çaplı, üç basınç delikli ve bir statik portlu prob, Elegoo Saturn 4 Ultra reçine yazıcıda ABS benzeri reçine kullanılarak üretilmiştir. Kalibrasyon, Eskişehir Teknik Üniversitesi Kalibrasyon ve Ölçüm Teknolojileri Uygulama ve Araştırma Merkezi'ndeki serbest jet kalibrasyon düzeneğinde, Mach 0,2, 0,3, 0,4 ve 0,5 olmak üzere dört jet hızında yapılmıştır. Her hızda prob, -50 ile +50 derece arasında 5 derecelik adımlarla toplam 21 sapma açısı konumuna getirilmiş; üç delikten, statik delikten ve jet toplam basıncından alınan basınçlar, kalibre edilmiş basınç sensörleriyle 200 Hz örnekleme hızıyla kaydedilmiştir. Hareketsiz ölçüm pencerelerindeki ortalama basınçlardan açı, toplam basınç ve statik basınç katsayıları hesaplanmış, her konum için sensör doğruluğuna dayalı belirsizlik sınırları belirlenmiştir.

Açı katsayısının sapma açısıyla -45 ile +45 derece arasında monoton olarak değiştiği ve sıfır derece civarındaki duyarlılığının derece başına yaklaşık 0,09 olduğu görülmüştür. Dört Mach sayısı için elde edilen katsayı eğrileri birbirine çok yakın bulunmuştur. Sapma açısının mutlak değeri 35 dereceye kadar olan aralıkta farklı jet hızları arasındaki açı katsayısı farkı 0,1'in altında kalmış, bu da yaklaşık bir derecelik açı farkına karşılık gelmiştir. Toplam ve statik basınç katsayıları da incelenen Mach aralığında hız değişiminden belirgin biçimde etkilenmemiştir. Büyük açılarda prob ucunda akış ayrılmış ve statik delikteki basınç dalgalanmaları artmıştır; bu nedenle katsayıların güvenle kullanılabileceği aralık yaklaşık -40 ile +40 derece olarak belirlenmiştir. Probun üretim maliyeti yaklaşık 10 ABD doları olmuştur; bu değer, yaklaşık 120 ABD doları olan benzer bir ticari probun maliyetinin yüzde 10'unun altındadır. Bu bulgular, prob özelinde kalibrasyon yapıldığında eklemeli imalatla üretilen üç delikli problemlerin laboratuvar ve eğitim amaçlı kullanım ile endüstriyel uygulamalardaki ön ölçümler için pratik bir alternatif olabileceğini göstermiştir.

Anahtar Kelimeler—Üç Delikli Prob; Eklemeli İmalat; Prob Kalibrasyonu; Düşük Maliyetli Enstrümantasyon; Basınç Ölçümü

ABSTRACT

Multi-hole pressure probes are widely used in aerodynamics and turbomachinery testing to measure flow direction, total pressure and static pressure. Conventional probes are produced by machining and joining small metal tubes, which makes them expensive, slow to obtain and difficult to adapt to special applications. Additive manufacturing, on the other hand, allows the probe tip, the internal channels and the stem to be produced as a single part. Thus, design changes can be tested within days at a much lower cost. However, the dimensional accuracy, surface quality and internal channel integrity of printed parts are limited, and it is not clear whether such probes can provide reliable data without proper calibration. In this study, the manufacturability of a low-cost three-hole probe produced by resin-based additive manufacturing, and its usability in two-dimensional flow measurements, were investigated through calibration in a free-jet facility. The probe, which has a diameter of 6 mm, three pressure holes and one static port, was produced from an ABS-like resin using an Elegoo Saturn 4 Ultra resin printer. The calibration was carried out in the free-jet calibration facility of the Calibration and Measurement Technologies Application and Research Center of Eskişehir Technical University, at four jet speeds of Mach 0.2, 0.3, 0.4 and 0.5. At each speed, the probe was set to 21 yaw positions between -50 and $+50$ degrees in steps of 5 degrees, and the pressures were recorded with calibrated sensors at 200 Hz. From the mean pressures in the stationary measurement windows, the angle, total pressure and static pressure coefficients were calculated with uncertainty limits based on sensor accuracy.

The angle coefficient was found to vary monotonically with the yaw angle between -45 and $+45$ degrees, and its sensitivity around zero degrees was approximately 0.09 per degree. The coefficient curves obtained for the four Mach numbers were very close to each other. For absolute yaw angles up to 35 degrees, the difference in the angle coefficient between the jet speeds remained below 0.1, which corresponds to an angle difference of about one degree. The total and static pressure coefficients were also not significantly affected by the speed change in the examined Mach range. At large angles, the flow separated at the probe tip and the pressure fluctuations at the static hole increased; therefore, the range in which the coefficients can be used reliably was determined to be approximately -40 to $+40$ degrees. The production cost of the probe was approximately 10 US dollars, which is less than 10 percent of the cost of a comparable commercial probe of approximately 120 US dollars. These findings showed that, when a probe-specific calibration is performed, three-hole probes produced by additive manufacturing can be a practical alternative for laboratory and educational use and for preliminary measurements in industrial applications.

Keywords—*Three-Hole Probe; Additive Manufacturing; Probe Calibration; Low-Cost Instrumentation; Pressure Measurement*