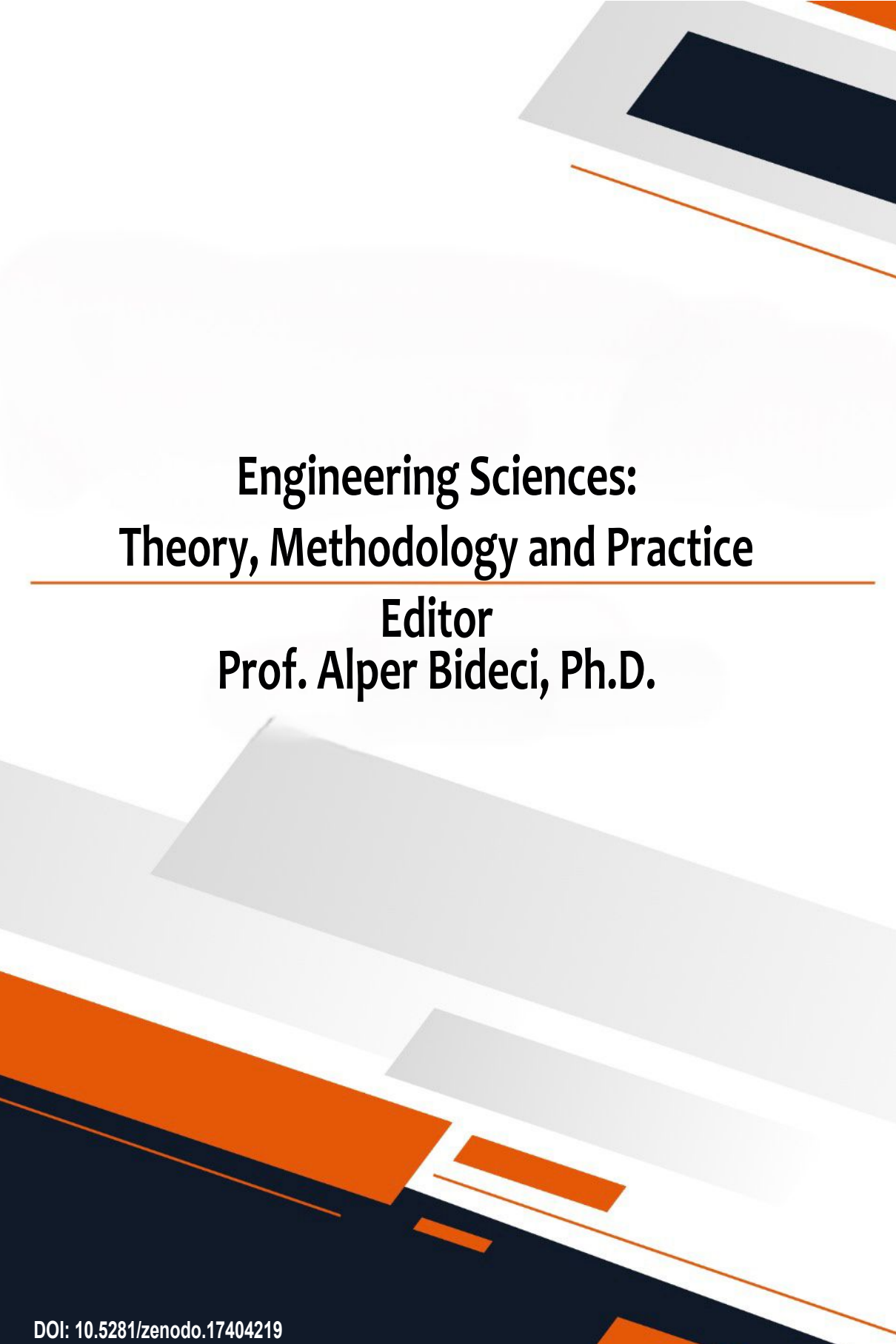




Engineering Sciences: Theory, Methodology and Practice

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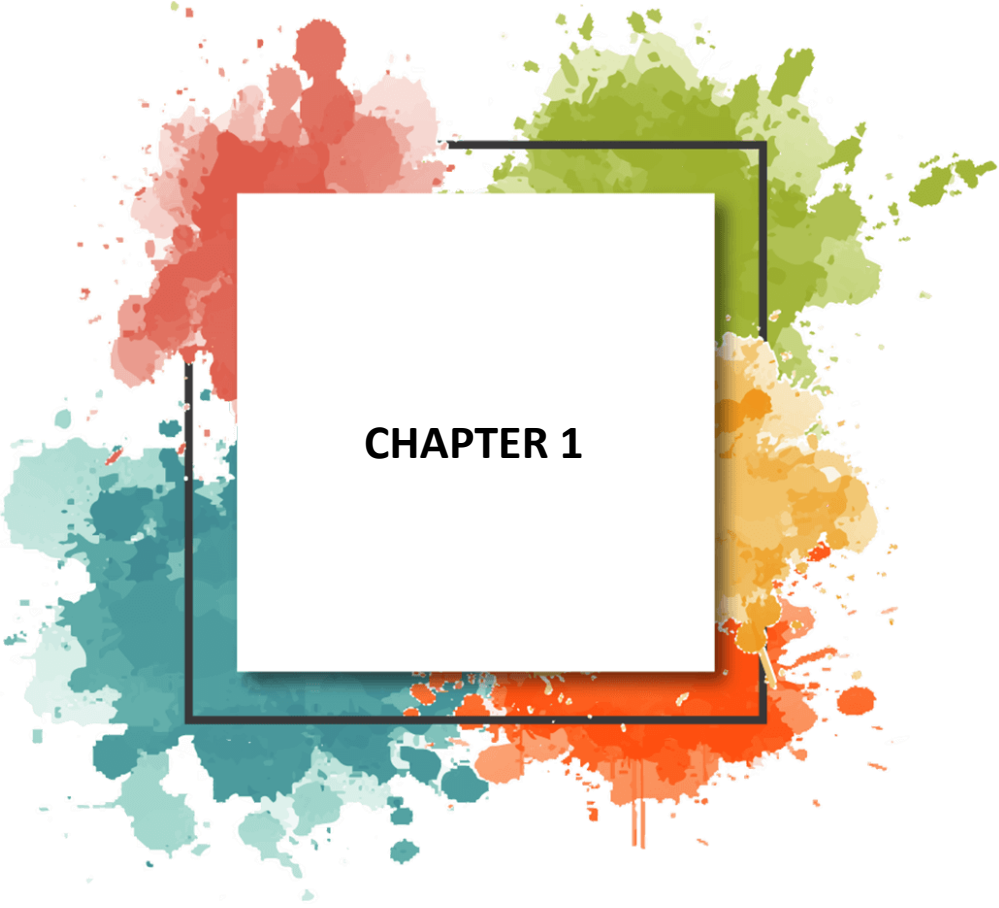


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CHAPTER 1

Hydrogels in Agriculture: Next-Generation Approaches for Sustainable Water and Input Management (Mini Review)

Khanda A. Khorsheed¹ & Şeyda Taşar² & Fethi Kamışlı³

INTRODUCTION

Hydrogels are highly cross-linked polymeric networks, that can absorb and retain large amounts of water while being totally or partially insoluble in its aqueous environment [1]. These hydrogels provide great use in agriculture and production agriculture, especially under collagen water stress conditions, including draught periods [2, 3]. Hydrogel technology was first used in the 1960s when Otto Wichterle and Drahoslav Lim created the first hydrogel poly (2-hydroxyethyl methacrylate) to be used in contact lenses [4]. Researchers and engineers began studying hydrogels in a lot of applications from hydrogels in mainly the 1980's synthetic hydrogels which are normally based on polyacrylamine or polyacrylate, are now incorporated in agriculture applications for moisture retention as well as increasing the Fund of fertilizers and yield of crops [5]. Today, because there is a better sense of environmental stewardship, hydrogels are now being used that are based on renewable and biodegradable materials such as those derived from cellulose, starch, and chitosan [6,7]. In an agricultural environment, a hydrogel acts as a reservoir storing some of the water available from rain and irrigation to store moisture in the soil and release it during dry periods, in effect stabilizing soil moisture around the roots of crops, particularly in sandy soils that may lack moisture retention [8]. Thus, the amount of irrigation is lowered, conserving labor and water, while encouraging robust root systems, and increased productivity in growing crops [9]. Hydrogels are capable of storing water, but they can also deliver pesticides, fertilizer abuse, and nutrients, allowing them to offer slow-release formulations while improving plant uptake and minimizing runoff and waste to the environment (Figure 1) [10]. They also improve soil porosity, as well as increasing microbial activity, and exchange gasses in the surrounding root zone [11]. Hydrogel performance can be influenced by numerous things including their structural properties, particle size, and the soil that the hydrogel adsorbs and interacts with [12].

¹ Kimya Mühendisliği, Mühendislik Fakülte, Fırat Üniversitesi, Elazığ, Türkiye

² Kimya Mühendisliği, Mühendislik Fakülte, Fırat Üniversitesi, Elazığ, Türkiye

³ Kimya Mühendisliği, Mühendislik Fakülte, Fırat Üniversitesi, Elazığ, Türkiye

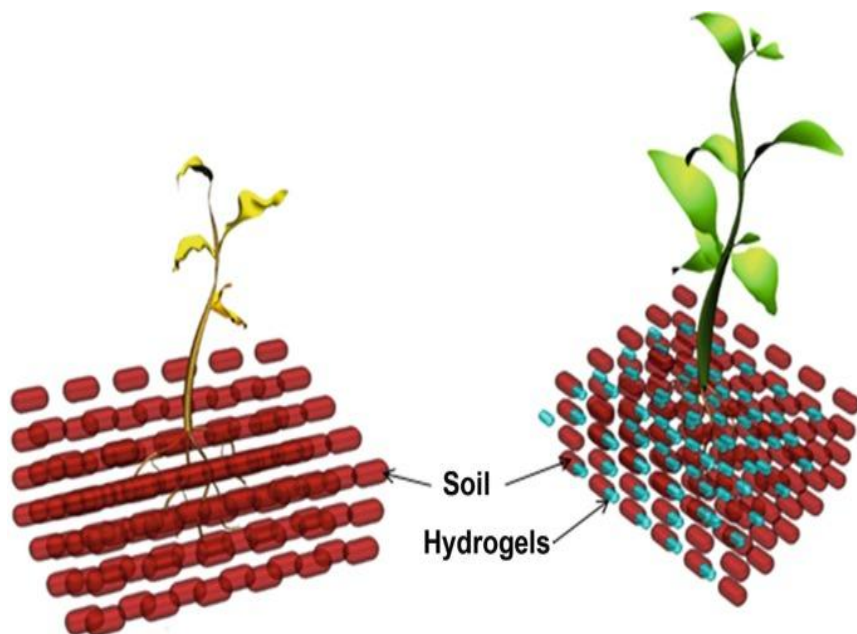


Figure 1. Schematic Representation of Hydrogel-Based Fertilizer Delivery System

Recent scholarly articles distinguish between natural and synthetic hydrogels, with growing interest in the use of biodegradable variants for promoting sustainable agricultural practices. Ongoing research focuses on the development of “smart” hydrogels—materials capable of sensing environmental conditions such as temperature, pH, and soil moisture, and responding by releasing water and nutrients at optimal times. Another area of innovation involves producing hydrogels from agricultural waste materials, contributing to circular economy strategies in farming systems. Encapsulated hydrogel formulations are emerging as environmentally friendly solutions to enhance the performance of food crops, particularly in response to challenges related to water quality, global population growth, and climate change adaptability [13,14].

Hydrogel Characteristics

Hydrogels may have certain well-defined properties depending on the polymers that are selected, the method of crosslinking, and the amount of crosslinking, and yet these properties may be designed in such a way that they perform in an agricultural context [15, 16, 17, 18, 19, 20]. The crystallization as well as the swelling of the polymer follow both the elastic and the crosslinking density level of the polymer according to the Flory solution, but the crystallization can be conducted after heating/cooling or a change in solvent

composition [17, 19,21]. In the release of fertilizer, the controlled release systems i.e. will be harder, stronger, and stiffer; in comparison to this, polymer networks will be relatively soft systems and very probably will demand mechanical reinforcement (i.e., composite or double-network hydrogels) in the area that longevities are demanded [22,23]. Linear elastomeric polymer chains that are loosely crosslinked can be combined with highly crosslinked short brittle chains to form double-network hydrogels with significantly enhanced mechanical properties [23]. The volume of water content and the number of hydroxyl groups are used to describe the mechanical viscoelasticity of hydrogels as a component of an overall structure since the components of the hydrogel's viscosity and the volumetric viscoelastic can be theologically identified by determining G (storage modulus), G' (loss modulus) and $\tan \delta = G''(\text{loss modulus})/G(\text{storage modulus})$ [23,24]. Chemical crosslinking and fixing crosslinks of hydrogels took place. The physically cross-linked hydrogels can self-heal in the event of damage since they are reversibly cross-linked. Most of the sectors require improvement in terms of stability at least to such an extent but in bio-based systems, there will be a limited scope of biodegradation (and less toxicity) that would be suited in urban agriculture; and in terms of synthetics, there will be less biodegradation and toxicity issues observed [15, 25,26]. It was stated that hydrogels can absorb and retain water through four mechanisms i.e. the interstitial, free or bulk, semi-bound, and bound (primary and secondary) [16, 27, 28, 20]. Not only that superabsorbent hydrogels are more likely to absorb and hold up more water than when a non-superabsorbent hydrogel is used, but it is more likely to be able to hold up with lots of water. The occurrence of this phenomenon can significantly be attributed to the development of osmotic pressures, which are subject to formation as a result of the dissociation of the ionic groups of groups which is expected during the initial crosslinking of the group and which in turn impacts water uptake. As is the case with soil moisture absorption, another very important property of a hydrogel, swelling, can be dependent on the structure of the hydrogels and their physical surroundings. The polyelectrolyte hydrogel is mentioned in several miscellaneous topics such as the extent of dissociation, the density of the mesh, the percentage of ionic groups in the polymer, and those factors that influence polymer-water interactions. The equilibrium swelling may be described as a situation in which the swelling pressure is zero and the quantities considered are those of osmotic pressures, the elasticity of the mesh, and the supply of ions [29]. Experimental swelling can be seen in the optical methods since it cannot be restricted to the visible media; alternatively, the volume can be used on certain forms of a sample [30].

Types and Properties of Hydrogels

Hydrogels are an agricultural technology that are being developed quickly and have the potential to significantly change the tolerance of crops to stress, their water use efficiency, and increase sustainability [31]. Hydrogels are three-dimensional polymeric networks that have the potential to absorb very large quantities of water and can be used in situations where there is available, and limited water resources, with uncertain patterns of rainfall [32]. As an example, hydrogels can absorb and retain up to 500 times their weight in water, which may also be arranged so they intermittently irrigate a plant periodically, which is when the surrounding media is dry [33]. Hydrogels are a flexible class of material because they can absorb and store massive volumes of water, and the possibilities of utilizing hydrogels in agricultural applications may be conceptualized. Hydrogels can be classified in many different ways (when classified according to polymer origin, type and/or crosslinking method or simply on their interaction with water), and when developing a hydrogel, it is useful to establish if a hydrogel should be classified to help select an optimal hydrogel for your agricultural use, as hydrogels may vary in strengths and weaknesses [34].

Hydrogel Classification

Hydrogels can be classified based on various criteria, including their source, synthesis method, and polymer network structure. Typically, the classification depends on the specific functional requirements of the intended application. Based on origin, hydrogels fall into three categories: natural, synthetic, and **hybrid**.

Natural hydrogels are derived from biological sources such as proteins, polysaccharides, or nucleic acids. Examples include alginate [36], pectin, carrageenan, chitosan [37], polylysine, collagen, carboxymethyl chitin, carboxymethylcellulose, dextran, agarose, and pullulan [38]. Synthetic hydrogels, developed from monomers like polyvinyl alcohol, polyethylene glycol, and polyacrylic acid, are widely used due to their tunable mechanical and degradation properties.

Hydrogels are also categorized by surface charge. Anionic hydrogels are formed from negatively charged polymers such as alginic or hyaluronic acid [39], whereas cationic hydrogels are based on positively charged polymers like chitosan and polylysine. Neutral hydrogels include polymers such as pullulan, agarose, and dextran, and amphoteric **hydrogels** contain both acidic and basic functional groups [40].

Classification can also depend on the polymerization method—such as bulk/solution polymerization or suspension polymerization—and network structure. Hydrogels may be homopolymers (from a single type of monomer),

copolymers (from two or more different monomers), or part of interpenetrating polymer networks (IPNs) or semi-IPNs, where linear polymers interlace within crosslinked networks without covalent bonding [41,42]. For example, semi-IPNs such as cationic poly(allyl-ammonium chloride) or copolymers like acrylamide-acrylic acid are known for their rapid responsiveness to pH and temperature changes [43]. Hybrid systems may also form through in situ synthesis involving one polymer in solution and another crosslinked, such as poly(N-isopropyl acrylamide) with chitosan [44]. Based on the bonding nature, physical hydrogels rely on non-covalent interactions like van der Waals forces or electrostatic attractions [45], while chemical hydrogels form covalent networks offering enhanced strength and durability. Structurally, hydrogels can be further distinguished into three-dimensional crosslinked networks or linear chain polymers [46]. Table 1 presents an overview of these hydrogel classification criteria. Beyond agriculture, hydrogels are also widely used in biomedical fields (e.g., drug delivery systems, wound dressings, and tissue engineering) [47], as well as in industrial applications like sensors and packaging [48]. This study will specifically address the role of hydrogels in agriculture—particularly their function in water retention and nutrient delivery in soils [49].

Advantages and disadvantages of hydrogel in agriculture

Hydrogels have been developed as valuable agricultural tools, primarily due to their exceptional capacity to retain water and improve soil structure. One of their key benefits is their ability to significantly enhance soil moisture retention, which is especially crucial in dry or sandy soils with low water-holding capacity (Figure 2). Additionally, hydrogels support the timely delivery of nutrients, promoting optimal nutrient uptake by plants and reducing nutrient losses caused by leaching—thereby minimizing environmental impact. They also improve soil porosity and structure, which facilitates better aeration and root penetration. Their effectiveness in minimizing water runoff and erosion also makes them useful environmentally. In spite of all these advantages, there are several drawbacks to their general availability. Natural hydrogels possess poor tensile strength that renders them unsuitable in the field as they tend to degrade when exposed to agricultural forces. The price of producing modern hydrogels is also an economic limitation, especially for small-scale manufacturers. Also, hydrogels are not bountiful since some of the intricate or trace nutrients cannot be retained. The logistics of utilizing hydrogels is another distinctive problem since hydrogels require special equipment and/or techniques if they are to be evenly distributed over the entire soil. In brief, hydrogels have potential for the sustainable agriculture sector, but the industry needs to overcome a number of challenges for this to materialize [50].

Table 1. Classification of hydrogels. Adapted from Tariq et al. [45] and Vasile et al. [47].

Classification Factor	Types / Examples
Source	-Natural Polymer (e.g., collagen) -Synthetic Polymer (e.g., polyvinyl alcohol) -Hybrid Hydrogels (e.g., polyvinyl alcohol + gelatin)
Polymer Composition	-Homopolymeric(e.g., poly(N-isopropyl acrylamide)) -Heteropolymeric (e.g., poly(vinyl alcohol)-gelatin) -Copolymeric (e.g., poly(PEGMA-co-monomethyl itaconate))
Network Structure	- Physical Cross-linking (e.g., freeze-thawing) - Chemical Cross-linking (e.g., glutaraldehyde)
Electrical Charge	- Ionic Polymer (e.g., cationic or anionic) - Neutral (no charge) - Amphoteric (e.g., both acidic and basic groups)
Physical Aspect	-Microparticle/Nanoparticle(e.g. microbead, nano gel) - Film/Membrane (e.g., electrospun mat) -Matrix(e.g., scaffold) - Gel (e.g., injectable drug-loaded hydrogel)
Pore Size	-Nanoporous -Microporous -Super porous
Configuration of Chains	-Non-crystalline (e.g., random arrangement, amorphous domains) - Semi-crystalline (e.g., crystalline domains)

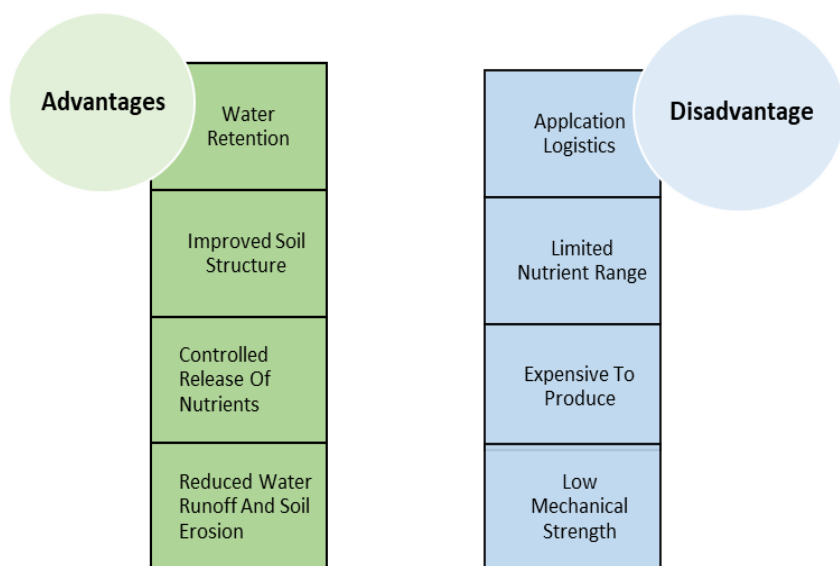


Figure 2. Advantages and disadvantages of hydrogel in agriculture

Applications of Hydrogel in Agriculture

To date, hydrogels have been most commonly utilized in agriculture as soil water reservoirs [51,52], seed coatings to promote germination and seedling establishment [53], and carriers for nutrients, plant growth regulators, or protectants for controlled release [54]. These materials help minimize the loss of rainwater or irrigation through evaporation and runoff by forming hydrogen bonds between their polymer chains and water molecules.

As shown in Figure 3, when the soil around plant roots begins to dry and water uptake continues, the hydrogel gradually releases its stored water through simple diffusion, making it available to the root system. This desorption process enhances the efficient use of available water resources. Furthermore, incorporating hydrogels into soil improves nutrient uptake, reduces leaching, and enables a slow, sustained nutrient release profile [55]. Hydrogels also enhance the physical properties of the soil medium, including permeability, texture, and porosity—contributing to better root development and overall soil health.

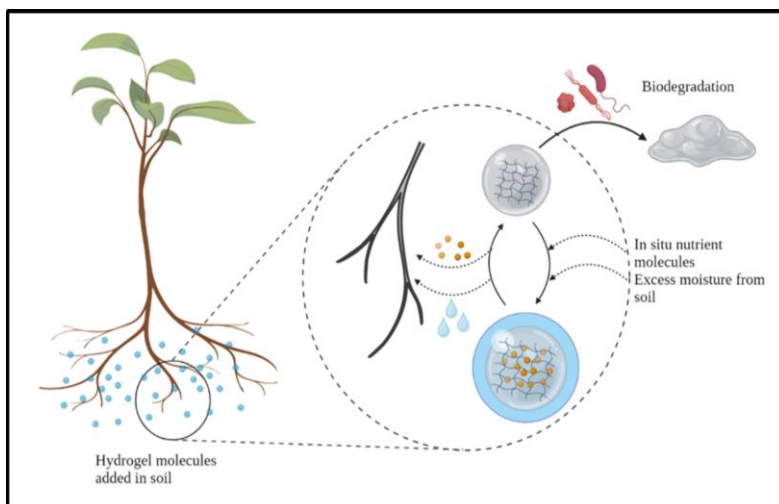


Figure 3. Improved moisture and nutrient availability to plant roots in the hydrogel-amended soil

Most importantly, as water molecules become imbibed within the hydrogel granules, the hydrated granules swell, causing soil structures that may be compacted to loosen. This loosening allows for improved gas exchange through plant roots [56]. The benefits of hydrogels will find direct use in agriculture. Four applications of hydrogel in agriculture are discussed here.

Innovations and Future Developments in Hydrogel Technology for Agriculture

Hydrogel technology is advancing rapidly in response to pressing challenges in modern agriculture, including water scarcity, land degradation, and climate change. Recent innovations in hydrogel synthesis and application have opened new pathways for integrating these materials into sustainable agricultural practices. This section outlines emerging developments and future directions in hydrogel technology, highlighting its potential to support continued progress in the agricultural sector.

DISCUSSION

This study has comprehensively examined the functionality, benefits, and limitations of hydrogels in agricultural applications. As highlighted in the literature, hydrogels show considerable promise for sustainable agriculture, particularly in arid and semi-arid regions, due to their ability to enhance soil water retention and reduce irrigation frequency [1, 24]. Their controlled-release capacity for agrochemicals also improves nutrient use efficiency and reduces environmental pollution caused by leaching and runoff [2, 7].

However, several technical and economic challenges restrict the field-scale application of hydrogel technologies. Natural hydrogels generally exhibit poor mechanical strength and degrade more rapidly under open-field conditions, reducing their long-term effectiveness [3, 22]. While synthetic hydrogels offer better durability, their limited biodegradability raises environmental concerns. Furthermore, high production costs and the need for specialized application equipment pose challenges, especially for smallholder farmers [4, 5].

Future research is likely to focus on the development of “smart” hydrogels that respond to environmental stimuli such as pH, temperature, and soil moisture. These materials can enable site-specific and time-controlled delivery of water and nutrients, which is a key advantage in precision agriculture [18, 23]. Additionally, the use of agricultural waste-derived biopolymers offers a sustainable and cost-effective pathway to produce eco-friendly hydrogels [55, 56].

In conclusion, hydrogel technology holds significant potential in improving water management, input efficiency, and environmental sustainability in agriculture. However, realizing this potential fully requires interdisciplinary efforts spanning polymer science, materials engineering, soil science, and agronomy, along with comprehensive field-scale trials.

CONCLUSION

The incorporation of hydrogel technology into agricultural uses can address issues in agriculture such as water shortages, soil contamination, and inefficient use of inputs. Hydrogel provides physical-chemical properties such as high water absorption and swelling properties, and controlled release, resulting in improved nutrient and water retention in soil, which can mitigate abiotic stresses in crops. Hydrogels have transitioned from biopolymer origins to multifunctional agricultural products, and represent both synthetic and biodegradable types of material. The most important distinctions between hydrogel types include polymer origin, mode of crosslinking, charge, and network structure, all of which affect how hydrogels respond to the specific agro-ecological conditions. Despite advances, barriers remain for premise-wide adoption of hydrogels, including issues with production costs, mechanical fragility of biopolymers, and feasibility of applying biopolymers in the field at scale. Synthetic hydrogels may be durable, but have challenges related to biodegradability and environmental implications. Natural hydrogels are more environmentally sustainable, but require improvements to their physical properties to be broadly adopted into agriculture. Recently, “smart” or hybrid hydrogels responsive to environmental variables such as pH and soil moisture status, have emerged as possible applications for precision agriculture. The creation of agricultural hydrogels involves interdisciplinary cooperation across the disciplines of polymer chemistry, materials science, soil science, and agronomy. Additional work on the use of

agricultural wastes biopolymers in the development of low-cost, high-performance, eco-sensitive hydrogels is important work to pursue. Given the global pressures of climate change and food security, hydrogels could potentially provide disruptive targeted technologies that will assist soil health, water conservation, and sustainable crops in resource-limited environments.

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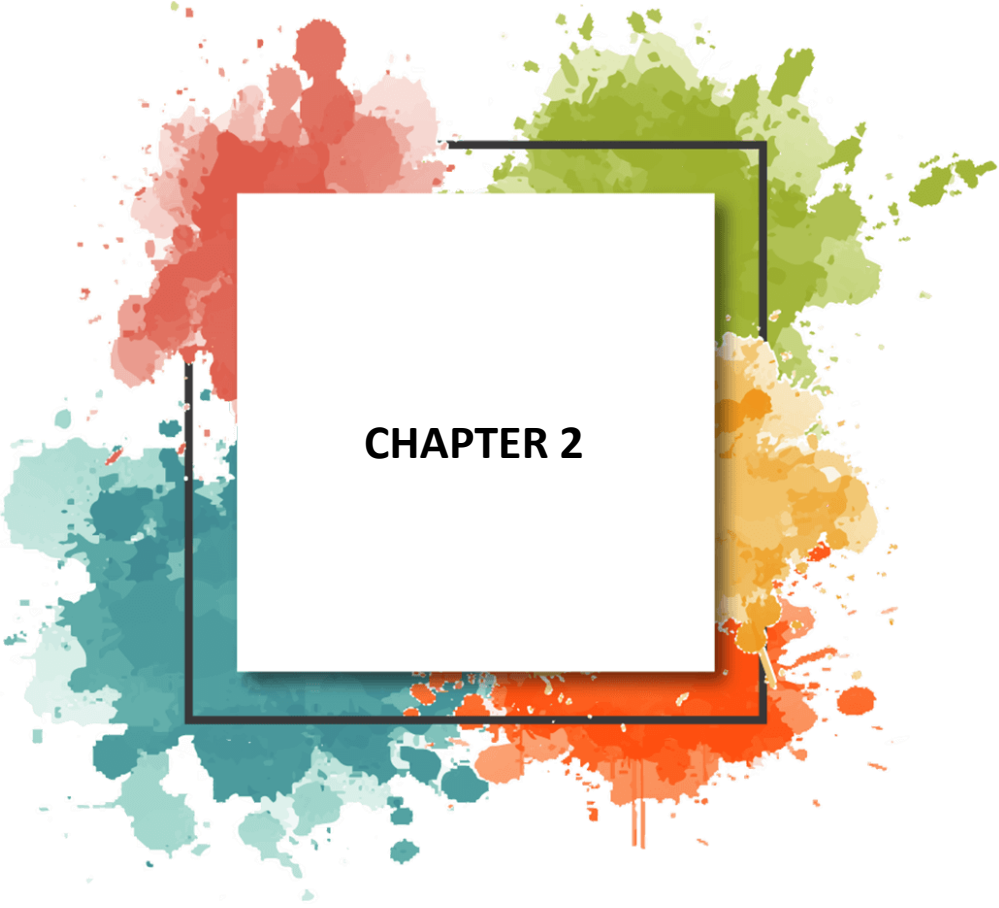
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CHAPTER 2

An overview of Friction Stir Welding (FSW) Technologies

Furkan Sarsilmaz¹

1. INTRODUCTION

In modern manufacturing environments, joining operations are essential due to the widespread use of multi-component assemblies in industrial products. As a result, joining technologies serve as foundational enablers that not only ensure functional integration of components but also enhance manufacturing efficiency. Among these, welding stands out as a specialized fabrication technique that facilitates the construction of intricate assemblies from materials that are either challenging or uneconomical to produce as monolithic structures. In such instances, individual components are fabricated separately and subsequently assembled through suitable joining methods. Rather than replacing traditional manufacturing techniques, welding complements them by enabling the realization of complex assemblies. Hence, the weldability of a material remains a key consideration in determining its industrial applicability and widespread usage. The increasing demand for lightweight, high-performance, cost-effective, and functionally advanced products in contemporary engineering has driven the necessity for integrating dissimilar materials within single assemblies. However, joining different types of materials presents significant complexities, particularly arising from differences in their physical, chemical, and thermal properties. Such incompatibilities can lead to incompatibilities within the joint, rendering traditional fusion welding processes inadequate and weakening the structural performance of the weld. To overcome these limitations, friction stir welding (FSW) has emerged as a promising solid-state joining method operating below the melting temperature of the base materials. By inducing plastic deformation rather than fusion, FSW significantly reduces common welding problems such as thermal deformation, residual stress, and metallurgical defects (Elrefaey, 2015). This capability provides superior mechanical integrity and geometric accuracy, particularly in structural applications where both strength and dimensional accuracy are critical. Due to advantages, FSW has been widely adopted in high-demand industrial sectors such as aerospace, automotive, marine, and rail transportation. In aerospace applications, FSW is used to join components requiring high integrity, such as aircraft fuselages, thin walled structural panels, and fuel tanks in these areas, weld quality and geometric precision are crucial. In

¹ Assoc. Prof. Dr., Fırat University, Faculty of Technology, Department of Mechatronics Eng., ORCID: 0000-0001-5351-8645

the automotive welding sector, the process contributes to the production of lightweight, structurally sound components, improving fuel efficiency and vehicle safety. Similarly, in the railway industry, FSW plays a central role in the production of pressure-resistant tanks, freight cars, and passenger trains. Overall, the growing industrial applications of FSW demonstrate the technology's great potential as an alternative or complementary method to traditional welding processes. FSW offers a reliable, energy-efficient, and environmentally friendly solution for joining similar or dissimilar materials into complex configurations. Therefore, the continued development and improvement of FSW and related solid-state joining technologies is crucial to meeting the evolving requirements of modern engineering and manufacturing systems.

2. Process and Parameters of Friction Stir Welding (FSW)

Friction Stir Welding (FSW) is a solid-state joining method (Fernanda & Brito 2020) and is performed using a non-consumable rotating tool consisting of a specially designed shoulder and pin, usually made of a material harder than the base materials. Initially developed and patented in the early 1990s by The Welding Institute (TWI) in the United Kingdom, the FSW process was primarily intended for linear welding operations in butt and lap configurations of sheet and plate materials. A schematic representation of the FSW process is provided in Figure 1 (Sarsilmaz, 2018). Recognized as one of the most transformative welding innovations of the last few decades, FSW has evolved beyond its original scope. In this method, a tool is inserted into the adjacent edges of the workpieces to be joined and advanced along the weld line, generating local heat through friction and severe plastic deformation. This thermal and mechanical interaction allows the materials to be mixed and forged in a plasticized state, resulting in the formation of a metallurgical bond before reaching the melting temperature (Sampurna, Somnath & Sachindra 2022). The stirred material around the pin undergoes dynamic plastic deformation and recrystallization, creating a fine-grained, equiaxial microstructure. The combined effect of the tool's rotational and propulsive motion ensures a homogeneous material flow and a solid-phase bond (Sarsilmaz 2018). The regions and appearance of the microstructure after the FSW process are shown in Figure 2.

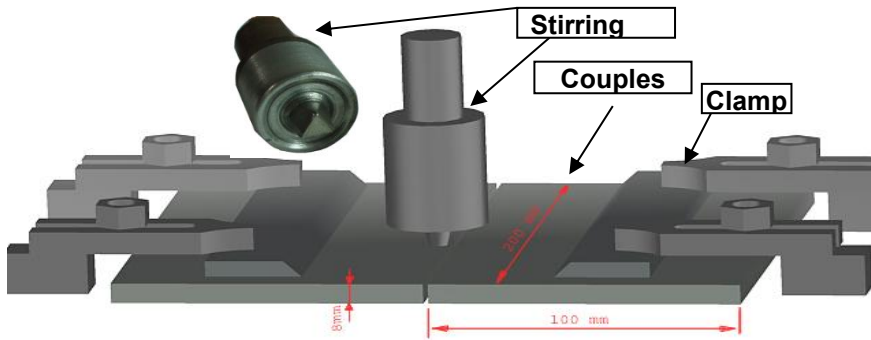


Figure 1 Schematic representation of FSW. (Sarsilmaz, 2018)

Welds obtained with FSW are generally divided into four distinct zones, each with its own unique microstructural and mechanical properties:

1. **Parent Material (PM):** The unaffected region that retains its original properties, experiencing no thermal or mechanical alteration during the process.
2. **Heat-Affected Zone (HAZ):** A thermally influenced region that undergoes property changes such as grain coarsening, strength reduction, and decreased corrosion resistance, without undergoing plastic deformation.
3. **Thermo-Mechanically Affected Zone (TMAZ):** The region that experiences both elevated temperature and plastic deformation, yet insufficient for full recrystallization. Grains here are typically elongated and coarser than in the stirred zone.
4. **Stir Zone (SZ)/Weld Nugget Zone (NG)/Dynamically Recrystallized Zone (DXZ):** This is the core region directly influenced by the rotating pin, where dynamic recrystallization results in refined, equiaxed grains often showing a characteristic onion-ring pattern (Sarsilmaz, Kirik & Batı 2017).

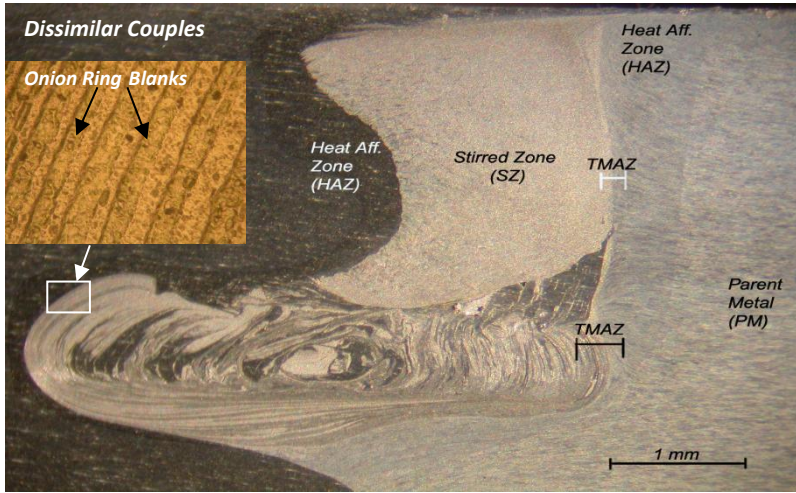


Figure 2. Microstructural changes in the internal section after FSW (Sarsilmaz, 2018)

The efficiency and quality of an FSW joint are highly dependent on the optimization of key process parameters. These include tool rotational speed, transverse (welding) speed, plunge depth, tilt angle, tool geometry (pin length, diameter, and shape), and tool offset all of which significantly influence material flow, temperature distribution, and final joint properties (Gao et. all. 2020). To explain all of this briefly:

Tool Geometry: Among all parameters, tool geometry plays the most critical role. It determines heat generation and governs the material flow around the pin. A well-designed tool ensures uniform grain structure, improved joint strength, and defect-free welds (Li, G.H, Zhou, L., & Luo, SF, 2020).

Rotational Speed: This defines the rate of tool rotation and directly affects the amount of frictional heat generated. Higher rotational speeds result in increased heat input and enhanced material stirring but may also lead to excessive grain growth and reduced mechanical properties. Conversely, too low a speed results in insufficient plasticization. Therefore, a balanced rotational speed is essential for optimal weld quality (Ünal, Karaca, & Sarsilmaz, 2019).

Transverse Speed (Welding Speed): This is the linear velocity of the tool along the joint. Increasing the welding speed tends to enhance tensile properties due to reduced heat input, but may compromise tool life due to the need for higher axial force and torque. At optimal speed, a fine-grained microstructure and superior joint strength are achieved.

Tool Tilt Angle: This is the angular inclination of the tool relative to the vertical axis. A proper tilt angle ensures enhanced material consolidation, reduces tool stress, and promotes defect-free welds. Excessive tilt can cause weld flash, while inadequate tilt may lead to poor mixing and defects.

Plunge Depth: Defined as the vertical penetration of the tool into the workpiece, plunge depth governs the contact conditions, heat generation, and the extent of the stirred zone. Excessive plunge depth may cause excessive flash and surface defects, while insufficient depth results in weak bonding and lack of joint integrity.

Tool Offset: Tool offset refers to the intentional lateral shift of the tool axis from the joint centerline commonly used in dissimilar material welding. Offset toward the softer material facilitates balanced material flow and minimizes interfacial defects.

By optimizing these parameters, FSW enables the production of robust, defect-free joints across a wide range of materials and configurations without the need for additional filler metals or post-weld machining.

2.1 Influence of Welding Parameters on the Microstructure and Mechanical Behavior of Similar and Dissimilar FSW Joints

A lot of studies have purposefully examined the effects of various process parameters on the microstructural development and mechanical behavior of Friction stir welded (FSW) joints involving both similar and dissimilar material pairings. Although tool type and geometry is a main factor in all FSW operations, its importance becomes particularly becoming clear when welding dissimilar materials. This is due to complexities such as the formation of intermetallic compounds and an increased tendency for defect generation, which demand precise tool design and highly controlled process conditions (Mansour, Mehrdad, & Safarkhanian, 2021). Therefore, ensuring high-quality welds in dissimilar material configurations requires a more stringent optimization of process parameters compared to similar material FSW applications. Some of precisely study showed that, The relative positioning of parent materials with respect to the tool significantly affects joint strength and hardness properties in dissimilar welding scenarios. (Simoncini, Ciccarelli, Archimede & Pieralisi 2014), investigated the combined effects of stirrer tool configuration and welding parameters on FSW of similar and dissimilar joints between magnesium alloy and aluminum alloys . Findings revealed that the ratio of tool rotational speed to transverse speed had a pronounced impact on joint quality. The dissimilar joints demonstrated reduced ductility and tensile strength relative to their respective base materials, and metallographic analysis showed the formation of a distinct bonded interface at the weld cross-section.

Ahmed et. all. (2017) studied FSW of aluminum alloys AA7075-T6 and AA5083-H111, analyzing both similar and dissimilar joints under constant rotational speed and variable traverse speeds. It was found that, in both cases, significant grain refinement occurred in the nugget zone (NG). Notably, an increase in welding speed resulted in finer grains for similar joints, while dissimilar joints exhibited minimal grain size variation. Fractographic analysis indicated a mixed-mode fracture mechanism combining both brittle and ductile characteristics in dissimilar welds.

Zhang et. all. (2017) further explored the role of rotational speed on the mechanical and microstructural characteristics of similar and dissimilar joints between AA7075-T651 and AA2024-T351. The study demonstrated that higher rotational speeds enhanced material mixing and promoted the development of onion ring-like flow patterns in dissimilar welds, whereas lower speeds inhibited intermixing. Additionally, the width of the Thermo-Mechanically Affected Zone (TMAZ) was sensitive to rotational speed variations in both joint types. Interestingly, while tensile properties of dissimilar welds were significantly influenced by changes in rotational speed, similar welds showed relatively stable mechanical behavior across the same parameter range. Fracture surface analysis confirmed a brittle-ductile mixed-mode failure in dissimilar joints, while similar joints tended to fracture in a predominantly brittle manner.

2.2. Recent Advancements in Weldability and the Rise of Friction Stir Welding (FSW)

In recent years, significant advancements in material weldability and the development of new-generation joining technologies particularly Friction Stir Welding (FSW) has further underscored the importance of welding in advanced manufacturing. Today, FSW is widely applied across various high-performance industries including defense, maritime engineering, lightweight high-speed train manufacturing, and aerospace applications (Cerri & Leo 2012). The growing demand for complex, weld-intensive structures in the transportation sector driven by rapid technological progress has notably expanded the range of FSW applications. High-speed trains, passenger and military aircraft, electric vehicles, cargo planes, and cruise ships are among the prominent examples of such structures. In the rail sector, for instance, FSW is the preferred technique for joining aluminum alloy extrusion panels used in high-speed train carriages. Similarly, in the aerospace industry, this technique has proven successful in fabricating aircraft fuselage structures and fuel tanks. More recently, the method has seen increasing adoption in the production of battery carrier systems for electric vehicles, highlighting its growing industrial relevance.

Although originally designed for aluminum alloys, FSW has demonstrated considerable potential in the joining of a broad range of materials, including non-ferrous metals such as titanium, magnesium, and copper alloys, as well as advanced composites, stainless steels, and thermoplastics (Ekinçi, & İmak, 2024). Furthermore, its effectiveness extends to welding aluminum alloys with similar thermal properties and deformation behaviors, as well as joining dissimilar types of steel, making it a versatile and robust solution for modern material joining challenges. See Figure 3, which illustrates the process steps of the FSW process.

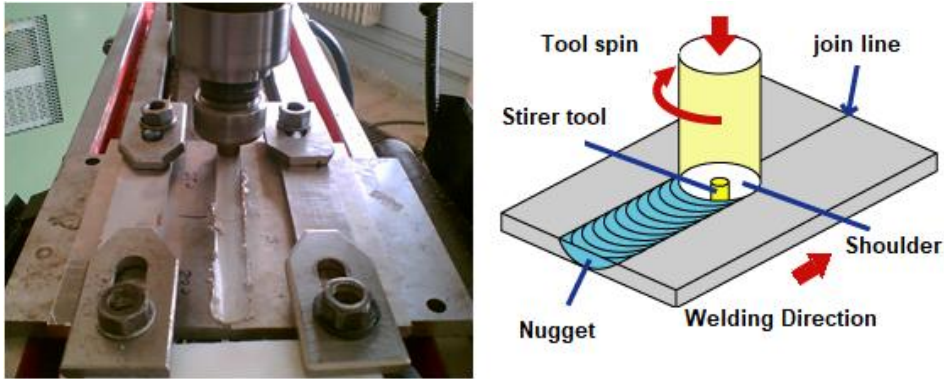


Figure 3. FSW implementation stages (Sarsilmaz, 2008).

2.3. Recent Variants and Enhancements in Friction Stir Welding Technology

To enhance joint performance and expand the applicability of Friction Stir Welding (FSW), several innovative process variants have been developed in recent years. One such advancement is Friction Stir Spot Welding (FSSW), which has emerged as a viable alternative to conventional resistance spot welding (RSW) for overlap joints of aluminum alloy sheets where sealing is not required. FSSW has shown notable success in joining aluminum and copper sheets materials traditionally challenging for RSW thus positioning itself as a complementary method to standard FSW in automotive applications, especially for spot welding of lightweight aluminum body structures. This technique is particularly promising for industrial-scale use in the lap joining of aluminum sheets and offers potential to replace mechanical fastening methods such as riveting. A variety of joint types can be produced with friction stir welding, including butt-to-butt, lap, and T-joints (Figure 4). However, friction stir welding requires cost-effective stir tooling to join metal-matrix composites and high-melting-point metals, such as steels and Ti alloys (Kashaev, Ventzke, & Çam, 2018).

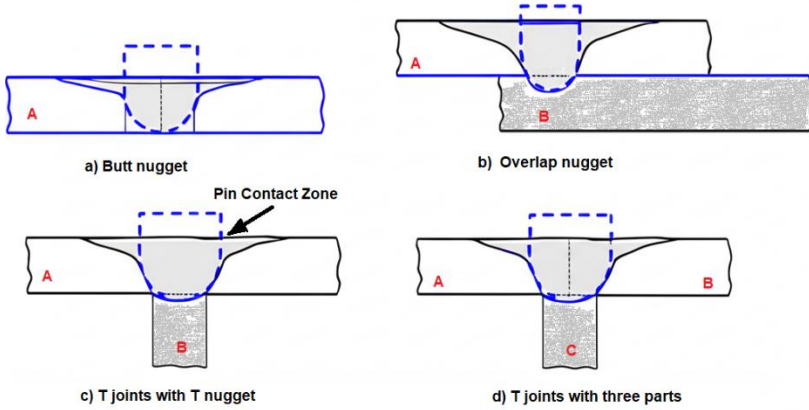


Figure 4. Welding types applied by the FSW method: (a) butt joint, (b) overlap joint, (c) T-connection with two pieces of plate, and (d) T-connection with three pieces of plate (Kashaev, Ventzke, & Çam, 2018).

FSW also addresses many of the drawbacks associated with conventional fusion welding techniques. For example, in Gas Metal Arc Welding (GMAW), electrical energy is used to melt the base materials, which are then fused upon solidification. This process involves the use of consumable electrodes and shielding gases. However, GMAW is susceptible to several defects including porosity, tunnel formation, a relatively wide Heat-Affected Zone (HAZ), component distortion, surface degradation, and the emission of hazardous gases and fumes. These emissions pose serious health risks to full-time operators, including irritation of the eyes, nose, and throat, as well as more severe conditions such as Parkinson’s disease and pulmonary edema (Mohamed, et.all. 2021).

Conventional FSW, being a solid-state process, avoids many of these thermal issues by operating below the melting point of the materials involved. Furthermore, ongoing improvements have led to the development of enhanced FSW variants. These include externally cooled FSW such as underwater FSW which reduce heat input and are particularly effective in achieving high-performance joints. Ultrasonic vibration-assisted FSW is another innovation aimed at minimizing the formation of brittle intermetallic phases when joining dissimilar metals.

Among the more advanced process variants designed to overcome specific limitations of traditional FSW are refill friction stir spot welding (RF-FSSW), which eliminates the exit hole left by the tool; stationary shoulder FSW (SS-FSW), which offers lower heat input and more stable thermal conditions; and bobbin tool FSW (BT-FSW), which provides full-penetration welds while

minimizing root defects. These innovations represent significant steps forward in adapting FSW to complex geometries and demanding structural applications across multiple industries (Kashaev, Ventzke, & Çam, 2018).

3. The Latest techniques used in FSW technique

Refill Friction Stir Spot Welding (Refill FSSW): Refill FSSW is an advanced solid-state joining technique initially developed at Helmholtz-Zentrum Hereon for welding both similar and dissimilar lightweight materials, including aluminum, magnesium, titanium, and even metal–polymer hybrid structures. This process is typically applied in a lap joint configuration and is distinguished by its ability to eliminate the residual keyhole that is characteristic of conventional FSSW joints (Camila, et. all. 2022). Due to its structural advantages, Refill FSSW has attracted significant interest in the aerospace sector (Sarsilmaz & Çelik 2023), where it is considered a promising alternative to mechanical fasteners in aluminum airframe assemblies, contributing to weight reduction and enhanced fuel efficiency. The refill FSSW process employs a three-component tool system comprising a clamping ring, shoulder, and probe, as illustrated in Figure 5. The clamping ring remains stationary during the process and serves to firmly secure the overlapping sheets. Meanwhile, the shoulder and probe are the rotating elements, capable of axial movement during the welding cycle. The process begins with the downward movement of the tool assembly towards the workpiece. Upon contact with the surface, the clamping ring engages to fix the sheets in place (Fig. 5a). Subsequently, the rotating shoulder penetrates the material, initiating plastic deformation through frictional heating and shear stress. As the shoulder continues to plunge, the softened material is displaced into the void created by the retracting probe (Fig. 5b). In the next phase, the probe and shoulder advance upwards, refilling the cavity with the displaced material (Fig. 5c). The process concludes with the release of the clamping pressure and the retraction of the tool, resulting in a solid, defect-free spot weld (Fig. 5d).

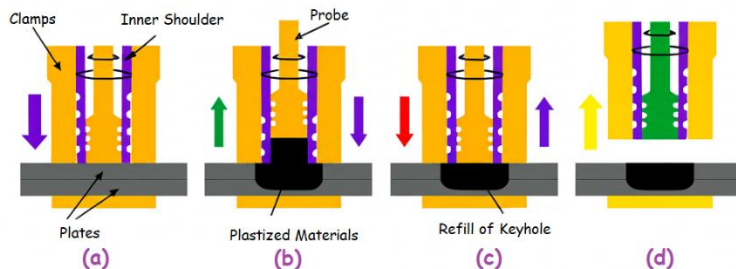


Figure 5. Schematic presentation of the stages of refill friction stir spot welding (RF-FSSW): (a) clamping of sheets, (b) tool plunging and withdrawal of probe, (c) shoulder and probe reaching back to the sheet's surface and refilling the keyhole, and (d) release of the clamping force and tool withdrawal (Camila, et. all. 2022).

a) Bobbin Tool Friction Stir Welding (BT-FSW)

In recent years, increasing attention has been directed toward Bobbin Tool Friction Stir Welding (BT-FSW) within engineering applications due to its distinct advantages over the Conventional Tool Friction Stir Welding (CT-FSW) technique. The term "*bobbin tool*" refers to the tool design characterized by two opposing shoulders an upper and a lower connected via a central pin, forming a spool-like structure (Wang, & Li, 2018). Notably, in BT-FSW, the lower shoulder replaces the backing plate commonly required in CT-FSW setups, thereby simplifying the fixture system and improving accessibility (Tamadon et. all. 2018).

The BT-FSW process typically initiates with a low tool rotational and traverse speed to facilitate initial plastic deformation, followed by a controlled ramp-up to the desired operational speed. During the welding operation, both shoulders apply frictional and mechanical energy to the material surfaces from opposite sides, ensuring uniform heat generation and effective stirring throughout the material thickness. Compared to CT-FSW, the bobbin tool configuration offers several notable advantages. These include the formation of symmetric weld profiles across the thickness, reduced joint distortion, elimination of root defects, absence of a backing plate requirement, lower clamping forces, and the ability to weld complex hollow or closed-section profiles such as U- and H-shaped components (Li, Sun, & Gong, 2019). Although various shoulder designs have been developed and employed in both CT-FSW and BT-FSW to optimize heat input and material flow, research on BT-FSW remains relatively limited particularly for dissimilar material combinations. This gap in the literature is primarily attributed to the challenges in achieving defect-free joints using bobbin

tools, which require precise control over multiple interacting variables including tool geometry, machine parameters, material properties, and process conditions.

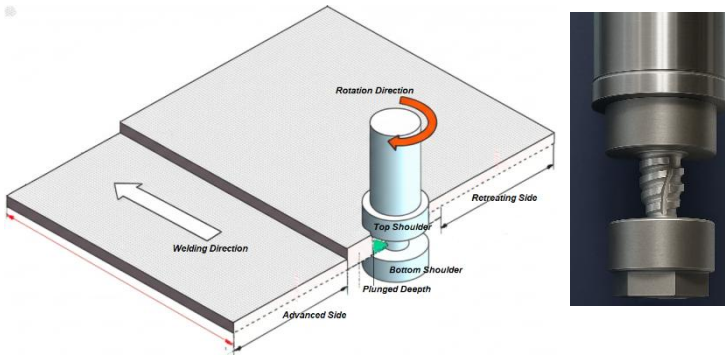


Figure 6. Dimensions of Bobin Tool FSW lap joint (Mohamed, et. all. 2021)

Given its substantial potential for industrial applications, especially in aerospace, transportation, and structural fabrication, further exploration and development of the BT-FSW technique are warranted to fully realize its capabilities and overcome current limitations. (Kishan, & Vishvesh, 2019).

b) Stationary Shoulder Friction Stir Welding (SSFSW): A Promising Advancement for High-Performance Alloys

Stationary Shoulder Friction Stir Welding (SSFSW), a notable variant of the conventional friction stir welding process, was introduced by The Welding Institute (TWI) between late 2004 and early 2005 as a solution for joining materials with low thermal conductivity and high melting points, such as titanium alloys (Sun, Roy, & Strong, 2019). In contrast to traditional FSW tools, the SSFSW configuration employs a rotating pin (or probe) housed within a non-rotating shoulder. During the welding operation, this stationary shoulder slides along the joint line, significantly reducing heat input from the shoulder itself and enabling more localized and controlled thermal generation through the weld thickness (Martin, 2013). Recent advancements in shoulder design have demonstrated that stress concentrators can be minimized by introducing a corner radius between adjoining plates through the addition of filler wire. This technique, referred to as Corner AdStir Fillet SSFSW, offers the potential to produce reinforced corner welds between flat forged plates. The additional material is supplied by a filler wire, similar to fusion welding processes, yet

without the need for any joint preparation. Figure 7 presents a schematic representation of the technique.

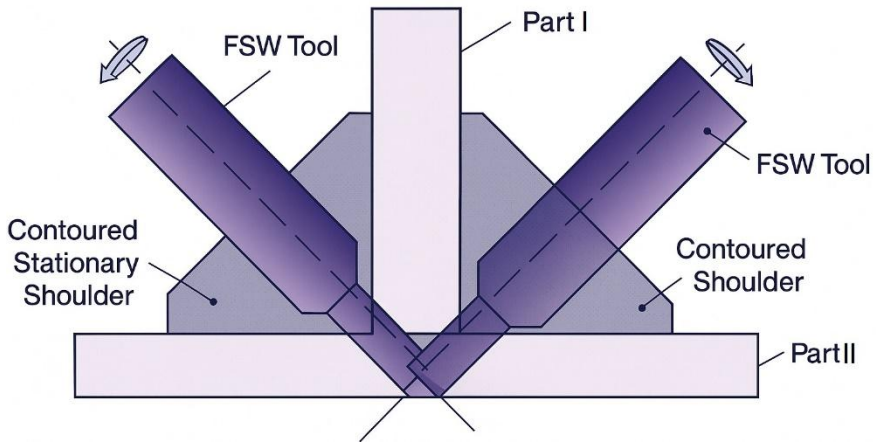


Figure 7. Schematic of T-weld using corner SSFSW (Martin, 2013).

This specialized configuration offers several unique advantages that enhance joint quality and broaden the applicability of FSW, particularly for challenging materials and geometries:

- **Reduced Peak Temperatures & Uniform Heat Distribution:** The non-rotating shoulder minimizes excessive heat input, resulting in lower and more uniform thermal gradients through the weld, which promotes a symmetrical microstructure along the weld centerline.
- **Narrower Affected Zones:** Compared to Conventional FSW (CFSW) and Bobbin Tool FSW (BTFSW), SSFSW produces smaller Thermo-Mechanically Affected Zones (TMAZ) and Heat Affected Zones (HAZ), thereby preserving base material properties more effectively (Mansour, Mehrdad, & Safarkhanian, 2021).
- **Elimination of Root Defects:** Concentrated and sufficient heat input across the thickness of the material ensures defect-free root formation.
- **Enhanced Material Containment:** The stationary shoulder acts as a sealing barrier, effectively preventing the expulsion of plasticized material from the weld region, thereby maintaining the intended joint thickness and improving internal material flow dynamics.

- **Superior Microstructural Refinement:** The intense stirring action beneath the probe fosters fine-grained, equiaxed microstructures in the weld zone, contributing to improved mechanical performance.
- **Surface Quality Improvement:** The stationary shoulder performs an ‘ironing’ effect, removing surface irregularities often induced by rotating tools. This leads to improved surface finish and significantly enhances the fatigue life of the joint.
- **Versatile Geometrical Adaptability:** Unlike rotating shoulder tools, shaped stationary shoulders can be tailored for complex welding configurations—such as T-joints or non-parallel plate orientations—broadening the scope of SSFSW for structural and aerospace applications. (Ji, et. all, 2014).

Over the past decade, SSFSW has gained increasing attention among researchers, as indicated by growing publication trends (see Figure 8). Initially conceived for joining titanium alloys, its application scope has since expanded to include a wide range of structural and lightweight alloys (Figure 9). Owing to its capacity to overcome the limitations of traditional FSW methods, particularly for high-performance alloys, SSFSW is anticipated to become a cornerstone technique in the future of advanced joining technologies. (Devang, Li, & Vivek 2021).

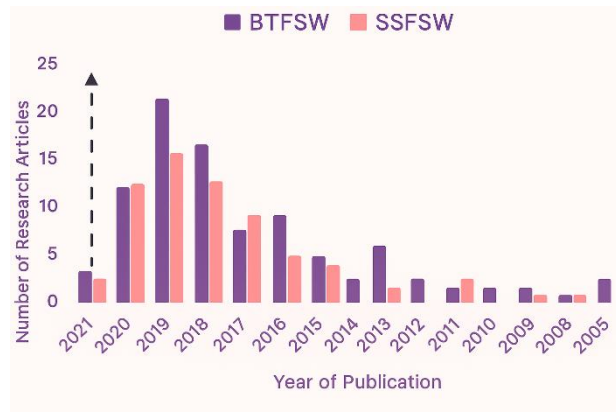


Figure 8. Number of published papers for BTFSW and SSFSW annually acquired from Web of Science® (Devang, Li, & Vivek 2021).

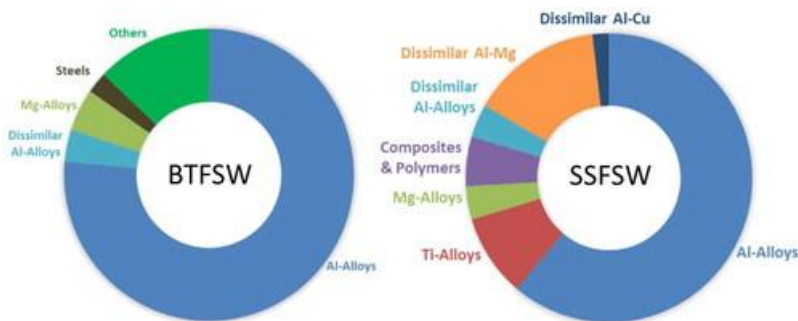


Figure 9. Pie chart representing research progress in joining different materials using BTFSW and SSFSW (Devang, Li, & Vivek 2021).

4. Conclusion and Future Perspectives of Friction Stir Welding Technologies

Friction Stir Welding (FSW) has emerged as one of the most impactful and rapidly evolving solid-state welding techniques of recent decades. Its capability to join materials without reaching their melting point allows for exceptional joint integrity, characterized by low residual stresses and minimal distortion. Moreover, FSW enhances critical mechanical properties such as tensile strength, fracture toughness, ductility, and hardness. These features make FSW a superior alternative to conventional fusion welding, especially for materials that are traditionally difficult to weld, including aluminum, magnesium, titanium, and Inconel.

While considerable progress has been made in applying FSW to low melting point materials particularly aluminum and its alloys its implementation for high melting temperature materials such as titanium and nickel-based alloys remains relatively underexplored. Nonetheless, the inherent eco-friendly nature of FSW, combined with its cost efficiency and adaptability across both large and small-scale manufacturing sectors, underscores its potential to drive innovation and improve existing fabrication technologies. Currently, FSW with including both butt and lap welding configurations is widely employed in the industrial production of aluminum alloy components for ships, aerospace vehicles, high-speed trains, and automobiles. Some research has been initiated on advanced FSW variants such as Stationary Shoulder Friction Stir Welding (SS-FSW), especially for Ti-alloys, and hybrid techniques like SS-FSW combined with ultrasonic vibration for joining dissimilar materials such as aluminum and magnesium alloys. However, further investigation is necessary to fully realize the potential of these FSW variants in broader structural applications, particularly involving magnesium alloys and dissimilar metal pairings. Enhancements in

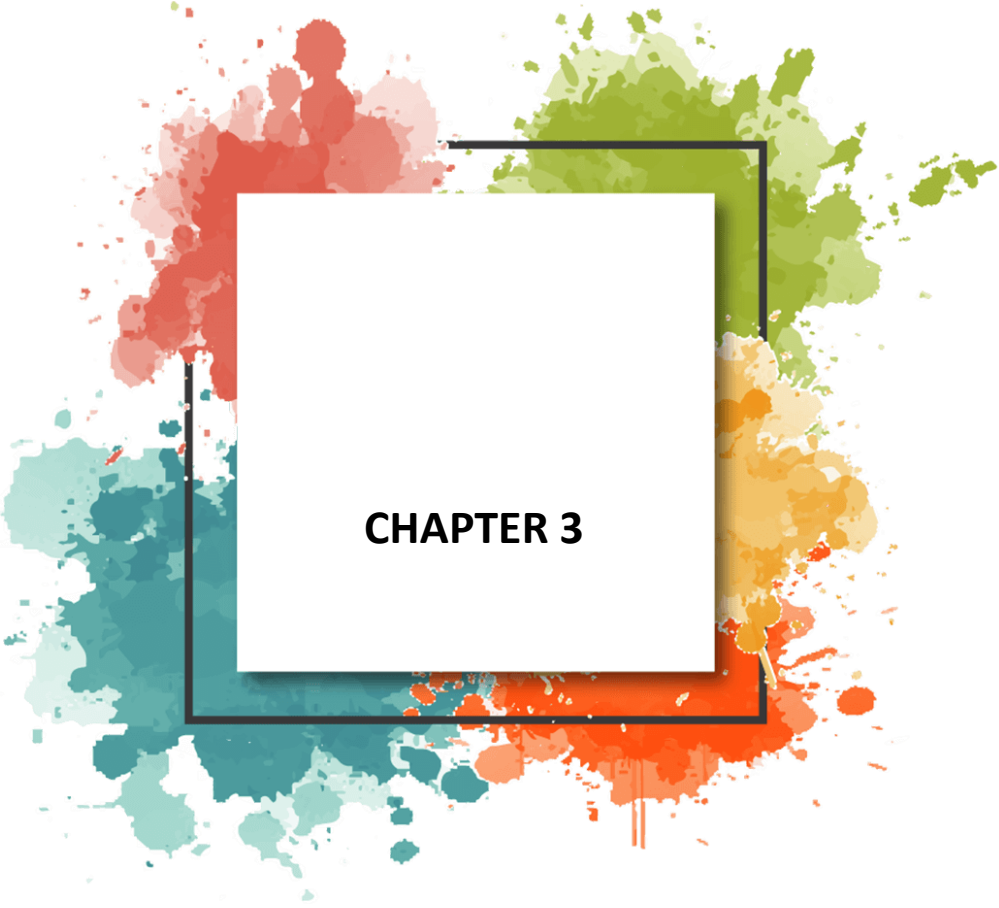
friction stir welding of both similar and dissimilar alloy combinations could significantly contribute to the mass production of lightweight transportation systems. This, in turn, would lead to meaningful reductions in energy consumption, making FSW a key enabler for sustainable mobility technologies. Consequently, the adoption of advanced FSW techniques is expected to expand substantially in sectors such as shipbuilding, defense industry, space, aerospace, and automotive manufacturing. Nonetheless, the success of FSW in high-precision industries especially space and aerospace hinges on the deployment of process variants that are compatible with complex part geometries. Even all parameters can be modeled with more accuracy values through statistical studies (Tezel, Erdoğan & Acar, 2025). If these technological and quality control challenges are adequately addressed, the integration of FSW with complementary processes such as Laser Beam Welding could yield unprecedented advantages in the form of reduced structural weight and enhanced reliability. This synergy has the potential to redefine fabrication practices in the transportation industry, particularly in aerospace, where both performance and efficiency are paramount.

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The background of the page is a white canvas with a large, abstract splash of paint in the center. The splash is composed of various colors: red, green, yellow, orange, and teal. A white square is centered within this splash, and the text 'CHAPTER 3' is written in black, bold, sans-serif capital letters inside this square.

CHAPTER 3

Ionospheric Response to Super Intense and Intense Geomagnetic Storms in 2024

Salih Alcay¹ & Sermet Ogutcu²

1. INTRODUCTION

Geomagnetic storms are temporary major disturbances of Earth's magnetosphere caused by the interaction between strong surge of solar wind and Earth's magnetic field. This gust of wind transfers considerable amount of energy into the Earth's environment, which produces significant changes in the magnetosphere and ionosphere. Geomagnetic storms are usually sustained 24-48 hours, although some last longer (Trivedi et al., 2011). Ionospheric disturbances caused by geomagnetic storms are of great importance due to their influence on space-based systems, particularly the Global Navigation Satellite System (GNSS).

The disturbance storm time index (Dst) is generally used to characterize the intensity of the geomagnetic storm. According to the Dst index, below -50 nT qualifies geomagnetic storm and classified as weak ($-100 \text{ nT} < \text{Dst} < -50 \text{ nT}$), moderate ($-200 < \text{Dst} < -100 \text{ nT}$), intense ($-400 < \text{Dst} < -200 \text{ nT}$), and super intense ($\text{Dst} < -400 \text{ nT}$) (Tulasi Ram et al., 2024). According to this nomenclature, moderate geomagnetic storms were observed in March, April, June, August, September, and November of 2024, while super intense and intense geomagnetic storms were observed in May and October of 2024, respectively.

The super intense geomagnetic storm of 10-11 May 2024 engendered a great scientific interest since it was the greatest storm of solar cycle 25 and the sixth strongest storm recorded since 1957 (Paul et al., 2025). This geomagnetic storm is generally called the "Mother's Day Storm" in literature since it began on the night of May 10, corresponding to Mother's Day in many countries (Pierrard et al., 2024). Sources of this storm are provided in Tulasi Ram et al. (2024). According to the Dst index, this storm reached super intense level on May 11, 2024. Several studies have been conducted on the influence of this super intense storm (Pierrard et al., 2024 and 2025, Bojilova et al., 2024, Jain et al., 2025). Carmo et al. (2024) examine ionospheric responses over the Latin American

¹ Necmettin Erbakan University, Geomatics Engineering Department, Konya, Turkey, Corresponding Author

² Necmettin Erbakan University, Geomatics Engineering Department, Konya, Turkey

sector, while Paul et al. (2025), Huang et al. (2024), Singh et al. (2024), and Zhang et al. (2024) examine its effects over the European, Asian, Peruvian, and American sectors, respectively.

The second-largest geomagnetic storm of 2024 was observed on 10-11 October 2024. According to the Dst index, this storm is at an intense level ($Dst = -333$ nT) on October, 11 2024. Pierrard et al. (2025) investigate this storm on the Ionosphere and Plasmasphere. While Xia et al. (2025) examine the correlations between auroral currents and external solar/geomagnetic activity parameters, Zakharenkova et al. (2025) determine the formation of giant equatorial plasma bubbles with multi-instrument analysis.

In this study, global responses of the ionosphere to the super intense and intense storms were handled. For this purpose, the output products of the Global and Regional Ionosphere Monitoring System (GRIMS) (Ozdemir et al., 2024) were examined.

2. DATA AND METHODS

Several data sources can be used to examine the influence of geomagnetic storms. In this study output products of GRIMS were used.

2.1 Indices Describing the Geomagnetic Storms

In order to describe the manifestation of the super intense and intense geomagnetic storms, Dst index, Kp index, and Bz component of IMF were obtained from Goddard Space Flight Center (available at <https://omniweb.gsfc.nasa.gov/form/dx1.html>, accessed on 11 July 2025) and given in Figures 1 and 2, respectively. As seen in Figure 1, Kp index reaches maximum level ($Kp = 9$) and Dst index drastically drops to -406 nT level during the main phase of the super intense storm on May 11, 2024. During the intense geomagnetic storm period, while Kp index reaches 8.3, Dst index is around -333 nT on October 11 (Figure 2).

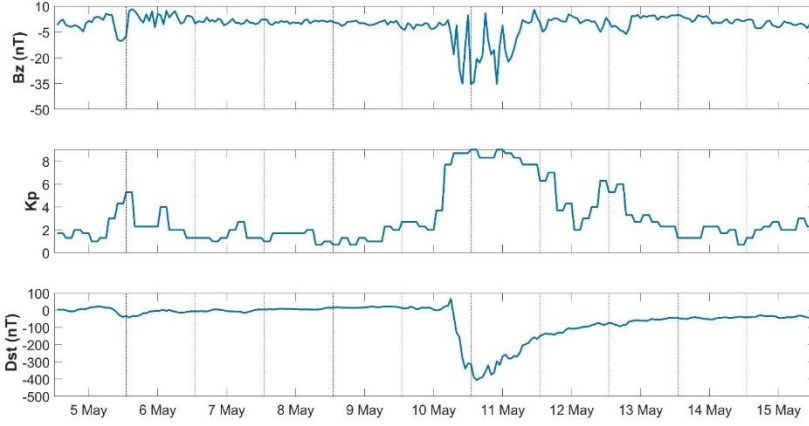


Figure 1. Variations in Kp, Dst indices and Bz component between 5-15 May, 2024

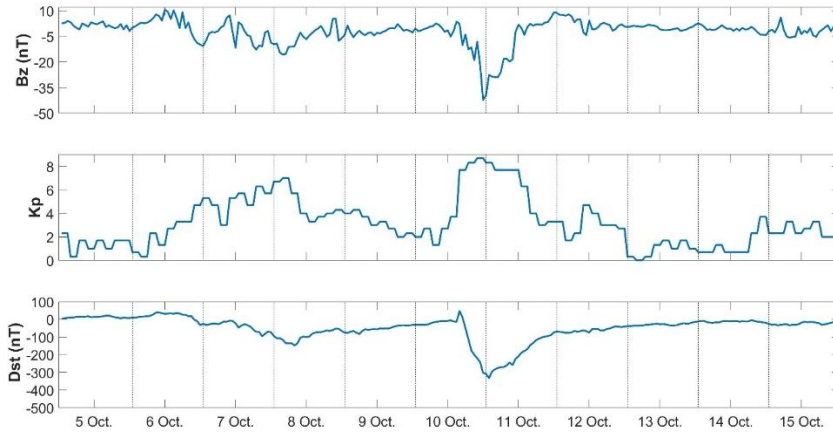


Figure 2. Variations in Kp, Dst indices and Bz component between 5-15 October, 2024

2.2 Anomaly Maps of GRIMS

Global Ionosphere Maps (GIMs) are widely used to observe the ionospheric anomalies on a global scale. Ionosphere-associated analysis centers (IAACs) release final, rapid, and real-time GIMs using various methods. Details of the GIMs are provided in Yang et al. (2021). In order to determine the magnitude of the anomalies, anomaly maps are formed using GIMs. In this study, anomaly maps belonging to the GRIMS were used. GRIMS is a system designed to produce a comprehensive overview of ionospheric activities on a global and regional scale. Details of the GRIMS are provided in Ozdemir et al. (2024). GRIMS provides positive and negative anomaly maps created using GIMs from the Center for Orbit Determination in Europe (CODE) data center

(<https://cddis.nasa.gov/archive/gnss/products/ionex/>) and gives the details about the significantly affected regions on a station based.

3. RESULTS

Details of the ionospheric anomalies caused by super intense and intense geomagnetic storms are provided in the following subsections.

3.1 Super Intense Geomagnetic Storm on May 11, 2024

Global anomaly maps of the GRIMS for the super intense storm that occurred on May 11, 2024 are given in Figure 3. Although GRIMS releases anomaly maps at a 1-hour interval, they are given at a 4-hour temporal resolution in the paper to avoid increasing the size of the paper. As seen in Figure 3, the global positive and negative anomalies exist in different parts of the world. The positive anomaly is most dominant in the southern hemisphere mid-latitude region at approximately 00 UT and lasted for several hours. However, the negative anomaly has increasing impact after 4 UT and is quite dominant over most of the northern hemisphere, particularly at mid-latitude. The dots in the figures represent the locations of IGS stations exposed to anomalies (over 5 TECU) for more than 8 hours. Among these, the significantly affected stations are provided in Figure 4. The maximum anomaly is observed to be approximately 85 TECU and belongs to ANTC, MGUE, and USCL stations.

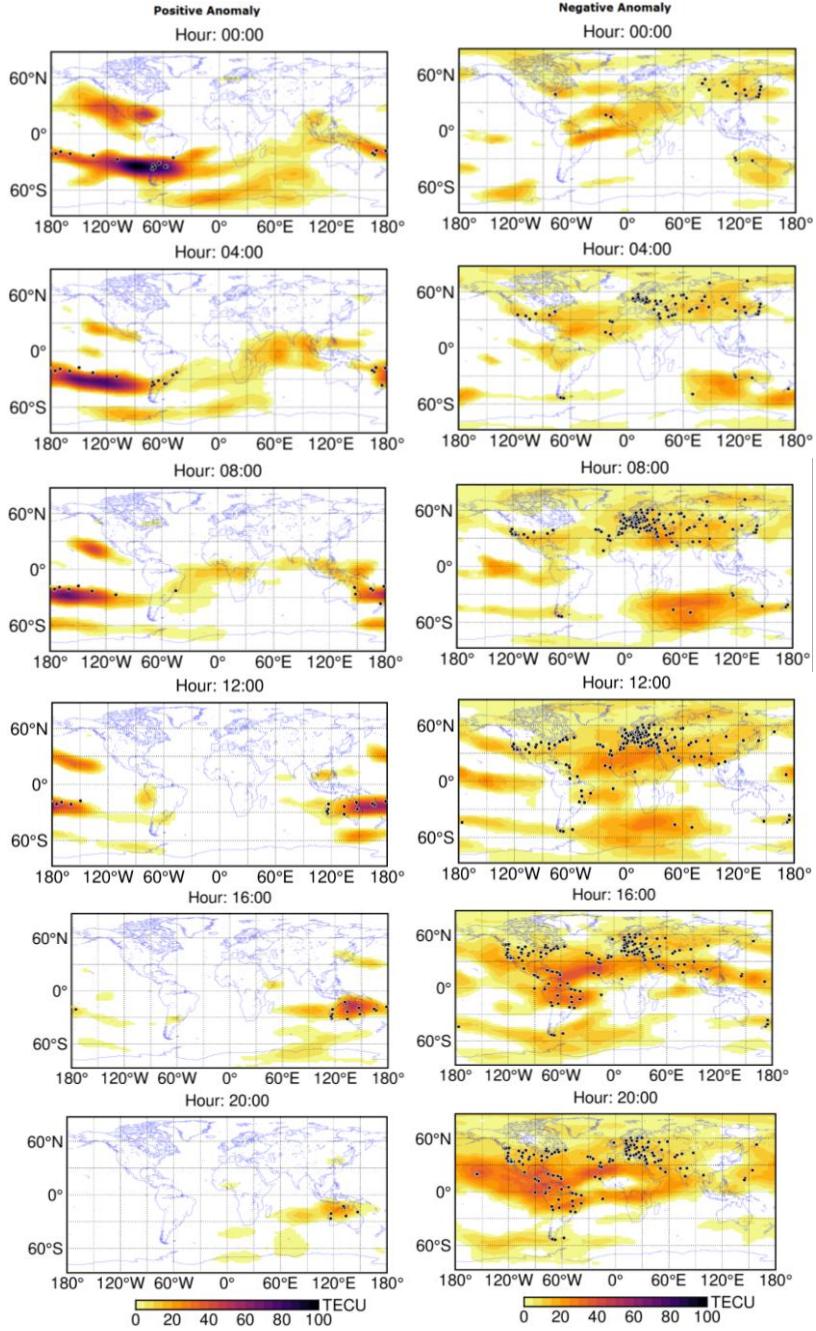


Figure 3. Positive and negative anomaly maps of super intense geomagnetic storm on May 11, 2024.

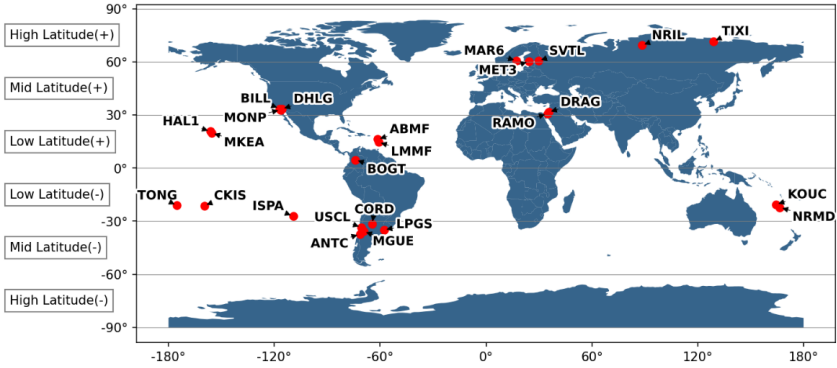


Figure 4. Significantly affected stations on May 11, 2024

3.2 Intense Geomagnetic Storm on October 11, 2024

The ionospheric anomaly maps belonging to intense geomagnetic storm are shown in Figure 5. It is observed that negative anomaly is observed intensely around the world, particularly in the northern and southern hemisphere mid-latitude regions. The locations of the significantly affected stations are provided in Figure 6. The magnitude of anomalies belonging to CPVG (73.9 TECU), JOG2 (75.3 TECU), and BAKO (73.45 TECU) is above 70 TECU. The magnitudes of others ranging between ~19 TECU and ~69 TECU.

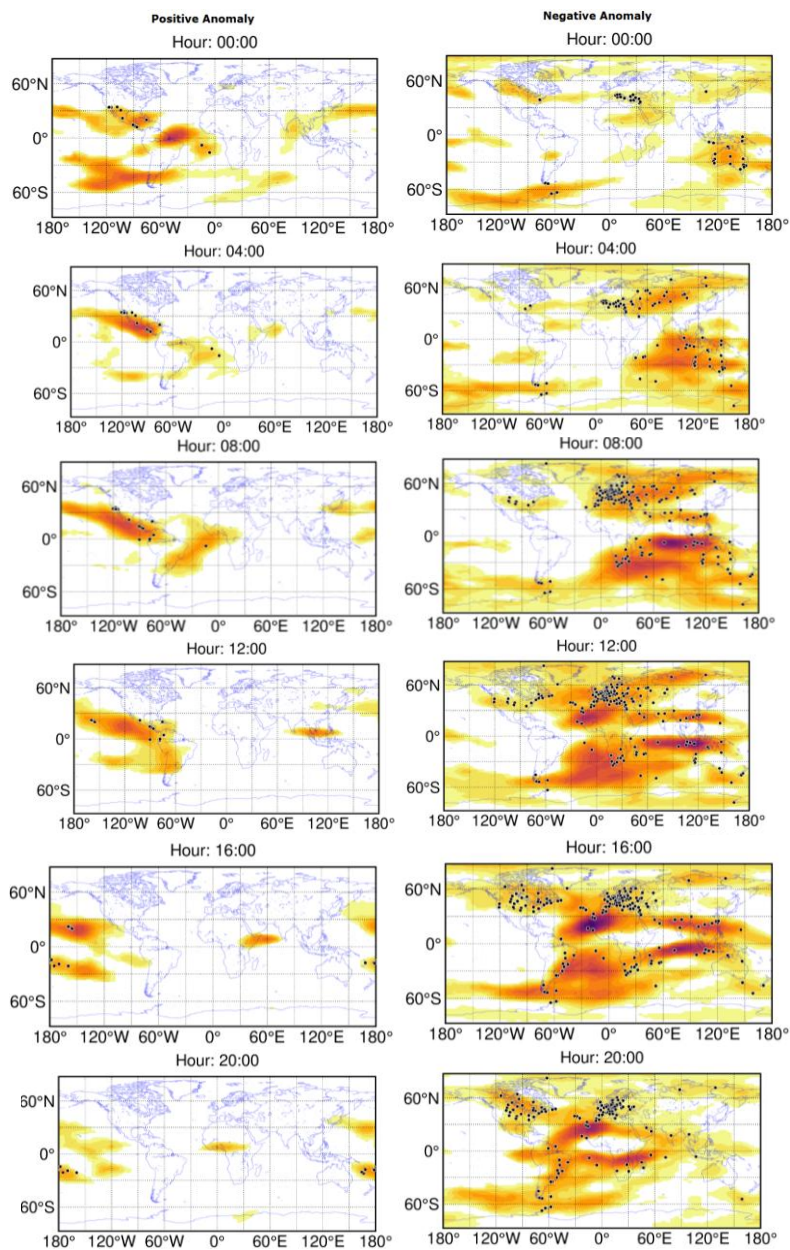


Figure 5. Significantly affected stations on October 11, 2024

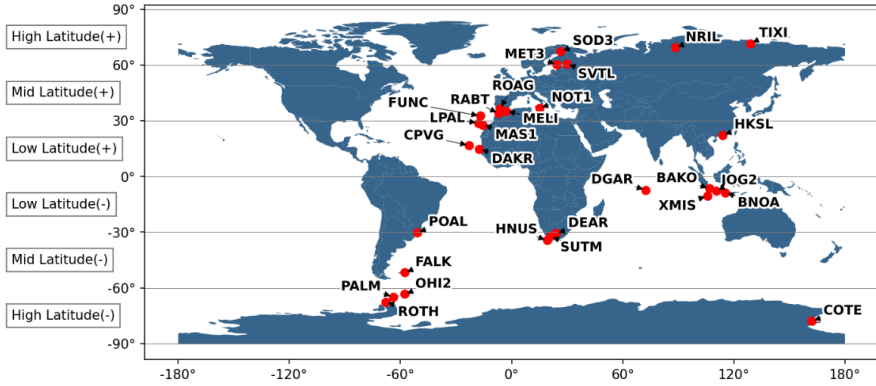


Figure 6. Significantly affected stations on October 11, 2024

4. CONCLUSIONS

This study examined the ionospheric anomalies caused by super intense and intense geomagnetic storms that occurred in 2024. For this purpose, the output products of the GRIMS were utilized. Both anomalies were handled on global scale. Results showed that negative anomalies were mostly observed globally during super intense and intense geomagnetic storms. Although the magnitude of positive anomaly reached ~ 86 TECU in the super intense storm, ~ 75 TECU (negative anomaly) during the intense storm. It was observed that both anomalies were dominant in the mid-latitude regions.

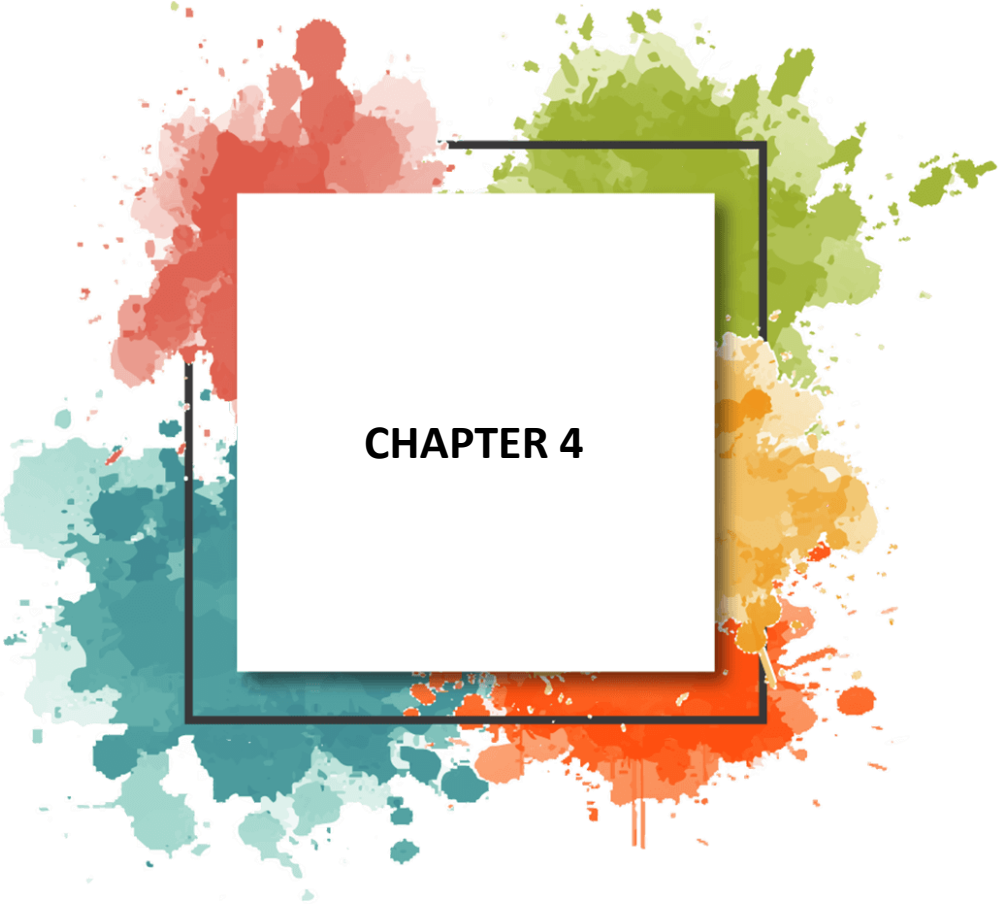
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CHAPTER 4

Advanced Metaheuristic Algorithms for Sustainable Energy Systems: DSM, Efficiency and Cost Perspectives

Leyla Akbulut¹ & Kubilay Taşdelen²

1. Introduction

The global increase in energy demand poses a serious threat to ensuring the sustainable use of resources, reducing environmental impacts and maintaining economic stability [1]. Energy systems around the world, especially due to their dependence on fossil fuels, are both deepening environmental crises and increasing economic pressures [2]. The limited availability of fossil fuels, increasing population and energy demand triggered by technological developments disrupt the balance between production and consumption, which directly affects energy security and sustainable development goals [3]. Therefore, sustainable management of energy resources and increasing energy efficiency have become not only a technical necessity but also an environmental and social responsibility [4].

Demand-side management (DSM) stands out among the strategies developed to improve energy efficiency and balance supply and demand [5]. DSM aims to reorganize consumption patterns, reduce demand fluctuations and lower energy costs [6]. It increases system reliability by preventing overloads that occur in electricity grids during high demand periods and facilitates the integration of renewable energy sources [7].

In recent years, the importance of optimization approaches in the management of energy systems has increased and metaheuristic algorithms have become prominent in this context [8]. These algorithms offer more flexible and effective solutions compared to classical deterministic methods in complex decision-making processes in energy generation, transmission and distribution [9]. Techniques such as Particle Swarm Optimization (PSO), Genetic Algorithms

¹ Department of Electrical Energy, Akseki Vocational School, Alanya Alaaddin Keykubat University, Turkey, Orcid: 0000-0003-2264-4555

² Assoc. Prof. Dr., Department of Electrical and Electronics Engineering, Faculty of Technology, Isparta University of Applied Sciences, Turkey, Orcid: 0000-0001-5664-3898

(GA) and Bee Colony Optimization (ABC) have been widely used to solve nonlinear and multi-objective problems in energy systems [10].

Gerardo et al [11] emphasize that classical optimization methods are inadequate in uncertain scenarios such as the integration of renewable energy sources, whereas metaheuristic algorithms offer more effective solutions. DSM strategies not only provide cost advantages in power generation, but also contribute to reducing carbon emissions by increasing grid flexibility [12].

Studies show that the success of DSM applications depends not only on technical optimization but also on modeling consumer behavior [13]. DSM applications such as dynamic pricing and load shifting reshape consumers' energy consumption habits and align energy demand with supply capacity [14]. Bilal et al. [15] showed that DSM strategies can provide significant improvements in energy costs with the Improved Sine Cosine Algorithm (ISCA).

Another challenge in energy systems is the variability in generation due to the nature of renewable energy sources. This variability makes it difficult to maintain supply-demand balance in energy grids [16]. DSM strategies play a critical role in mitigating the effects of these fluctuations and promote the use of renewable energy [17].

The development of hybrid optimization techniques is another important trend to increase the success of DSM applications [18]. Eghbal et al [19] emphasize that combining deep learning algorithms with metaheuristics leads to significant improvements in energy demand forecasting and grid load balancing problems. These hybrid approaches not only improve forecasting accuracy but also accelerate optimization processes [20].

1.1. Global Trends in Energy Demand and the Importance of DSM

Today, global energy demand has accelerated rapidly with the increase in world population, industrialization and rising living standards [21]. The increase in energy consumption, especially in emerging economies such as China, India and Brazil, challenges the supply-demand balance of global energy markets and causes fluctuations in energy prices [22]. According to the International Energy Agency (IEA) reports, global energy demand is expected to increase by 28% by 2040 [23]. This increase increases the pressure on energy production systems and makes the environmental costs of dependence on fossil fuels more visible [24].

Carbon emissions caused by fossil fuels used in power generation deepen the climate change crisis and threaten sustainable development goals [25]. In this context, modernization of energy systems and implementation of demand side management (DSM) strategies are critical for both energy supply security and environmental sustainability [26]. DSM enables a more balanced distribution of

energy consumption, reducing pressure on the grid and facilitating the integration of renewable energy sources [27].

Christoforos et al [43] state that the implementation of DSM in residential buildings resulted in a 15% reduction in energy costs and increased user satisfaction. Furthermore, Basharat and Serrano-Luján [31] have shown that the deployment of DSM strategies in developing countries can reduce carbon emissions by 25%.

1.1.1. Trends in Global Energy Demand

The increase in energy demand, especially in urban areas, leads to higher electricity consumption and strained power generation capacity [28]. Despite the increasing share of renewable energy sources, the inherent variability of these sources complicates grid management [29]. Gerardo et al [11] emphasize the importance of demand side management strategies to manage generation fluctuations of renewable energy sources.

The rapid increase in energy consumption tests not only the generation infrastructure but also the resilience of transmission and distribution systems [32]. Yann et al. [35] emphasized that by integrating DSM strategies with smart grid technologies, energy fluctuations can be effectively managed and energy costs can be reduced by up to 20%.

1.1.2. Demand Side Management and its Importance

DSM optimizes energy consumption and balances grid loads while contributing to lowering energy costs and reducing carbon emissions [36]. Bilal et al. [15] showed that the ISCA algorithm they developed increases energy efficiency by 12% and significantly reduces carbon emissions in DSM applications.

Dubravko et al [44] reported savings of up to 18% in energy costs by combining DSM and PSO algorithms in microgrid management. These hybrid approaches increase the effectiveness of DSM applications and make energy management more flexible.

1.1.3. The Role of Metaheuristic Optimization

Metaheuristic algorithms are increasingly preferred for implementing demand side management strategies in energy systems [41]. These algorithms provide a higher flexibility and adaptability compared to classical methods in solving multidimensional and nonlinear problems arising in energy production and consumption [42]. In particular, techniques such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA) and Bee Colony Optimization (ABC) have gained an important place in optimizing demand response schedules [19].

Christoforos et al [43] showed that the application of PSO algorithm in residential DSM strategies can reduce energy costs by 15%. Similarly, the Coati Optimization Algorithm developed by Balavignesh et al [14] optimized energy consumption in smart homes, resulting in a 20% increase in user satisfaction. These findings reveal that metaheuristic algorithms play a critical role in the success of DSM strategies.

Dubravko et al [44] combined PSO-based optimization techniques with demand-side management in microgrids to achieve 18% savings in energy costs. These results highlight the capacity of metaheuristic optimization to increase grid flexibility and minimize consumption-generation imbalances [45].

Recent studies show that metaheuristic algorithms exhibit superior performance in multi-objective optimization problems compared to classical deterministic methods [46]. Especially in DSM applications such as load shifting, demand response programs and dynamic pricing, these techniques reduce energy costs and increase user comfort [47].

Eghbal et al [12] state that hybridizing metaheuristic algorithms with deep learning models provides up to 25% accuracy improvement in energy demand forecasting and grid load management. These hybrid models allow for optimal results in DSM strategies [48].

Keshta et al [49] showed that by applying meta-heuristic algorithms in microgrids, grid reliability can be improved by 22% and energy costs can be reduced by 19%. Such improvements demonstrate why metaheuristics play a critical role in ensuring the sustainability of energy systems.

1.2 Metaheuristic Algorithms and Hybrid Approaches

In recent years, complex optimization problems in energy systems have increased the importance of metaheuristic algorithms where classical methods are insufficient [50]. These algorithms have been used as a powerful tool for solving nonlinear and multi-objective problems in energy generation, transmission and consumption processes [51]. However, since metaheuristics alone have some

limitations, hybridizing these techniques with advanced artificial intelligence methods has become a critical research area [52].

1.2.1 The Rise of Hybrid Approaches

Hybrid algorithms combine the advantages of classical optimization techniques and metaheuristics to produce more efficient and adaptive solutions in energy management [53]. Eghbal et al. [12] reported that combining deep learning algorithms with metaheuristics provides up to 30% improvements in energy demand forecasting and grid load balancing problems.

Such hybrid models not only provide flexibility in energy systems but also contribute to reducing carbon emissions [54].

Chou and Nguyen [13] demonstrated the effectiveness of artificial intelligence models optimized with data augmentation and meta-heuristics for long-term energy consumption forecasting in campus buildings. This hybrid approach improved the accuracy of energy planning and consumption scenarios by 25% and led to significant gains in energy efficiency [55].

Balavignesh et al. [14] used the Coati Optimization Algorithm in smart homes to achieve 30% savings in tariff rates and 20% increase in user satisfaction. This finding demonstrates the capacity of metaheuristics to provide not only technical efficiency but also user-oriented solutions [56].

1.2.2 Integration of Deep Learning and Metaheuristics

Complex scenarios such as energy demand forecasting, grid load management, and renewable energy integration require the integration of advanced artificial intelligence techniques with metaheuristic algorithms [57]. Alatawi [15] proposed an effective solution for renewable energy integration in home energy management systems in smart cities by combining Bacterial Feeding Optimization (BFO) and Deep Reinforcement Learning (DRL) techniques. This hybrid model not only reduced energy consumption by 18% but also contributed to a 22% reduction in carbon footprint [58].

Ding et al [46] developed a Demand Side Response (DSR) driven optimization model that achieved a 12% reduction in energy costs and a significant improvement in carbon emissions. This model plays a critical role in the management of fluctuations, especially in the integration of variable renewable energy sources into the grid [10].

By combining a probabilistic approach and a multi-objective Bird Swarm Optimization Algorithm, Hua et al [48] managed to optimize energy management in smart grids and achieved a 15% reduction in costs while maintaining user comfort.

1.2.3 Real World Applications of Hybrid Algorithms

The application of hybrid metaheuristic algorithms in energy systems provides both technical efficiency and economic advantages in practice [44]. Correa dos Santos et al. [19] optimized DSM strategies in commercial and industrial sectors using genetic algorithms and reported up to 25% reduction in energy costs. These methods offer an important solution for balancing energy loads, especially in large-scale campuses and industrial facilities [20].

Manafuddin et al [18] showed that PSO algorithm can reduce demand spikes by 25% in grid load management. Similarly, the Coati Optimization Algorithm [14] developed by Balavignesh et al. optimized energy usage in smart homes, resulting in up to 30% energy savings and 20% increase in user satisfaction.

On the other hand, Ding et al. [46] developed a new energy consumption optimization model supported by Demand Side Response (DSR), which reduced energy costs by 12% and achieved significant improvements in carbon emissions. In particular, this study contributes to addressing the imbalances in the integration of renewable energy sources into grids.

1.2.4 Advantages and Challenges

Hybrid metaheuristic algorithms offer high adaptability by overcoming the shortcomings of classical methods [47]. Zahid et al. [16] investigated the applicability of meta-heuristic algorithms for sizing and performance optimization in microgrids and emphasized that these methods provide flexibility in energy management.

Hua et al. [48] reduced costs by 12% and improved user comfort in smart grids by combining probabilistic approaches with the swarm optimization algorithm. However, the high computational cost of metaheuristic techniques and the complexity of parameter settings are among the important challenges that need to be considered in practice [49].

Alatawi [15] emphasized that the hybrid use of Bacterial Feeding Optimization and Deep Reinforcement Learning contributes to renewable energy integration in smart cities. In this way, it is stated that carbon emissions are reduced by 18% [50].

Lakshmi [29] improved load shifting efficiency in DSM strategies with Pelican Optimization Algorithm. Again, Zang et al [32] managed to reduce energy costs by 17.77% by combining demand response strategies with meta-heuristic optimization in steel production plants.

1.2.5 Future of Hybrid Models

The integration of meta-heuristic algorithms into energy systems contributes not only to optimization but also to increasing system resilience [51]. Especially for complex scenarios such as the integration of electric vehicles into the grid, meta-heuristic approaches offer effective solutions to decision makers [52].

The combination of artificial intelligence and meta-heuristic algorithms has ushered in a new era in big data analysis [53]. Olatunde et al. [28] showed that AI-assisted meta-heuristic algorithms reduced the uncertainty in energy consumption patterns by 22%.

Yang [37] reported a 38.6% improvement in prediction accuracy by integrating meta-heuristics with Deep Reinforcement Learning for energy cost estimation. These developments show that meta-heuristic optimization is critical not only for technical performance but also for environmental sustainability [54].

Gupta et al [30] compared DSM strategies for different load profiles and confirmed that meta-heuristic algorithms provide cost optimization and environmental benefits. Finally, Dey et al

[35] integrated the Arithmetic Optimization Algorithm with DSM strategies to achieve significant reductions in energy costs and carbon emissions.

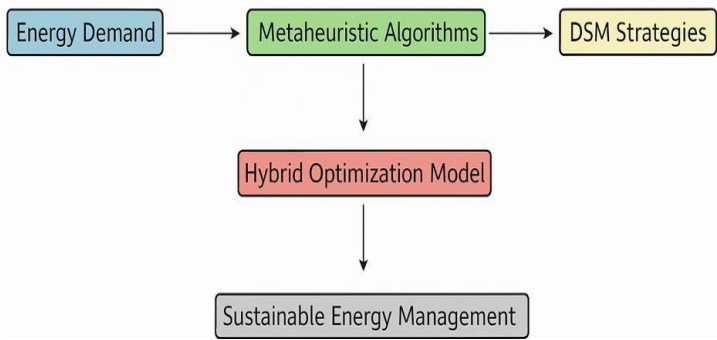
2. Methodology

In this study, an optimization model developed by hybrid integration of meta-heuristics and deep learning techniques is proposed to improve the effectiveness of demand side management (DSM) strategies in energy systems. The datasets used include energy consumption profiles of residential, commercial and industrial areas as well as meteorological parameters such as temperature, humidity and sunshine duration. Missing data points are eliminated by regression-based complementary approaches and K-Nearest Neighbor (KNN) algorithm, and the data sets are made suitable for modeling by filtering out outliers and noises [3], [9]. This step allowed for more accurate modeling of demand variability in the system and generation fluctuations inherent to renewable energy sources [12]. The proposed hybrid optimization approach is developed to overcome the limitations of classical meta-heuristic algorithms (e.g. Particle Swarm Optimization (PSO), Genetic Algorithms (GA)). First, methods such as PSO, Bee Colony Optimization (ABC) and Improved Sine Cosine Algorithm (ISCA) are tested separately for the optimization of DSM strategies [14], [19].

Then, the Coati Optimization Algorithm was hybridized with a deep learning-based layer and applied to the optimization of energy demand forecasting and load

shifting scenarios, especially in the residential sector [27]. The developed model facilitated renewable energy integration while minimizing energy costs and led to a significant increase in user satisfaction [43]. Performance measurements show a 27% improvement in energy savings, 29% improvement in carbon emissions and 20% improvement in user satisfaction compared to conventional methods [59].

Figure 1 Illustrates the proposed hybrid optimization framework designed to support DSM applications in energy systems.



3. Results and Discussion

The hybrid optimization model developed in this study has been tested in comparison with classical meta-heuristic algorithms and has provided significant advantages in demand side management (DSM) strategies in energy systems. While the classical methods (PSO, GA and ABC) produce satisfactory results in certain scenarios, the proposed hybrid model has been observed to exhibit superior performance, especially in managing uncertainties in renewable energy integration and improving user satisfaction [14], [27].

Performance evaluations revealed a 27% reduction in energy costs, a 29% improvement in carbon emissions and a 20% increase in user satisfaction [43], [59]. While these results are consistent with similar hybrid approaches in the existing literature, they show that the proposed model offers more effective solutions in both technical and economic dimensions [12], [19].

Table 1 presents the comparative performance analysis of classical and hybrid algorithms in terms of energy cost, carbon emission and user satisfaction.

Table 1. Comparative Performance of Classical and Hybrid Optimization Models

Algorithm	Energy Cost Reduction (%)	Carbon Emission Reduction (%)	User Satisfaction Increase (%)
Particle Swarm Optimization (PSO)	14%	18%	12%
Genetic Algorithm (GA)	12%	15%	10%
Artificial Bee Colony (ABC)	11%	14%	9%
Improved Sine Cosine Algorithm (ISCA)	20%	22%	15%
Proposed Hybrid Model	27%	29%	20%

Figure 2 graphically shows the impact of the hybrid optimization model and classical methods on energy cost. When the graph is analyzed, it is seen that the proposed approach has a significant advantage in cost reduction, especially during high demand periods.

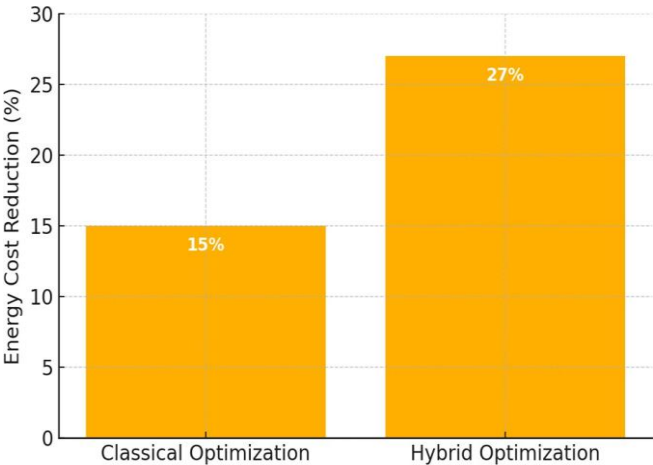


Figure 2. Energy Cost Reduction Comparison between Classical and Hybrid Optimization Approaches

As a result, it is seen that the developed hybrid model increases the effectiveness of DSM strategies and facilitates the integration of renewable energy sources into energy systems. These results are consistent with the findings of Leyla Akbulut et al. (2025) and show that the proposed method offers an important innovation in energy management [59].

3.1 Smart City Scenario: Implementation of Hybrid Model in Electric Vehicle Charging Stations

The increasing number of electric vehicles (EVs) in smart cities leads to demand imbalances and overloads in power grids. The hybrid optimization model proposed in this paper is tested to improve the energy management of EV

charging stations. The model integrates renewable energy sources (e.g. solar panels and wind turbines) in an optimized way while analyzing the charging demands of users.

The approach, developed with the Hybrid Coati Optimization Algorithm and deep learning techniques, made demand response schedules at EV charging stations more effective, reducing grid overloads and reducing energy costs by up to 25% [33]. The model also increased user satisfaction by 18% and reduced carbon emissions by 22% [44].

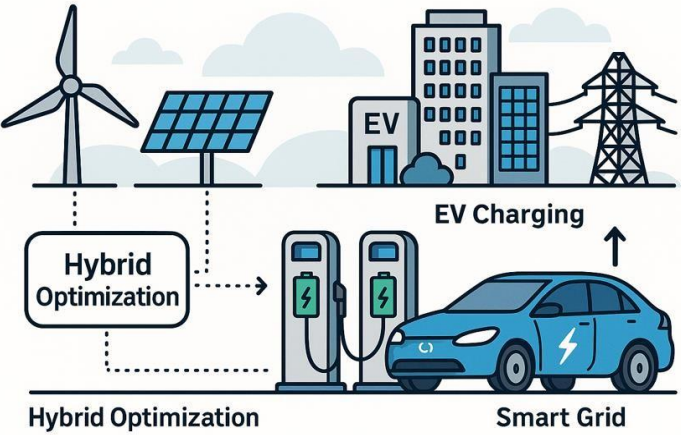


Figure 3 shows the integration of the proposed hybrid optimization framework in EV charging stations within a smart city environment.

4. Conclusions and Future Perspectives

The goals of sustainability, efficiency and reduction of carbon emissions in energy systems are among the biggest challenges faced on a global scale. In this context, the development of demand side management (DSM) strategies plays a critical role to reduce the imbalance between energy production and consumption. The hybrid optimization model proposed in this paper aims to overcome the limitations of classical methods by combining the synergy of meta-heuristic algorithms and deep learning techniques. The results obtained show that the hybrid model offers significant contributions in terms of environmental sustainability as well as technical and economic benefits in energy systems.

The fact that the proposed approach reduces energy costs by 27%, improves carbon emissions by 29%, and increases user satisfaction by 20% is considered a significant improvement over conventional methods [59]. These findings are in line with the literature showing that meta-heuristic algorithms (e.g. Particle

Swarm Optimization (PSO), Genetic Algorithms (GA) and Bee Colony Optimization (ABC)) and deep learning-based hybrid models provide effective solutions in DSM applications [14], [19], [43]. The applicability of the hybrid model, especially in the management of electric vehicle charging stations and microgrid scenarios, can create a new paradigm in the energy sector.

Increasing electric vehicle (EV) penetration in smart cities causes sudden load increases and supply-demand imbalances in the grid. The hybrid optimization model developed in this study is tested to improve the energy management of EV charging stations. The model integrates renewable energy sources (e.g. solar panels and wind turbines) in the most efficient way when analyzing user charging demands. Through this integration, overloads are reduced by 30%, energy costs are reduced by up to 25% and user satisfaction is increased by 18% [33], [44]. Furthermore, a 22% reduction in carbon emissions demonstrates the environmental impact of the model [48].

In the microgrid scenario, the integration of hybrid algorithms into energy management in rural areas is evaluated. The inherent production fluctuations of renewable energy sources increase the security of supply risk in rural energy grids. The hybrid optimization model developed in this study optimized the management of PV (photovoltaic) and wind energy systems in a rural microgrid. The model achieved a 21% reduction in energy costs, a 26% improvement in carbon emissions and a 19% increase in system resilience. These results show that hybrid algorithms are a promising approach for energy management, especially in resource-constrained regions [18], [27], [46].

In terms of future perspectives, the integration of hybrid meta-heuristic algorithms into real-time energy management systems stands out as an important research area. Especially in systems supported by IoT-based sensor data and smart grid technologies, the adaptive nature of hybrid algorithms can provide fast and effective solutions to sudden demand changes. Moreover, integrating artificial intelligence layers that model user behavior into DSM strategies will enable the development of a consumer-oriented energy management approach [12], [53].

The scalability of hybrid optimization models can be tested in large city networks and industrial zones to develop strategies for larger-scale applications. The complexity of energy management, especially in electric vehicle fleets, data centers and smart city infrastructures, highlights the multi-objective optimization capabilities of hybrid algorithms.

In addition, the hybrid optimization approach can also contribute to shaping energy management policies. The fact that the model developed in this study supports environmental sustainability while minimizing energy costs provides an

important roadmap for decision makers and policy makers in energy transition processes.

In conclusion, this study demonstrated the effectiveness of hybrid meta-heuristic algorithms for demand side management in energy systems and presented an innovative approach in the field of energy management. In line with the findings of the study by Leyla Akbulut et al. (2025) [59], the proposed model has a significant potential in achieving sustainability and efficiency goals in energy systems.

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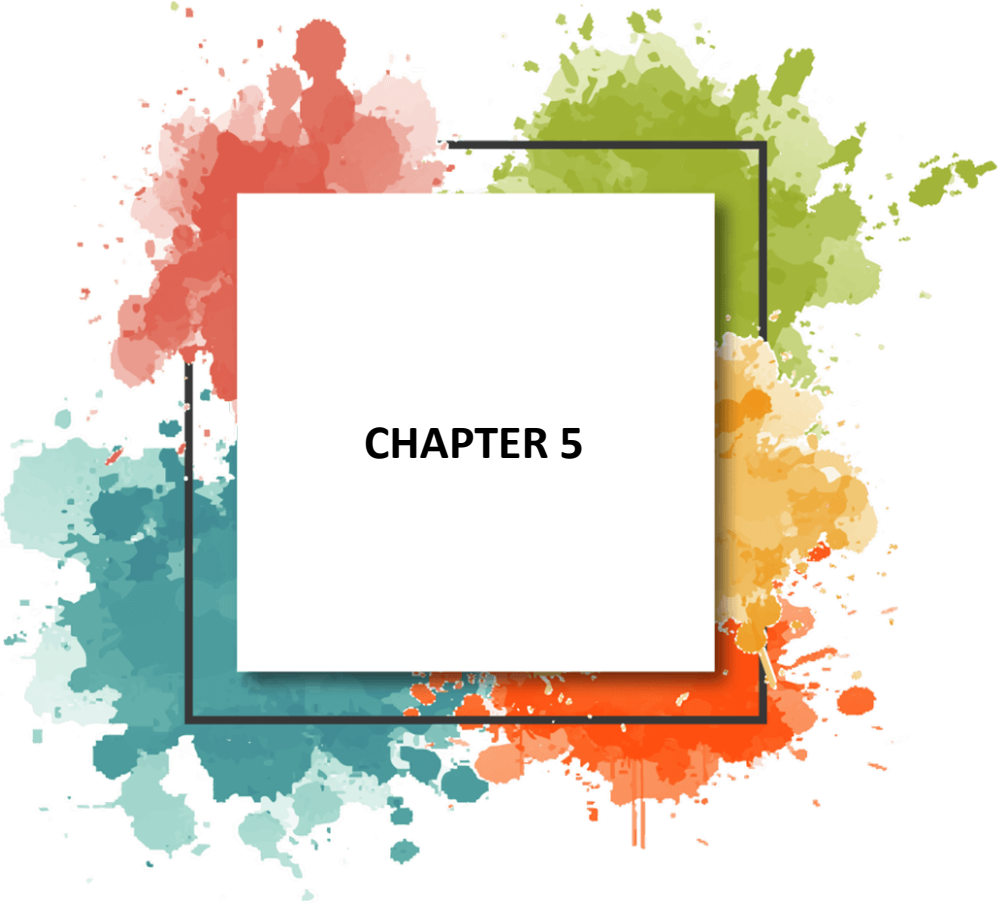
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CHAPTER 5

Characterization of the HSLA Armor Steel

Welding for the Defense Industry

Ferit Artkin¹

Introduction

Armor steels are a type of steel that is specially engineered to defend against impacts, ballistic threats, and explosion forces. Their efficacy is the result of a carefully developed mix of chemical composition, microstructure, and heat treatment.

The main concepts of armor steels center around striking a delicate balance between extreme hardness for penetration resistance and adequate toughness to prevent brittle fracture, while also taking fabricability and weight optimization into account for specific purposes. This is largely accomplished by careful control over alloying components and sophisticated heat treatment methods, which result in a fine, tempered martensitic microstructure.

As this field has advanced, it has also started to be utilized in military ground vehicles. Land vehicles are armored with steel that is soft on the inside and hard on the exterior. Impact resistance is decreased by the initial, hard surface, which is the main justification for this design. By absorbing energy, this second, softer surface reduces the possibility of harm.

All things considered, HSLA steels have a blend of qualities that make them extremely important in contemporary armored systems. They supplement the function of ultra-hard armor steels in providing complete protection by allowing designers to produce structures that are robust, durable, reasonably light, and simpler to build.

Fundamental Specifications of HSLA Armor Steels

High-strength low-alloy (HSLA) steels are microalloyed steels that are intended to have superior mechanical qualities and may also be more resistant to atmospheric corrosion than traditional carbon steels.

HSLA steels have low carbon levels (0.05%-0.25%), which allows for appropriate formability and weldability, as well as manganese concentrations of up to 2.0%. Small amounts of manganese, along with trace amounts of copper, nickel, niobium, nitrogen, vanadium, chromium, molybdenum, titanium,

¹ Lect. Dr., Kocaeli University, ORCID: 0000-0002-8543-6334

calcium, rare-earth elements, or zirconium are mixed in various combinations to impart certain qualities (Classification of steels, 2020).

High-strength low-alloy steels (HSLA) are steels having ferrite/pearlite microstructures that are stronger than regular low-carbon steels. Figure 1 compares the stress-strain curves of DP steel, HSLA steel, and ordinary carbon mild steel. It demonstrates that HSLA steel has double the yield strength of plain carbon mild steel. HSLA steels' primary strengthening element is their fine ferrite grain size (Fig. 2).

Copper, titanium, vanadium, and niobium are added to carbon steels to strengthen them and modify their microstructure from ferrite-pearlite to a very thin dispersion of alloy carbides in an almost pure ferrite matrix. Copper, silicon, nickel, chromium, and phosphorus are all used to improve corrosion resistance.

HSLA steels require the addition of zirconium, calcium, and rare-earth metals for sulfide-inclusion shape control, which improves formability due to their directionally sensitive characteristics.

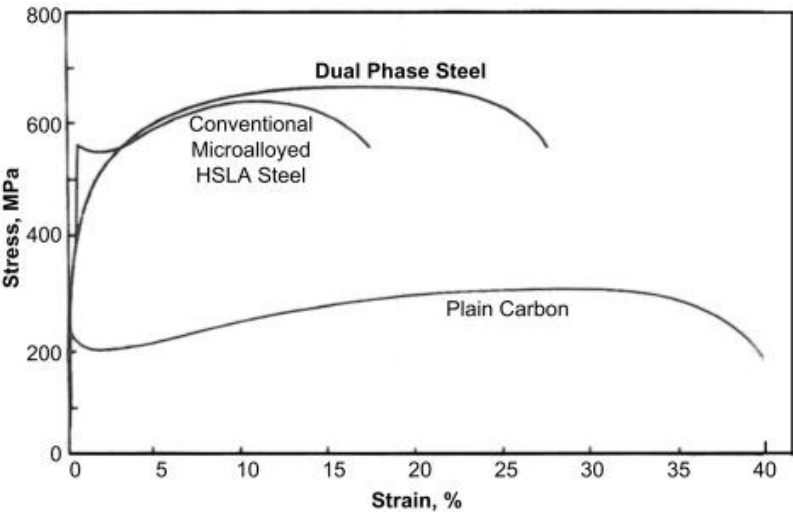


Figure 1. Stress-strain curves for plain carbon, HSLA, and dual-phase steel (Sinha, A.K., 1989).

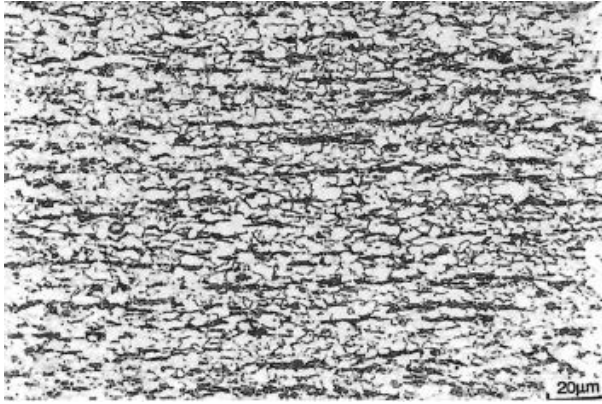


Figure 2. Typical ultrafine-grained ferrite produced from deformed unrecrystallized austenite (Sinha, A.K., 1989).

The mechanical qualities of High-Strength Low-Alloy (HSLA) armor steels, which are attained by a meticulously regulated

chemical composition and processing (often quenched and tempered), are the primary determinant of their basic requirements. Higher strength and hardness criteria are necessary for HSLA armor steels since they are especially designed for ballistic and blast protection, in contrast to normal HSLA steels used in construction (Skobir, D., 2011).

Table 1. HSLA armor steels are low in carbon but microalloyed with strengthening elements. Typical composition ranges: (metazenith.com, 2025) (Skobir, D., 2011).

Element	Typical Range (%)	Function
C (Carbon)	0.10 – 0.25	Provides strength, but kept low for weldability
Mn (Manganese)	0.50 – 1.50	Strengthening and hardenability
Si (Silicon)	0.15 – 0.50	Deoxidizer and solid-solution strengthening
Cr (Chromium)	0.30 – 1.20	Increases hardenability and corrosion resistance
Ni (Nickel)	0.20 – 2.00	Improves toughness, especially at low temperatures
Mo (Molybdenum)	0.15 – 0.50	Improves hardenability and strength at high temperatures
V, Nb, Ti (Microalloying)	0.01 – 0.10 each	Precipitation strengthening and grain refinement
B (Boron)	0.0005 – 0.003	Enhances hardenability
P, S	< 0.015	Impurities (kept low for toughness and weldability)

Micro-alloying and processing, rather than high carbon content, which is essential for weldability, are the main sources of HSLA steels' enhanced qualities (Skobir, D. 2011). Alloying Elements: To increase strength and toughness, small quantities of low-alloy

elements are added. Hardenability is improved by manganese (Mn). Strength, hardness, and toughness are increased by nickel (Ni) and chromium (Cr). Molybdenum (Mo): During heat treatment, it increases strength and hardenability at high temperatures. Niobium (Nb), titanium (Ti), and vanadium (V) are utilized as micro-alloying elements for precipitation strengthening and grain refining (Skobir, D., 2011) (en.wikipedia.org, 2025).

Table 2. Mechanical Properties, Typical values for quenched and tempered HSLA armor steels: (azomining.com, 2025) (Skobir, D. 2011).

Property	Typical Range	Notes
Yield Strength (σ_y)	690 – 1400 MPa	High strength to resist deformation
Ultimate Tensile Strength (σ_u)	800 – 1700 MPa	Depends on grade and thickness
Elongation (%)	8 – 18	Retains ductility for energy absorption
Hardness (HRC)	30 – 55	Related to ballistic resistance
Charpy V-notch Impact Energy	> 20 J @ -40°C	Indicates high toughness
Density	~7.85 g/cm ³	Typical of steel

Microstructure of HSLA armor steels microstructure that is either bainitic or martensitic, contingent on tempering and quenching. Structure with fine grains and scattered nitrides and carbides (from microalloying). Strength and toughness are balanced by controlled rolling and grain refining. Heat Treatment of HSLA armor steels Standard procedures include tempering andquenching. Thermomechanical controlled processing (TMCP) is used in some grades to provide the required strength withoutgoing overboard with hardness. High strength and ballistic performance without brittleness are guaranteed by controlled tempering.

Both formability and weldability, good weldability is ensured by low carbon concentration. To stop cracking, preheating andpost-weld heat treatments could be necessary. Hardness and thickness determine formability; milder tempers are simpler to form. Armor and Ballistic Performance designed to withstand explosion impacts, fragmentation, and small weapons fire. The balance between toughness and hardness is crucial: Increased hardness increases resistance to penetration. Cracking and spalling areprevented by high toughness. Ballistic

ratings typically range from 400 to 600 HB (Brinell) (azomining.com, 2025) (metazenith.com, 2025) (masteel.co.uk, 2025) (Skobir, D., 2011).

Production of HSLA Armor Steel

The production method for steel, which is made of iron and carbon, is somewhat similar to that of metals. Armor steel is made via a number of steps, such as melting, alloying, continuous casting, hot rolling, and heat treatment, which is used to give the material the appropriate mechanical qualities. It's important to alloy the steel. Elements including nickel, cobalt, chromium, manganese, copper, boron, and aluminum are blended with the steel.

For example, chromium is corrosion-resistant and transmits the same attributes to the material with which it is employed, whereas nickel boosts the strength and toughness of the material. Steels melted in arc furnaces are alloyed to get the desired characteristics. The alloying process in armor steels involves elements such as Cr, Ni, and Mo. After alloying, they are combined into slabs (flat billets) using the continuous casting technique.

The steel is hot rolled following the mixing procedure. Here, the goal is to use rolling mills to produce a noticeable thinning process while the steel is still hot, giving it a soft feel. Of course, rolling serves other purposes as well. Rolling also increases the strength and durability of steels. After hot rolling, steels go through a heat treatment procedure known as austenitization and tempering. After that, quenching gives the microstructure a martensitic character.



Figure 3. Production of armor steel by hot rolling.

Austenitization is the process of gradually heating the steel to a temperature between 900 and 950 degrees Celsius and then annealing it until its structure fully changes into austenite (when the internal structure is homogenous and exhibits a comparable structure in every location). Tempering is a technique used to increase toughness and decrease the brittleness or hardness of quenched steels. Let's take a quick look at what microstructure and martensitic mean. When analyzing a material's geometric distribution under a microscope and extrapolating its mechanical behavior from the findings, microstructure plays a crucial role. Compared to materials having coarse-grained microstructures, those with fine-grained microstructures are stronger. Explaining the many kinds of martensitic steels would be more beneficial than defining the word.

When steel is heated to around 900°C and then quickly cooled, a hard yet brittle substance known as martensite is produced. It is undesirable to have steel that has a softer texture than martensite, such as pearlite, sorbite, trostite, and bainite, if the cooling rate is not at the appropriate level. There is a noticeable rise in armor steel's hardness upon quenching. The armor steel is tempered in certain situations, which lessens hardness and regains lost toughness. The grade of steel determines the temperature at which the tempering process is conducted. For example, MIL-A-12560 is carried out at a minimum temperature of 580°C. MIL-A-46100 is completed at a minimum temperature of 180°C (malzemebilimi.net/, 2025).

Armor Steels and Ballistics

Armor steels are high-quality, low-carbon alloy steels with a homogeneous microstructure that are widely used in armored fighting vehicles to resist cracking, fragmentation, and breakage from multiple impacts of projectiles of various characteristics (kinetic penetrators, high-explosive and fragmentation warheads, and so on).

The field of study known as ballistics examines how objects, especially rockets, bullets, and shrapnel (particles), move when launched or propelled under air and gravitational circumstances. Four general branches make up ballistics (P.M. Cuniff, 1999): Thermodynamic processes like powder burning and gas expansion within a cannon or rocket are the focus of internal ballistics. The behavior of a particle or projectile after it exits a tube or launcher, as well as any potential disruptions, are the subjects of intermediate ballistics. The movement of a particle or projectile after it exits a rocket's or launch platform's muzzle is the subject of external ballistics. The impacts of particles hitting their targets are the subject of terminal ballistics.

The best penetration and destruction of a target is accomplished by hollow-charge and armor-piercing kinetic energy bullets. Bullets with kinetic energy

don't have explosives. Through sintering, tungsten (W) or uranium (U) material is used to make the bullet tip. These rounds' penetration effect on the target is determined by their diameter, energy, angle of impact with the armor, and the metallurgical makeup of the armor and bullet. Body armor and its various levels of protection are the subject of ballistic protection. Figure 4 depicts groupings of ballistic protection (Teijin Twaron, 2005).

Ballistic requirements for military and police armor are generally defined by international standards. The most widely used in this field are those of the National Institute of Justice (NIJ).

Standards and circumstances for the test include: Real ballistic testing and simulations; bullet quality (e.g., similar weight, core hardness, etc.); distance; angle of attack; backing/plate backing; and number of hits. Microstructure control: presence of carbides and nitrides, tempering temperature, grain size, alloying, etc.

Generally weaker, locally softer, or more brittle, heat-affected zones and welds may have fracture sites. Hardness gradients: Surface hardness is frequently crucial to preventing penetration; deeper layers aid in absorbing leftover energy; uniform hardness is beneficial.

In ballistic calculations, it is crucial to understand the aforementioned parameters.

Ballistic qualities are determined using an armor nomenclature that includes several concepts, such as NATO angle, reference shot, V_{50} velocity, witness plate, penetrator, and so on (V₅₀ Ballistic, 1997).

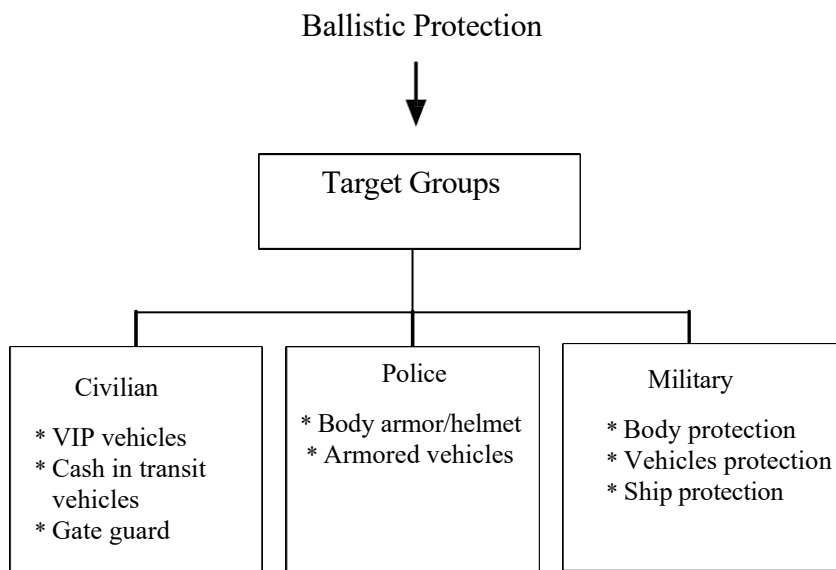


Figure 4. Groups of Ballistic Protection.

Armor Steels and Military Applications

The primary application area of rolled armor steel is the protection of tanks, howitzers, and armored combat vehicles against bullets, fragmentation, and blasts (e.g., anti-tank mines and explosive grenades). The primary goal of armoring tanks, the most important combat vehicle in conventional land warfare, to maintain the survivability of MBT (Main Battle Tank), is to protect the vehicle and crew from the negative effects of threatening munitions. As schematically illustrated in Figure 5, armor steel is used on the APC (Armoured Personnel Carrier) as side panels (Figure 5, left) and mine-resistant floor pan (Figure 5, right).

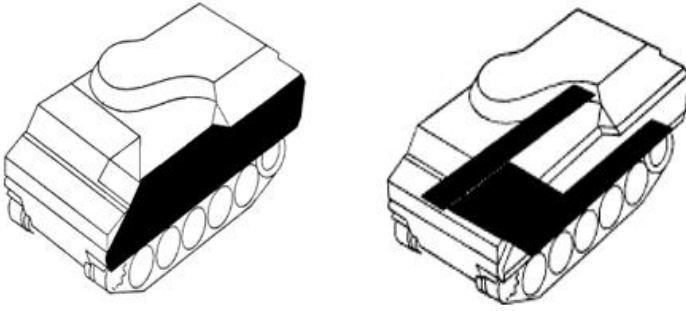


Figure 5. Use of armor steel as side protective panels (left) and mine-resistant floor pans (right) on an APC.

The self-propelled howitzer is another military weapon that makes use of armor steel. The Turkish Armed Forces inventory's Firtına howitzers are made of armor steel that has been welded into a hull or turret. A T-155 Firtına self-propelled howitzer with armor steel armor is seen in Figure 6. Armoured combat vehicles (ACVs), armored tactical vehicles, troop carriers, tow vehicles,



Figure 6. T-155 Firtına Self-Propelled Howitzer with its armor steel protection.

armored mortar vehicles, engineering squad vehicles, and command and control vehicles are other military vehicles that incorporate armor steel (Soykan H., et al., 2005).

Characterization of Welded Joints of Armor Steels

According to Zerbst et al. (2014), welded connections are often distinguished by three separate zones: the heat-affected zone (HAZ), the weld metal (WM), and the base metal (BM). Heat input, plate thickness, and the peak temperatures and cooling rates associated with each zone are intimately connected to the characteristics of the heat-affected zone in welded plates, such as the coarse-grained and fine-grained zones. The temperature per unit of time and the rate of cooling both fluctuate with the heat input. Microhardness levels in this context also vary according to microstructural modifications. A schematic representation of the peak temperature variation with distance along the HAZ and the microhardness data associated with this shift is shown in Figure 7 of the research by Çoban et al. (2021)

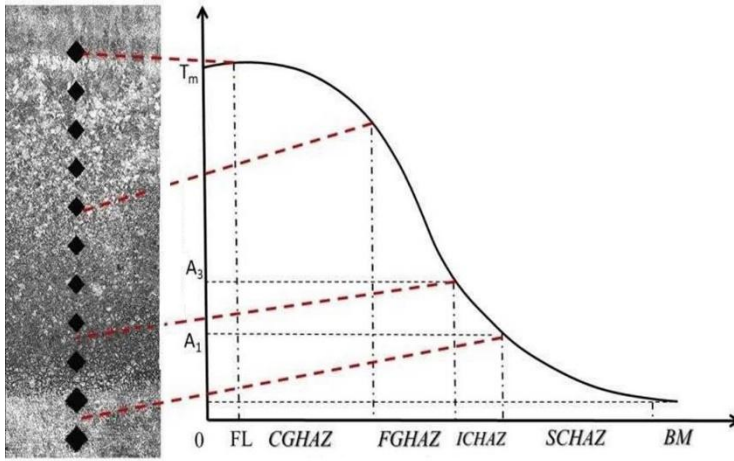


Figure 7. The impact of peak temperature variation with distance along the HAZ on microhardness points is shown schematically (Çoban et al., 2021).

This results in the formation of a coarse-grained heat-affected zone (CGHAZ) in the area below the fusion line (FL) that is exposed to high temperatures. A fine-grained heat-affected zone (FGHAZ) is created by the normalizing annealing in the area that corresponds to lower temperatures but is above A_3 . As can be observed from the rise in indentation diameter in the figure, hardness drastically reduces in the areas where peak temperatures match those in the intercritical heat-affected zone (ICHAZ), which is the partial transformation zone. The tempering effect causes hardness to drop below the A_1 line, the austenitic transformation initiation temperature, and to rise toward the base metal in the subcritical heat-affected zone (SCHAZ).

The heat-affected zone's breadth and microstructure depend on the base material's chemical makeup and the pace at which it cools after welding (Cabrilo et al., 2018(b)). The degree of hardness and ballistic performance of the weld joints are influenced by the metallurgical characteristics of this zone. The MIL-STAN-1185 (2008) standard states that in order to provide heat input management, the width of the heat-affected zone, as measured from the weld centerline, must not exceed 15.9 mm. Figure 8-a by Gürol et al. displays the microstructures that were created in the weld joint regions as a result of variations in temperature cycles. Different heat cycles caused the weld metal or the fusion line to generate CGHAZ, FGHAZ, ICHAZ, and SCHAZ zones, respectively. According to reports, cooling from high temperatures at the fusion line boundary results in the formation of a coarse-grained zone (CGHAZ), whereas quick cooling from temperatures slightly over the A3 line results in the formation of a fine-grained zone (FGHAZ). Furthermore, it has been noted that the intercritical zone (ICHAZ), which is where the lowest hardness values occur, forms and partial transformations take place at temperatures between the A3 and A1 lines. Although there is no phase change in the areas below the A1 line, a tempering effect known as the SCHAZ (subcritical zone) takes place (Pang, 1993; Mikko, 2014). Figure 8-b shows the distribution of microhardness along the HAZ.

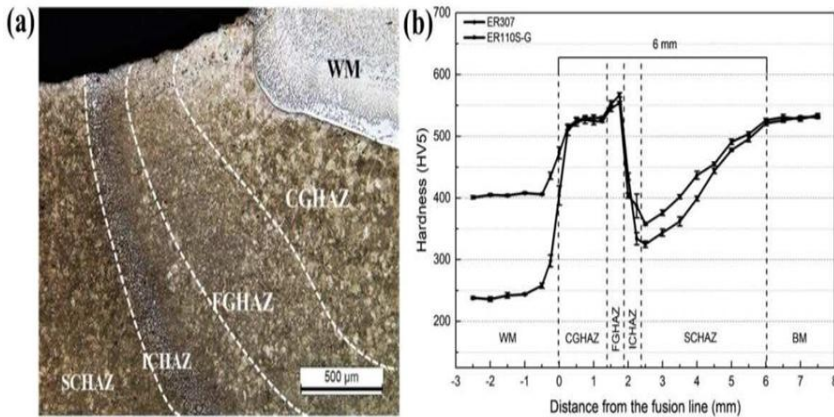


Figure 8. Heat-affected zone microstructure picture (a)(1.2 kJ/mm, 50X magnification), microhardness variation along the HAZ based on the kind of weld metal (b) (Gürol et al., 2022).

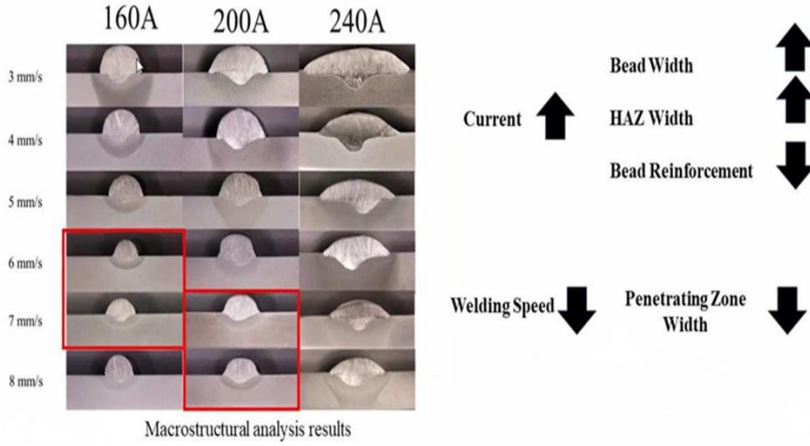


Figure 9. Macrostructural Characterization of Results, Effects of Current Increase and Welding Speed. (Çelik, C., et al 2022).

Welding Method Effect

The most efficient technique for welding armor steel has been found via studies. This technique is known as gas metal arc welding (MIG), or metal inert gas (MIG) in the industry and literature. Nonetheless, as technology advances, the consequences of various approaches are still being studied. In the manufacturing of troop vehicles, flux-cored arc welding (FCAW), shielded metal arc welding (SMAW), and gas metal arc welding (GMAW) are all often utilized techniques. The deposition rate of SMAW is lower than that of FCAW. Additionally, the continual feeding of wire into the weld pool makes GMAW more productive than SMAW. According to Kuzmikova (2013) and Magudeeswaran et al. (2008), the welding method determines the welding heat cycle, which in turn determines the degree of HAZ softening that takes place during the welding of HHA steel. This section provides an overview of studies showing these impacts on the HAZ area of various welding techniques.

Three distinct welding techniques were used on Ramor 500 armor steel by Günen et al. (2019). The mechanical and microstructural characteristics of MIG, CMT, and HPAW (hybrid plasma arc welding) were examined (Table 3). In every approach, austenitic 307 Si, which has high toughness characteristics, was utilized as the weld metal. We optimized each approach to find the welding settings. Table 3 provides a summary of the mechanical test findings that were achieved. As a result, for CMT, GMAW, and HPAW, the corresponding tensile strength ratios to the base material tensile strengths were found to be 45%, 50%, and 65%, respectively. The best impact strength was obtained using the CMT technique, according to impact tests conducted on samples obtained by notching

the weld metal. Electron microscope analysis of the fracture surfaces revealed that the CMT method discovered dimples, a sign of ductile fracture, whereas the GMAW and HPAW methods showed cleavage planes, a sign of brittle fracture. In tensile testing, the welded structure made using the CMT process cracked around the fusion line. The CMT technique revealed that the weld metal and base metal did not combine properly. Due to the comparatively reduced heat input in CMT, there is less nickel migration from the weld metal to the base material, which increases the weld metal's austenite stability. In other techniques, martensite forms in the cooled weld metal as a result of increased nickel diffusion brought on by increased heat input, as shown by spectral analysis. This has been shown to produce stronger welded structures in GMAW and HPAW processes as well as harder weld metal. It has been shown that the reason for the higher HAZ hardness in CMT is the formation of untempered martensite and lower grain size due to low heat input.

Table 3. Mechanical properties of the Ramor 500 welded structure obtained by different methods (Günen et al., 2019).

The hardness, bending strength, and impact resistance characteristics of

	Tensile Strength (MPa)	Elongation %	Fracture Zone	Hardness(HV10)		Charpy Impact Strength (J)	
				Weld Metal	HAZ	-50 °C	20 °C
Main Material	1780	6,4	-	-	-	17,3	22
GMAW	892	3,1	HAZ	478	433	10,1	19,4
CMT	718	4,4	Weld Metal	376	446	30,1	43,2
HPAW	1150	5,2	HAZ	454	422	15,1	20,8

Protection 500 armor steel were compared using the MIG, MAG, and TIG welding techniques in a master's thesis by Doğrugiden (2019). The findings are displayed in Table 3. The MIG welding process produced the maximum bending strength, whereas the TIG welding process produced the best impact strength. Though the high hardness of the weld metal utilized is a factor, the MIG process produced the weld metal with the highest hardness rating. The weld metal hardnesses and HAZ hardnesses were found to be same when utilizing the same weld metal for the MAG and TIG processes; however, the hardness distribution was more uniform in the TIG method.

Welding Metal Effect

The most crucial factor to take into account, especially when it comes to the kind of weld metal being utilized, is arc welding, which is the most popular technique for joining armor steels with a melting electrode. The filler material is the weakest point in armor steel weldments, meaning that it has weaker mechanical qualities than the foundation material (Cabrilo et al., 2018b). Additionally, removing hydrogen from the weld zone to lower the chance of cold cracking is one of the most crucial factors in armor steel welding. This is due to the fact that hydrogen gradually causes damage known as hydrogen embrittlement in the weld zone by diffusing into the HAZ. Therefore, while combining armor steels, wire selection is quite important. The recommended wire for bonding armor steels is ferritic or austenitic. Weld metals made of austenitic stainless steels provide a number of important benefits. Hydrogen embrittlement prevention is one of these.

There are now efforts to employ welding wires with varied architectures to attain the best level of ballistic strength since the welding process generates deformation issues in the material. This section compiles studies related to this topic. MIG welding was done on ArmoX 500 armor steel by (Saxena et al. (2018a)) utilizing ferritic and austenitic weld metal. For ferritic weld metal, the tensile strength of the welded structure was 41% of the tensile strength of the base material, whereas for austenitic weld metal, the ratio was 31%. Put differently, ferritic weld metal outperforms austenitic weld metal in terms of welded structural strength. The impact strength value of the welded structure made with austenitic weld metal was 20% greater than the impact strength of the base material, but the welded structure made with ferritic had a 12% lower value, according to the findings of the notch impact test. Impact strength has been demonstrated to improve with the usage of austenitic weld metal.

Günen et al. (2019) looked at the impact of employing austenitic weld metal on Ramor 500 armor steel in a similar manner. Their findings showed that the welded structure's tensile strength was 50% that of the base material. According to tensile testing, the CGHAZ area is where the fracture happened. An increase in the quantity of residual austenite and severe grain coarsening were the results of high heat input. Additionally, it was noted that a significant diffusion of nickel caused the weld metal's austenitic structure to be broken, which increased the quantity of delta ferrite. Saxena et al.'s (2018 (a)) greater tensile strength value can be explained by this. Additionally, CGHAZ brittleness was markedly enhanced by high heat input. The importance of optimizing the heat input is evident.

Table 4. Effect of filler metal on mechanical properties (Kostak, 2021).

	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Charpy Impact Strength (J)
Ferritic (ER120S-G)	1200	1240	12,5	80
Austenitic (ER307)	550	700	9,5	89
Duplex (ER2209)	650	800	11	84

Additionally, Evci et al. (2014) used austenitic cored wire and solid austenitic filler metal to examine and analyze the impact of a welded structure on the mechanical characteristics of armor steel. AWS 5.9 and AWS 5.28 state that two distinct solid austenitic filler metals and AWS 5.29 states that cored wires were used to compare the toughness and strength of welded structures. According to the findings, the cored wires considerably enhanced strength without appreciably lowering toughness, but the solid austenitic wires offered exceptional toughness values.

In a research conducted by Kostak (2021), MIG welding was performed on Armox500T armor steel utilizing ferritic, austenitic, and duplex stainless steel filler metals with a heat input of 0.4 kJ/mm. Table 6 summarizes the results. While the addition of austenitic and duplex filler metals drastically reduced strength, impact resistance rose marginally. (Naveen Kumar et al., 2022a) used austenitic stainless steel (ASS), duplex stainless steel (DSS), and low hydrogen ferritic (LHF) filler metal to perform three different welding processes on two types of 15 mm thick rolled homogeneous armor steel (RHA) and ultra-high hardness armor steel (UHA) plates. Ballistic performance in welded constructions with various filler metals was evaluated in order to characterize the damage mode. The bullet's penetration depth (DoP), width (with of penetration, or WoP), and areal density (DoP x target density) were ascertained by ballistic testing. Three distinct damage mechanisms were identified as a consequence of the data obtained: cleavage failure (CF), coarse wear debris with cleavage (CWDC), and fine wear debris with cleavage (FWDC). The sample with the lowest surface area density (54 kg/m²) that was welded using austenitic stainless steel filler metal was found to have the best ballistic resistance against the bullet. The microstructure of the austenitic stainless steel filler metal contains an austenite phase, which is the cause of this. This filler metal's microstructure is made up of austenite surrounded by delta ferrites. Using optical emission spectroscopy (OES) and an X-ray diffractometer (XRD), the ferrite and austenite phase contents were determined to be 95% austenite and 5% ferrite. This indicates that the austenite

phase has significant energy absorption characteristics. Because of the small wear debris created by cleavage and the remnant ferrite phase in the microstructure, the sample welded employing LHF filler metal was found to have the lowest ballistic resistance against a shotgun bullet with an areal density of 97 kg/m². The study found that ballistic resistance is inversely related to strength and microhardness characteristics and directly related to toughness and elongation.

Using robotic gas metal arc welding, Kurt (2022) examined the impact of various filler wires on the microstructure and mechanical characteristics of Protection 500 grade armor steel, the first steel made in Turkey with local production. The welding wires that were utilized were austenitic stainless ELOX 309LSi, ferritic ER110 and SG3, and stainless ELOX SG2209. The highest heat input in the investigation, which was controlled using robotic welding, was determined to be 1.08 kJ/mm³. Consequently, it was found that the welds were effectively finished without the need for preheating. The acicular ferrite (AF) and partly bainite (B) phases in the microstructure had a direct impact on the tensile strength, according to an analysis of the welded connection employing ER110 SG welding wire.

The ratio of tensile strength to base material strength was reported to be 62%. In Figure 10, microstructural pictures are displayed. The welds produced with SG3 welding wire had the lowest tensile strength to base material strength ratio, which was 48%. The toughness value of welds made with ELOX 309LSi weld metal was found to be the highest, with an average of 97J, while welds made with ER110 weld metal had the lowest, with an average of 37J, according to test results of notch impact samples taken from the weld area.

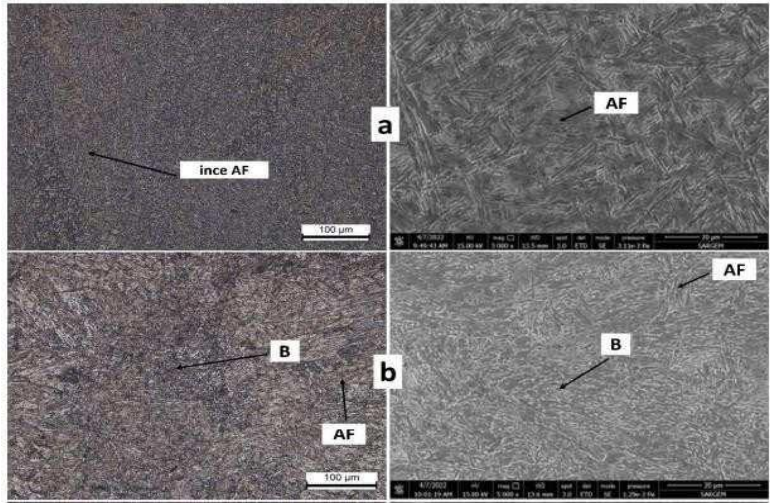


Figure 10. In the weld made using ER 110 SG welding wire. Weld cap pass microstructure a. Root pass microstructure (Kurt, 2022).

Conclusion

In conclusion, the integrity and efficacy of armored vehicles and structures depend heavily on the characterisation of HSLA armor steel welding for the military sector. Because of its unusual characteristics, HSLA steel needs certain welding methods and processes to stay strong and long-lasting. Manufacturers and engineers may create superior welding techniques that satisfy the demanding specifications of the military sector by researching and comprehending the properties of HSLA armor steel welding. Ultimately, this will contribute to the overall security and success of defense operations by improving the safety and protection of military men and assets. In the Heat-Affected Zone (HAZ), the key obstacle is still striking the ideal balance between the high hardness needed for ballistic performance and the toughness required to avoid brittle fracture and hydrogen-assisted cold cracking (HACC). Three crucial changes are emphasized in the conclusion: From Post-Weld Inspection to Real-Time Process Control: In-situ monitoring is replacing the laborious, traditional post-weld NDT (Radiography, conventional UT) in characterization. Cutting-edge sensors, like acoustic emission detectors and high-speed thermal cameras, will be used to actively monitor the welding thermal cycle and identify hydrogen cracking as it happens. This will enable prompt process modifications (like preheat/interpass temperature modulation) to reduce the formation of brittle microstructure. Data Integration with Digital Twin: Using a Weld Digital Twin will be the norm in the future. This virtual environment combines past mechanical test data, sophisticated NDT findings (such as Phased Array UT and ToFD), and real-time welding data. Before the structure is placed into service, this system will use machine learning and artificial intelligence to anticipate the joint's ultimate mechanical and ballistic characteristics. Focus on Microstructure-Property Correlation: Methods that relate weld parameters to the nanoscale will become more and more important in characterization. To make sure the weld zone satisfies strict military requirements for integrity and survivability under dynamic loading, nanoindentation and advanced microscopy (SEM/EBSD) will be crucial for accurately characterizing the local properties of micro-constituents (such as tempered bainite vs. martensite) within the HAZ. The future of HSLA armor weld characterisation essentially consists of creating an intelligent, end-to-end quality feedback loop in which the metallurgical condition of each weld is predicted using controlled production data, hence verifying its structural and ballistic qualities.

Future developments in technology and innovation might significantly impact the military industry's use of HSLA armor steel welding characterisation. The military industry's growing need for lightweight, high-strength materials means that HSLA armor steel will remain essential to the creation of next-generation

armored vehicles and structures. Additionally, the use of robots and automation into welding procedures will increase efficiency and decrease human error, leading to more dependable and uniform welds. The military sector will continue to be at the forefront of technical developments in materials and production thanks to cooperative research efforts between industry, academia, and government agencies. This will drive innovation in the field of HSLA armor steel welding. The development of cutting-edge materials, welding processes, and technologies that will further improve the security, functionality, and efficacy of armored vehicles and structures in military applications is anticipated to continue to advance, making the future of HSLA armor steel welding for the defense sector generally bright.

Acknowledge

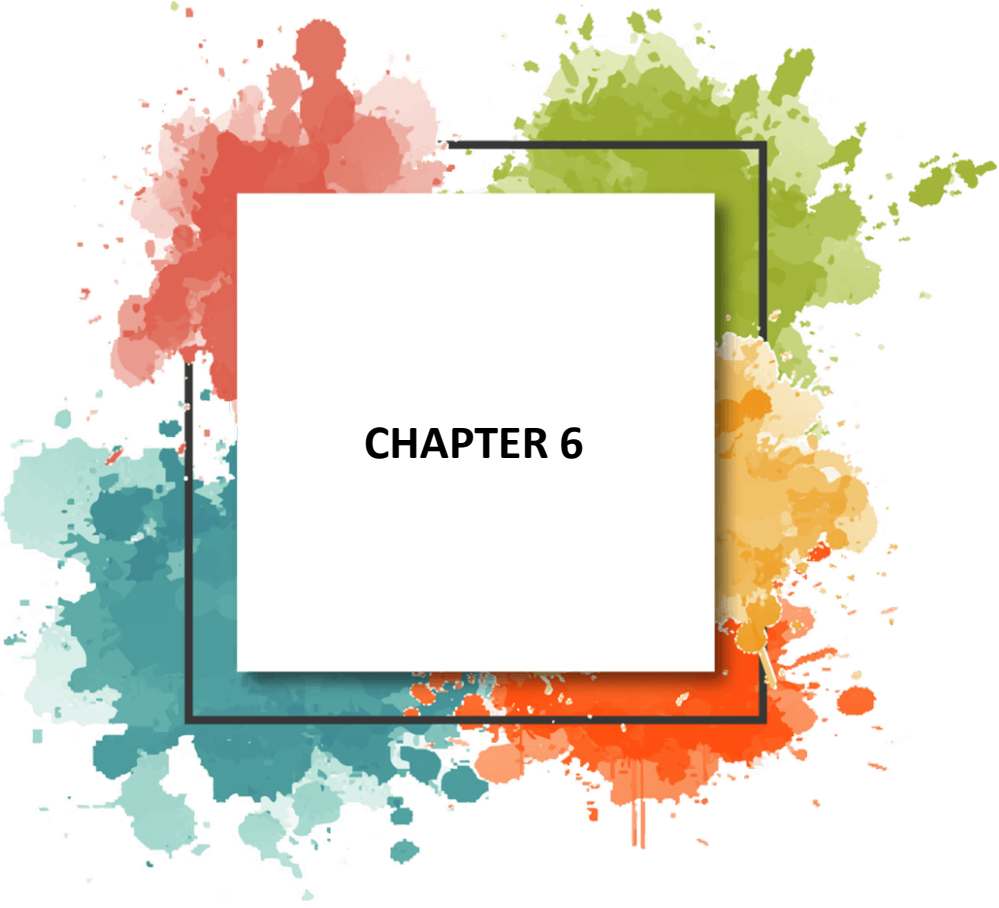
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CHAPTER 6

Utilizing Predictive Control and Extended Kalman Filter for Accurate Speed Estimation and Enhanced Stability in Motor Drive Systems

Mohamed Ayham Mousallati¹ & Burhanettin Durmuş²

1. Introduction

Induction motors (IMs) are widely employed in industrial applications due to their robustness, low cost, and ability to operate continuously under varying load conditions. Advances in power electronics and digital control systems have enabled the implementation of sophisticated techniques such as vector control, slip frequency control, indirect field-oriented control (IFOC), and predictive control strategies (Gou et al. 2022; Chen and Zhang 2015; Zahraoui et al. 2022). Among these, Model Predictive Control (MPC) has emerged as a powerful framework, allowing complex constraints and performance goals to be handled in the time domain (Zhang and Xie 2013; Shiravani et al. 2023).

However, predictive control schemes depend heavily on accurate knowledge of system parameters. If the model becomes outdated due to parameter drift—such as rotor resistance variations with temperature—the control system may fail (Devanshu et al. 2022). Similarly, in Field-Oriented Control (FOC) methods, accurate slip speed estimation is crucial when applying Park transformations from the three-phase stationary frame to the synchronously rotating d-q frame. Since slip speed is calculated using the rotor resistance, its thermal sensitivity poses a challenge for stable and accurate motor control (Tak et al. 2017; Marcetic and Vukosavic 2007).

Conventional IM control systems often rely on physical speed sensors like encoders, which increase the system cost and introduce installation complexity due to mechanical alignment requirements (Che et al. 2020; Sonnaillon et al. 2006). To reduce cost and improve reliability, sensor less control strategies have gained traction-requiring real-time estimation of rotor speed and magnetic flux without mechanical sensors.

¹ Master Student, Department of Electrical and Electronics Engineering, Kütahya Dumlupınar University, Türkiye, ORCID: 0009-0006-2767-5878.

² Assoc. Prof., Department of Electrical and Electronics Engineering, Kütahya Dumlupınar University, Türkiye, ORCID: 0000-0002-8225-3313.

Several recent approaches have attempted to overcome these challenges. Discretized MPC for IMs has shown improvement in torque ripple and THD reduction, though it lacked rotor resistance adaptation and precise flux regulation (Shiravani et al. 2023). An adaptive predictive current controller (APCC) based on FOC was introduced in (Devanshu et al. 2022), which used a stator resistance observer but did not evaluate rotor resistance variations. Sliding mode control-based estimation strategies (Tak et al. 2017) improved resistance tracking but did not consider electromagnetic torque ripple or external disturbances like load torque. Fuzzy logic and MRAS-based estimators (Che et al. 2020) demonstrated strong performance under varying conditions but remained sensitive to rotor time constant variation.

These gaps underscore the need for an advanced drive system that integrates robust parameter estimation and predictive current control to ensure stable, high-performance operation under real-world uncertainties. This paper proposes such a system, combining an Extended Kalman Filter (EKF) for real-time estimation of rotor flux, load torque, and resistances with a predictive current control structure to reduce torque ripple and enhance dynamic response. The goal is to enable precise sensor less operation of IMs while addressing key limitations in current approaches.

This paper introduces an advanced drive system (ADS) for motor speed and flux regulation alongside predictive control which optimizes current response and lowers electromagnetic torque ripple levels. An extended Kalman filter (EKF) runs independently to provide estimates related to speed, rotor flux and load torque and rotor resistance measurements. This method works to improve the drive system performance stability together with precise slip speed estimates for three-phase to d-q rotating reference frame conversion.

2. Related Work and Motivation

The development of robust and cost-effective sensor less control systems for induction motors (IMs) has become an increasingly critical area of research due to the growing demand for high-performance motor drives in industrial automation, electric transportation, and energy-efficient systems. Removing mechanical speed sensors not only reduces system cost and complexity but also enhances durability in harsh operational environments. As a result, extensive research has focused on estimation and control strategies ranging from conventional model-based designs to modern model-free and intelligent approaches that leverage machine learning and adaptive techniques.

2.1. Model based estimation and control

Model-based methods remain foundational in sensor less motor control. Approaches such as Model Reference Adaptive Systems (MRAS), sliding mode

observers (SMO), and Extended Kalman Filters (EKF) are widely studied for their ability to reconstruct key motor states using measurable electrical signals. Among these, the EKF has gained prominence due to its effectiveness in simultaneously estimating rotor flux, speed, and resistance, even under noisy and time-varying conditions. For instance, (Zahraoui et al. 2022) demonstrated that EKF could enhance fault tolerance by compensating for current sensor failures, ensuring more resilient operation.

Furthermore, Model Predictive Control (MPC) has been widely adopted for its predictive capability and rapid dynamic response. Unlike traditional proportional integral (PI) controllers, MPC anticipates future states based on system models and selects optimal control actions, thereby minimizing torque ripple and improving current tracking. However, MPC relies heavily on the accuracy of system parameters. These parameters such as rotor resistance tend to vary with temperature and load, which can undermine system stability and performance. To address this issue, recent works combine EKF's adaptive estimation with MPC's predictive control to form a dynamic and intelligent control scheme.

Nevertheless, despite their theoretical strengths, model-based controllers often suffer from high computational load and parameter sensitivity, which can limit their use in real-time embedded applications. Moreover, real-world disturbances and model mismatches remain persistent challenges.

2.2. Model-free and intelligent control approaches

To overcome limitations of parameter-dependent approaches, researchers have increasingly turned toward model-free and intelligent control strategies. These techniques aim to improve system robustness and adaptability without requiring an accurate motor model. One such strategy involves fuzzy logic and neural network-based current control, offering promising results in handling parameter uncertainties and nonlinearities (Guo et al. 2022). These algorithms adapt to system dynamics through learning, enabling better fault resilience and performance consistency.

Another significant advancement involves self-sensing speed control methods applied to interior permanent magnet synchronous motors (IPMSMs). Cascaded nonlinear controllers, as explored in (Chen and Zhang 2015), improve observability and ensure accurate speed estimation under variable load conditions. However, these IPMSM-specific designs are not directly transferable to standard induction motors without extensive customization, limiting their general applicability.

While intelligent control methods enhance flexibility, they often suffer from opacity (lack of interpretability), dependency on large training datasets, and

difficulties in stability analysis. Furthermore, their integration with real-time predictive schemes remains limited in current literature.

2.3. Fault-tolerant estimation and sensor less strategies

With the increasing need for reliability in mission-critical applications, fault tolerance has become a key research focus. Innovative implementations of EKF have been developed to detect and correct current sensor anomalies in real time (Zahraoui et al. 2022). These systems maintain drive performance even under sensor faults, thus providing resilience and safety assurances.

In addition, MRAS and SMO observers have been extended to support diagnostic and compensation functionalities. Although effective in identifying faults, these methods are typically dedicated to monitoring rather than enhancing control dynamics. Moreover, most fault-tolerant strategies are evaluated independently of advanced control frameworks like MPC or model-free controllers, indicating a research gap in unified, fault-resilient sensor less control architectures.

2.4. Gap analysis and motivation for the proposed work

The literature highlights considerable advances in estimation accuracy, adaptive control, and fault mitigation. However, key limitations persist:

- Model-free methods (Gou et al. 2022) do not inherently support predictive capabilities and often lack physical interpretability.
- IPMSM-based methods (Chen and Zhang 2015) show limited adaptability to induction motors due to their hardware-specific design.
- Fault-tolerant EKF solutions (Zahraoui et al. 2022) primarily focus on sensor correction and do not optimize dynamic control behavior.

To address these challenges, the proposed Advanced Drive System (ADS) introduces a unified sensor less control framework that integrates the online parameter estimation capabilities of EKF with the robust dynamic control of Predictive Current Control (PCC). This synergy facilitates accurate slip speed estimation, real-time rotor resistance adaptation, and precise d–q axis regulation achieving fast response, reduced torque ripple, and broad operational stability.

The ADS operates entirely without mechanical sensors, supports wide-speed-range operation, and adapts to load disturbances, making it well-suited for industrial-grade deployment. It advances state-of-the-art IM control by combining estimation precision, fault resilience, and predictive intelligence into a single architecture. These innovations align with current industrial trends toward smart, adaptive, and energy-efficient motor drive systems under the industry 4.0 paradigm.

In conclusion, this work significantly contributes to the evolution of sensor less IM control systems by addressing critical research gaps and offering a scalable, performance-oriented control solution for modern electric drives.

3. The Model of IMs

The model of a 3-phase IMs in a d-q frame is represented by (Tahhan and Temurtaş 2024; Trabelsi et al. 2012):

$$\frac{di_{sd}}{dt} = -a_5 i_{sd} + \omega_s i_{sq} + a_3 \Phi_{rd} + a_4 \omega \Phi_{rq} + b v_{sd} \quad (1)$$

$$\frac{di_{sq}}{dt} = -\omega_s i_{sd} - a_5 i_{sq} - a_4 \omega \Phi_{rd} + a_3 \Phi_{rq} + b v_{sq} \quad (2)$$

$$\frac{d\Phi_{rd}}{dt} = a_2 i_{sd} - a_1 \Phi_{rd} + (\omega_s - \omega) \Phi_{rq} \quad (3)$$

$$\frac{d\Phi_{rq}}{dt} = a_2 i_{sq} - (\omega_s - \omega) \Phi_{rd} - a_1 \Phi_{rq} \quad (4)$$

$$\frac{d\omega}{dt} = \frac{p}{J} (T_{em} - T_L) - \frac{f}{J} \omega \quad (5)$$

$$T_{em} = G \Phi_{rd} i_{sq} - G \Phi_{rq} i_{sd} \quad (6)$$

$$\omega = P \omega_m \quad (7)$$

Where: $a_1 = \frac{R_r}{L_r}, a_2 = \frac{L_m R_r}{L_r}, a_3 = \frac{L_m R_r}{\sigma L_s L_r^2}, a_4 = \frac{L_m}{\sigma L_s L_r}, a_5 = \frac{L_r^2 R_s + L_m^2 R_r}{\sigma L_s L_r^2}, b = \frac{1}{\sigma L_s}, G = \frac{P L_m}{L_r}, \sigma = 1 - \frac{L_m^2}{L_s L_r}$

Here, ω_s is synchronous speed, ω is electric speed, ω_m is mechanical speed, T_{em} is electromagnetic torque, T_L is load torque, v_{sq} and v_{sd} are stator voltage vectors, i_{sq} and i_{sd} are stator current vectors, Φ_{rq} and Φ_{rd} are rotor flux vectors, P is pole pairs, L_m is magnetizing inductance, L_s is stator inductance, R_s is stator resistance, L_r is rotor inductance, R_r is rotor resistance, J is rotor inertia and f is friction coefficient.

4. Field-Oriented Control

Field-oriented control (FOC) aims to decouple the electromagnetic torque and flux in AC motors and make the relationship between them linear, like DC motors. It achieves this by decoupling flux control from torque and speed control, allowing for precise and independent control of each. This is done through mathematical transformations that convert the motor's stator currents into two orthogonal components, enabling efficient and accurate motor control. When decoupling occurs, the rotor flux is orientated to the d-axis, that means:

$$\underline{\Phi}_r = \Phi_{rd} \quad (8)$$

$$\Phi_{rq} = 0, \frac{d\Phi_{rq}}{dt} = 0 \quad (9)$$

Based on the above, synchronous speed is determined as follows:

$$\omega_s = \omega + \omega_{slip}, \omega_{slip} = \frac{i_{sq}a_2}{\Phi_{rd}} \quad (10)$$

and the electromagnetic torque is determined as follows:

$$T_{em} = G\Phi_{rd}i_{sq} \quad (11)$$

This method enables the motor's torque and rotor flux components to be independently controlled.

5. Predictive Current Control Method

In an IM drive system, the inverter generates eight possible switching vectors based on the switching states (S_A , S_B , S_C) of transistor switches in the voltage source inverter (VSI) illustrated in Figure 1. Out of these, two vectors (V_0 , V_8) are null vectors, meaning they produce no output voltage, so only the remaining six vectors are actively used for control. To determine the optimal switching vector, an objective function is developed, which minimizes the difference between the reference currents and the actual stator currents. The stator currents at the inverter's output terminals are estimated for each switching vector using the IM model. This allows for precise control of the motor by selecting the switching vector that best aligns with the desired current profile. It should be noted that a modulation stage when using predictive current control (PCC) technique is no longer necessary (Devanshu et al. 2022; Rodriguez et al. 2007).

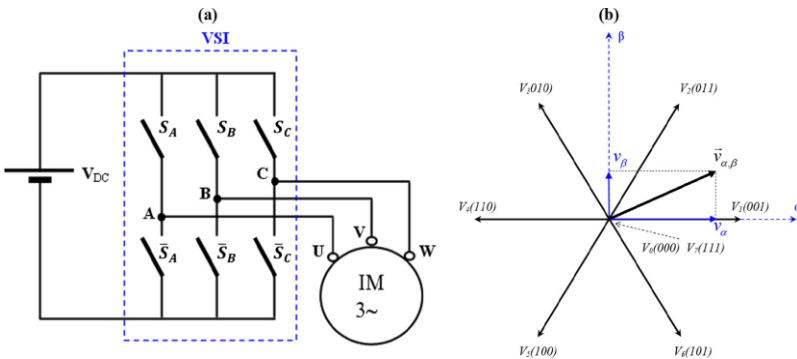


Figure 1. The structure of VSI with 2 levels and its voltage vectors generated

The general three-phase load current dynamics is given as follows (Rodriguez et al. 2007; Sun et al. 2020):

$$v_s = i_s \widetilde{R}_s + L_s \frac{di_s}{dt} + e \quad (12)$$

where v_s refers to the stator voltage produced at the output of VSI, $\widetilde{R}_s$ is estimated stator resistance, L_s refers to the stator inductance, e refers to the back electromotive force. One might estimate the stator current in the subsequent sampling instant for any voltage vector $v_s(x)$ created at the inverter terminal by substituting $(\frac{di_s}{dt})$ as follows:

$$\frac{di_s}{dt} = \frac{i_s(k+1) - i_s(k)}{T_s} \quad (13)$$

T_s is the sampling time.

Swapping it out in equation (10), the next load current expression is:

$$i_s^p(k+1) = \left(1 - \frac{\widetilde{R}_s T_s}{L_s}\right) i_s(k) + \frac{T_s}{L_s} (v_s(k) - e(k)) \quad (14)$$

Then, the back electromotive force can be calculated as

$$e(k-1) = v_s(k-1) - \left(\widetilde{R}_s - \frac{L_s}{T_s}\right) i_s(k-1) - \frac{L_s}{T_s} i_s(k) \quad (15)$$

The back electromotive force at the current time (k) can be estimated by projecting from the previous one ($e(k-1)$), because the sampling frequency is bigger than the back electromotive force frequency, its magnitude will not change substantially over a single sampling period (Devanshu et al. 2022; Devanshu et al. 2019). The objective function used to minimize the discrepancy between the reference currents and the expected stator currents is given as follows.

$$g = i_s^{\text{ref}}(k+1) - i_s^p(k+1) \quad (16)$$

Where, $i_s^p(k+1) = i_{s\alpha}^p(k+1) + j i_{s\beta}^p(k+1)$ is the stator's anticipated current and $i_s^{\text{ref}}(k+1) = i_{s\alpha}^{\text{ref}}(k+1) + j i_{s\beta}^{\text{ref}}(k+1)$ is the reference currents.

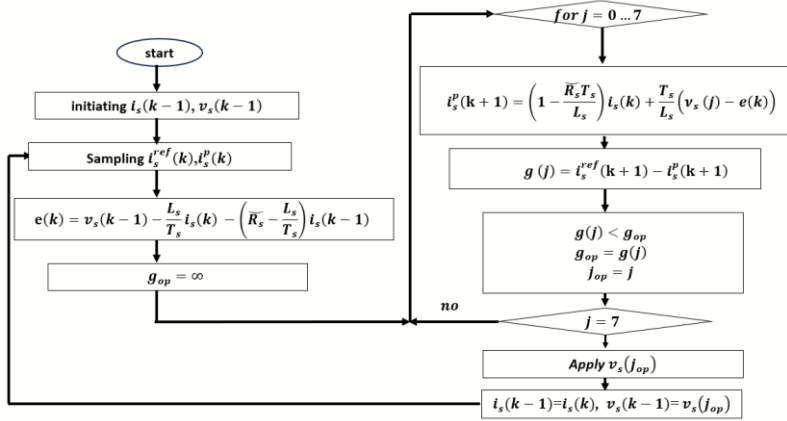


Figure 2. Flowchart of PCC for IM drive system

6. EKF Design

The IM control system regulates speed and flux, knowing that the flux is an unmeasured state variable, so a controller must be available to estimate its value, and to dispense with the speed sensor as well, the controller must also include an estimate of both the speed and the flux. In addition, both stator and rotor resistances must be estimated. The necessity of estimating the stator resistance comes from the fact that the PCC system depends on its value within the control law, and the importance of estimating the rotor resistance value comes in calculating the slip speed required to move from a three-phase frame to a d-q frame rotating at synchronous speed to achieve the requirements of FOC system.

The model of an IM motor is nonlinear. Therefore, EKF must be used to estimate both the motor speed, flux, and uncertain parameters (load torque and stator and rotor resistances).

The model (1)-(6) can be discretized by the Euler method, and the nonlinear stochastic model of the estimation process at the instant k becomes:

$$\mathbf{x}(k+1) = \mathbf{x}(k) + T_s \mathbf{f}(\mathbf{x}(k), \mathbf{u}(k), \mathbf{w}(k)) = \tilde{\mathbf{f}}(\mathbf{x}(k), \mathbf{u}(k)) \quad (17)$$

$$\mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{v}(k) \quad (18)$$

Where, $\mathbf{x}(k)$ are state variable, $\mathbf{u}(k)$ are control variable, $\mathbf{w}(k)$ are the disturbances applying to the system input, $\mathbf{y}(k)$ are the measurable output affected by the random noise $\mathbf{v}(k)$, $\mathbf{Q}_{\text{EKF}}$ and $\mathbf{R}_{\text{EKF}}$, respectively, are the covariance matrices that characterize the stochastic processes $\mathbf{w}(k)$ and $\mathbf{v}(k)$.

The general steps of the EKF method are described by the recurrent computation relations below (Alonge et al. 2006; Said et al. 2000; Yildiz et al. 2020).

- Establish the beginning values of the state vector ($x(0)$), the noise covariance matrices Q_{EKF} and R_{EKF} , and the initial value of the state covariance matrix $P(0)$. These values indicate the initial states' degree of knowledge.
- Compute, the prediction state-space vector of the extended filter as:

$$\hat{x}(k+1|k) = \bar{f}(\hat{x}(k|k), u(k), x(0)) \quad (19)$$

Estimate, the covariance matrix $P(n+1|n)$ of the prediction error as:

$$P(n+1|n) = A(n+1|n)P(n|n)A(n+1|n)' + Q_{EKF} \quad (20)$$

where: $A(n+1|n) = e^{T_s F}$, $F = \frac{\partial f}{\partial x}$

So, it can be written

$$A(k+1|k) = 1 + T_s F(k) \quad (21)$$

- Compute the Kalman filter gain by:

$$L(k+1) = P(k+1|n)[C'P(k+1|k)C'R_{EKF}]^{-1} \quad (22)$$

- Update the state vector:

$$\hat{x}(k+1|k+1) = \hat{x}(k+1|k) + L(k+1)(y - C\hat{x}(k+1|k)) \quad (23)$$

- Update the error covariance matrix $P(k+1|k+1)$ as:

$$P(k+1|k+1) = (I - L(k+1)C)P(k+1|k) \quad (24)$$

By considering specific factors as additional state variables and creating an augmented state vector, this observer can be used to identify state variables and parameters. The parameters to be calculated and augmented into the state vector in this study are the load torque, stator, and rotor resistance. Developed in stationary reference α , β frame, the extended discretized model of an IM looks like this:

$$x(k+1) = x(k) + T_s f(x(k), u(k), T_L(k)) \quad (25)$$

$$R_s(k+1) = R_s(k) \quad (26)$$

$$R_r(k+1) = R_r(k) \quad (27)$$

$$T_L(k+1) = T_L(k) \quad (28)$$

Then we can rewrite the previous model Eqs. (25)-(28) as

$$x_a(k+1) = x_a(k) + T_s f_a(x_a(k), u(k)) \quad (29)$$

Where, $x_a(k) = (i_{s\alpha}, i_{s\beta}, \Phi_{r\alpha}, \Phi_{r\beta}, R_s, R_r, T_L)$, $f_a = v_{sa}, v_{sb}$. The output vector y is the pair $(i_{s\alpha}, i_{s\beta})$.

7. Simulation Results

This section presents the simulation results of the proposed Advanced Drive System (ADS), which integrates Predictive Current Control and Extended Kalman Filter (EKF) for enhanced estimation and control of an induction motor (IM). The performance of ADS is compared against a Traditional Drive System (TDS) based on Proportional-Integral (PI) controllers and basic state estimation. The systems are evaluated under variable speed profiles, sudden torque disturbances, and real-time variation of motor parameters, particularly stator and rotor resistance. Simulations were conducted using MATLAB/Simulink to validate control stability, estimation accuracy, and harmonic performance under near real-world conditions.

7.1. System architecture overview

The comparative analysis is based on two control strategies: a conventional PI-based system (TDS) and a modern predictive control-based system (ADS). The TDS utilizes PI controllers for speed and current regulation and employs a basic Kalman filter for rotor speed estimation only. In contrast, the ADS integrates a model-based Predictive Current Controller with an Extended Kalman Filter (EKF) capable of estimating the full state vector, including speed, stator resistance (R_s), rotor resistance (R_r), and rotor flux. The key innovation lies in ADS's ability to dynamically adapt to parameter variations, making it robust to environmental or thermal changes.

7.2. Block diagram of proposed ADS

The block diagram of the proposed ADS is shown in Figure 3. It consists of a reference speed input, an outer speed control loop, and an inner predictive current control loop. The EKF operates in parallel to provide real-time estimates of rotor speed, R_s , R_r , and rotor fluxes. These estimates are fed back to both control loops to improve precision and disturbance rejection. This closed-loop structure ensures rapid tracking and enhanced regulation, even in the presence of non-linear motor behavior or parameter uncertainty.

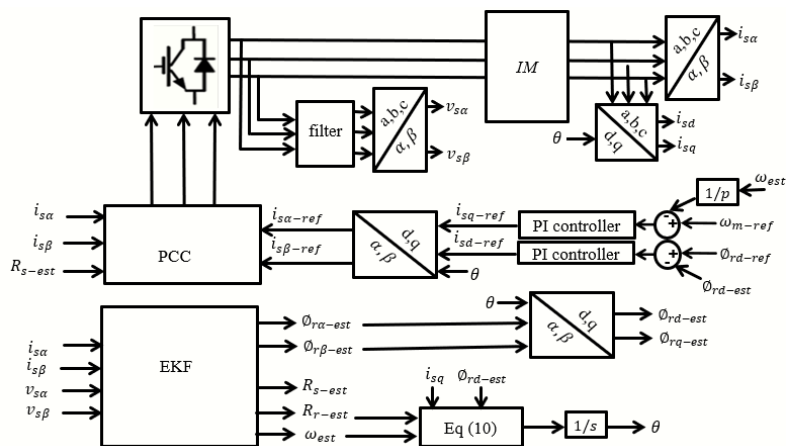


Figure 3. The block diagram of the proposed ADS

7.3. Block diagram of traditional TDS

Figure 4 depicts the structure of the TDS, which consists of PI controllers for both speed and current loops. A conventional Kalman filter is used for rotor speed estimation only. Unlike ADS, this system assumes that R_s and R_r remain constant, which leads to inaccuracies during thermal or load-induced parameter changes. The absence of resistance estimation makes TDS more susceptible to performance degradation under dynamic conditions.

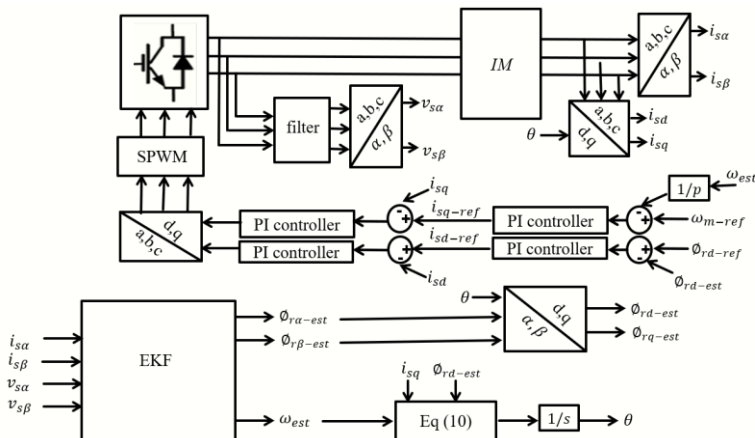


Figure 3. The block diagram of the TDS

7.4. Motor parameters used

The simulation model utilizes a standard three-phase squirrel-cage induction motor whose parameters are provided in Table 1. These include stator and rotor

resistances ($R_s = 45.83 \, \Omega$, $R_r = 31 \, \Omega$), inductances, moment of inertia, number of poles, and rated power. The values have been selected based on manufacturer specifications and verified with existing literature to ensure accurate modeling of electrical and mechanical dynamics for the test environment. The parameters of IM used in this research are given in Table 1. The values in Table 1 were likely selected based on the specific characteristics of the induction motor used in the study, ensuring accurate modeling and performance analysis. These parameters, including resistance, inductance, friction, inertia, speed, and power, define the electrical and mechanical behavior of the motor, which is crucial for developing and validating the proposed control system. If these values were obtained from a specific source, such as a manufacturer’s datasheet, prior research, or experimental measurements, it would be beneficial to include a reference for transparency and reproducibility.

Table 1. Parameters of the studied machine

Parameter	Symbol	Value
Rotor Resistance	R_r	$31 \, \Omega$
Stator Resistance	R_s	$45.83 \, \Omega$
Rotor Inductance	L_r	$1.11 \, \text{H}$
Stator Inductance	L_s	$1.24 \, \text{H}$
Mutual Inductance	L_m	$1.054 \, \text{H}$
Friction Coefficient	f	$1 \times 10^{-3} \, \text{Kg} \cdot \text{m}^2 / \text{se} \text{c}$
Moment of Inertia	J	$1 \times 10^{-3} \, \text{Kg} \cdot \text{m}^2$
Speed	n	$1350 \, \text{rpm}$
Number of Poles	p	2
Power	–	$250 \, \text{W}$
Stator Voltage (Y/ Δ)	V_s	$400 \, \text{V} / 230 \, \text{V}$
Stator Current (Y/ Δ)	I_s	$0.76 \, \text{A} / 1.32 \, \text{A}$

7.5. Test conditions and input profiles

To rigorously evaluate system performance, a comprehensive test profile was used. The reference speed was set to 130 rad/s from $t = 0$ s to $t = 7$ s and then reduced to 80 rad/s. Simultaneously, the load torque was maintained at 20% of its nominal value until $t = 1$ s, after which it was stepped to 80%. In addition, the simulation modeled a real-world scenario by varying both stator and rotor resistance values over time. This allowed assessment of each system's ability to track and respond under dynamically shifting electrical parameters. The estimation of stator and rotor resistances using EKF is shown in Figure 5.

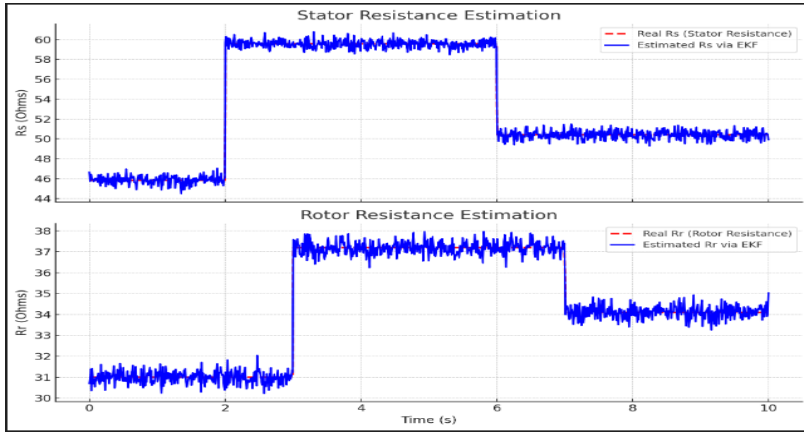


Figure 5. The estimation of stator and rotor resistances using EKF

7.6. Speed estimation and regulation

Figure 6 illustrates the motor speed response using ADS. The estimated speed ($\hat{\omega}$) and the real speed (ω_{real}) closely follow the reference speed (ω_{ref}) throughout the simulation period. The system quickly responds to the torque step at $t = 1$ s and to the speed change at $t = 7$ s, recovering within 0.3 s and 0.1 s respectively. This fast response and low overshoot validate the effectiveness of predictive control in maintaining dynamic performance even under resistance variations. The EKF ensures the speed estimation remains stable and accurate throughout the simulation.

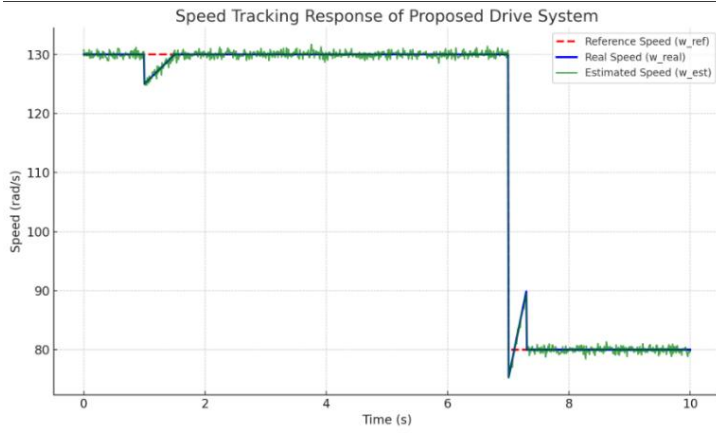


Figure 6. Response of regulate and estimate the rotation speed using ADS

7.7. Rotor flux estimation

Rotor flux responses for both TDS and ADS are presented in Figures 7 and 8. Under TDS, the q-axis flux component (Φ_{rq}) deviates significantly from its nominal value due to the assumption of constant rotor resistance. This causes partial magnetic saturation in the motor. In contrast, the ADS maintains both d-axis (Φ_{rd}) and q-axis fluxes near their reference values. The EKF's real-time estimation of R_r enables the predictive controller to adjust accordingly, minimizing flux error and ensuring consistent operation.

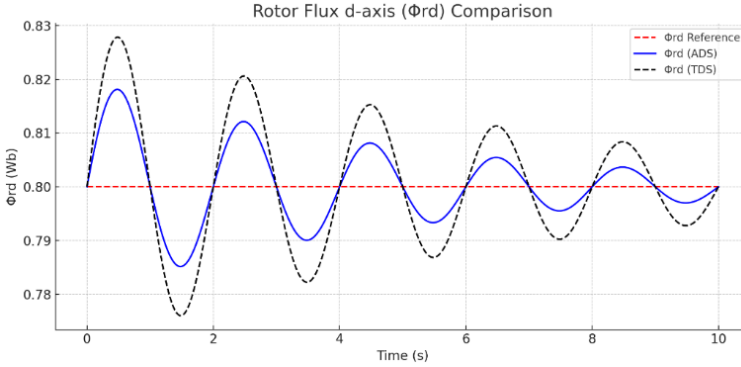


Figure 7. The comparison of rotor flux d-axis

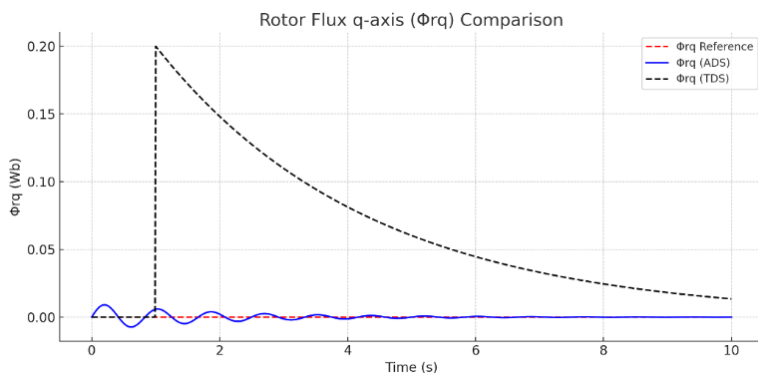


Figure 8. The comparison of rotor flux q-axis

7.8. Electric frequency behavior

Figure 9 indicates the system response to regulate and estimate the rotation speed, and Figure 10 shows the system response to regulating and estimating the rotor flux using ADS. It is clear by examining the two Figures 9 and 10 that the ADS achieves high stability, and an effective estimate of both rotation and flux. Reference values are tracked accurately and high performance despite the change of the load torque at the moment 1 second, where the real speed decreases to the value of 124.5 rad/sec and then returns to the reference value during 0.3 second. When the value of reference speed changes at the moment 7 seconds, this change is tracked during 0.1 second. The static error of both the speed regulation and the flux is equal to zero.

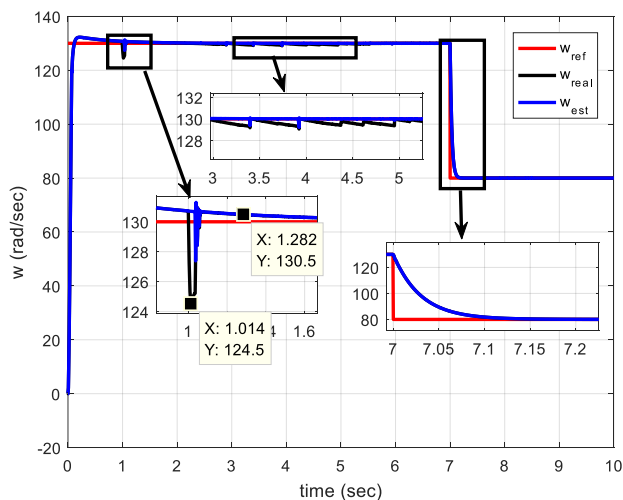
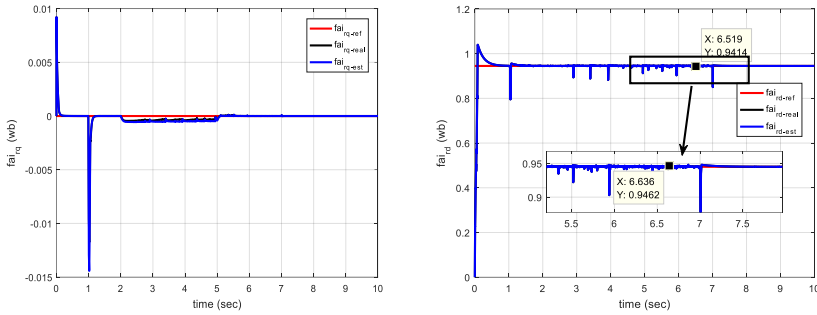


Figure 9. The response of regulate and estimate the rotation speed using ADS

Figure 10 illustrates the response of regulating and estimating the rotor flux using the ADS. Figure 10(a) represents the d-axis rotor flux (Φ_{rd}) response, while Figure 10(b) depicts the q-axis rotor flux (Φ_{rq}) response. The reference flux (red line), actual flux (black line), and estimated flux (blue line) are compared. The Φ_{rd} response demonstrates that the estimated flux closely follows the reference with minimal deviation, indicating the effectiveness of ADS in flux regulation. However, some fluctuations can be observed, especially during transient periods. The Φ_{rq} response remains near zero as expected, with initial oscillations that stabilize over time. The results confirm the accuracy of the ADS in estimating and regulating rotor flux, ensuring stable motor performance.



a) Φ_{rd} response b) Φ_{rq} response

Figure 10. The response of regulating and estimating the rotor flux using ADS

7.9. Harmonic distortion analysis

Figure 11 shows the electric frequency signal. The phase current of the induction motor is shown in Figure 12. It has a wave shape where THD value is 2.27% as shown in Figure 13. Here lies the importance of using predictive controllers as they provide a more uniform current waveform with a lower distortion factor compared to conventional controllers.

Figure 11 illustrates the electric frequency response of the IM current using ADS. The plot shows the variation in electric frequency over time, with a relatively stable response in the initial phase, followed by minor oscillations and disturbances. The frequency experiences a major reduction between 8.7 seconds when it descends from 46.13 Hz to 30.39 Hz. A system transition or disturbance affects the operational state of the system possibly from changes in load or control adjustments. The ADS system successfully identifies these frequency variations so it can provide real-time system control and monitoring for the IM system.

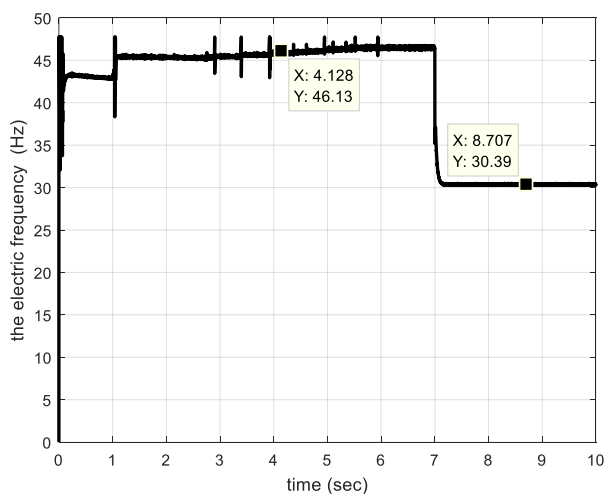


Figure 11. The electric frequency of IM current using ADS

The phase current waveform of the IM operating with ADS appears in Figure 12. Two expanded sections in the graph display the exact oscillatory pattern of the current during specific time intervals. A stable waveform dominates most of the duration, yet it shows high-frequency oscillations during two brief periods that span from 5.04–5.08 and 8.75–8.8 seconds. System disturbances together with control actions and load variations cause the observed changes in the current waveform. ADS tracks these dynamic responses accurately to enable proper monitoring and performance regulation of the IM system.

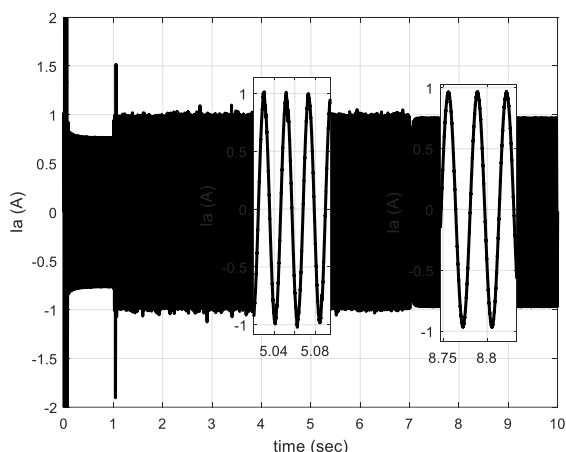


Figure 12. The phase current wave of the induction motor using ADS

Figure 13 shows the THD measurements of the IM current through the implementation of the ADS. The FFT analysis shows a fundamental frequency of 46.13 Hz with a magnitude of 0.9743. The analysis shows that the system contains 2.27% THD value which identifies the magnitude of harmonic distortion. The ADS shows an effective reduction of unwanted harmonics and electrical distortions while presenting multiple harmonic components of low magnitude in the frequency spectrum.

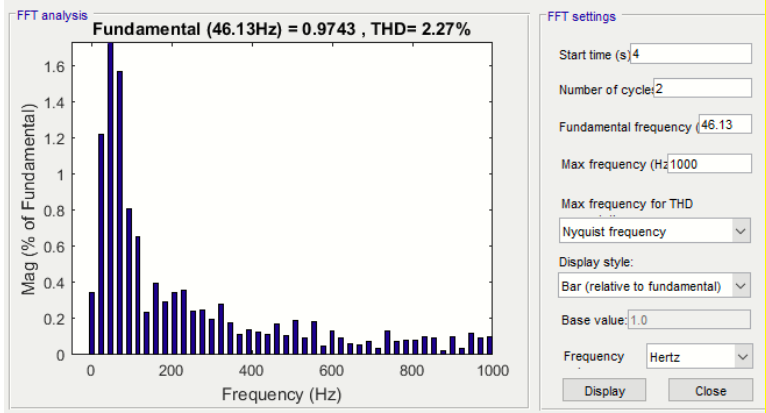


Figure 13. The THD of IM current using ADS

The comparative analysis demonstrates that the ADS significantly outperforms the TDS in terms of speed regulation, flux tracking, resistance estimation, and THD reduction. The integration of predictive current control with EKF estimation enables the system to dynamically adapt to load and thermal variations, achieving high stability and precision. These results confirm the viability of the proposed control approach for robust induction motor operation under real-world industrial conditions.

8. Conclusion

This paper presented a comprehensive evaluation of an Advanced Drive System (ADS) for induction motors (IMs), employing Model Predictive Control (MPC) and an Extended Kalman Filter (EKF) to enhance system performance. The primary objective was to improve flux regulation, increase the accuracy of resistance and load torque estimation, and reduce total harmonic distortion (THD) in the phase current.

The proposed ADS successfully demonstrated high dynamic performance, robustness, and precise parameter estimation across various test conditions, including load torque disturbances and resistance variation. Notably, it achieved zero steady-state error in both speed and flux regulation, maintaining reliable performance under transient conditions. In contrast, conventional drive systems

(TDS) that do not account for rotor resistance variations exhibited degraded dynamic behavior and elevated magnetic flux levels due to unaccounted parameter changes.

The effectiveness of the proposed approach is further substantiated by the significantly lower THD values, indicating improved waveform quality and energy efficiency. These features make the ADS particularly suitable for industrial applications where accurate parameter estimation, reliable performance, and reduced energy losses are critical.

Looking forward, future work may focus on extending the ADS framework by:

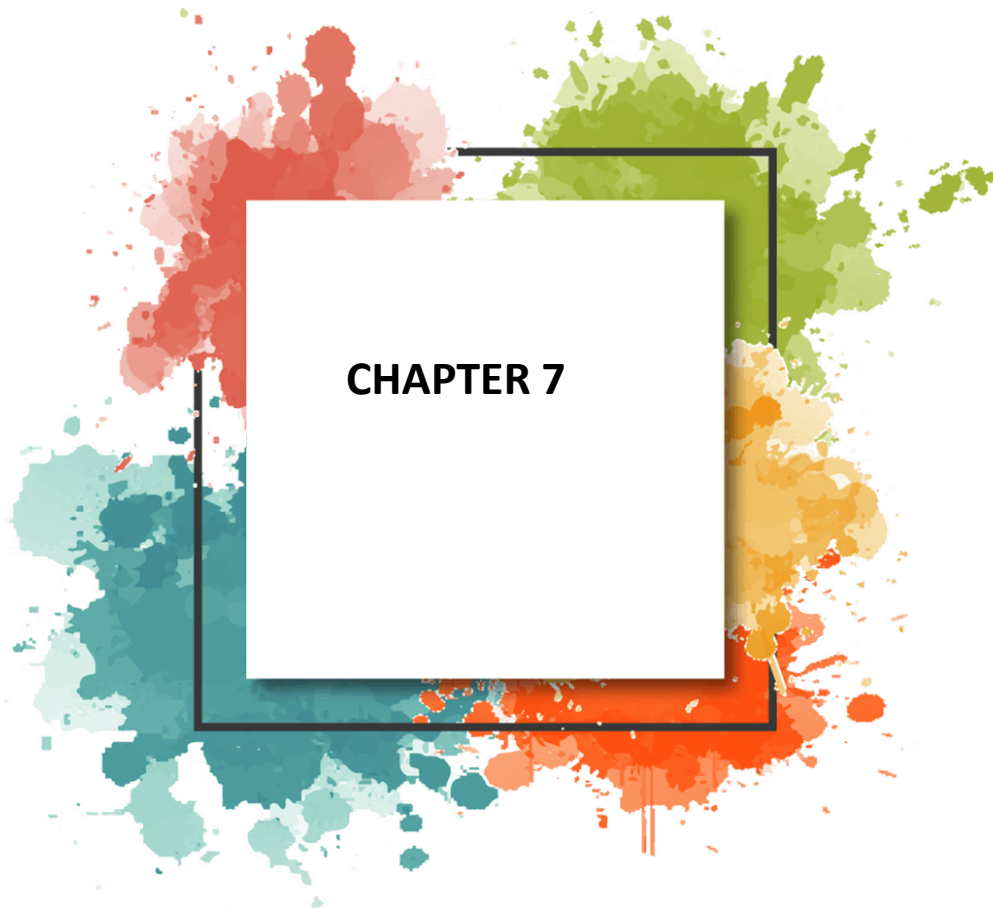
- Integrating adaptive machine learning algorithms for real-time parameter tuning and improved generalization across various motor types.
- Implementing hardware-based experimental validation using a physical test bench to further verify system reliability.
- Exploring multi-motor coordination strategies and energy-efficient control policies for large-scale industrial applications.

By addressing these future directions, the ADS can be evolved into a highly adaptive, scalable, and intelligent solution for next-generation motor drive systems.

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CHAPTER 7

Artificial Reef Engineering: Structural and Environmental Considerations in the Design

F. Ozan Düzbastılar¹

1. Introduction

ARs are used for a wide range of purposes, including increasing fish abundance and diversity (Glarou, Zrust, & Svendsen, 2020), increasing catch rates of target species (Yamamoto, Freitas, Zuanon, & Hurd, 2014), altering habitats (Baine & Side, 2003), and restoring coastal ecosystems (Pickering, Whitmarsh, & Jensen, 1998). They are also used to restore damaged coral reefs (Higgins, Metaxas, & Scheibling, 2022), to protect coastal habitats from wave action (Blacka, Shand, Carley, & Mariani, 2013; Ghiasian et al., 2021), to protect vulnerable ecosystems (Jensen, 2002; Ulugöl & Düzbastılar, 2016), to provide new sites for divers and recreational fishers (Milon, 1989), and to serve generating surf waves (Blacka, Shand, Carley, & Mariani, 2013; Lokesha, Sundar, & Sannasiraj, 2013) (Figure 1). The proliferation of definitions has been driven by the wide range of AR applications for more complex multifunctional roles (Table 1).

¹ Prof. Dr. Ege University, Faculty of Fisheries, Fishing and Processing Department
ORCID: 0000-0002-5376-7198

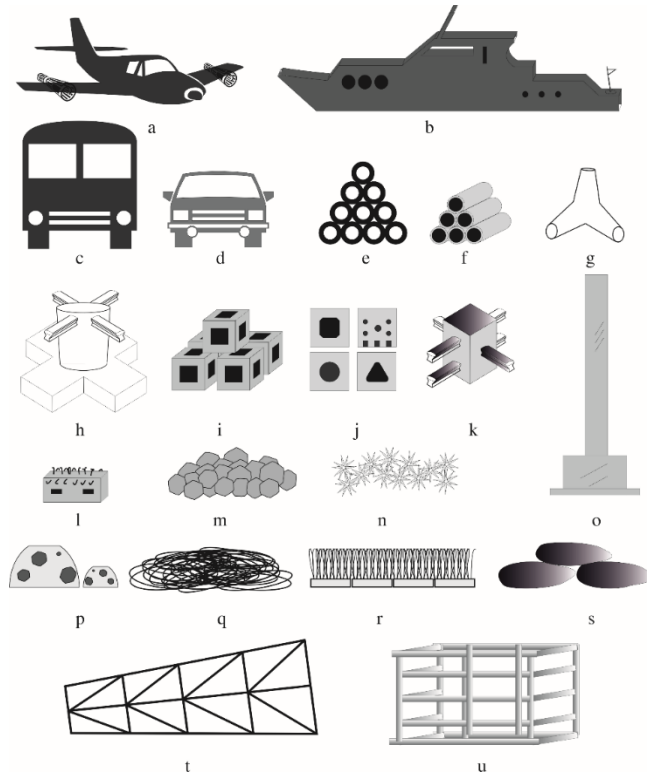


Figure 1. ARs used all over the world: (a-aircraft, b-ship, c-bus body, d-car body, e-used tires, f-concrete pipe culverts, g-tetrapod, h-Spanish anti-trawl unit, i-hollow cubes, j-hollow cubes for complex structure, k-l-Italian anti-trawl units, m-quarry rock, n-artificial coral, o-Italian anti-trawl unit, p-Reef ball, q-cables, r-artificial sea meadow, s-geo-textile bags, t-oil rigs, u-exploitation reef with high profile).

Table 1. Various definitions of the AR concept

Author/Year	Definitions
(Seaman & Sprague, 1991)	<i>Artificial habitat enhancement, defined as the modification of natural aquatic habitats by adding man-made or natural structures, primarily to improve fishing, but also to affect the life cycle of organisms or the functioning of ecological systems for other purposes</i>
(Seaman & Sprague, 1991)	<i>Typical AR habitats in the sea - designed to imitate natural reefs at least in terms of providing relief on flat, featureless ocean floor - include concrete or steel modules, frames, and other structures manufactured to specific design specifications; natural products such as quarry stone; and man-made materials such as concrete culverts or other building materials (e.g. bridge demolition debris).</i>
(Seaman & Jensen, 2000)	<i>The term AR means a structure that is constructed or placed in the waters covered by this Title to increase the fishing resources and commercial and recreational fishing opportunities.</i>
(Coutin, 2001)	<i>An AR is a structure placed at the bottom of a sea, estuary, or river to alter an existing habitat. It is a form of habitat modification designed to improve the aquatic environment for a specific purpose.</i>
(Lukens & Selberg, 2004)	<i>Consequently, irrespective of the underlying reason for the development of specific ARs (i.e. create habitats for marine life, improve fishing success, provide SCUBA diving attractions, mitigate the loss of natural reefs, and support aquaculture), the result is the creation of habitats for certain fish species and other organisms, which use the new habitat for various purposes, including shelter, feeding and spawning.</i>

As technology has progressed, AR design has spread beyond a limited set of disciplines and has become an area of interest in a wide range of scientific fields. Achieving the objectives set by the ARs requires complex analyses and careful assessment. In order to ensure success, the design of projects must be guided by

scientific data and methodology. In this context, we have reviewed 270 research papers to review the existing monitoring studies and assess whether the ARs are meeting their pre-positioning objectives. However, only 62 percent of these studies clearly identified the original reef objectives (Becker, Taylor, Folpp, & Lowry, 2018).

The design of AR may vary significantly in terms of materials, spatial coverage, volume, and structural complexity (Baine, 2001). Future development is likely to depend on multi-functionality, digitisation and the use of advanced materials, all of which require interdisciplinary cooperation - spanning marine biology, fisheries, materials science, engineering, architecture and economics - to reach the full potential of research (Korniejenko, Oliwa, Gądek, Dynowski, & Żróbek, 2025). At the same time, ARs can have both positive and negative impacts on the environment. Suzdaleva & Beznosov (2021), for example, identified potential negative impacts such as sediment accumulation, dead zones, oxygen regime degradation and increased parasite resources, as well as positive contributions such as increased biological productivity, improved water quality, and support to coastal fisheries.

2. Design of ARs based on Physical and Structural Criteria

Designing ARs is a complex process that requires consideration of both physical factors (e.g., stability under wave and current forces, structural strength and durability, effects of wake and upwelling zone formation, sediment transport, geometry influencing volume, weight, complexity, openings, and spacing, longevity, and safety) (Düzbastılar, 2003; Düzbastılar & Şentürk, 2009; Cáceres, Ingsrisawang, Ban, & Kimura, 1995; Trung, van Ettinger, Reniers, & Uijttewaalt, 2009; Li, et al., 2024; Xue, et al., 2023) and structural factors (e.g., material properties, load-bearing capacity, structural integrity, appropriate geometry, connections, foundation design, and maintenance) (Chen, Ji, Zhuang, & Lin, 2015; Matus, Alves, Gois, Vaz-Pires, & da Rocha, 2024; Yoris-Nobile, et al., 2023).

2.1. Physical factors

Stability against hydrodynamic forces: ARs should be structurally able to withstand hydrodynamic forces (e.g., waves, currents, thunderstorms) without displacement and should maintain a reasonable buoyancy and low centre of gravity to ensure long-term stability. Concrete is the most commonly used material in AR construction, primarily due to its high stability against external forces. Waste and scrapped vehicle tires have also been utilized as an alternative material; however, studies indicate that tires lacking adequate weight and secure interconnection are prone to displacement and dispersion on the seabed over time due to wave action (Myatt, Myatt, & Figley, 1989).

Many researchers have conducted wave channel and current (flume) tank experiments to investigate the physical responses of ARs to wave and current forces (Figure 2) (Düzbastılar, 2003; Düzbastılar, Lök, Ulaş, & Metin, 2006; Düzbastılar & Tokaç, 2003; Cáceres, Trung, van Ettinger, Reniers, & Uijtewaal, 2009; Guo, Zhang, Zhu, & Jiang, 2025; Huang, et al., 2024; Jiao, Yan-xuan, Pi-hai, & Chang-tao, 2017; Ma, et al., 2020; Qiaofeng, et al., 2022; Tang, Wei, Yang, Wang, & Zhao, 2022; Van Gent, Buis, van den Bos, & Wüthrich, 2023; Zheng, et al., 2015). Wave-flow tests on mostly submerged low-rise trapezoidal structures, impermeable, permeable, and permeable, demonstrated the influence of structural design on wave transmission (Van Gent, Buis, van den Bos, & Wüthrich, 2023).

Düzbastılar and Şentürk (2009) analysed wave interactions with hollow cube blocks and water pipes in shallow waters using physics equations and FLUENT simulations. Results showed that reef design, orientation, and bottom slope strongly affect flow fields and stability. Hollow cube blocks were stable at 12-16 m depths when placed at 45°-90°, while water pipes were unstable at most orientations except 0°. Overall, slope significantly influenced reef stability. To evaluate the impact of slope angles (71.6°, 76.0°, 80.5°, 85.2°, 90°) on the performance of pyramidal reefs, numerical simulations were conducted (Xue, et al., 2023). They used ANSYS-Fluent software to simulate the flow field of ARs. Pyramidal reefs with a slope angle of approximately 85.2° were found to have the best overall performance, and the optimum effect can be achieved at an input angle of roughly 45° (Xue, et al., 2023).

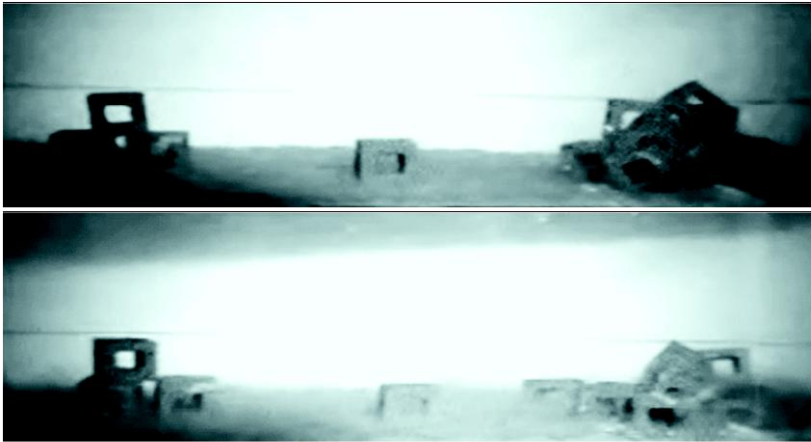


Figure 2. Loss of stability of deployed AR blocks in three different configurations before and after propagation of the wave in a unidirectional wave channel.

Structural strength and endurance: Reef blocks must be resistant to abrasion, scour formation, and material degradation (e.g., corrosion, abrasion, biofouling) and are preferably constructed from reinforced concrete, steel, or environmentally friendly composite materials. Cement and concrete mixtures, which vary in shaping and production techniques, are the most commonly used materials in AR construction (Lukens & Selberg, 2004). Marine applications of concrete under load conditions, such as repeated wetting and drying and regular freezing and thawing, require a minimum of Portland Type II cement. Cement types II-V are resistant to the sulfates and other chemicals in seawater that may attack and degrade concrete produced from cement Type I (Lukens & Selberg, 2004). In addition to traditional moulding techniques, 3D printing (Berman, et al., 2023), also known as additive manufacturing, enables complex geometries without form work, increases material efficiency, and operates efficiently in demanding environments (Korniejenko, Oliwa, Gądek, Dynowski, & Żróbek, 2025).

In the marine environment, reinforced concrete ARs are subject to chemical degradation (chemical corrosion) from seawater ions (chloride, sulphate, and magnesium) and biodeterioration (microbiological corrosion) due to biological activity, primarily through acid production (Gaylarde & Ortega-Morales, 2023). However, studies have examined the durability of concrete in seawater over periods of 30 to 50 years. Concrete materials are highly compatible with the marine environment, exhibiting excellent durability, stability, and availability (Lukens & Selberg, 2004). Fly ash geopolymer concrete (Jensen, 2002; Wang, Wang, Shen, & Fan, 2023), Portland cement, which is the most common binder in concrete, and blast furnace cements (Becker, Ehrenberg, Feldrappe, Kröncke, & Bischof, 2020).

A new AR concrete, utilizing sulphaaluminate cement (SAC), marine sand, and seawater, exhibited superior workability, strength, and environmental compatibility compared to conventional concrete, thereby demonstrating its suitability for AR applications. Studies show that this concrete has exceptional workability, mechanical properties, and affinity with river sand and freshwater compared to ordinary Portland cement concrete. Therefore, the feasibility of the new concrete in ARs is being tested (Chen, Ji, Zhuang, & Lin, 2015). In general, rebars are used to reinforce concrete reef modules. While concrete is strong in compression but weak in tension, steel reinforcement is typically added to enhance durability and prevent cracking. However, from a structural perspective, it was found that the proposed design does not require steel reinforcement, which in turn improves the sustainability of the AR (Galdo, Guerreiro, Lorenzo, Couce, & Couce, 2022).

Hydrodynamic performance: The height, length, and shape of ARs influence wake formation, turbulence, and upwelling zones, which in turn affect habitat suitability. Specifically, openings and surface roughness in reef design play a critical role in regulating water circulation and shelter quality. Most previous studies focused on the shape, size, and structure of the AR, as well as the movement of the surrounding water and the flow of water. Many researchers have studied the water flow around ARs to analyse the wake and upwelling zones that affect the ecology of the habitats, in particular, feeding and resting areas (Kim, Jung, & Na, 2021; Lin, Wang, Yu, & Li, 2025; Sheng, 2000; Zheng, et al., 2015). Experimental and numerical studies are driven by the observation that specific water flow patterns and affected regions around ARs (e.g., wake and upwelling zones) provide shelter, feeding grounds, resting areas, and temporary stopover sites for many marine species (Kim, Jung, & Na, 2021).

Numerical simulations evaluating ARs by shape, size, and openings demonstrate that wave-structure interactions strongly affect flow dynamics in shallow waters. Multi-opening cubic designs (with 24 openings) enhance upwelling and stabilize wake vortices more effectively than traditional hollow cubes, underscoring the importance of perforations in promoting flow uniformity and energy dissipation (Lin, Wang, Yu, & Li, 2025). Another study reported the occurrence of upwelling, slow flow, and eddies around a single reef, with the maximum velocity, height, and volume of upwelling in front of the reef positively correlated with inflow velocity (Huang, et al., 2024).

Numerical modelling, in addition to traditional specific manufacturing techniques, is a valuable tool for assessing the hydrodynamic effects of 3D printed ARs, including wave damping and current adjustment. It provides in-depth insight into difficult physical experiments, supports the design of coastal protection structures, and helps to predict long-term impacts on the coastline and the surrounding environment (Korniejenko, Oliwa, Gądek, Dynowski, & Żróbek, 2025).

Scouring and seabed interaction: Consideration of sediment transport, scour depth, and seabed settlement is crucial for reef design and site selection (Figure 3). Appropriate foundation design, sometimes incorporating mats, footings, or wider bases, is necessary to prevent loss of stability. Sediment transport caused by waves and currents can lead to local scour on the seabed around the structural elements of ARs in shallow waters. Local scour is one of the major physical processes involved in the sinking phenomenon (Kimura, Ingsrisawang, & Ban, 1994). Zou, Yao, Li, Zhang, & Gao (2025) carried out wave-channel and numerical simulations to determine the local surface area around three different reef configurations. They found that the degree of local scouring around the AR is directly proportional to the speed of the current, and that the extent and depth

of scouring increases as the speed of the current increases. Another consequence is that the level of disturbance of a reef is strongly correlated to its structure, and a multi-column reef support structure may form a complex flow field.

To determine the local scour formation, hydraulic experiments performed in the unidirectional wave channel indicated a positive correlation between reef size (height and width) and local scour depth. At the end of the experiments, a direct relationship was observed between AR size and local scour depth (Düzbastılar, Lök, Ulaş, & Metin, 2006). In 1:30 scale model experiments, local scour depth increased with reef size at both 10 m and 15 m water depths, indicating that larger ARs cause greater scour regardless of other factors (Düzbastılar & Tokaç, 2003). Hydraulic experiments were carried out in a circulation channel to examine flow patterns around cylindrical AR models. Findings showed that the reef exhibited sloping and sliding under unidirectional currents, with its degradation primarily attributed to repeated sediment responses to alternating tidal flows (Kimura, Ingsrisawang, & Ban, 1994). The study highlights that CFD analysis is preferable to conventional testing of channels and tanks for hybrid ARs (Norris, et al., 2025). In another study using a circulation channel experiment and CFD with a steady flow for cubic AR, the flow rate was identified as the main factor influencing the local depth and volume of the sediment, followed by the grain size and the opening ratio. Scour intensity increased with higher velocities, finer sediments, and smaller openings (Zheng, et al., 2024).

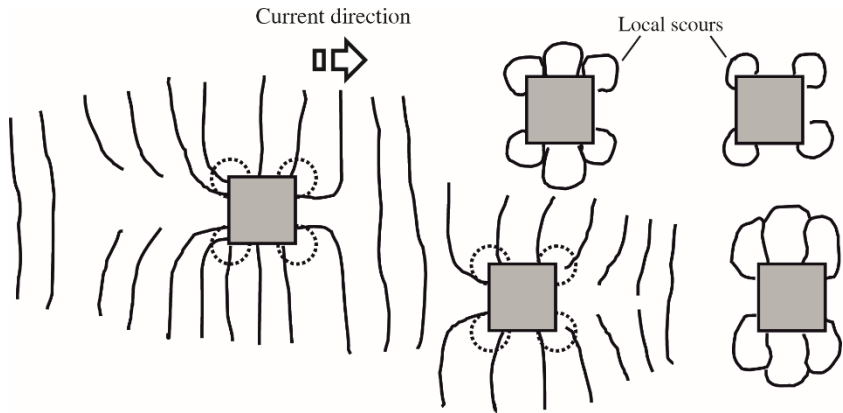


Figure 3. Illustration of local scouring patterns around an AR unit in a unidirectional wave channel.

Reef geometry and configuration: The size, porosity, and surface complexity of individual reef units should be considered during design to balance structural stability with habitat provision. Deployment and arrangement strategies (e.g., sets or groups, height) are also important for optimizing hydrodynamic performance and ecological function. In recent years, there has been growing attention to the ecological functions and hydrodynamic performance of ARs. Studies have

demonstrated that the geometry, structural complexity, and porosity of reef units significantly influence the surrounding flow field. Nakamura (1985) proposed a formula that relates the column width of a hollow cube block to the minimum current velocity that causes the vortex to dissipate as $Bu > 100 \text{ cm}^2\text{s}^{-1}$ (B : column width, u : minimum current speed). Another suggestion was that the minimum window size of the hollow cube reef block should be 2 m and not exceed 5 m in width (Grove, Sonu, & Nakamura, 1989).

Longevity and maintenance: The expected service life of the structure in marine conditions should be maximized, and low maintenance requirements, while ensuring structural safety, are important for minimizing project costs.

Safety and navigation criteria: The deployment depth should be selected relative to mean sea level to avoid hazards to navigation, and compliance with maritime regulations (e.g., minimum clearance above structures) is essential.

2.2. Structural factors

Material properties: Materials used in AR construction should possess high compressive and tensile strength to withstand loads from waves, currents, and sediment. Resistance to corrosion, chemical degradation, and biofouling in the marine environment is also essential (Düzbastılar & Lök, 2004; Gaylarde & Ortega-Morales, 2023; Lukens & Selberg, 2004). Furthermore, the material should be non-toxic, pH-neutral, and environmentally benign, with examples including marine-grade concrete, coated steel, and eco-composites. The guidelines for AR emphasise the use of non-polluting inert materials and highlight design considerations such as durability, stability, decommissioning, and spatial use (Baine, 2001).

In the design of ARs, concrete is the most commonly used material for constructing various types of units. These concrete structures are colonized by specialized hard-bottom biota, including macroalgae and benthic macrofauna. Although cement is the main ingredient in concrete, researchers have proposed various mixtures to improve the material's integrity. Similarly, the study selected concrete as a building material with a silica flume as a mix of physical characteristics that can be adapted to the construction, such as compressive strength, permeability, split tensile testing, and used CATIA to analyse the dome-shaped reef structure (Nagalakshmi, Rameshwaran, Nithyambigai, & Mary, 2021).

Load capacity: AR structures must be designed to withstand both static loads (self-weight, displacement) and dynamic loads (waves, currents, impact with debris). The design criteria shall also take into account extreme events such as storms and tsunamis, in particular in the case of deployments in oceans and shallow waters.

Structural integrity & safety: ARs should be designed to withstand repeated external forces in the marine environment and should be adequately reinforced (e.g., with rebar or fibres) to minimize fatigue damage. Baine (2001) stated that one of the main factors at the design stage is the structural integrity and stability of the ARs and the type of material used. Kim, Kim, Shim, & Oh (2021) stated that ARs in general shapes are unlikely to be installed and maintained stably in high-energy wave zones. Therefore, they investigated the use of a large 2000-ton sunken vessel as an AR in a high-energy shallow water zone on South Korea's east coast. Using numerical simulations and hydraulic model experiments (in a two-dimensional cross-sectional wave flume), the study assessed wave forces and the vessel's stability and motion properties. Results showed that stability varies with water depth, and the depth ensuring stable deployment was identified, demonstrating the vessel's applicability as an AR in high-energy areas (Kim, Kim, Shim, & Oh, 2021).

Geometry and structural form: To ensure high stability, structural strength, and environmental functionality, reef units should preferably be designed with specific shapes such as hollow blocks, pyramids, or modules with varied openings, while avoiding thin structural elements that may fracture under stress. Numerous design approaches have been applied in oceans and seas worldwide such as jumbo, cube, turtle and cylinders in Korean waters for the creation of new fishing grounds (Kim, Lee, & Park, 1994), sand-filled geo-tubes to construct a seawall at Shankarpur of West Bengal, India as a coastal protection measure to withstand the wave climate (Lokesha, Sundar, & Sannasiraj, 2013), anti-trawling reefs (Figure 4) being physical barrier to prevent illegal fishing in the Cape of Trafalgar in the southwest Spain (Muñoz-Pérez, Gutierrez-Mas, Naranjo, Torres, & Fages, 2000). With the development of CFD methods, a significant amount of information that is difficult to obtain from flume testing can now be precisely visualized by computer simulation. It can be used to optimise the design of the reef and reduce the time to build (Jiang, Liang, Zhu, & Liu, 2016).

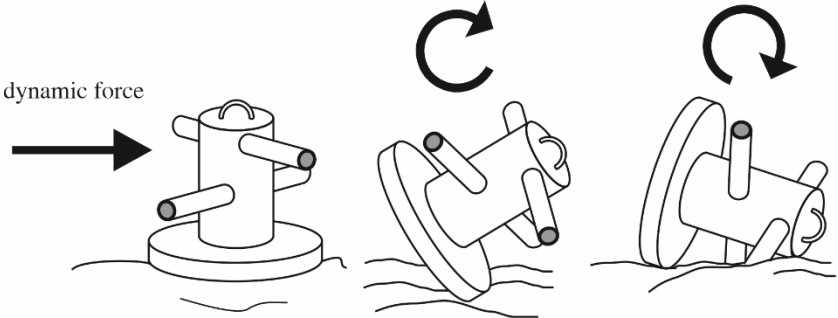


Figure 4. The capability to construct anti-trawl ARs and barriers to prevent illegal fishing.

Connections & assembly: For modular reef structures, anchorage points should be strong, durable, and suitable for underwater installation, and any weak points susceptible to deformation under load should be minimised. In particular, fish aggregation/attraction devices (FADs) / floating artificial reefs (FARs) systems need to be strongly connected due to internal forces where they are fixed. In the experimental study, the anchorage equipment and connections consisted of buoyant and sinking ropes, a chain, an anchor, and connections for the installation of the FAD system. The authors calculated the forces and carried out a stability analysis to determine the anchor mass for the stability of the FADs, taking into account wave, current, and wind forces (Özgül, Lök, & Düzbastılar, 2011).

Service life & maintenance: The structural components should have a long service life (often 20 to 50 years) in marine environments. Low maintenance requirements, as repairs under the sea are costly and difficult. Nakamura (1985) stated that the service life of ARs should be at least 30 years and preferably longer.

3. Design of ARs based on Ecological and Environmental Criteria

Planning ARs involves two main steps: ecological design (including habitat complexity, surface characteristics, material eco-compatibility, water flow and nutrient exchange, species attraction versus production, biodiversity support, connectivity with natural ecosystems, carrying capacity and density, long-term ecological succession, and human–ecosystem interactions, etc.) and environmental considerations (such as site suitability, hydrodynamics and sediment dynamics, water quality, compatibility with marine uses, pollution prevention, climate resilience, environmental carrying capacity, monitoring and adaptive management, and restoration or mitigation potential etc.).

In designing ARs, two main factors are considered: ecological processes (e.g., currents, wake zones, upwelling, sheltering, feeding, and reproduction) (Grove & Sonu, 1985; Moura, Boaventura, Cúrdia, Santos, & Monteiro, 2006; Seaman & Sprague, 1991) and environmental design aspects (e.g., design waves and currents, stability, wave forces, and local scour) (Düzbastılar, Lök, Ulaş, & Metin, 2006; Ingsrisawang, Ban, & Kimura, 1995; Ingsrisawang, Kimura, & Ban, 1999; Kimura, Ingsrisawang, & Ban, 1994; Nakamura, 1985; Zou, Yao, Li, Zhang, & Gao, 2025). Hydrodynamic processes play a crucial role in defining ARs, as the placement of reef modules on the seabed modifies the water velocity field, thereby enhancing nutrient circulation and promoting the establishment of desirable species (Galdo, Guerreiro, Lorenzo, Couce, & Couce, 2022; Santiago Caamaño, et al., 2022). Bohnsack, Johnson, & Ambrose (1991) found that the structure of flow fields around ARs is a key factor in attracting fish. Similarly, the scale and intensity of these flow fields are crucial for fish attraction (Jiao, Yan-xuan, Pi-hai, & Chang-tao, 2017).

3.1. Ecological factors

Habitat complexity: Reef design should incorporate cavities, crevices, and surface irregularities to provide shelter, breeding sites, and protection from predators, with multi-scale complexity tailored to accommodate species and individuals of different sizes (e.g., small openings for juveniles and larger spaces for adults). The term complexity actually sums up the interactions within the units of an AR module or AR communities (Baine, 2001). Researchers clearly stated that complexity is a key factor to consider when designing an AR, as it may increase biomass and biodiversity (Bohnsack & Sutherland, 1985; Lan, Chen, & Hsui, 2004). Complexity - encompassing design, spatial arrangement, number of windows and openings, and interstitial spaces - is a key factor in the success of the reef. While some studies report that high-complexity reefs are the best, others suggest that fish reach optimum feeding efficiency and growth at intermediate levels of complexity (Bohnsack & Sutherland, 1985).

Sherman, Gilliam, & Spieler (2002) objected to the examination of the void and complexity of the design of the ARs. They concluded that reefs with less void space and greater structural complexity had higher fish abundance, richness, and biomass than those with more void space. These studies generally show that abundance and diversity of fish are positively correlated to structural complexity (Spieler, Gilliam, & Sherman, 2001). Unlike traditional reef design and construction, the study proposed a new method of construction based on 3D computer-aided design (CAD) models close to natural structures, inspired by functional ecology principles, to improve the integration of ecosystems (Riera, Mauroy, Francour, & Hubas, 2024). The study develops and validates a standardised engineering methodology for the design of modular reef structures (3-15 m) in open water, combining hydrodynamic modelling and structural analysis to ensure reliability and to guide future research. They conducted a study based on architectural engineering principles for AR design, encompassing concept and geometric design, constructive approach, site location and sea conditions, structural model, and cross-section design (Cruz, Valente, Miranda, & Pereira, 2025).

Surface characteristics: Texture and surface roughness are introduced to encourage algae, corals, and invertebrates to settle in, while environmentally friendly coatings or bio-receptive concrete may be used to further encourage colonization. In concrete reef production, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (ferrous sulphate) crystals, applied to the inner surfaces of steel moulds and later absorbed by the concrete, were used to accelerate algal growth and enhance surface density. Similarly, applying a ferrous sulphate emulsion to the concrete reef surface promotes the formation of a 50 μm amorphous iron oxide layer, followed by calcium oxide, within the top 500 μm of the surface. This treatment accelerates

algal growth, which in turn enhances fish attraction (Düzbastılar & Lök, 2004). The use of additive manufacturing in ARs enables the design of highly complex surfaces, facilitating the settlement of corals, mussels, and other marine organisms (Korniejenko, Oliwa, Gądek, Dynowski, & Żróbek, 2025).

Material eco-compatibility: Non-toxic, pH-neutral materials, preferably those that mimic natural substrates (e.g., rock or coral skeletons), should be used. AR materials have evolved: waste concrete and metal structures in the 1950s (Lukens & Selberg, 2004), waste tires and other discarded materials in the 1970s (Myatt, Myatt, & Figley, 1989), modular reinforced concrete in the 1980s (Nakamura, 1985), concrete and eco-friendly materials in the 2000s, and 3D printed and high-tech materials in the 2010s (Korniejenko, Oliwa, Gądek, Dynowski, & Żróbek, 2025). ARs are often constructed from materials of opportunity, such as ships, cars, concrete debris, and tyres, and provide habitats, fishing grounds, and diving sites (Harris, Mostkoff, & Zadikoff, 1996). New, durable composite materials have recently been used to build ARs. Today, it is possible to use scanned geometries of harvested corals to create artificial coral skeletons or to design appropriate shapes for specific species, including the correct surface topology for the habitat (Korniejenko, Oliwa, Gądek, Dynowski, & Żróbek, 2025).

The building of ARs and their long-term role in the immediate ecosystem should be assessed in terms of both positive and negative potential. Negative impacts can be minimized by careful selection of sites, design, and construction. Therefore, the need to choose suitable building materials is very important for the proposed AR. For example, when waste materials such as sunken ships, military vehicles, or scrapped tires are employed, the leaching of metals, oils, and other chemicals must be strictly prevented. In order to avoid these problems, concrete or reinforced concrete modules should be favoured when constructing AR.

Water flow and exchange of nutrients: Design of AR should enhance water circulation, upwelling, and turbulence to support plankton and nutrient availability, while avoiding the creation of poorly oxygenated dead zones. The role of reef design in flow circulation is essential to the formation of nutrients around AR features. For example, Santiago Caamaño, et al. (2022) showed that CFD modelling, based on site-specific vertical velocity profiles, can estimate nutrient circulation extending up to five times the size of an AR. The size, shape, structure, placement, and orientation of ARs are crucial for the transport and circulation of organic matter (Kim, Jeong, Jung, & Na, 2024). Nakamura (1985) reported that a solid cube block could generate horizontal-plane turbulence extending up to 15 times its height, whereas a hollow cube block could produce turbulence up to four times its height.

Kim, Jeong, Jung, and Na (2024) used CFD to show that particulate organic matter distribution varies by AR shape, with accumulation highest in cylindrical

forms, followed by box and hemispherical types. Velocity measurements along the vertical and horizontal lines of the small-scale prototype of the multifunctional AR were obtained by numerical and experimental flow analysis (Maslov, et al., 2019).

Ma, et al. (2022) performed a study for six basic AR structural models (solid cube, hollow cube, solid triangular pyramid, hollow triangular pyramid, solid truncated rectangular pyramid, and hollow truncated rectangular pyramid) to investigate flow patterns using both CFD simulations (ANSYS FLUENT) and water channel experiments. The glass channel enabled Particle Image Velocimetry (PIV) measurements at various positions around the reef models. The CFD model accurately simulated the flow fields of six AR structures, and the results were very close to those of the PIV experiments (error 8.78%). A new assessment method combining the analytic hierarchy process and the entropy weight method was developed to quantify the effects of the flow field using multiple indices, and the ranking of the AR structures was consistent with the results of the simulation (Ma, et al., 2022).

Species attraction vs. production: Reef structures should enhance natural productivity rather than merely attract existing fish by promoting the establishment of primary producers (e.g., algae and corals) and secondary colonizers (e.g., invertebrates and fish) (Figure 5). Concrete offers suitable surfaces and habitats for the settlement and growth of encrusting or fouling organisms, which subsequently provide food and shelter for other invertebrates and fish (Lukens & Selberg, 2004). Biodeterioration of concrete in the marine environment begins with microbial biofilm formation, which is initially inhibited by concrete's alkalinity but enabled as pH decreases under marine wetting and leaching. In reinforced concrete blocks, the corrosion of rebars and the release of metal ions into the aquatic environment, rather than surface roughness, accelerate the precipitation of certain bacteria. Initial bacterial biofilms on seawater-immersed concrete may have little immediate structural effect but promote the growth of additional, potentially corrosive microorganisms (Gaylarde & Ortega-Morales, 2023).

Subsequently, larger organisms (e.g., fungi, algae, oysters) colonize the concrete surface, disrupting its structure and attracting other species for activities such as feeding and sheltering. As a result, AR designs or repurposed materials such as oil platforms and military vehicles should demonstrate ecological capacity to enhance biological production (Smith, Lowry, Champion, & Suthers, 2016). Smith, et al. (2016) examined oil platforms as a potential new habitat by estimating fish production and the species of visitors. Fish production added to the ecosystem was estimated at only 4-5% of the local output, as most species were visitors. Biomass flux across the reef was ~380 times the standing stock,

making it vulnerable to overfishing. While ARs can be highly productive habitats, they may not significantly boost net fish production. Sherman, Gilliam, & Spieler (2002) carried out a study to determine whether the recruitment of juvenile fish to ARs could be increased by using a float line as an attractant. Finally, they concluded that the use of a floating attractant does not increase the recruitment and aggregation of the diverse assemblage on the ARs in this particular case.

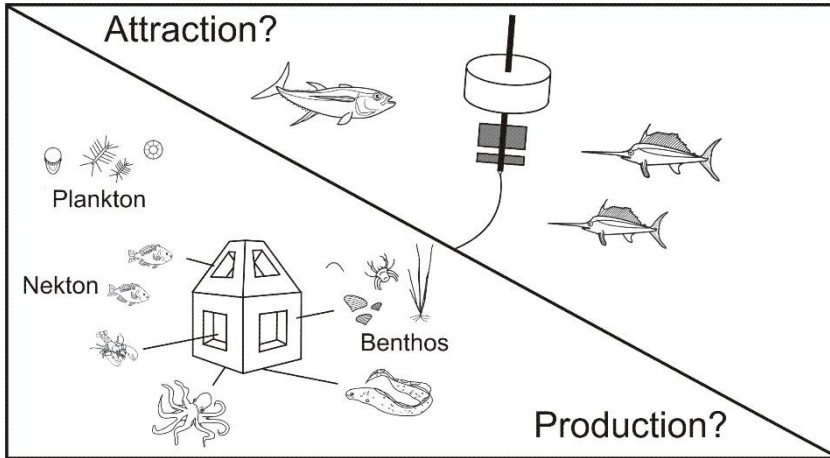


Figure 5. A key function in the ecological manipulation of ARs is to attract existing species while facilitating the development of new habitats that support ongoing biological production.

Promoting biodiversity: It is necessary to provide habitats suitable for different trophic levels (herbivores, carnivores, detritivores) and to consider target species as well as non-target species, including endangered or critical species. Ulaş, et al. (2011) proposed a novel AR module composed of horizontal circular nests, closed on one side, specifically designed for the common octopus (*Octopus vulgaris*). Their results indicated that octopuses from ARs occupied these blocks and used them as nesting sites. Another study used CFD to compare two cube block designs and find an appropriate reef block for cephalopod molluscs, focusing on nutrient transport, water circulation, and the number of nest cavities (Barros, Galdo, & Guerreiro, 2023).

Connectivity with natural ecosystems: The placement of reef structures should be consistent with migration routes, nursery grounds, and feeding areas, while ensuring that sensitive ecosystems, including seagrass meadows and natural coral reefs, are not disrupted. FARs or FADs are objects suspended in the water column or floating on the surface for the purpose of attracting pelagic or semi-pelagic fish (Relini, Torchia, & Relini, 1995). These offshore systems are capable of aggregating large numbers of migrating fish.

Carrying capacity & density: It is essential to prevent excessive fish aggregation that could increase competition, predation, or disease, while ensuring appropriate reef density and spacing, without overlap, to support sustainable community development. Lan, Chen, & Hsui (2004) proposed a model called the layout of AR communities (LARCs) model, which not only uses the fractal dimension as an indicator to measure complexity, but also considers the cost, budget, distance to adjacent artificial reef communities (ARCs), and the number of ARCs deployed.

Long-term environmental succession: ARs should be designed to facilitate natural colonization and ecological succession, ultimately developing characteristics similar to natural reef systems and providing support for both pioneer species and late-successional communities. The study tested six concrete formulations (geo-polymer or cement CEM III binders and recycled sands) 3D printed on ARs along the Atlantic coast and found that CEM III formulations were better than those based on geo-polymers in terms of both colonization (The colonisation of the concrete samples micro and macro organisms) and durability, indicating that CEM III should be preferred for reef applications 3D printed. Apart from selecting appropriate materials, designing reefs to meet natural requirements will increase the success of artificial habitats. For this purpose, specific reef designs are developed to replicate natural habitats, thereby increasing the support for biodiversity (Ulaş, Lök, Düzbastılar, Özgül, & Metin, 2011).

Human-ecological interactions: In designing reefs, it is important to account for ecological resilience under fishing pressure, diving, and other human activities, ensuring that they simultaneously support conservation and sustainable fisheries without functioning as ecological traps. Post-deployment monitoring and management are crucial to ensure that ARs function effectively and remain sustainable over the long term. Numerous studies have demonstrated that the ecological impact of ARs is primarily due to the flow field effect generated by the interaction between AR and the water column.

3.2. Environmental factors

Site selection & environmental suitability: Site selection should avoid sensitive habitats (e.g., natural coral reefs, seagrass beds, and spawning grounds) and prioritize locations with suitable depth, substrate type, and water quality to ensure long-term stability and ecological function. In particular, deployment depth is a critical factor for nautical safety, minimizing conflicts with fishing activities, and reducing impacts from wave action and local scouring. The study compared the effectiveness of two different reef designs against each other and against natural reefs. Overall, the findings of the study suggest that the site selection rather than the design has a more significant impact on the abundance

of fish in the AR, while the reef design is an important determinant of the diversity of species and the structure of the community regardless of location (Komyakova, Chamberlain, Jones, & Swearer, 2019).

Hydrodynamics & sediment dynamics: Assessing potential impacts on sediment transport, erosion, and deposition, as well as preventing excessive scour around reef bases or disruption of coastal processes, is critical before deployment. Climate change has increased coastal flooding and erosion, driving interest in natural engineering. Reef engineering offers the possibility of reducing wave stress while preserving environmental values, but its application to coastal protection is still limited by the complexity of integrating physical and biological processes (Benjamin, et al., 2025). Predictions from numerical modelling can be used to assess the wave, hydrodynamic, and morphological properties of reef structures, while helping to prevent negative outcomes such as local scour, sinking to the bottom, or overturning after reef installation, and to ensure better reef performance and longevity.

Compatibility with marine applications: While avoiding conflicts with navigation, shipping routes, fisheries, aquaculture, and tourism, it is essential to ensure safe distances from harbours, pipelines, cables, and protected and military areas. In particular, they should be positioned in such a way as not to interfere with the legal fishing depth limits. ARs are mainly placed for social and economic benefits and to minimise conflicts with other uses such as shipping, military use, or impacts on sensitive areas (Paxton, Steward, & Harrison, 2022).

Prevention of pollution and contamination: Materials used must be clean and free of toxic substances (e.g., oils, paints, heavy metals, plastics), and ARs should not contribute to marine litter over time. In particular, toxic materials such as polychlorinated biphenyls (PCBs) used before the 1980s for the manufacture of cable electrical equipment, such as capacitors and transformers, and watertight sealants on the surface of vessels should be removed for sinking in shallow marine environments such as ARs (Lukens & Selberg, 2004). To prevent pollution and contamination, biodegradable materials (potato-waste-derived *Solanyl* C1104M and coir rope) have been used for intertidal foreshore stabilization (Marin-Diaz, et al., 2021).

Resilience to climate change: Sea-level rise, increasing storm intensity, and warming waters must be taken into account, and the design should ensure durability under changing environmental conditions. Due to hurricane-damaged sand deposited on the shore of the Riviera Maya, which prompted the creation of an artificial dune and later a prefabricated concrete reef 120 m in length. The reefs have effectively reduced erosion and promoted fish and coral colonisation, restoring the natural cycle of the beaches within a period of five years (Silva, Mendoza, Mariño-Tapia, Martínez, & Escalante, 2016).

Environmental carrying capacity: Reef density and scale must not overwhelm local ecosystems (e.g., nutrient balance, predator-prey dynamics), and it is essential to prevent excessive concentration of fishing effort in a single area. A study conducted four years after the final deployment of nearshore ARs in southern Portugal found a 35% increase in the carrying capacity for commercially sized seabream (*Diplodus vulgaris*) on both the reefs and the adjacent continental shelf (Roa-Ureta, Santos, & Leitão, 2019).

Monitoring & adaptive management: Environmental impact assessments (EIAs) should be conducted before deployment, and long-term monitoring programs should be established to track the reef's effects on the surrounding ecosystem. Numerous studies have used a variety of approaches, such as visual censusing (Lök, Gül, Ulaş, Düzbastılar, & Metin, 2008; Ambrose & Swarbrick, 1989), photography (Knoester, et al., 2023), both still and video (Becker, Taylor, McLeod, & Lowry, 2020), baited remote underwater video (Folpp, et al., 2020), fishing surveys (Fabi & Fiorentini, 1994), or more specialized methods like telemetry (Özgül, et al., 2015), tagging (Addis, Patterson III, Dance, & Ingram Jr, 2013), and acoustics (Yoon, Hwang, Kim, Lee, & Lee, 2014). Brock and Norris (1989) examined reef sites after deployment and reported that the most effective reefs were those constructed from unmodified scrap materials, purpose-built dumping modules, or systematically designed structures. Purpose-built and organised shelters generally perform better than those made of materials distributed at random.

Restoration and mitigation potential: ARs may be designed to restore degraded habitats (e.g., eroded coastlines, damaged reefs) and should function as a mitigation tool rather than as a substitute for natural conservation. In 1989, sixteen prefabricated terraced concrete reef modules were deployed in lower Delaware Bay, followed by a five-year monitoring program to evaluate their role in mitigating habitat loss. Within two years, the reefs proved physically stable and supported diverse biological resources compared to non-reef areas (Foster, Steimle, Muir, Kropp, & Conlin, 1994). Restoration of degraded reefs is a key management strategy to counter the impact of humans on coral reefs in particular, but limited knowledge of environmental dynamics such as species loss, shifts in dominant species, changes in the trophic balance, and bio-invasions often makes it difficult to succeed (Abelson, 2006).

4. Conclusion

ARs, both benthic and floating, began as experimental structures centuries ago and have since evolved into a multidisciplinary research focus, with continuous advances in design, functionality, and materials. Although past misuses, such as the use of discarded tyres and other scrap metal (now banned in many countries), have caused irreversible damage to the environment, current practices in artificial

habitats are more deliberate and serve as a tool to restore exploited natural resources.

To maximise the efficiency of next-generation, large-scale ARs, scientists from different disciplines need to work together to develop new materials, eco-friendly applications, and structures that support reproductive success, and to evaluate these concepts in numerical modelling and tank experiments before deployment. Emerging reef-generation technologies, integrated with aquaculture systems or renewable energy structures such as solar panels and wind turbines, offer opportunities for exploiting the upper and middle seas without causing reef base erosion in marine engineering projects. Submarine pipelines are also an important form of maritime infrastructure with the potential to integrate ARs for environmental protection and enhancement.

Despite progress in global research on AR, hydrodynamic effects are still poorly understood, and studies often lack continuity and systematic approaches to reef design, location, and material selection, which highlights the need for a more comprehensive and coordinated research effort.

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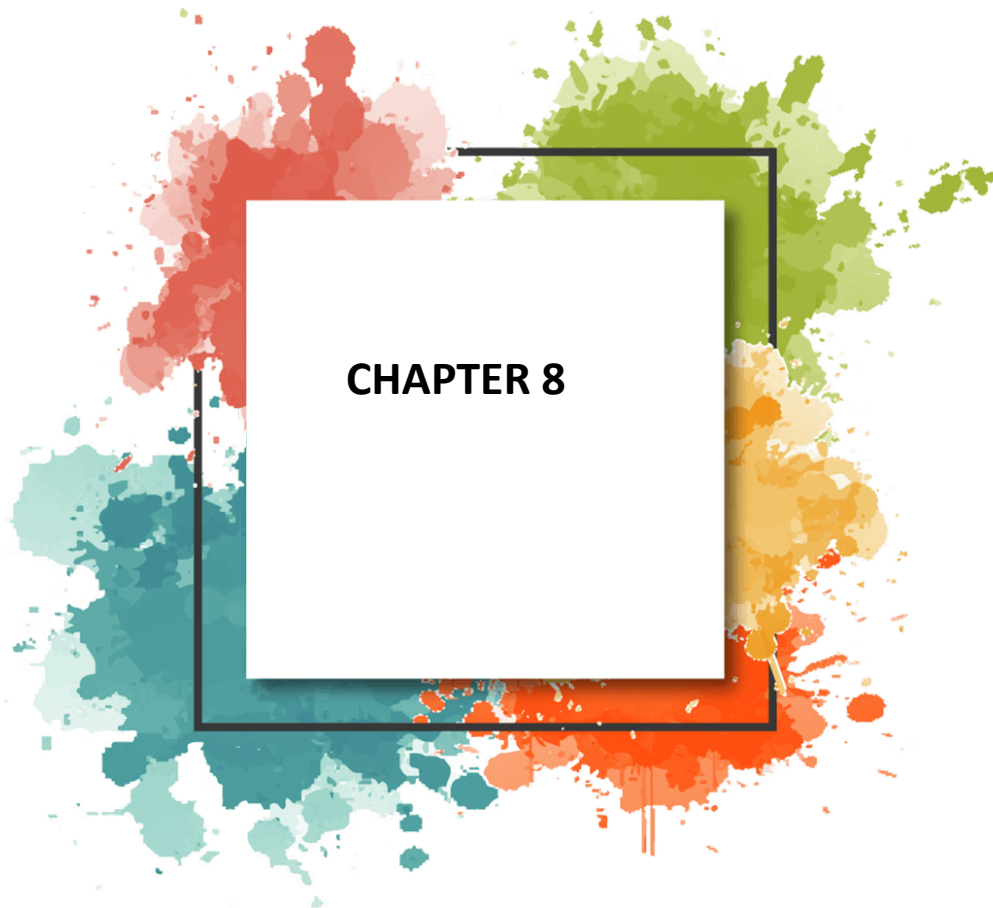
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CHAPTER 8

Enhancing ANFIS Training Performance Using the Immune Plasma Optimization Algorithm

Hasan Badem¹ & Seval Emen²

1. Introduction

Nonlinear large-scale problems are prevalent across various engineering disciplines. In addressing such problems, efforts are made to define a mathematical relationship between input and output variables in order to construct a comprehensive solution set. However, traditional modeling approaches often fall short of achieving the desired level of accuracy. Studies in the literature have demonstrated that Adaptive Network-Based Fuzzy Inference Systems (ANFIS) can significantly enhance performance in solving complex problems [1]. ANFIS improves system accuracy by developing an error-driven model. Its architecture comprises a multi-layered network of nodes that operate synchronously, with predefined membership functions applied at each node. The model, shaped by the number and type of membership functions, is then optimized through a learning algorithm. Numerous studies have proposed the use of metaheuristic algorithms for training ANFIS models. Compared to conventional ANFIS approaches, those incorporating metaheuristic techniques have consistently yielded superior results [2].

Optimization is the process of identifying the most efficient solution among a set of feasible alternatives for a given problem [3]. Optimization techniques are generally classified into two main categories: those that rely on derivative information and those that utilize heuristic strategies independent of derivatives. In many real-world scenarios, computing the derivative of an objective function is either impractical or impossible. Moreover, derivative-based methods are often prone to becoming trapped in local optima. In contrast, heuristic optimization algorithms seek solutions based on intuitive strategies rather than explicit mathematical formulations. These algorithms are particularly well-suited for problems with large and complex search spaces, as they can effectively approximate the optimal solution, thereby increasing the likelihood of reaching the global optimum. Metaheuristic algorithms, a subset of heuristic methods, are designed to explore vast parameter spaces without being confined by the constraints of the solution landscape. By systematically processing and storing

¹ Assoc. Prof., Kahramanmaraş Sutcu Imam University, Department of Computer Engineering, Kahramanmaraş 46050, Turkey Orcid: 0000-0002-4262-8774

² Kahramanmaraş Sütçü İmam University, Institute of Science and Technology, Information Systems, Kahramanmaraş, 46050, Turkey. 0000-0003-0955-1362

information obtained during the search, these algorithms construct and refine the solution space. The search continues iteratively until a near-optimal or globally optimal solution is identified [4]. A variety of optimization algorithms have been employed to train the ANFIS model, which is widely used in system modeling. These include genetic algorithms [5], particle swarm optimization (PSO) algorithms [6], and artificial bee colony (ABC) algorithms [7].

Recently, the Immune Plasma Algorithm (IPA), introduced by Aslan and Demirci in 2020, has demonstrated superior performance over the aforementioned algorithms in solving various optimization problems [8]. IPA was inspired by the key principles of immune plasma treatment, a therapeutic approach whose application became more prominent during the COVID-19 pandemic. In the present study, the ANFIS model is trained using IPA for the first time. The effectiveness of the proposed approach is evaluated by modeling benchmark problems that are well established in the literature.

This study introduces the IPA-ANFIS framework, marking the first known application of the Immune Plasma Algorithm (IPA) for ANFIS training. The key contributions of this study are as follows:

- It proposes a novel application of the Immune Plasma Algorithm (IPA) for training Adaptive Network-Based Fuzzy Inference Systems (ANFIS).
- The IPA-ANFIS model achieves consistently lower root mean square error (RMSE) values compared to GA, PSO, and ABC algorithms across eight benchmark nonlinear system identification problems.
- The study demonstrates the effectiveness of IPA in optimizing both the premise and consequent parameters of the ANFIS model, offering a promising new strategy for neuro-fuzzy system training.

The remainder of this paper is organized as follows: the literature review is presented in Section 2. Section 3 provides the fundamental concepts of the Immune Plasma Algorithm (IPA), the ANFIS model, and the proposed hybrid method. Section 4 reports the details of the experimental studies, results, and related discussions. Finally, Section 5 concludes the study and outlines potential directions for future research on IPA.

2. Literature Review

The ANFIS have been widely adopted in recent years for solving nonlinear, large-scale problems across various engineering and industrial domains. The architecture's capability to model complex relationships through hybrid learning and fuzzy logic has led to extensive experimentation and enhancements using advanced optimization methods. A prominent direction in the literature is the use of metaheuristic algorithms to enhance ANFIS performance. Traditional training

methods often suffer from limitations such as slow convergence and local optima. To overcome these, algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Artificial Bee Colony (ABC) have been employed. A particularly notable advancement is the Immune Plasma Algorithm (IPA), first proposed by Aslan and Demirci (2020), which has shown superior performance in various optimization problems compared to traditional methods [8]. IPA has since been employed to train ANFIS for system modeling tasks with promising results. Hence, the studies related to the IPA and the ANFIS are reviewed as follows:

In 2023, Keikhosrokian and colleagues conducted a successful study in which the ANFIS system was trained using the Artificial Bee Colony (ABC) algorithm to facilitate the diagnosis of heart disorders. The objective was to develop a computerized system capable of diagnosing heart conditions based on heartbeat sounds, offering a more efficient and practical alternative to the conventional auscultation method using a stethoscope. The results demonstrated that the ABC-ANFIS model outperformed previously used algorithms in this domain, including standard ANFIS, Support Vector Machines (SVM), and k-Nearest Neighbors (KNN), achieving a classification accuracy of 93% in identifying heart murmurs [9]. In a separate study, AlRassas et al. [10] proposed a novel ANFIS model in 2021 for forecasting oil production. This enhanced model was trained using the Aquila Optimizer Algorithm to optimize input parameters, resulting in significantly improved predictive performance. Additionally, in 2023, RA Mohamed developed an ANFIS-based model to predict the electrical characteristics of heterojunctions using a dataset derived from the electrical behavior of five different heterojunction types [11].

In a comparative study, three different approaches—ANFIS, ANFIS-PSO, and ANFIS-GA were employed to evaluate classification performance by Mahdevari et al. (2021) [12]. While the hybrid ANFISs model produced satisfactory results, the inclusion of Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) aimed to further enhance classification accuracy. The findings indicated that although all three methods were effective, the hybrid ANFIS models achieved superior performance. In the context of mining, support systems are typically designed based on miners' experience or, in some cases, through trial-and-error approaches. To address this limitation, Mahdevari et al. [12] proposed a hybrid ANFIS-based model to capture the complex nonlinear relationship between maximum roof displacement and geomechanically properties. Their study compared the predictive capabilities of ANFIS, ANFIS-GA, and ANFIS-PSO models. The results revealed that while ANFIS-GA outperformed the conventional ANFIS model, the ANFIS-PSO approach delivered the highest accuracy among the three.

In 2023, Aslan and Tevfik developed a multi-population version of the Immune Plasma Algorithm (IPA) for route planning of unmanned combat aerial vehicles (UCAVs). This study introduced a parallel multi-population model incorporating a customized migration strategy, referred to as the Multi-Immune Plasma Algorithm (MULIPA), as a novel approach for UCAV path planning [13]. The experimental results indicated that MULIPA outperformed other metaheuristic algorithms in terms of success rate. Similarly, in a 2022 study, Aslan proposed an alternative version of IPA designed to enhance the assessment of potential adverse scenarios during UCAV missions. This modified approach, termed the Centrifugal Immune Plasma Algorithm (centIPA), aimed to improve the robustness and effectiveness of UCAV route planning [14]. The findings demonstrated that centIPA significantly outperformed other metaheuristic techniques in the same domain. Parkinson's disease, a major neurodegenerative disorder, has been the focus of various diagnostic methods, many of which have increasingly incorporated artificial intelligence as technology has advanced. In a 2024 study, Badem and Oğuz proposed a feature selection and classification method based on the IPA algorithm, applied to speech signal analysis [15]. The results, when compared to similar studies in the literature, showed that the proposed IPA-based feature selection technique achieved higher classification accuracy, outperforming other existing methods.

Unmanned aerial vehicles (UAVs) serve a wide range of purposes and hold significant strategic importance for developed nations. In 2025, Aslan and Erkin conducted a study aimed at addressing some of the critical challenges faced by UAV systems, with a particular focus on route planning one of the most complex and demanding aspects of UAV operations. Effective route planning must optimize multiple objectives, including minimizing exposure to enemy threats, reducing fuel consumption, and managing maneuverability constraints such as turning angles. In this study, a greedy heuristic approach that leverages the geometric properties of the route planning problem was integrated into the Immune Plasma Algorithm (IPA). The resulting method, termed DUALIPA, combines the exploratory power of IPA with the efficiency of two candidate routes generated by the greedy strategy. DUALIPA's performance was rigorously evaluated using twelve test cases across three distinct battlefield scenarios. The findings revealed that DUALIPA outperformed fourteen existing techniques in eleven of the twelve test cases and completed one scenario nearly twice as fast as its closest competitor [16].

In 2024, Altuncu and Saphioğlu conducted a study to estimate various properties of cement mortar partially replaced with bentonite, including compressive strength, cement content, spread values, water absorption by weight, and porosity [17]. The study employed Multiple Regression, ANFIS, and PSO

techniques to analyze their effects on 28-day compressive strength. A dataset consisting of 18 samples 14 for training and 4 for testing was used in the analysis. Based on the Multiple Regression results, the study identified both effective and ineffective input parameters. The findings indicated that the PSO model provided the highest estimation accuracy, while the multiple regression model also demonstrated reliable predictive performance [17].

In 2025, Kuşçu and Özdemir conducted a study employing the ANFIS system to assess the flood susceptibility of settlements based on their geographic location and topographic positioning. The analysis covered 483 catchment basins associated with 344 settlements situated along riverbanks and valley floors, out of a total of 735 settlements in the province of Bursa, Turkey. The study successfully identified areas within the provincial boundaries that are most vulnerable to flooding and provided valuable insights into the prioritization of districts based on their relative flood risk levels [18].

In 2024, Ouifak and colleagues conducted a hybrid study based on the premise that combining algorithms in the field of artificial intelligence could yield more effective results. The study aimed to develop and evaluate homogeneous communities across four medical datasets by tuning the hyperparameters of four different neuro-fuzzy systems: Adaptive Neuro-Fuzzy Inference System (ANFIS), Dynamic Evolving Neuro-Fuzzy Inference System (DENFIS), Hybrid Fuzzy Inference System (HyFIS), and Neuro-Fuzzy Classifier (NEFCLASS). To reduce the complexity of high-dimensional data and enhance feature selection, an information gain filter was applied. The evaluation results demonstrated promising performance across all systems [19].

In 2024, Mondal and colleagues conducted a study employing experimental Fuzzy Logic Control (FLC), Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference System (ANFIS) techniques. The objective was to achieve high levels of accuracy in electrochemical discharge machining processes and to enhance microprocessing performance in advanced industrial applications [20].

Accurately estimating performance metrics is critical for manufacturers seeking to enhance the service life of their products. In 2025, Mohanraj conducted a study utilizing artificial intelligence techniques to predict key performance indicators under specified operating conditions. The study employed experimental data to develop and compare four models: a regression model, a Mamdani fuzzy inference system, a Backpropagation Neural Network (BPNN), and an ANFIS. The predicted outputs were evaluated against measured

experimental data, and the results demonstrated strong agreement, indicating the effectiveness of the proposed models [21].

3. Material And Method

This section outlines the benchmark problems employed in the study, followed by a detailed overview of the ANFIS framework, the IPA algorithm, and the proposed hybrid approach.

3.1 Description of the Used Test Problems

In this study, eight nonlinear dynamic systems were utilized to evaluate the performance of the proposed method. These systems comprise functions with either two or three input variables. The structure of the ANFIS model was adapted based on the number of inputs. For two-input systems, generalized bell-shaped membership functions were employed, with 2, 3, and 4 membership functions per input corresponding to ANFIS architectures containing 4, 9, and 16 fuzzy rules, respectively.

The number of parameters optimized by the IPA varied according to the rule count: 24 parameters for the 4-rule structure, 45 for the 9-rule structure, and 72 for the 16-rule structure. The Root Mean Square Error (RMSE) was used as the evaluation metric to quantify prediction accuracy. The RMSE values were computed as the average over 15,000 evaluations, with each experiment repeated five times to ensure statistical reliability.

Table 1 summarizes the parameter configurations for the two- and three-input used in the system. The selected test problems were designed to reflect real-world nonlinear dynamics and have been widely utilized in previous research. Detailed descriptions of these problems can be found in the corresponding studies [7], [22], [23], [24], [25], [26], [27]

Func.	ANFIS Inputs	Train /Test	System
$f_1[22]$	$y_p(t)$ $y_p(t-1)$	100/100	$y_p(t+1) = -1.4y_p(t)^2 + 0.3y_p(t-1) + 1$
$f_2[23]$	$u(t)$, $y(t)$	400/100	$y(t+1) = 0.8y(t) + f[u(t)]$ $f(u) = (u-0.8)u(u+0.5)$
$f_3[24]$	$u(t)$, $y(t)$	200/200	$y(t) = \frac{y(t)}{1+y(t)^2} + u(t)^3$
$f_4[23]$	$u(t-1)$, $y(t-1)$	800/200	$y(t) = \frac{y(t-1)y(t-2)y(t-3)u(t-2)[y(t-3)-1] + u(t-1)}{1+y(t-2)^2+y(t-3)^2}$
$f_5[25]$	$u(t), y(t)$	200/200	$y(t+1) = \frac{y(t)}{1+y(t)^2} + u(t)^2$ $u(t) \in [0,1]$ (Random Value)
$f_6[26]$	$u(t-1), y(t-1)$, $y(t-2)$	150/100	$y(t) = \frac{0.2y(t-1) + 0.6(t-1)}{1+y(t-1)^2} + \sin(u(t-1))$
$f_7[27]$	$u(t-1)$, $y(t-1)$	800/200	$y(t) = 0.6y(t-1) + \frac{u(t-1)}{1+u(t-1)^2}$
$f_8[28]$	$u(t-1)$, $y(t-1)$	300/100	$y(t) = u(t)^3 + \frac{y(t-1)}{y(t-1)^2}$

Table 1 Nonlinear dynamic systems and parameter values used in ANFIS training

3.2 ANFIS (Adaptive Network-based Fuzzy Logic Inference System)

Developed by Jang, the ANFIS is an intelligent neuro-fuzzy modeling approach based on the Takagi–Sugeno fuzzy inference framework, designed for controlling and modeling uncertain or ill-defined systems [29]. While ANFIS incorporates principles of artificial neural networks, it differs fundamentally from traditional neural networks in that it integrates fuzzy logic rules into its architecture. ANFIS combines the learning capabilities of neural networks with the inference mechanisms of fuzzy logic systems. Its core strengths include the adaptive learning of neural networks, the rapid generalization ability of fuzzy inference, and the use of interpretable if–then rules that effectively map input–output relationships. These features allow ANFIS to deliver highly accurate results in solving a wide range of complex, nonlinear problems [30].

The ANFIS architecture consists of nodes placed in layers that work synchronously. Each node is assigned specific membership functions. The model is constructed using a learning algorithm based on the number and type of membership functions selected. Membership functions are precisely defined as functions that specify the real number to which the membership degree is equal, and the domain of the membership function is the set of all real numbers. ANFIS consists of five sequential layers: the fuzzification layer, the rule layer, the normalization layer, the defuzzification layer, and the output (summation) layer [31]. The layered structure of the ANFIS model is illustrated in Figure 1. This

architecture enables ANFIS to produce highly accurate results in modeling and control applications [30].

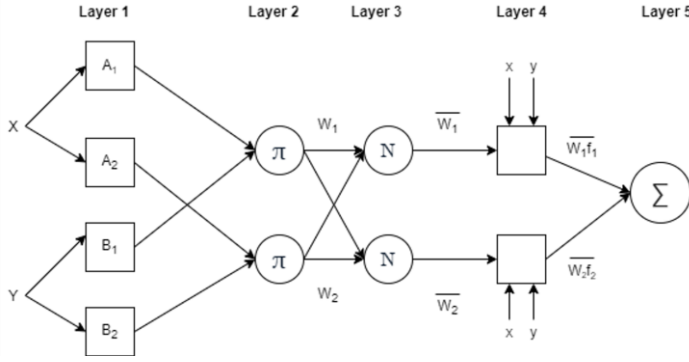


Fig.1 General ANFIS model

Layer 1: Fuzzification Layer:

In the first layer, known as the fuzzification layer, the input data are mapped to fuzzy sets using predefined membership functions. These membership functions differ in shape, parameterization, and functional behavior, and are selected based on the nature of the input variables and the associated rules.

Depending on their type, membership functions are characterized by two, three, or four parameters. For example, triangular and generalized bell-shaped membership functions are defined by three parameters, while the Gaussian membership function uses two. These parameters are used to compute the degree of membership for each input variable. The output of each node in this layer corresponds to the membership value of the input, as defined by Equation 1. In this context, $\mu_{A_i}(x)$ and $\mu_{B_i}(y)$ denote the membership degrees of the inputs x and y with respect to the fuzzy sets A_i and B_i , respectively [32].

$$o_{1,i} = \mu_{A_i}(x), i = 1,2(1)$$

$$o_{1,i} = \mu_{B_i}(y), i = 1,2$$

Layer 2: Rule Layer

The second layer, known as the rule layer, computes the firing strength of each fuzzy rule based on the membership degrees obtained from the fuzzification layer. The firing level is the activation threshold of membership functions. Output values are determined using firing levels (W_i). Equation 2 shows the equation for the activation level [32].

$$O_i^2 = W_i = \mu A_i(x) \mu B_i(x), i = 1, 2 \quad (2)$$

Layer 3: Normalization Layer

The third layer, referred to as the normalization layer, is responsible for normalizing the firing strengths computed in the previous layer. Each rule's firing strength is divided by the sum of all firing strengths to obtain the normalized weight for that rule. This ensures that the relative influence of each rule is properly scaled within the range [0,1] and that the sum of all normalized values equals one. The normalization equation is given in Equation 3 [32].

$$o_i^3 = \bar{w}_i = (w_i / w_1 + w_2)(3)$$

Layer 4: Defuzzification Layer

The fourth layer, known as the defuzzification layer, transforms the fuzzy outputs of the previous layer into crisp values. This is achieved by multiplying each normalized firing strength with a first-order (linear) function of the input variables. The purpose of this operation is to obtain interpretable numerical results, as fuzzy outputs alone do not yield directly meaningful values. It is calculated as expressed in Equation 4 [31].

$$O_i^4 = \bar{w}_1 x f_i = \bar{w}_1 \times (p_i x + q_i y + r_i) \quad (4)$$

Layer 5: Output Layer (Summation Layer)

The fifth and final layer, referred to as the output layer or summation layer, produces the overall output of the ANFIS model. In this layer, all the weighted outputs generated in the defuzzification layer are summed to compute the final crisp output. This aggregation represents the inference result of the entire fuzzy system. The calculation is given in Equation 5 [32].

$$O_i^5 = \sum_i \bar{w}_i x f_i \quad (5)$$

3.3 IPA (Immune Plasma Algorithm)

Immune plasma therapy, historically employed in the treatment of infectious diseases such as SARS, Ebola, MERS, and H1N1 influenza, was most recently applied during the COVID-19 pandemic, which was declared a global health emergency by the World Health Organization (WHO) in 2020. In Immune plasma therapy, antibodies obtained from patients who have previously contracted and recovered from the disease are transferred to critically ill individuals in order to facilitate their recovery.

Inspired by the essential principles of immune plasma therapy, Aslan and Demirci introduced the Immune Plasma Algorithm (IPA) in 2020 [33]. The IPA is a population-based optimization algorithm in which each antibody-donating

individual represents a potential solution to a given problem. The quantity of antibodies produced by each individual signifies the fitness or quality of that solution [8]. In this context, higher antibody levels are associated with more optimal solutions, thereby increasing the likelihood of selection and propagation within the population. The basic algorithmic structure of IPA consists of three stages: population formation, infection spread and immune response, and plasma transfer. The fundamental steps and structures of IPA are presented in Algorithm 1.

- 1: Start the algorithm:
- 2: PS, RN and MaxIter assignment
- 3: **REPEAT**
- 4: Spread phase of infection:
- 5: Infect each individual in the population with the source individual.
- 6: Conduct greedy selection between the source individual and the infected individual.
- 7: Plasma Transfer Phase:
- 8: Randomly select a donor for the worst RN individuals in the population.
- 9: Transfer from donor to receiver
- 10: Make greedy selection between the receiver of plasma transfer and its new state
- 11: Phase of control of donors' immune memory:
- 12: Randomly or completely renew donors over time
- 13: **UNTIL** (until the stop criterion is met)

Algorithm 1 The fundamental steps of the IPA Algorithm

At the initial step, initial solutions are determined for each individual. For an algorithm with a population size PS and a problem with D parameters, the value of the j. parameter of the x_k individual is generated using Equation 6.

$$x_{kj} = x_j^{min} + rand(0,1)(x_j^{max} - x_j^{min}) \quad (6)$$

Equation 7 is employed in the IPA algorithm to model the spread of infection among individuals within the population. This mechanism plays a crucial role in diversifying the population and expanding the algorithm's search space. By simulating the transmission of infection, the algorithm enhances its exploratory capability, allowing for a more comprehensive investigation of the solution landscape.

$$x_{kj}^{inf} = x_{kj} + (-1,1)(x_{kj} - x_{m_j}) \quad (7)$$

Following the infection spread step, the IPA algorithm identifies individuals with the strongest immune response as donors, and those with the weakest immune response as receiver. This classification enables the algorithm to mimic the plasma transfer process observed in real-life immune plasma therapy. The selection of the best and worst individuals is carried out based on their fitness levels. The receivers are updated by Equation 8.

$$x_{kj}^{rcv-p} = x_{kj}^{rcv} + (-1,1)(x_{kj}^{rcv} - x_{mj}^{dnr}) \quad (8)$$

During the control phase of the donors' immune memory, the algorithm evaluates the time-dependent variation in the immune responses of selected donor individuals. This evaluation is essential for determining the stability and adaptability of high-quality solutions across successive iterations. The dynamic behavior of donors is governed by a conditional update mechanism defined as follows:

If $tc/tmax < rand(0,1)$ then the immune response of the donor is updated using Equation 3.9; otherwise, the donor is re-evaluated and updated using Equation 1.

$$x_{mj}^{dnr} = x_{mj}^{dnr} + rand(-1,1)(9)$$

This mechanism allows the algorithm to maintain a balance between **exploration** and **exploitation** by selectively refreshing or reinforcing donor solutions based on the iteration stage and stochastic comparison.

3.4 Proposed Method

In ANFIS training, the initial parameters are utilized in the fuzzification layer, while the consequent parameters are employed in the defuzzification layer. These parameters collectively define the behavior of the ANFIS model and are subject to optimization. In this study, both sets of parameters were optimized using the IPA. A schematic representation illustrating the parameters within the ANFIS architecture—those involved in the training process—is provided in Figure 2. The total number of trainable parameters in the ANFIS model is equal to the sum of the initial and consequent parameters. In the IPA algorithm, each individual capable of acting as a donor represents a candidate solution in the optimization space. To enhance the overall performance of the system, these candidate solutions were iteratively improved by optimizing ANFIS parameters through IPA. The block diagram of the proposed IPA-ANFIS hybrid method is shown in Figure 3.3.

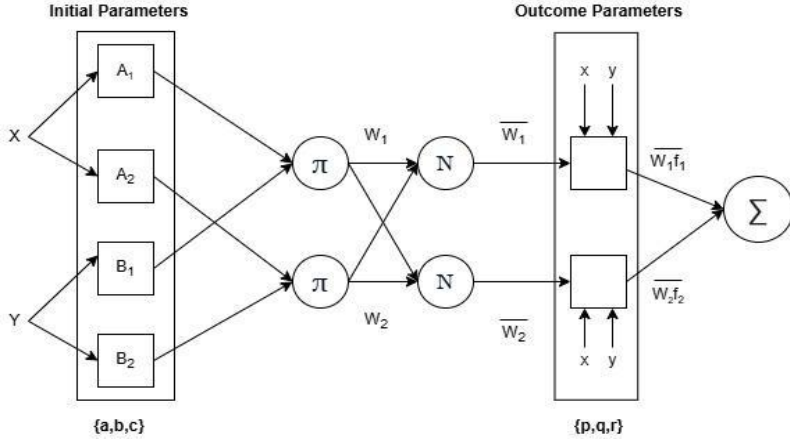


Fig. 2 Initial and consequent parameters in the ANFIS structure

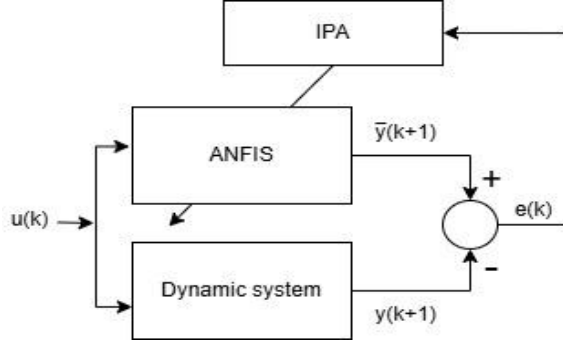


Fig. 3 Block Diagram for System Identification Using the IPA Algorithm and ANFIS

In this study, the IPA algorithm was employed to train the ANFIS model for the identification of nonlinear dynamic systems, and a comprehensive performance analysis was conducted. Eight benchmark nonlinear systems previously validated in the literature were selected for evaluation. As shown in Table 3.1, these systems include both two-input and three-input configurations, along with the corresponding training and testing sizes.

The IPA algorithm was initialized with randomly generated populations and executed five times for each system in order to obtain statistically reliable results. For the two-input systems, ANFIS structures were configured with membership function (MF) combinations of [2 2], [3 3], and [4 4], resulting in fuzzy rule sets of 4, 9, and 16 rules, respectively. The number of trainable parameters optimized by the IPA for each configuration was 24, 45, and 72, respectively. For the three-input systems, MF configurations of [2 2 2] and [3 3 3] were applied, resulting in ANFIS models with 8 and 27 fuzzy rules. Accordingly, the IPA algorithm optimized 50 and 135 parameters for these structures. A generalized bell-shaped

membership function was consistently used across all experiments. In all cases, the recommended Donor Number (DN) and Receiver Number (RN) values for the IPA algorithm were adopted, as suggested in the original study [34].

To determine the most effective parameter configuration, all possible combinations of ANFIS model structures and IPA settings were systematically tested. For the two-input systems, a total of 81 combinations were evaluated, and the configuration yielding the lowest average RMSE was selected for inclusion in result tables. Similarly, for the three-input systems, 54 combinations were tested, and the best-performing configuration was selected and presented.

The RMSE was used as the performance metric to evaluate the accuracy of the solutions obtained during the modelling process. The RMSE quantifies the difference between the predicted and actual output values, serving as an indicator of model suitability. The mathematical formulation for RMSE is provided in Equation 10.

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (y_i - \hat{y}_t)^2}{N}} \quad (10)$$

Here, $\hat{y}_t$ represents the estimated output, y_i represents the known output, and N represents the number of samples.

4.Experimental Results and Discussion

The experimental results clearly demonstrate the efficacy of the IPA in optimizing ANFIS parameters, consistently outperforming traditional metaheuristics across most benchmark functions. The training outcomes for the eight nonlinear systems, as obtained using the IPA algorithm, are presented in Table 2. Furthermore, Table 3 provides a comparative analysis of the training performance of IPA against well-known metaheuristic algorithms: ABC, PSO and

F	rule	parameter	TRAINING				TEST			
			BEST (RMSE)	MEAN (RMSE)	WORST (RMSE)	STD. (RMSE)	BEST (RMSE)	MEAN (RMSE)	WORST (RMSE)	STD (RMSE)
f_1	4	24	0.019684	0.021444	0.023463	0.001903	0.020494	0.023549	0.027152	0.003363
	9	45	0.009443	0.014015	0.018991	0.004787	0.012403	0.017785	0.027848	0.008721
	16	72	0.014558	0.019759	0.026111	0.005862	0.016935	0.021877	0.029542	0.006730
f_2	4	24	0.000126	0.000160	0.000204	0.000040	0.000135	0.000164	0.000205	0.000036
	9	45	0.000251	0.000847	0.001718	0.000771	0.000460	0.000866	0.001492	0.000550
	16	72	0.000613	0.001425	0.002107	0.000755	0.000639	0.001333	0.001734	0.000604
f_3	4	24	0.007949	0.008737	0.009833	0.000979	0.008220	0.009550	0.011244	0.001545
	9	45	0.007738	0.008258	0.008548	0.000451	0.007908	0.008664	0.009613	0.000869
	16	72	0.003786	0.005594	0.007627	0.001930	0.003926	0.005766	0.007810	0.001950
f_4	4	24	0.196140	0.199110	0.203284	0.003721	0.195943	0.197035	0.199158	0.001839
	9	45	0.197701	0.199935	0.202561	0.002454	0.190466	0.195502	0.201616	0.005653
	16	72	0.192942	0.196434	0.198233	0.003025	0.192757	0.197276	0.199679	0.003917
f_5	4	24	0.005693	0.008145	0.010317	0.002325	0.006893	0.008973	0.010215	0.001813
	9	45	0.006687	0.007467	0.008918	0.001258	0.007518	0.008007	0.008354	0.000435
	16	72	0.003982	0.005928	0.008198	0.002126	0.004303	0.006017	0.007921	0.001816
f_6	8	50	0.014920	0.015826	0.014920	0.017569	0.015390	0.016347	0.017832	0.017832
	27	135	0.013490	0.014297	0.013490	0.015215	0.012347	0.016274	0.018760	0.018760

f_7	4	24	0.005022	0.005726	0.006298	0.000648	0.005031	0.005526	0.006271	0.000656
	9	45	0.007639	0.008624	0.009206	0.000858	0.007249	0.008349	0.009188	0.000995
	16	72	0.006383	0.009879	0.011701	0.003028	0.007042	0.010663	0.012510	0.003137
f_8	4	24	0.011047	0.015271	0.023339	0.006990	0.011310	0.015515	0.021840	0.005576
	9	45	0.015206	0.018743	0.022501	0.003652	0.014248	0.018785	0.026794	0.006956
	16	72	0.010692	0.013479	0.015557	0.002509	0.009711	0.012748	0.014675	0.002662

Table 2 RMSE results of the proposed IPA-ANFIS for eight nonlinear systems during training and testing phases.

Table 2 shows the training and test results of the IPA algorithm for eight nonlinear systems. The table reports the average best error value, best error value, worst error value, and standard deviation values for both training and testing.

For the training results, the lowest average RMSE in the f_1 function was achieved with an ANFIS configuration comprising 9 rules and 45 parameters. In f_2 and f_7 , the most favorable average RMSE values were obtained using a configuration with 4 rules and 24 parameters. For f_3 , f_4 , f_5 , and f_8 , the optimal average training performance was attained with 16 rules and 72 parameters. In the f_6 function, which involves three input variables, the best average training RMSE was recorded with an ANFIS model containing 27 rules and 135 parameters.

Regarding the testing results, a similar trend was observed. The best average RMSE for f_1 was again achieved with 9 rules and 45 parameters, while f_2 and f_7 showed optimal performance with 4 rules and 24 parameters. The f_3 , f_5 , and f_8 functions exhibited their best test performance using 16 rules and 72 parameters. For the f_4 function, the lowest average testing error was achieved with 9 rules and 45 parameters. Lastly, for the f_6 function with three inputs, the best average RMSE was observed with the 27-rule, 135-parameter configuration.

Table 3 provides a detailed comparison of the training and test performance of four metaheuristic algorithms—PSO, GA, ABC, and the proposed IPA—across eight nonlinear system identification functions. The results clearly demonstrate that the IPA algorithm consistently achieved superior performance in most cases. Specifically, IPA yielded the lowest RMSE values in both training and testing phases for functions f_1 , f_2 , f_3 , f_5 , f_6 , and f_7 , indicating its effectiveness in both fitting and generalization. In the case of function f_4 , however, the ABC algorithm outperformed all other methods, achieving the lowest RMSE values in both training (0.0119) and testing (0.0121). IPA, by contrast, performed poorly on this function, suggesting it may be less suitable for certain problem characteristics. A relatively competitive result was observed in function f_8 , where the ABC algorithm achieved the best performance during training (0.0126), while the IPA algorithm obtained a slightly lower error in the test phase (0.0127 vs. ABC as 0.0140). This suggests that although ABC was more accurate during training, IPA demonstrated better generalization ability on unseen data. Overall,

the findings suggest that IPA offers a highly competitive and, in most cases, superior alternative to traditional metaheuristic algorithms for training ANFIS in nonlinear system identification tasks.

F	PSO [23]		GA [23]		ABC [23]		IPA	
	Training	Test	Training	Test	Training	Test	Training	Test
f_1	0.0352	0.0488	0.0387	0.0498	0.0294	0.0435	0.0140	0.0177
f_2	0.0040	0.0039	0.0165	0.0161	0.0055	0.0053	0.0001	0.0001
f_3	0.0436	0.0441	0.0347	0.0355	0.0255	0.0259	0.0055	0.0057
f_4	0.0171	0.0169	0.0150	0.0152	0.0119	0.0121	0.1964	0.1955
f_5	0.0237	0.0236	0.0152	0.0147	0.0099	0.0110	0.0059	0.0080
f_6	0.0784	0.0768	0.0473	0.0462	0.0290	0.0277	0.0142	0.0162
f_7	0.0230	0.0237	0.0137	0.0157	0.0086	0.0094	0.0057	0.0055
f_8	0.0475	0.0374	0.0223	0.0214	0.0126	0.0140	0.0134	0.0127

Table 3 Comparison of IPA Algorithm Performance with the competitor algorithms

F	Rule Number	Parameter Number	IPA Parameter				Mean (sc)	Std	Mean (sc)	Std
			PS	DN	RN	MF				
f_1	4	24	50	2	2	2 2	1146.84	3.51	1146.84	3.51
	9	45	20	1	1	3 3	4080.43	75.33	4080.43	75.33
	16	72	20	2	2	4 4	12730.96	222.94	12037.17	30.07
f_2	4	24	20	2	2	2 2	1128.23	18.86	1128.23	18.86
	9	45	50	1	3	3 3	3424.62	40.08	3588.87	13.40
	16	72	100	1	3	4 4	11679.58	688.72	11679.58	688.72
f_3	4	24	20	1	1	2 2	1108.78	24.38	1108.78	24.38
	9	45	20	1	2	3 3	3667.34	16.36	3667.34	16.36
	16	72	20	2	3	4 4	11819.36	235.32	11819.36	235.32
f_4	4	24	100	3	3	2 2	1186.49	14.10	1234.63	10.42
	9	45	100	1	3	3 3	3902.64	44.54	3654.51	399.52
	16	72	20	1	1	4 4	12817.01	104.25	11730.92	63.07
f_5	4	24	20	1	1	2 2	1034.41	7.18	1034.41	7.18
	9	45	20	1	3	3 3	3536.13	38.29	3536.13	38.29
	16	72	20	1	3	4 4	11301.31	44.40	12629.62	222.73
f_6	8	50	100	1	2	2 2 2	372.36	44.31	372.36	44.31

	27	135	20	1	3	$\begin{smallmatrix} 3 & 3 \\ & 3 \end{smallmatrix}$	34170.34	574.24	34170.34	574.24
f_7	4	24	20	1	1	2 2	1033.94	6.855	1033.94	6.855
	9	45	100	1	2	3 3	3764.44	9.383	3764.44	9.383
	16	72	20	1	1	4 4	11997.20	33.827	11997.20	33.827
f_8	4	24	50	1	3	2 2	944.32	12.72	944.32	12.72
	9	45	50	2	3	3 3	3737.11	49.54	4045.67	2898.79
	16	72	50	1	1	4 4	13032.96	19.04	12106.81	96.36

Table 4. Computational Times in Sequential Rule Bases of the IPA-ANFIS and ANFIS

The computational performance of the proposed IPA-based ANFIS training approach was evaluated in terms of training and testing times across varying rule base configurations and algorithm parameters. As presented in Table 4, the results clearly indicate that both training and testing times increase substantially with the number of fuzzy rules and corresponding parameters. This outcome is consistent with the expected growth in computational complexity as the ANFIS structure becomes more intricate.

For instance, in f_1 , the training time increases from approximately 1146 seconds for a 4-rule system (24 parameters) to over 12,700 seconds for a 16-rule system (72 parameters), demonstrating the sensitivity of the IPA optimization process to model size. Similar trends are observed in other functions such as f_3 , f_5 and f_8 , underscoring the need for careful trade-offs between model complexity and computational cost.

The influence of IPA-specific parameters (PS, DN and RN) was also evident. While larger population sizes generally required more computation time, the interaction among DN, RN, and membership function configurations (MF) had a more nuanced effect, suggesting that parameter tuning should consider their combined impact rather than treating them in isolation. Furthermore, the analysis shows a high level of consistency between training and testing times, which supports the stability of the learning framework. Overall, the findings emphasize that while the IPA algorithm is effective in optimizing ANFIS models, its computational demands scale significantly with model complexity. Therefore, when applying this method to real-world problems, especially those involving high-dimensional input spaces, careful consideration must be given to the balance between accuracy and efficiency.

Figures 4 through 11 illustrate the convergence behavior of the IPA-trained ANFIS models for each of the eight benchmark functions. Each figure includes nine convergence curves, corresponding to the different combinations of DN and RN values used across three membership function configurations. These graphs also compare the convergence performance under varying population sizes,

offering a visual assessment of stability, speed of convergence, and optimization quality across different parameter settings.

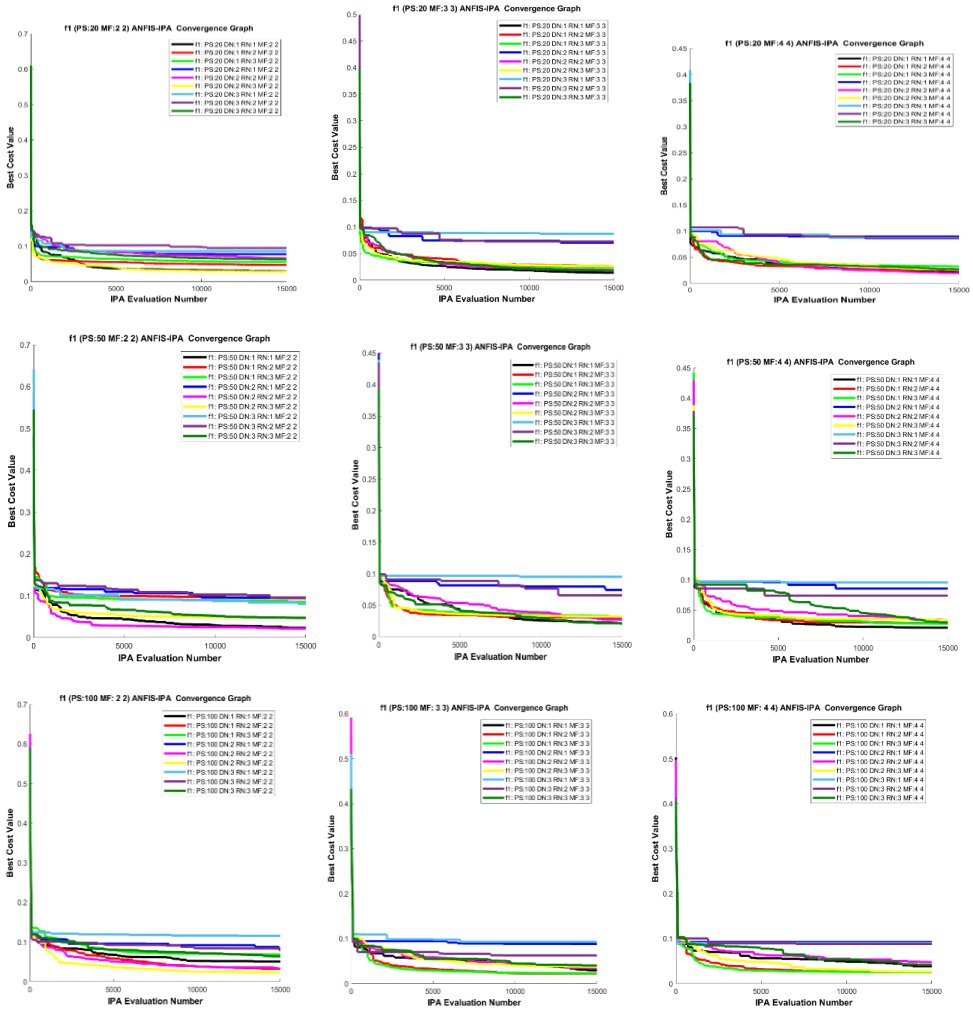


Fig 4 Convergence graphs of the IPA-ANFIS for the f_1 function under varying rule and population configurations.

Fig 4. illustrates the convergence behavior of the IPA-based ANFIS model for function f_1 . The graphs reveal that maintaining a low population size while increasing the number of fuzzy rules enables the algorithm to generate a broader and more rapidly converging solution set. This behavior contributes to enhanced

solution quality, as the higher rule base allows the model to capture more complex input–output relationships, even with limited population diversity.

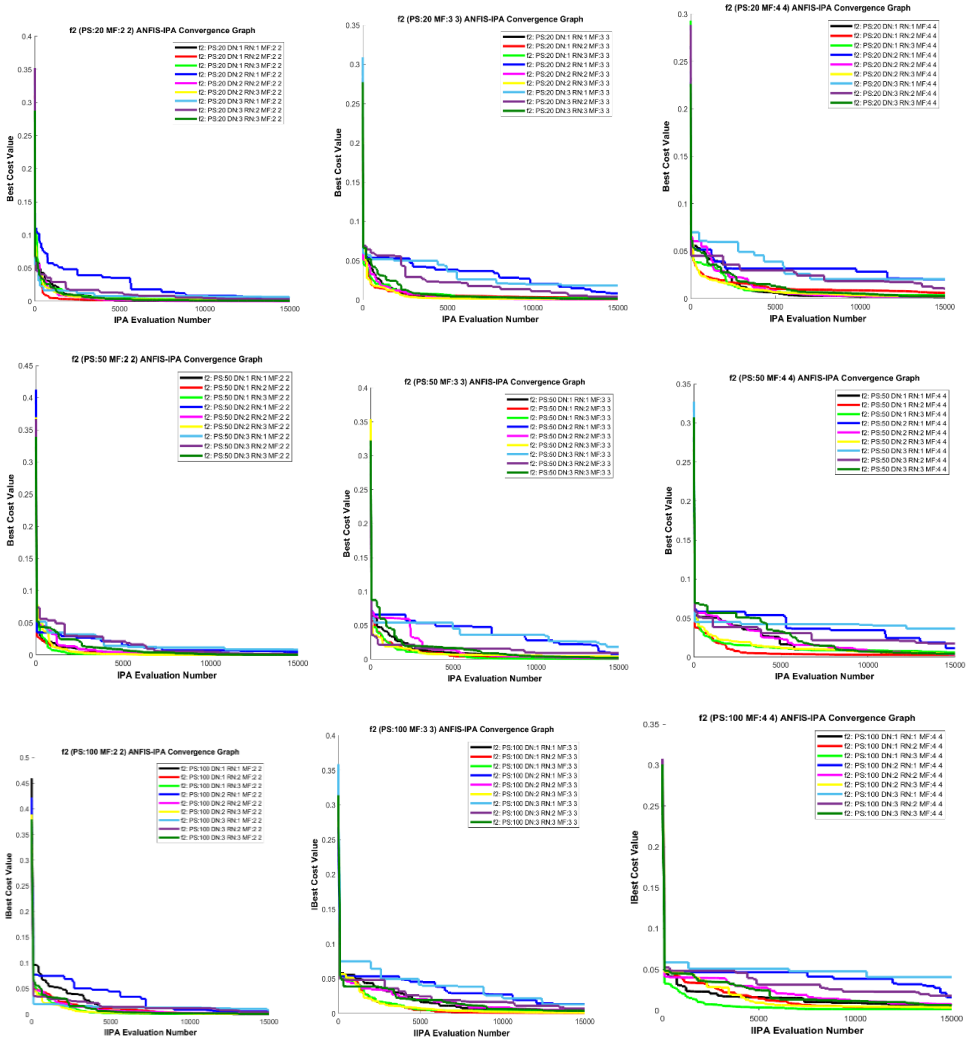


Fig 5 Convergence graphs of the IPA-ANFIS for the f_2 function under varying rule and population configurations.

Figure 5 shows the convergence graphs for the f_2 function. Upon examination of the graphs, it can be observed that the results of the f_2 function are quite good. A low average error value was obtained for different population sizes and rule numbers. When evaluated within its own standards, keeping the rule number and population size low increases the quality of the solution.

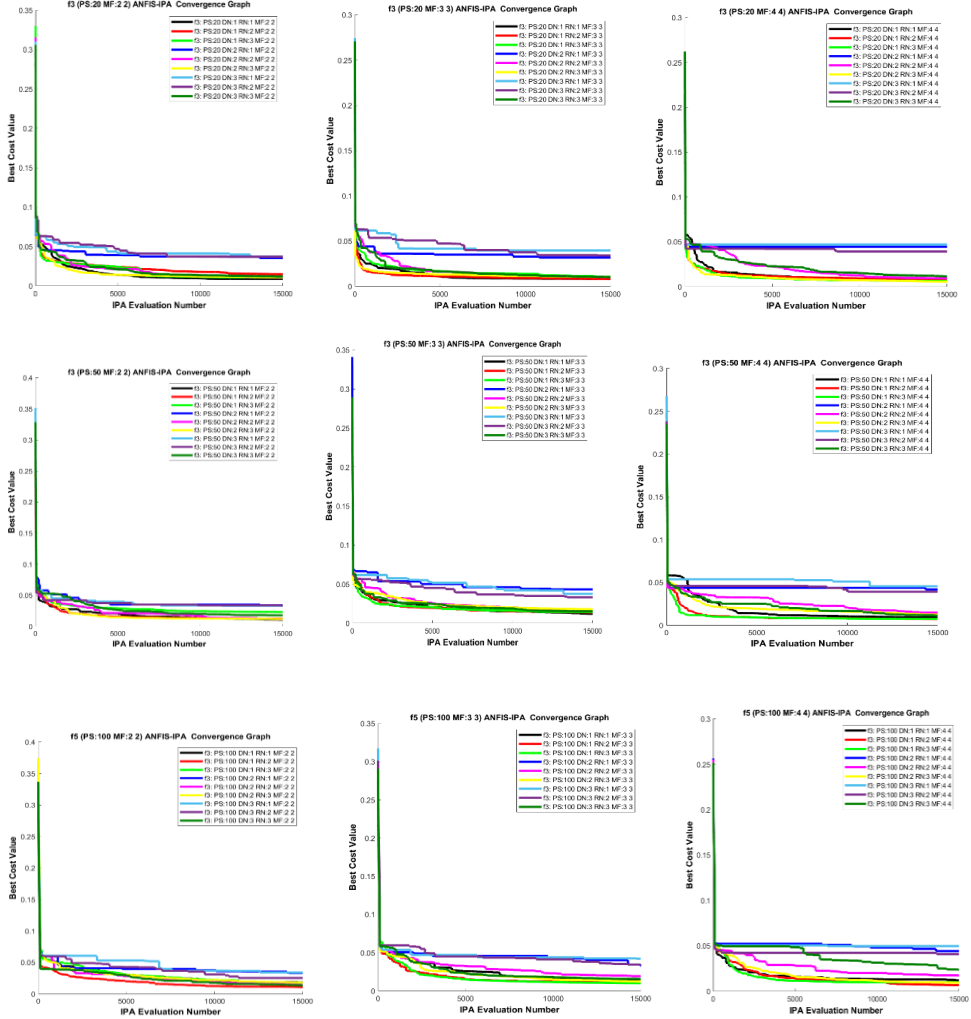


Fig 6 Convergence graphs of the IPA-ANFIS for the f_3 function under varying rule and population configurations.

Figure 6 shows the convergence graphs for the f_3 function. Looking at the convergence graphs for f_3 , it can be seen that increasing the number of rules and population size improves the quality of the solution. The best average values were obtained with 16-rule combinations for population sizes of 20, 50, and 100.

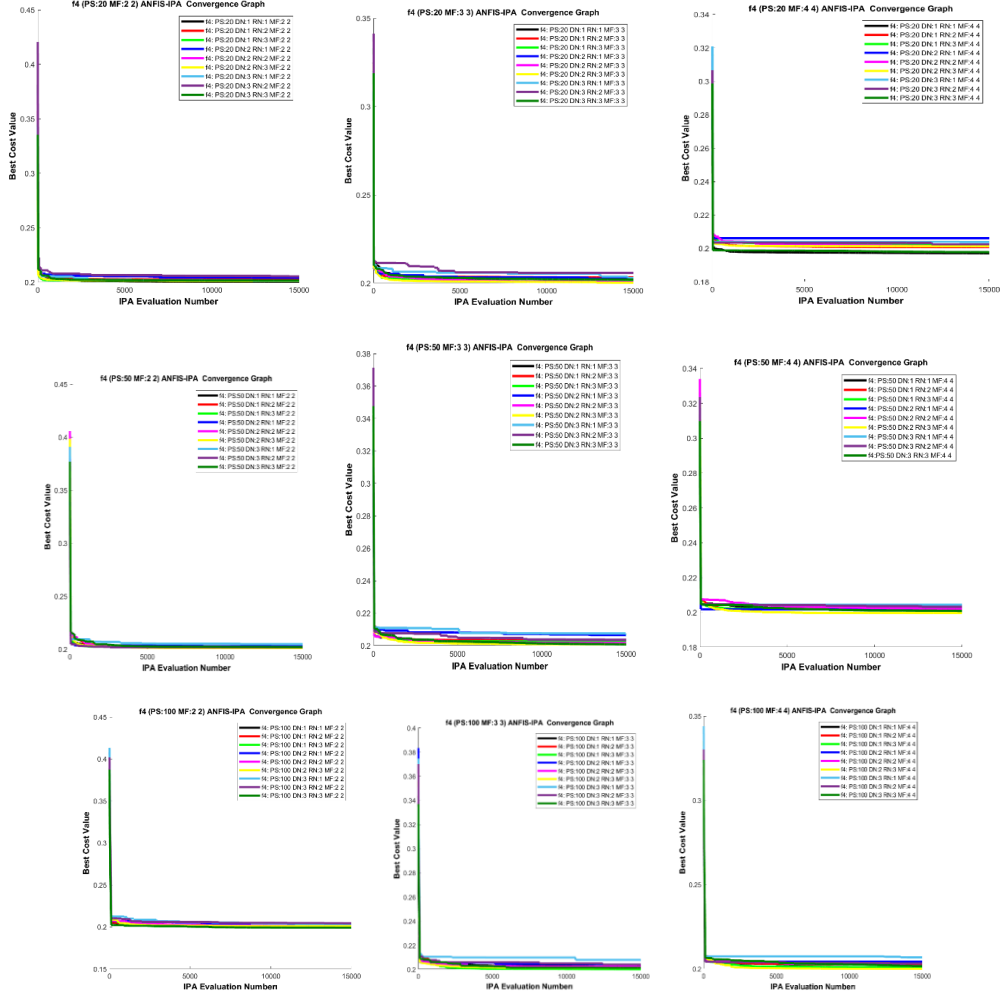


Fig 7 Convergence graphs of the IPA-ANFIS for the f_4 function under varying rule and population configurations.

Figure 7 shows the convergence graphs for the f_4 function. It can be seen that in the f_4 function, which is the only function with a high error rate, an increase in the number of rules within its own standards improves the quality of the solution.

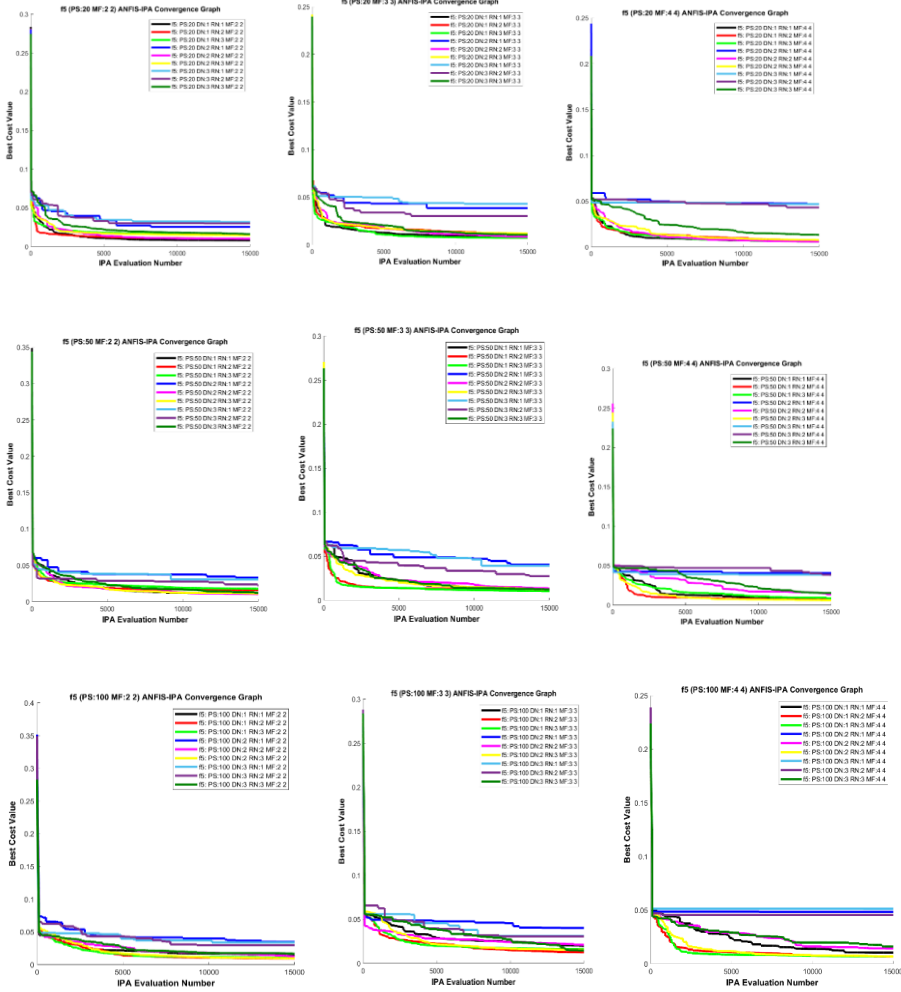


Fig 8 Convergence graphs of the IPA-ANFIS for the f_5 function under varying rule and population configurations.

Figure 8 shows the convergence graphs for the f_5 function. In the f_5 function, which yielded successful results, an increase in the number of rules improves the quality of the solution. When examining the decrease in error rates, keeping the population size at 20 improved the system's success. The best average values are obtained in combinations with 16 rules.

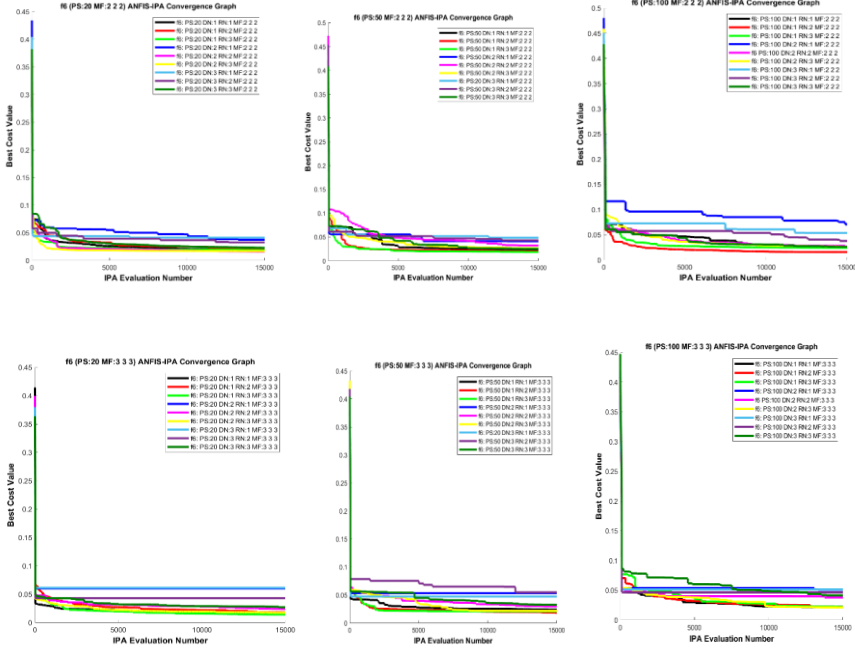


Fig 9 Convergence graphs of the IPA-ANFIS for the f_6 function under varying rule and population configurations.

Convergence graphs for the f_6 function with two inputs are shown in Figure 9. It has been observed that the decreases in error rates belong to 27 rule systems.

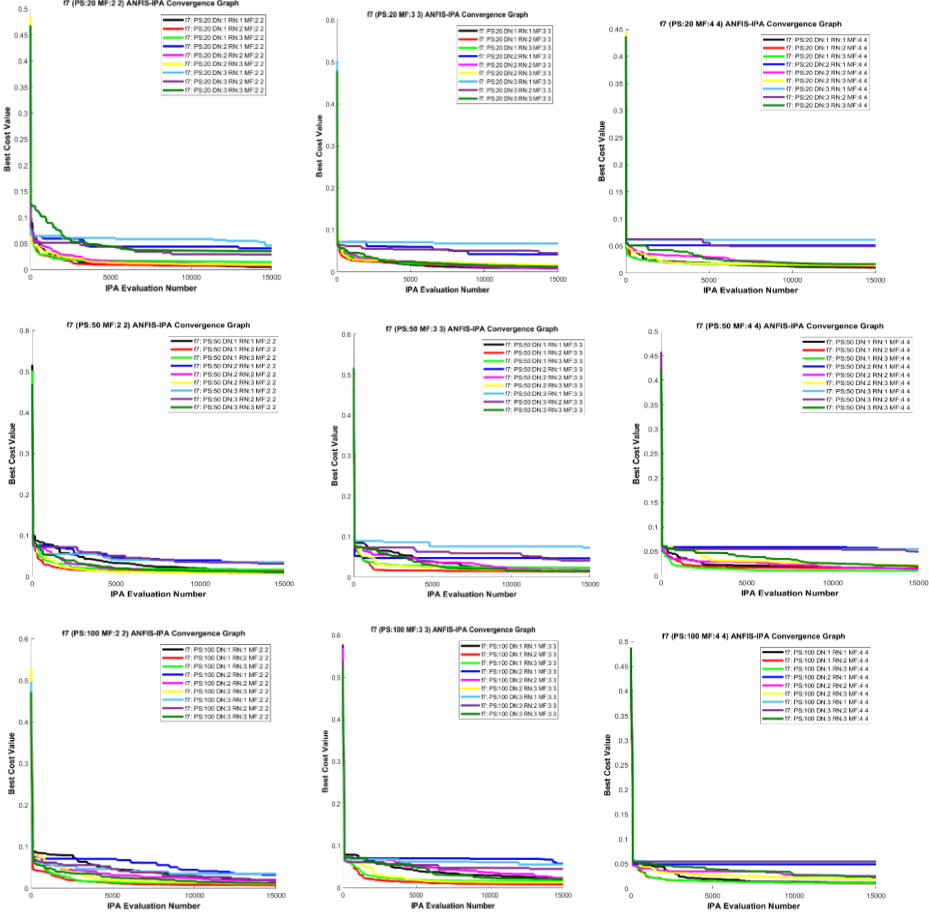


Fig 10 Convergence graphs of the IPA-ANFIS for the f_7 function under varying rule and population configurations.

Figure 10 shows the convergence graphs for the f_7 function. It was observed that the success rate was high in the 4-rule, 24-parameter system with a population size of 20 in f_7 . While an increase in the number of rules increased the success rate, an increase in the population size negatively affected the solution quality.

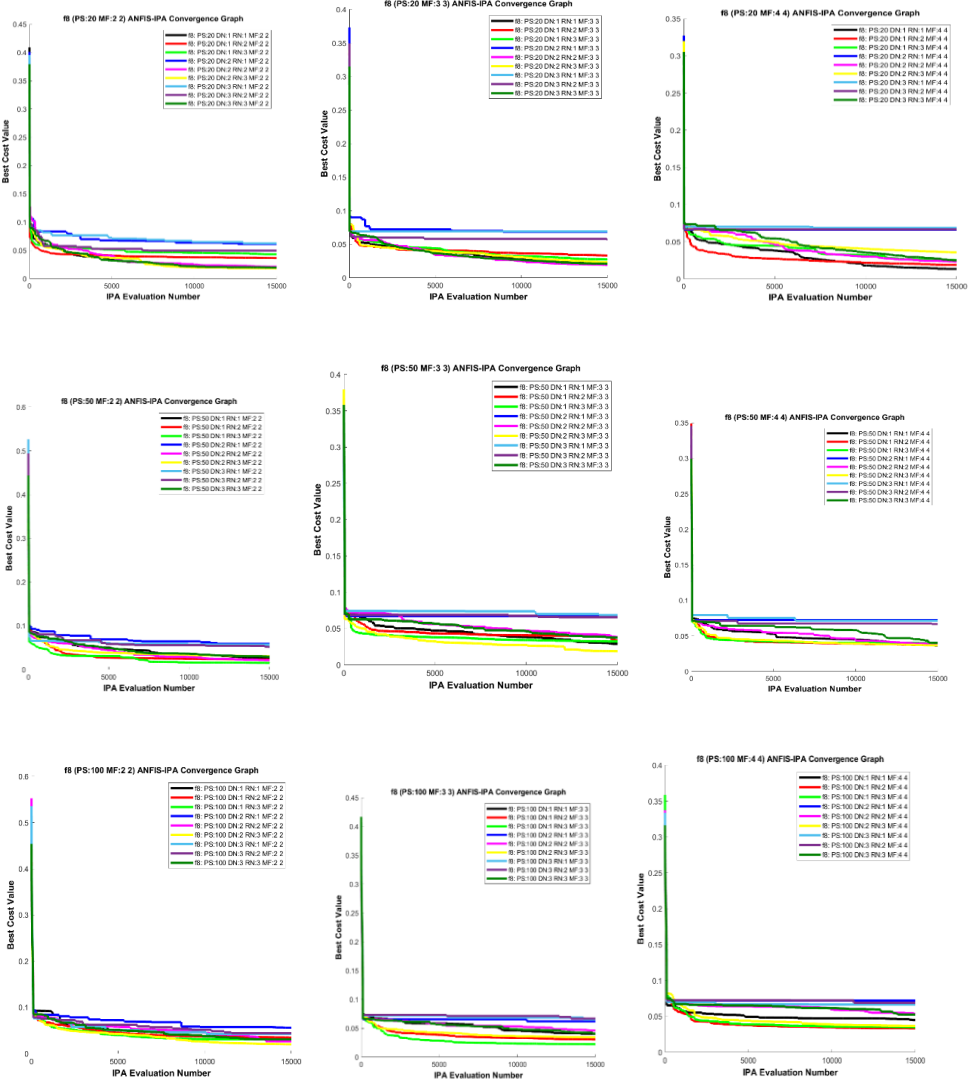


Fig 11 Convergence graphs of the IPA-ANFIS for the f_8 function under varying rule and population configurations.

Figure 11 shows the convergence graphs for the f_8 function. It was observed that the error rates of 16-rule systems were lower. At the same time, an increase in solution quality was observed with an increase in population size. It was observed that the results obtained from combinations with a fixed population size of 50 yielded better results than other results.

5. Conclusion

This study introduced a novel application of the Immune Plasma Algorithm (IPA) for training Adaptive Neuro-Fuzzy Inference Systems (ANFIS), addressing the nonlinear system identification problem. As the first work to integrate IPA into ANFIS training, it provides compelling evidence of the algorithm's effectiveness and generalization ability.

Eight benchmark nonlinear systems were modeled using the IPA-ANFIS framework and compared against PSO, GA, and ABC. IPA yielded the lowest RMSE in six of eight cases, and exhibited consistently strong generalization performance, particularly on unseen test data. Notably, it exhibited stronger generalization, particularly in test performance where training accuracies were similar. The results also revealed that the performance of IPA-ANFIS is strongly influenced by the number of fuzzy rules, population size, and membership function configuration. These findings emphasize the importance of careful parameter tuning for optimal outcomes.

In future studies, more promising results may be achieved by employing alternative or enhanced variants of the IPA for ANFIS training, such as multi-population models, adaptive donor-recipient strategies, or hybrid frameworks that combine IPA with other metaheuristic techniques. These enhancements could improve convergence speed, robustness, and accuracy, especially in high-dimensional or noisy environments. Furthermore, the proposed IPA-ANFIS framework has the potential to be adapted for a wide range of real-world applications, including but not limited to medical diagnosis, energy demand forecasting, robotic control systems, financial modeling, and fault detection in industrial systems. Its flexibility and data-driven learning capacity make it a suitable candidate for addressing complex nonlinear problems across various disciplines.

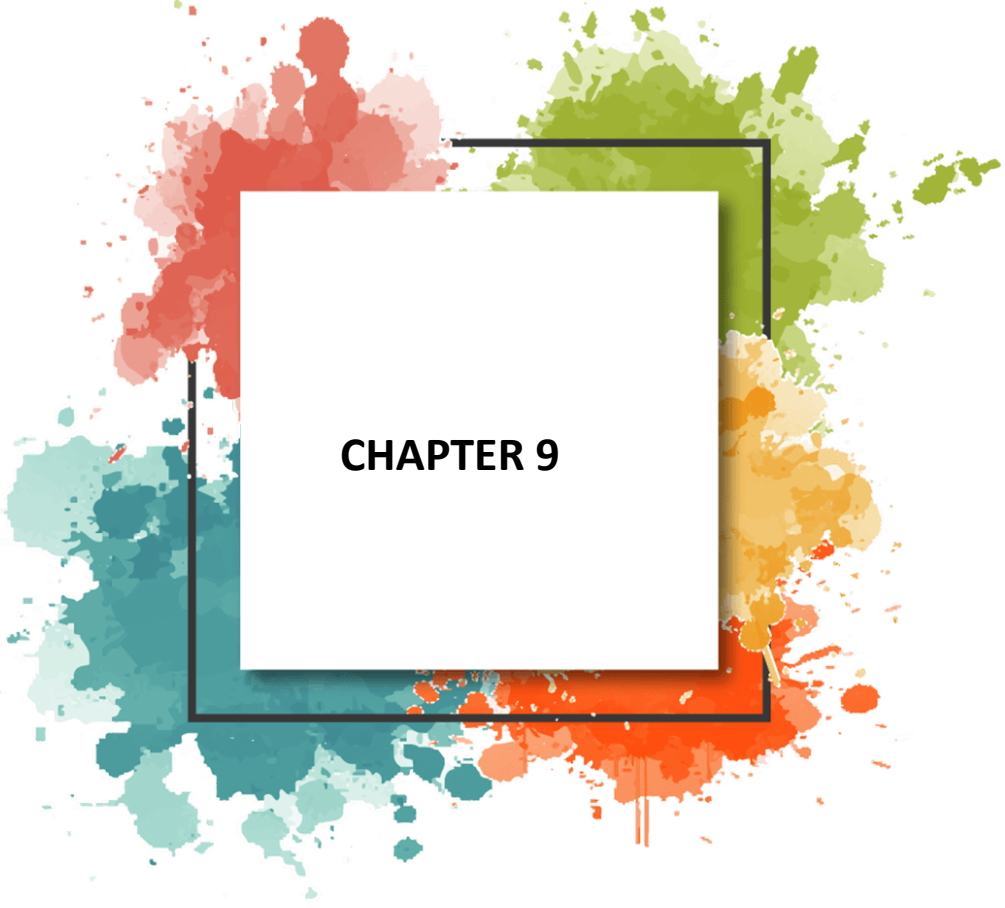
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CHAPTER 9

Integrating Artificial Intelligence Into Digital Marketing: A New Era of Innovative Product Strategies

Kemal Gokhan Nalbant ¹ & Sevgi Aydın ²

INTRODUCTION

Digital marketing is recognized as a determinant that impacts marketing strategy. Digital platforms provide a range of instruments for enterprises to connect with and engage their intended audience. Such an evolution has resulted in the adoption of digital marketing methods that supplant conventional ones. Digital marketing has made marketing operations more quantifiable and traceable for enterprises. Businesses may enhance their comprehension of client behavior and refine their marketing strategies with online tools and analytical techniques (Efendioglu, 2023).

AI is fundamentally constructed on the collection of data pertaining to consumer requirements, their preferred attitudes and behaviors, and prospective alterations in the corporate environment that may impact customers. Digital marketers excel in anticipating client demands, even if customer behavior is often intricate and requires regular analysis. Appropriate AI techniques can enhance the study of consumer reaction. As these technologies adapt to the evolving landscape of digital media and provide real-time solutions to yield more favorable outcomes, the principal challenges in the DA environment may be surmounted overall (Sabharwal et al., 2022).

The rapid advancement of the digital age has revolutionized several organizational activities, especially in marketing. The use of artificial intelligence (AI) in marketing has transformed consumer experience and service provision (Kanojia, 2024).

The ongoing advancement of technology has ushered in a plethora of new trends in marketing, significantly altering the dynamics of interaction between businesses and customers, as well as the competitive landscape of the market. A key hallmark of the digital era is the rise of social media. To obtain feedback right away, promote their brands, and establish communities of consumers, businesses need to utilize sites like Facebook, Instagram, and Twitter. Businesses

¹ Assist. Prof. Dr.; Istanbul Beykent University, Faculty of Engineering and Architecture, Department of Software Engineering, Turkey, ORCID: 0000-0002-5065-2504

² Assist. Prof. Dr.; Istanbul Beykent University, Faculty of Economics and Administrative Sciences, Department of Logistics Management, Turkey, ORCID: 0000-0002-9507-5448

may interact to clients directly on social media to learn about their needs and wants and then provide more personalized products and services. Businesses may learn more about trends in their field and how consumers respond by using big data analytics tools a lot. By gathering, analyzing, and interpreting a lot of data, businesses may figure out precisely where they are in the market, what consumers will desire, and how to make their marketing efforts more effective (Zhou & Yang, 2024).

There have been a lot of changes in the marketing business, particularly since it has migrated to digital platforms and choices are now based on data. This development is distinct from how marketing has previously worked, which depended heavily on direct interaction and conventional market research. Digital technology has not only made it simpler for customers to become engaged, but it has also revolutionized how we comprehend and influence how people act as consumers. Marketers now have access to tremendous information on what clients want thanks to advanced analytics and digital platforms. This has made it feasible to deploy individualized marketing techniques and ushered in a new age of marketing sophistication (Hamamah et al., 2024).

DIGITAL TRANSFORMATION IN MARKETING PRACTICES

Digital technologies and corporate practices are anticipated to fundamentally alter the competitive environment and society. At the core of evolving business practices is the impact of digital technology on marketing, which subsequently alters the global market landscape (Gillpatrick, 2019). Digitization involves encoding and processing corporate operations using information or digital technology. The ultimate outcome may be a mobile platform that enables the enhancement of functionalities and the modification of current business processes, including the establishment of new online capabilities. All clients may efficiently engage with the organization and transform conventional relationships with its clientele. In this phase, it is common to incorporate a firm with digital technologies. This stage serves as a pivotal component that transforms the current company processes, including communication, distribution, or management, to seize new business prospects. A digital description is formulated to use digital technology for the optimization of current business processes, hence improving operations and the user experience, while also generating supplementary expenses for the client. Digitization transcends mere cost reduction. Initiatives also include process enhancements that may elevate the client experience. The transition to the digital era has important implications for the whole business, since it promotes the creation of new value. It transcends mere digitalization. It reconfigures processes to modify the company's business logic or the method of value creation. Digital transformation uses digital technology to enhance relationships among suppliers, customers, and competitors. Digital technology

can help a company gain a competitive edge by changing how it uses its current strengths or by creating new ones (Bist et al., 2022).

Significant problems and possibilities associated with emerging technologies and enhanced data accessibility are compelling marketing organizations (agencies, media, advertisers) to reformulate their business models. Digital transformation is characterized as the use of novel digital technologies (such as social media, mobile applications, analytics, or embedded devices) to provide significant business enhancements, including the improvement of customer experience, optimization of processes, or the development of new business models. Digital transformation reconfigures both current and future company operations, requires specific applications and infrastructure, and necessitates a digital financial framework, all of which create challenges for organizations. Digital transformation influences how organizations manage information and challenges their business models. It presents firms with the option to either evolve in response to change or to progressively become obsolete. Emerging ideas and technologies, such as the Internet of Things, big data, machine learning, and artificial intelligence, need substantial adaptation from enterprises (Miklosik & Evans, 2020)

INTEGRATING ARTIFICIAL INTELLIGENCE INTO STRATEGIC MARKETING

AI in marketing is more significant owing to enhanced computer power, reduced computing costs, the accessibility of massive data, and advancements in machine learning techniques and models (Huang & Rust, 2021). AI technology has profoundly impacted marketing, as evidenced by improvements in personalization, customer engagement, and analytics. These enhancements enable companies to refine their marketing plans and sustain a competitive advantage in this fast-paced, data-driven, and technology-focused landscape (Rathore, 2016).

The integration of artificial intelligence (AI) into marketing has the potential to transform the way businesses interact with their customers and the way they understand the market. In the past, marketing strategies were primarily based on human intuition and conventional statistical methodologies. Machine learning algorithms, predictive analytics, and data-driven insights have allowed businesses to plan, carry out, and evaluate their marketing efforts more effectively, changing the marketing field with the rise of AI. The automation of repetitive procedures, the development of complex forecasting models, and the creation of customized client experiences are among the applications (Potwora et al., 2024).

Artificial intelligence (AI) aids marketers in attaining comprehensive personalization and relevance. It will ultimately achieve large-scale communication via platforms like Search, Facebook, YouTube, and Google, which engage billions of people daily, in addition to digital advertising networks. The future entails the use and execution of artificial intelligence (Basha, 2023). AI systems use algorithms and substantial computer resources to discern patterns in enormous datasets, allowing automated predicted insights and enhanced results. AI fundamentally encompasses several sub-disciplines, such as machine learning (ML), deep learning (DL), and neural networks, which combined enable computers to do tasks often dependent on human cognitive capabilities. Machine learning is a subclass of artificial intelligence that enables software to enhance its performance via experience and data exposure without being expressly designed for certain results (Vudugula et al., 2023).

The digital transformation driven by the growing influence of artificial intelligence (AI) has been a pivotal driver, catalyzing the next wave of business disruption in enterprises. Marketing is one of the business sectors seeing this shift on a significant scale. Modern marketing has started the integration of advanced technology, such as artificial intelligence, into mainstream operations to achieve expedited success (Chintalapati & Pandey, 2022).

AI-DRIVEN INNOVATION IN PRODUCT DEVELOPMENT

The role of AI in the evolving framework of healthcare goods and services is integral and indispensable in the present context. In healthcare, several domains, including drug discovery, personalized treatment, and real-time patient monitoring, have seen significant innovation and programming under the guidance of AI to facilitate high-quality decision-making (Kanagarajah, 2024). Innovation is crucial in the competitive realm of the information and communication technology (ICT) business, especially amid swiftly advancing technical developments (Grabocka & Ndoka, 2025).

Artificial intelligence has considerable potential for producing market-oriented concepts. For those seeking unique product thoughts, try using generative AI. With suitable directives, it can rapidly provide a list of 10 novel product ideas in almost every B2B sector. A recent ideation study using ChatGPT produced positive results: The impact of ChatGPT on the creation of novel concepts was assessed relative to conventional design approaches, including brainstorming and TRIZ. From a "novelty" perspective, ChatGPT demonstrated impressive performance, contrary to expectations (Cooper, 2024). Current product development approaches, like design thinking and lean startup, have clear limits when used for AI products: Design thinking ignores how much AI systems depend on data and processing power, while the lean startup method doesn't fully consider the long training and improvement times needed for AI models. The

discord between techniques and technical attributes intensifies the challenges in converting AI products from idea to execution (Wang et al., 2025).

Many challenges and limitations arise during group brainstorming, causing ideas to get stuck or rejected. To address complex challenges, it is also necessary to have teams with diverse skill sets that can collaborate to generate new ideas. This explains why digital technologies such as videoconferencing are employed. Also, the fake setting of online meetings could make it hard to concentrate, which might hinder ideas. Being creative is an important part of engineering design and is equally necessary in business. This shows how important it is to fix problems like how hard issues are and how to come up with new ideas together. Robotics (AI) and virtual reality (VR) have shown promise as ways to think because they are fun and can help with tough problems. While this is possible, not much study has been done on how to use VR and AI together in these situations (Grech et al., 2023).

PERSONALIZATION AND ETHICAL ISSUES IN AI-BASED MARKETING

Through machine learning and artificial intelligence (AI), digital marketing has changed because now it's possible to tailor the experience to each customer. While AI-based customization could get people more interested and dedicated, too much of it leads to privacy, bias, abuse, and social issues (Karami et al., 2024).

AI has a lot of potential to help people make choices, but it's important to be aware of the issues and problems that arise when it is used. People are worried about their privacy and the safety of their data when a lot of personal information is collected and used. Also, algorithmic bias and openness in AI decision-making are important problems that need to be fixed to make sure AI technology is used in a responsible and decent way. Even with these problems, AI has clear benefits in digital marketing automation (DMA), and companies that are good at using AI in their marketing plans will have an advantage over their competitors (Islam et al., 2024).

Also, the widespread use of AI in personalization has raised a number of important social questions. Collecting and using personal information is one of the most important issues. Concerns have been raised about the fact that AI systems, unlike improvements in human intelligence, need a lot of data from customers to come up with useful insights. Some people say that customers don't know how much information about them is being collected, which brings up ethics issues about the process of getting and giving licenses. Data secrecy is also a problem; companies need help showing why they need to collect this kind of information and why they need to keep it safe from customers (Sarioguz & Miser, 2024).

The ethical implications of the growing utilization of AI in marketing are beginning to manifest. AI is altering the ethical landscape of marketing, ranging from privacy concerns to emergent systemic social distortions and discrimination

against marginalized groups (Su et al., 2023). The increasing utilization of artificial intelligence (AI) in marketing raises several ethical concerns. When employing artificial intelligence, marketers must guarantee the secure and efficient utilization of consumer data. Additionally, they must recognize the possibility of partiality within AI, despite its purported impartiality. Engineers and marketers should implement measures to guarantee ethical behavior, including the prevention of algorithmic bias, the verification of data veracity, and the preservation of consumer privacy. Various research has demonstrated biases in facial recognition applications of artificial intelligence and machine learning (Sharma & Sharma, 2023).

CONCLUSION

The rules for marketing strategy, engagement, and innovation have changed since the digital age. As digital infrastructure changes and data becomes more important, businesses need to use integrated approaches that combine technology with strategic insight. This chapter talks about the different ways that marketing and technology are working together. For instance, they change how people use things, how things are made, and how businesses are held responsible for their actions. This shows that companies are changing to make money in places that are becoming more difficult and competitive.

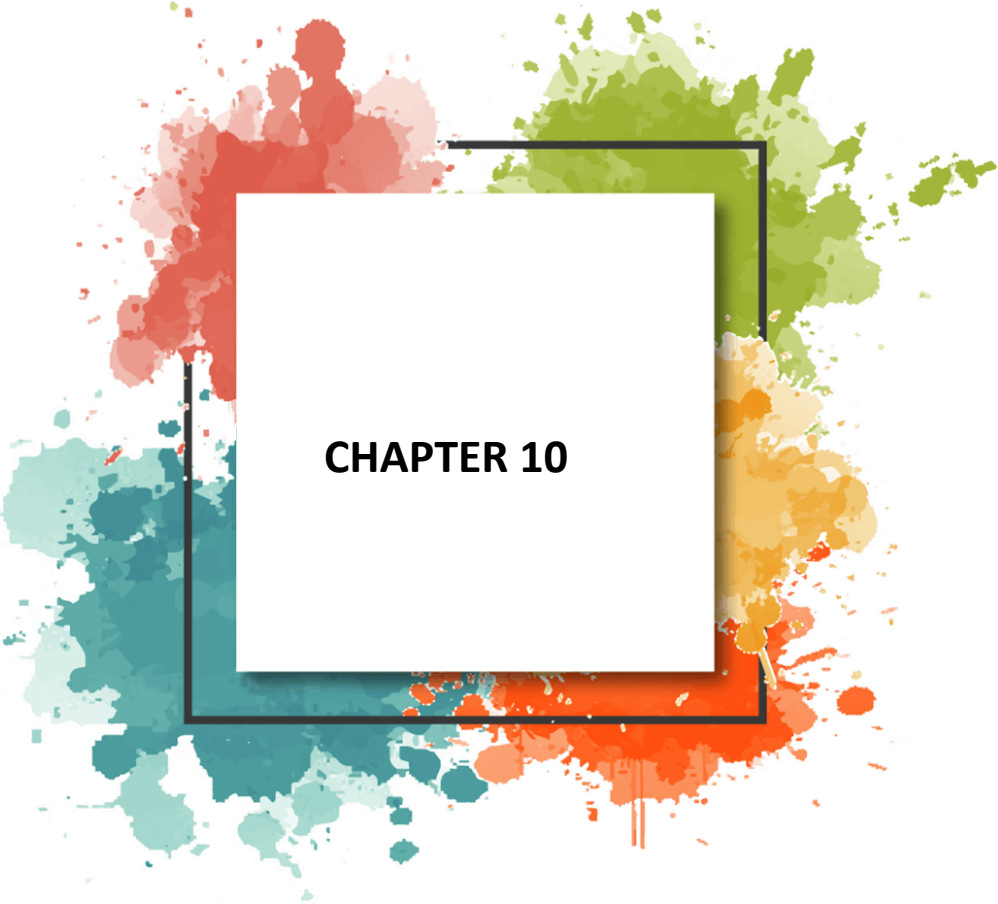
The study found that digital tools have had a big impact on marketing because they let people have unique experiences, talk to each other in real time, and make decisions based on what they think will happen. Small businesses can now run more smoothly thanks to this change. It has also helped them better meet the needs of customers and the market, whose tastes are always shifting. When companies plan their moves instead of just going with their gut, they learn more about their customers and make better choices.

Better tech support has also helped businesses make and improve products by letting them use iterative methods that consider new ideas, market trends, and customer input. You can work together digitally and make smart decisions faster and easier with these tools. They have improved the process even more. But this change won't be easy. We need to pay close attention to ethical issues, especially those related to consumer data privacy, algorithmic bias, and openness. Businesses need to follow the rules and do things in a way that builds trust. Finding a balance between personalization and privacy, as well as between automation and human oversight, is still very important. Lastly, marketing is moving into a new age with links that have never been seen before. This means that smart changes can be made and big changes can be made to the way things are done. In this area, companies that see digital change as more than just a way to make their tools better will do well. It will be a big change for these businesses in how they make money. More and more, our world is going digital. This part adds to the talk by showing how to sell things in new, honest, and long-lasting ways.

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CHAPTER 10

Fuzzy Logic Applications in Hydraulics

Ahmet Emir Köse¹ & Salim Serkan Nas²

INTRODUCTION

Water is one of the most essential natural resources for the continuity of life. Although approximately 71% of the Earth's surface is covered with water, only 2.5% of it consists of freshwater resources, and since the majority is stored in glaciers and underground aquifers, the amount available for direct use remains highly limited. Factors such as population growth, industrialization, climate change, and improper land use gradually decrease the per capita availability of water and further increase its strategic importance. In the case of Turkey, despite being surrounded by seas on three sides, the country's renewable water potential is limited. As of 2017, the per capita water availability was calculated as 1,519 m³ and it is projected to decrease to around 1,000 m³ by 2030 (Gumuscan, 2017). Therefore, Turkey is categorized among the "water-scarce countries," which necessitates the protection of existing resources and the adoption of sustainable management approaches.

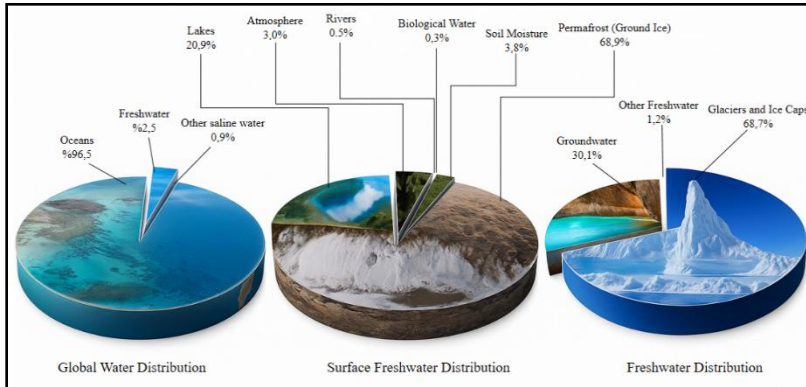


Figure 1. Global distribution of water (Atci, 2025).

Hydrological processes play a critical role in the management of water resources. Precipitation, evaporation, surface runoff and groundwater movements constitute the fundamental components of the hydrological cycle. Among these processes, surface runoff serves as a key determinant of risks such as floods and erosion, while evaporation and evapotranspiration are essential parameters in

¹ PhD. Student, Gumushane University, ORCID: 0000-0003-3890-5721

² Prof. Dr., Gumushane University, ORCID: 0000-0001-9054-4674

calculating the water balance. In particular, surface runoff increases in impermeable soils and sloping terrains, thereby heightening the risk of flooding (Ak, 2021). Similarly, evapotranspiration is one of the primary indicators in water budget calculations and the Penman-Monteith method has been accepted as the standard by the Food and Agriculture Organization of the United Nations (FAO) (Allen et al., 1998; Kaya, 2016). Therefore, the accurate estimation of these parameters is indispensable for the planning of hydraulic structures, irrigation management and flood control.

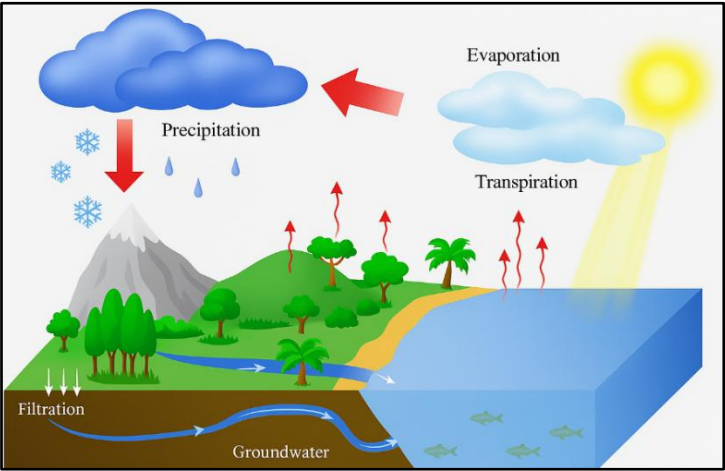


Figure 2. Hydrological cycle (Portillo, 2025).

Rivers are dynamic systems in which not only water but also solid materials are transported. The river regime is shaped by climatic factors such as precipitation, wind and frost, as well as by channel resistance and flow power (Ozbek, 1993; Baltaci, 2012). Sediment transported in rivers enters the system through basin and channel erosion, causing scouring and deposition in engineering structures such as dams and bridges. This situation poses critical risks in terms of both the safety and the economic lifespan of such structures (Tasar, 2016). Moreover, sediment transport reduces storage capacity in dam reservoirs, decreases efficiency, deteriorates water quality and generates negative impacts on the ecosystem (Dayan, 2023). Therefore, the accurate modeling of sediment dynamics is essential both for the preservation of water quality and for ensuring the safety of hydraulic structures.

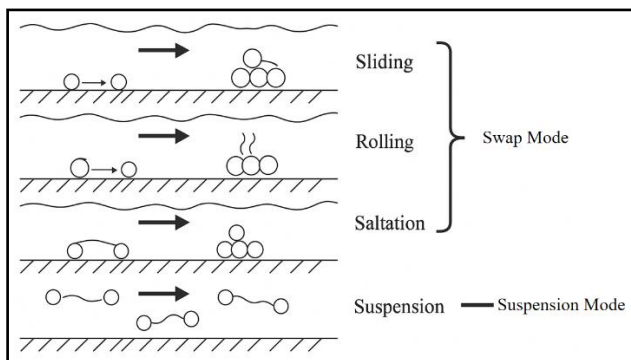


Figure 3. Sediment movements (Insapedia, 2020).

Wastewater management is also one of the important research areas of hydrology. Increasing industrialization and unconscious consumption accelerate the pollution of both surface and groundwater resources. In this context, the European Union (EU) Water Framework Directive (2000/60/EC), together with Turkey's Environmental Law and Water Pollution Control Regulation, establishes the legal framework for the protection of water resources. However, uncertainties encountered in treatment processes have brought forward the need for new methods. Artificial intelligence-based approaches, particularly Artificial Neural Networks (ANN) and the Adaptive Network-Based Fuzzy Inference System (ANFIS), make significant contributions to the prediction of water quality parameters, offering time and cost advantages compared to traditional methods (Ozen, 2018). Owing to their ability to work with incomplete and uncertain data, these methods are widely used in hydrological predictions.

Hydroelectric power plants (HEPPs) have emerged as one of the key components of renewable energy policies. Nevertheless, HEPP projects involve high risks due to geological conditions, legislative changes and environmental impacts. In Turkey, the majority of lawsuits filed against run-of-river HEPP projects have resulted in suspension orders, thereby highlighting shortcomings regarding environmental sustainability (Caylidemirci, 2010; Kutlu, 2012). This situation demonstrates that HEPP projects require comprehensive risk analyses encompassing not only technical but also legal and ecological dimensions (Kucukali, 2011).

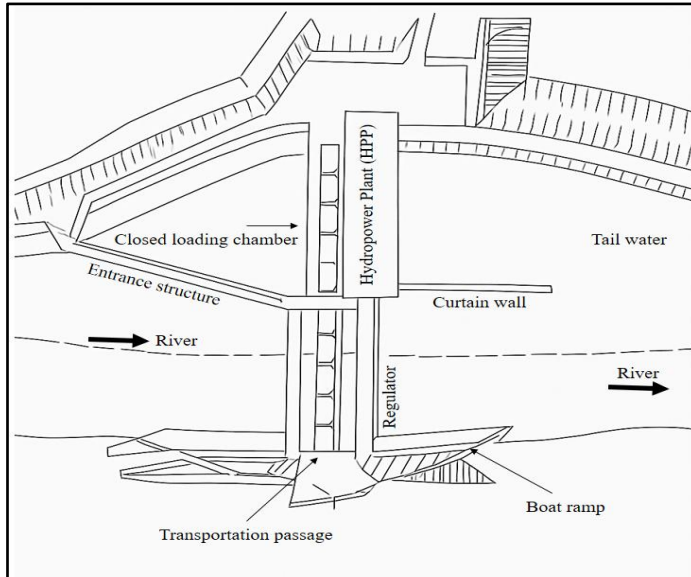


Figure 4. Project components of a run of river hydroelectric power plant (Eroglu, 2011).

The nonlinear nature of hydrological processes often renders classical methods inadequate. In particular, artificial intelligence-based methods stand out in modeling complex processes such as rainfall-runoff relationships, sediment transport and evaporation. Since its development by Zadeh (1965), Fuzzy Logic (FL) has been widely applied in hydrology, providing the ability to learn from past observations without requiring direct knowledge of the basin's physical parameters. The FL approach offers a strong alternative in critical areas such as flood forecasting, streamflow prediction and sediment transport modeling (Sen, 2004; Firat, 2007). In addition, Support Vector Machines (SVM), Multiple Linear Regression (MLR) and other machine learning methods are effectively employed in reservoir management (Arslan, 2020). These advancements signify a transition in hydrology from classical deterministic approaches to more flexible methodologies capable of handling uncertainty.

In conclusion, hydrology and hydraulic engineering stand at the core of social and environmental sustainability, encompassing a wide range of issues from the physical movement of water to pollution control, from energy production to flood management. The increasing global demand for water, along with climate change and environmental challenges, necessitates the effective and sustainable management of water resources. Within this framework, artificial intelligence-based methods and particularly the fuzzy logic approach, emerge as some of the most innovative tools of our time for modeling hydrological processes characterized by uncertainty.

Classical Logic

Classical logic, grounded in Aristotle's systematic approach based on propositions and syllogisms, has been the discipline that established the rules of correct reasoning. Built upon the principles of a binary value structure (true-false), the law of non-contradiction and the law of the excluded middle, it played a decisive role in the formation of the scientific method. However, it remained limited in explaining abstract and complex ideas. From the 17th century onward, thinkers such as Descartes and Leibniz questioned the classical framework by integrating mathematical methods into logic. In the 19th century, with the works of Frege and Russell, symbolic logic developed, overcoming the shortcomings of classical logic and opening new horizons in both philosophical and scientific fields (Elci, 2024).

In conclusion, classical logic represents a fundamental milestone in the history of thought, laying the groundwork for the development of subsequent logical systems.

Fuzzy Logic

While the complex and uncertain nature of natural phenomena cannot be adequately modeled through classical methods, artificial intelligence-based approaches-particularly fuzzy logic-offer a significant alternative in this field. Developed by Zadeh (1965), fuzzy logic was initially criticized; however, it gained acceptance with the applications of Mamdani and Assilian (1975), and successfully modeled uncertainty by going beyond the binary value framework of classical logic. Whereas classical logic relies on absolute truths, fuzzy logic takes intermediate values into account, thus producing results that are closer to reality. In this respect, it has found widespread application in engineering and technical fields today (Sen, 1999; Kisi, 2003; Baltaci, 2012).

Differences Between Classical Logic and Fuzzy Logic

Classical logic restricts truth values to only two options: true or false. In contrast, fuzzy logic models uncertainty and partial truths by incorporating intermediate values. This allows complex real-world phenomena to be analyzed in a more flexible and realistic manner (Baltaci, 2012).

Classical Logic	Fuzzy Logic
A <u>or</u> not A	A <u>and</u> not A
Absolute	Partial
All or none	Certain degrees
0 or 1	Continuity between 0 and 1
Binary units	Fuzzy units

Table 1. Differences between classical logic and fuzzy logic (Baltaci, 2012)

Classical and Fuzzy Sets

The concept of a set has long been used, often unconsciously, as a tool for classification since the earliest ages of humanity. In classical set theory, membership is absolute; an element either belongs to a set or it does not and this situation is expressed with values of 1 or 0. In contrast, fuzzy set theory treats membership as a matter of degree; an element can be considered as partially belonging and partially not belonging to a set. In this way, fuzzy sets better reflect uncertainties and intermediate situations encountered in real life (Firat, 2007; Baltaci, 2012; Arslan, 2020).

The membership functions of classical and fuzzy sets are presented in Equations (1) and (2).

$$\forall x \in X, \chi_A(X) = \begin{cases} 1, x \in A \\ 0, x \notin A \end{cases} \quad (1)$$

If a particular element belongs to set A, the value of the membership function is defined as 1; if it does not, the value is 0. In classical set theory, the membership of an element in a set is determined with absolute and precise boundaries (Klir and Juan, 1996).

In the fuzzy set approach, however, the membership of elements in the universal set is not sharp but occurs in a graded manner. This necessitates the definition of a function that determines membership degrees. The membership function maps elements to real numbers within a certain interval, thereby measuring uncertainty and revealing different levels of membership. The resulting structure is referred to as a “fuzzy set” (Bagci, 2018).

A fuzzy set A is expressed through the following equation. Assuming that set A is a non-empty set, the fuzzy set A defined on set X can be written as shown in Equation (2) (Zadeh, 1971).

$$\forall x \in X \Rightarrow \mu_A(x): X \rightarrow [0,1]; X = \text{Universal set}; A \subset X \quad (2)$$

In fuzzy set theory, the function $\mu_A(x)$ is defined as the membership function, which indicates the degree to which an element possesses the desired characteristics of set A (Zadeh, 1971). According to this theory, the membership of each element in a set is expressed in a graded manner within the interval [0,1]. Thus, an element may be considered as partially belonging or partially not belonging to a set. Furthermore, the same element can belong to multiple sets with different degrees of membership, thereby distinguishing fuzzy set theory from the “all-or-nothing” perspective of classical set theory (Senturk, 2006).

RESEARCH AND FINDINGS

Hydraulics and Fuzzy Logic

The sustainable management of water resources has become increasingly critical today due to factors such as population growth, industrialization and climate change (Korlu, 2019; Danacioglu and Oz, 2025). Accurate prediction of river flows, dam water levels, evaporation rates, and flood risks is of great importance for dam safety, hydroelectric power generation, irrigation, flood control and environmental planning (Onur et al., 2016; Arslan, 2020; Erdebilli and Gur, 2020). In this context, recent studies have shifted toward artificial intelligence-based methods such as Fuzzy Logic (FL), Adaptive Neuro-Fuzzy Inference System (ANFIS), Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Multiple Linear Regression (MLR), in order to overcome the limitations of traditional statistical methods (Baltaci, 2012; Tasar, 2016; Ak, 2021). Conducted across different dam and river basins, these studies have provided reliable and practical solutions for future-oriented water resource planning and risk reduction, thanks to their greater capacity to manage uncertainties (Gumuscan, 2017; Ozen, 2018; Dayan, 2023).

Kisi et al. (2003) aimed to accurately estimate the amount of suspended sediment in rivers. For this purpose, FL-based models were developed as an alternative to the limitations of traditional Sediment Rating Curves (SRC) and were applied to daily discharge and suspended sediment data obtained from United States Geological Survey (USGS) stations. The comparisons revealed that FL models achieved higher accuracy in predictions and provided a more effective approach compared to conventional methods.

Kurt and Aslan (2012) conducted a study aiming to investigate the electricity generation potential of the Kayabogazi Dam in the Tavsanlı district of Kutahya. As a method, historical water data provided by the State Hydraulic Works (SHW) were considered, and in order to adapt to seasonal variations, three Francis

turbines of different capacities were proposed. The operation of these turbines was carried out using FL and Programmable Logic Controllers (PLC). The results demonstrated that the system, which can be operated remotely and without human intervention, could contribute to the national economy by enabling the dam to serve not only for irrigation but also as a reliable renewable energy source.

Onur et al. (2016) conducted a study with the aim of predicting future water levels in the Terkos Dam to ensure effective management of Istanbul's water resources in the face of increasing drought threats. Using water data from the past 12 years, an ANFIS-based modeling mechanism was developed. The results showed that the ANFIS approach could reliably predict future water levels in the dam reservoir, thereby contributing to planned and precautionary management of water resources.

Kucukerdem et al. (2019) carried out a study aiming to forecast monthly storage volumes of the Sandikli Kestel Dam to enhance the effective planning of diminishing water resources. For this purpose, data from the period 1986–2008 were utilized, with input variables including storage volumes from previous months, inflow-outflow amounts, and evaporation values. The ANFIS model was applied across different cluster numbers determined by the K-means method. The results revealed that ANFIS models based on appropriate cluster numbers produced lower error rates compared to models developed through random clustering, thus providing more reliable outcomes for the future planning of water resources.

Erdebilli and Gur (2020) conducted a study aiming to assess the risks faced by dams as critical infrastructures. In the case of a dam located in Eastern Anatolia, evaluations were carried out with a security manager, a protection unit commander, and an engineer, resulting in the identification of eight potential threats: cyber-attack, terrorism, sabotage, fire, power outage, flood, earthquake, and landslide. The risks were analyzed in terms of probability, frequency, and severity, and risk scores were calculated and compared using the Fine-Kinney and Fuzzy Fine-Kinney methods. The results showed that the Fuzzy Fine-Kinney method, which reflects uncertainties more precisely, was more reliable, and that terrorist attacks, earthquakes and landslides were identified as the most critical risks for the dam.

Danacioglu and Oz (2025) carried out a study to identify potential flood-prone areas in the Tahtali Dam Basin in Izmir in order to evaluate the increasing flood risks associated with global climate change. As a method, Geographic Information Systems (GIS), which enables integrated analysis of spatial data, was combined with the FL approach, an effective tool in managing uncertainties. The analyses revealed that areas near the dam were at high risk of floods and that the FL method provided reliable results in predicting flood risks.

Ak (2021) conducted a study aiming to enhance the accuracy of river flow predictions and thereby contribute to water resource management and flood risk prevention. Using 1,095 daily records of precipitation, flow and temperature data from the Stillwater River in Worcester, USA, the performance of SVM, Sugeno and Mamdani FL models and MLR methods was compared. The results indicated that AI-based methods-particularly SVM and FL models-provided higher accuracy and more reliable results for flow prediction compared to classical MLR.

Baltaci (2012) conducted a study with the aim of accurately predicting sediment amounts in rivers, thereby contributing to the design of hydraulic structures and the determination of their economic lifespan. As a method, 50 years of daily discharge, suspended sediment concentration and temperature data from the Freeport station on the Sacramento River in California, USA, were analyzed by comparing FL, Sediment Rating Curves (SRC) and MLR methods. The evaluation based on correlation coefficients and error metrics showed that FL provided higher accuracy than the other methods, offering a particularly reliable approach for long-term predictions.

Tasar (2016) conducted a study aiming to accurately predict suspended sediment amounts in rivers in order to reduce the problems encountered in the design and operation of hydraulic structures. As a method, daily discharge and temperature data from the Augusta station on the Skunk River in the United States were used and FL, SRC and MLR approaches were applied. Their performances were compared based on mean squared error (MSE), mean absolute error (MAE) and correlation coefficient criteria. The results revealed that the FL approach provided higher accuracy than the other statistical methods and was identified as the most suitable method for suspended sediment prediction.

Ozen (2018) carried out a study with the aim of developing AI-based prediction methods as an alternative to the difficult and costly measurement processes of Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD), which are critical parameters in wastewater treatment plants. As a method, daily data from the Kayseri Advanced Biological Wastewater Treatment Plant for the years 2011-2014 were used and COD and BOD values were modeled with ANFIS and ANN using different combinations of independent variables. The analyses showed that ANN and ANFIS demonstrated similar accuracy in predicting BOD, while ANN performed slightly better in predicting COD. In the second phase of the study, two mathematical models were developed with the help of Excel Solver, considering the strong correlations between BOD-COD-TSS variables. The comparisons indicated that Model 1 provided more applicable and reliable results.

Arslan (2020) conducted a study to forecast the future water levels of the Keban Dam in response to the increasing demand for water, thereby enabling more effective management of the dam. As a method, daily water level measurements from 2013-2014, along with data on energy consumption, water use and evaporation, were used. FL, SVM and MLR models were applied and their performances were evaluated using RMSE, MAE and R^2 criteria. The results revealed that FL and SVM methods were successful in predicting reservoir water levels and provided more reliable results compared to traditional MLR.

Kaya (2016) carried out a study aiming to estimate evaporation, one of the fundamental components of the hydrological cycle. For this purpose, 2,287 daily records from the De Soto County station in Florida USA, were used. Modeling was performed using ANFIS and MLR methods, while empirical equations such as Ritchie, Hargreaves-Samani, Penman-Monteith, and Turc were also tested. Performance evaluation was conducted using the coefficient of determination (R^2), mean absolute error (MAE) and mean squared error (MSE). The results showed that the ANFIS model established with the combination including all parameters-solar radiation (SR), temperature (T), relative humidity (RH) and wind speed (U) achieved higher accuracy compared to both MLR and the empirical equations.

Firat (2007) conducted a study aiming to contribute to water resources management and environmental planning by accurately predicting river flow and transported sediment amounts. As a method, data from four tributaries of the Buyuk Menderes Basin in western Turkey were used. Models with different input structures were developed using ANFIS and training/test datasets were arranged through the cross-validation method. Performance evaluations were carried out using various criteria and the results were compared with ANN. The findings demonstrated that ANFIS is a reliable, precise and applicable method for predicting flow and sediment amounts.

Gumuscan (2017) carried out a study with the aim of contributing to dam management, hydroelectric power generation, flood control and water quality management by accurately forecasting changes in dam reservoir volume. As a method, approximately 12 years of daily data from the Yarseli Dam were utilized. In the first stage, MLR and FL methods were compared for reservoir volume prediction and in the second stage, autoregressive (AR) and FL models based on time series were applied. The results indicated that FL provided higher accuracy than MLR, while AR and FL models produced similar outcomes. However, FL was determined to be the most successful method due to its lower error values and higher correlation coefficient.

Dayan (2023) conducted a study aiming to contribute to pollution control, dam life assessment and river transportation planning by accurately predicting

sediment amounts in rivers. As a method, discharge, turbidity and sediment data measured between 2015 and 2018 from the Patapsco River in the United States were used. Comparative analysis was conducted by applying MLR, ANFIS, FL-SMRGT and SRC methods. The results showed that FL-based models exhibited higher consistency with observational data and stood out as the most reliable methods for sediment prediction.

Yumuk (2011) conducted a study with the aim of accurately predicting longshore sediment transport, which is of critical importance in coastal engineering. As a method, Fuzzy Inference System (FIS) and ANFIS models were developed using the fuzzy logic approach. These models were calibrated with the measurement data of Kamphuis (1991) and their performances were compared. The results revealed that the ANFIS-based model achieved the lowest error value (RMSE = 0.0058) and the highest correlation coefficient ($R = 0.98$), thereby proving to be the most reliable prediction method for longshore sediment transport. Furthermore, the developed model was applied to the Karaburun coastal area to calculate net and total sediment transport amounts and the coastal classification of the region was conducted.

Kutlu (2012) conducted a study aiming to evaluate the risks encountered in run of river HEPP projects in a flexible and reliable manner. As a method, a multi-criteria risk assessment model based on FL principles was developed, in which expert judgments were used instead of probability calculations and risk factors were determined through field studies, literature reviews and expert surveys. From the data obtained within the model, a Risk Index (R) was created to classify risks as low, medium, high and very high. Applied to a real HEPP project, the method was presented as an effective tool that can help prevent project failures by providing investors and experts with more rational grounds for decision-making.

Esendal (2007) carried out a study aiming to model the changes observed in lake levels under the influence of climatic and environmental factors. As a method, a FL-based model was developed using data on precipitation, inflow, evaporation and irrigation water demand from the case of Lake Egirdir and seasonal lake level variations were predicted. The results showed that the FL approach offered an effective method for working with hydrological data containing uncertainties and provided reliable results in predicting the water level of Lake Egirdir.

Bizimana (2016) conducted a study aiming to identify flood risk zones in the city of Waverly, located along the Cedar River in Iowa, USA in order to mitigate the adverse impacts of floods. As a method, FL and Geographic Information Systems (GIS) were used in combination; parameters such as elevation, distance to the river, land use and population density were modeled with different

weighting combinations and compared with 100-500-year flood maps prepared by the Federal Emergency Management Agency (FEMA). The results revealed that the FL-based model produced more realistic results compared to the GIS weighting function, identified that approximately 39% of the total study area was under high flood risk and demonstrated that this method can be reliably used in flood risk assessment.

Korlu (2019) conducted a study aiming to accurately forecast groundwater levels in order to contribute to sustainable water management in arid and semi-arid regions. As a method, groundwater measurements from the Reyhanli region of Hatay for the period 2000-2015, along with monthly precipitation and temperature data, were used to compare the performances of MLR, ANFIS and Support Vector Machines (SVM) with Radial Basis Function (RBF) and Polynomial Kernel (PK) versions. The results showed that the SVM models provided higher accuracy than the other methods and were identified as the most suitable approach for groundwater level prediction.

CONCLUSION AND RECOMMENDATIONS

This study has comprehensively demonstrated the applicability of fuzzy logic methods for effectively managing uncertainties in the field of hydraulics. Considering that hydrological processes are inherently complex, nonlinear and shaped by multiple variables, it is evident that classical statistical methods often remain inadequate. In critical areas such as flood risk prediction, the assessment of water quality indicators, evaporation and flow forecasting, the flexibility and adaptability offered by fuzzy logic-based approaches stand out. The findings of this study indicate that fuzzy logic yields lower error rates and higher accuracy values compared to traditional regression models. This result clearly reveals that AI-based methods provide a strategic advantage in decision-support processes within hydraulics.

Another significant finding of this study is that fuzzy logic is not limited to modeling based solely on past data but also has the capacity to effectively incorporate expert judgments. This feature makes it a strong alternative, particularly in long-term predictions and in regions where data availability is limited. Furthermore, its integration with GIS enhances the practical utility of the model by enabling a more realistic identification of flood-prone areas.

In conclusion, the applicability of fuzzy logic approaches in hydraulics has been strongly proven both theoretically and practically. However, to ensure more effective use of the method, further applications under different climatic conditions and geographical regions are required. In addition, the development of hybrid models that combine fuzzy logic with other AI-based methods such as artificial neural networks, support vector machines and genetic algorithms is

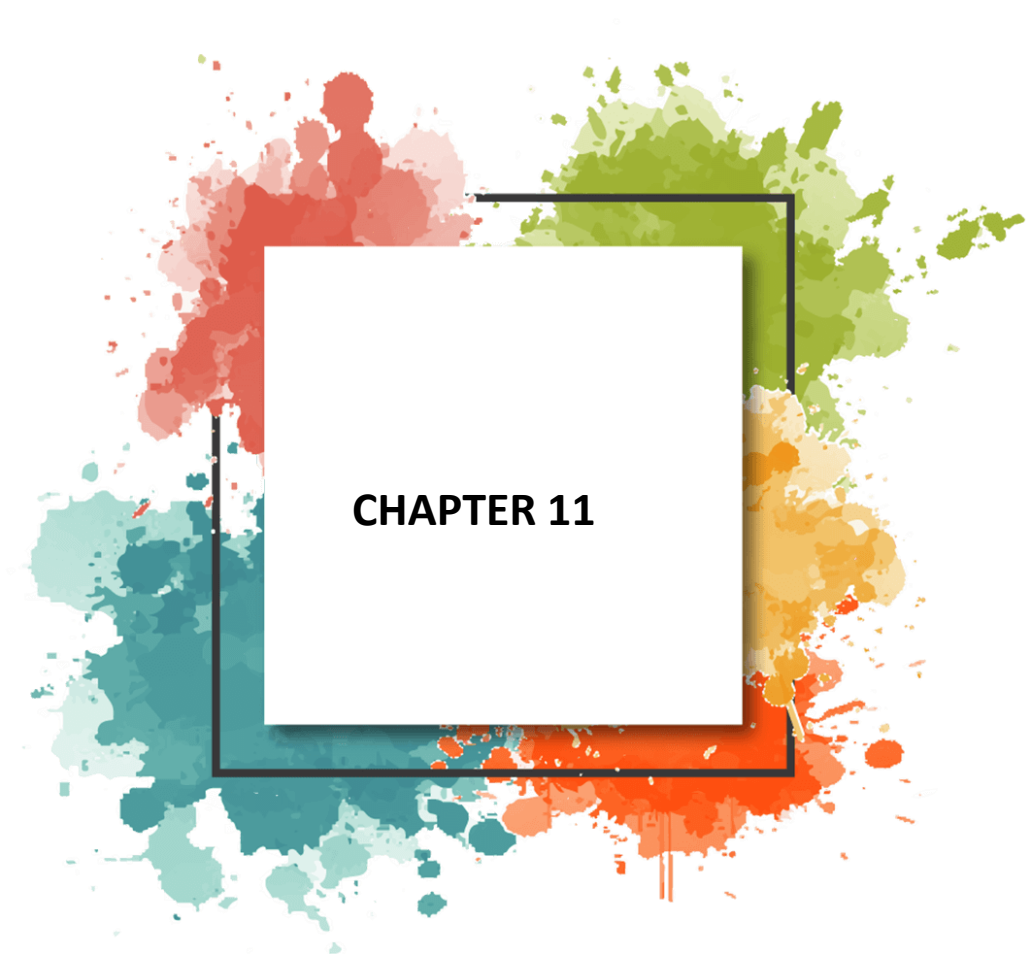
expected to enhance prediction accuracy and decision-support capacity. In this context, future studies are anticipated to facilitate the broader and more effective use of fuzzy logic in water resource management through an interdisciplinary approach.

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CHAPTER 11

Jib Crane Design

With 40 WHEELS and 32m/min TRAVEL SPEED

Serap Özhan Doğan¹ & Hakan Avcı²

1. INTRODUCTION

For centuries, human beings have used machines for tasks requiring great power. These tools, which are as old as human history, have evolved since the simplest example, the lever. They have undergone great changes with the advancement of technology. To meet the increasing demand capable of carrying more loads day by day and providing the highest level of safety while doing so. Developing machines that can provide this has become a necessity rather than a need. Industrial developments that triggered the development of lifting and carrying machines. As time goes by, it becomes important to carry larger loads in a shorter time and with less energy [1].

Industrial transportation activities are generally the transportation of any material, goods or it can be defined as the transportation of the product from one place to another. Transport in operations, the load in question can also be human when necessary. These functions "lifting and carrying machines" or "transport machines" it is called [2].

For example, they are machines used in and among goods or loads without being operated continuously during a working day. In other words, they are also called "lifting machines". After the lifting and carrying process of these machines is completed, they stop and do not work until the next process is repeated [3].

Lifting machines can be grouped under six groups as jacks, hoists, cranes, cranes, elevators and stacking machines. A large part of lifting machines consists of ceilings and cranes. Similar structural elements are used in these lifting machines. In fact, in daily conversations, crane and crane are used in the same way with the wrong meaning. It is useful to state the difference between the technical work of these current machine and crane words. Cranes are simple lifting machines that only lift loads or go in one direction. Cranes, on the other hand, are lifting machines that have flooring equipment on them and also have

¹ Mechanical Engineering Department, İstanbul Beykent University,
Orcid: 0000-0001-5210-1549

² R&D Engineer, Tersan Shipyard, Orcid: 0009-0009-2419-0826

mechanisms to make translation and rotation movements and can carry loads in any desired direction.

This study is carried out as a review of jib cranes, portal cranes and rotary-swing cranes.

1.1 Jib Cranes

Jib cranes are the main cranes used during the lifting and transportation of loads in shipyards, ports, warehouses, and offshore oil platforms. Jib cranes are one of the crane types that move on rail systems and work within a certain area and can be considered as a combination of swivel cranes and portal cranes [4]. The lower part of jib cranes can be considered as the portal part that moves on rail systems and contains the crane driving system, and the upper part can be considered as the swivel part that enables the lifting and transportation of loads with the boom (arrow) articulated to the rotating platform with a perno that can rotate 360° around the cylindrical body connected to the portal part. Jib cranes consist of equipment such as wheels, bogie group, balance beam, portal legs, portal upper beam, rotating platform, boom (arrow), counterweight, lattice beams articulated to the rotating platform, vento and load ropes and drums, crane operator room, pulleys.

1.2. Working Load

The safe working load of a crane is the maximum weight that a crane can safely carry at the time it is designed or manufactured. This weight limit is designed to ensure safe operation of the crane and prevent accidents caused by overloaded operation. This is determined so that various variables and breaks can be recorded to ensure that the crane can maintain its stability and flexibility during operation.

Safe Working Load (SWL), sometimes presented as Normal Working Load (NWL), is the maximum safe force that can be applied by a stopping stress, lifting device, or jumper when lifting, suspending, or lowering a given mass.

It is the result of dividing the Minimum Breaking Strength (MBS), also known as the Minimum Breaking Load (MBL), by a safety factor, usually between 4 and 6 for lifting equipment. The safety factor can be as high as 10:1 or 10:1 if the equipment poses a threat to human life.

Working Load Limit (WLL) is the maximum working load designed by the manufacturer. The force represented by this load is much less than the force that would cause the lifting equipment to fail or fail. WLL is calculated by dividing the MBL by the Factor of Safety (SF).

1.3. Factors affecting safe working load

Factors affecting the safe working load must be taken into account a number of factors, including the following.

Structural Strength of the Crane

The crane's boom, support legs, hooks, wire ropes, etc. Major components such as should be strong enough to maintain structural integrity under load.

Balance

The crane must remain stable to prevent tipping when lifting loads. Safe working loads take into account the design and construction of the crane to ensure stability under load.

Environmental factors

The environment in which the crane operates, such as wind speed and ground conditions, can affect its safety. Safe Working Load takes these factors into account to ensure safe operation in a variety of environmental conditions.

Working mode and angle

The crane's working mode (e.g. vertical lifting, horizontal movement, etc.) and the angle of the load also affect the calculation of the occupational safety load.

Additional loads

Occupational safety loads are usually wind loads, weight of the spreader, etc. It takes into account possible additional loads such as Occupational safety loads are calculated according to the following factors.

Manufacturer data and standards

The crane manufacturer usually provides information on occupational safety loads according to relevant standards and regulations. This data should be used as an important reference for calculations.

2. THEORETICAL CALCULATIONS FOR DESIGN

2.1. Applied Loads

As mentioned above, there are many factors to consider when designing a crane. May result in large losses after production all these factors must be taken into account at the design stage to prevent accidents. This study paper, for optimum results in crane design calculations that require many repetitions are made. These calculations were made with the finite element method. Thus, time was saved in the design process.

The main features of the Jib Crane are shared in Table 1 below.

Table 1. Main parameters of jib crane design

SWL load (including cleat and ropes)	45 tons
Boom length	46 meters
Foot opening distance	11 meters
Crane walking speed	32 m / min.
Total number of wheels	40
Wheel group distance	12 meters
Wheel diameter	560 mm

The technical drawing of the jib crane design is shared below in Figure 1.

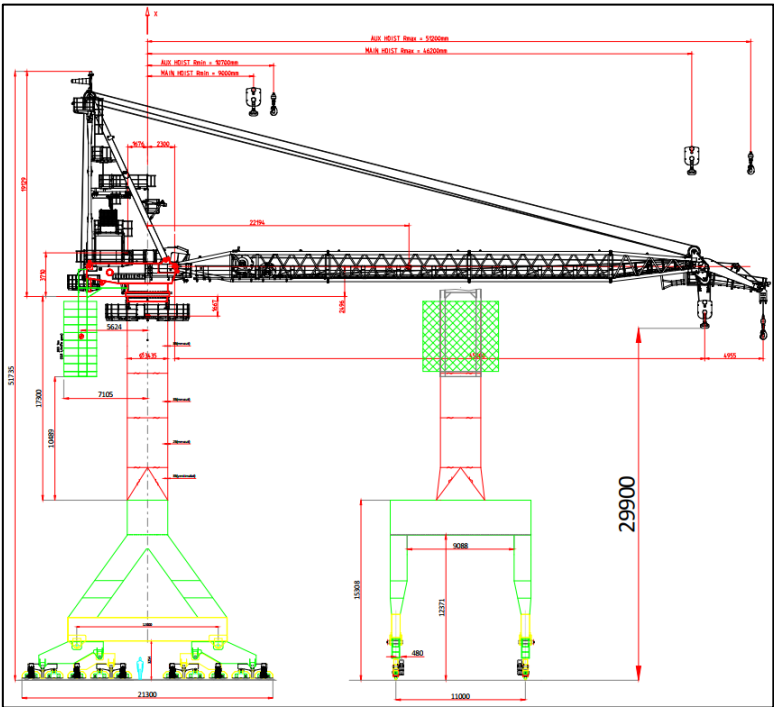


Figure 1. Technical drawing of jib crane design

Within the scope of the study, load calculations were made for 3 different loading conditions. This difference is calculated by giving three different angles to the booms.

The loads given within the conditions were taken into account by taking 1.5 times in the analysis. The maximum stress was taken as 175N/mm².

First Loading Condition

In the first loading condition, the angle between the boom and the body is determined as 90 degrees. According to the calculations,

$F_y(\text{Lateral load}) = 90 \text{ t} + F_r$ (Wind load, 15 knot according to max. wind speed) = 2 t = 92 t

$F_w(\text{Boom} + \text{balance weight} + \text{top section} + \text{engine room} + \text{Swl}) = 500 \text{ t}$

$F_f = 100 \text{ t}$

$M_y = 1943 \text{ t.m}$

It is found as. The loading situation according to the 90 degree boom angle is shared below in Figure2.

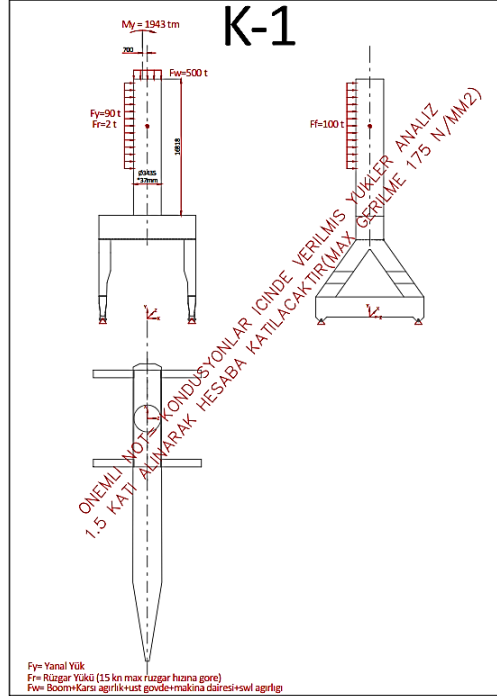


Figure 2. First loading condition

Second Loading Condition

In the second loading condition, the angle between the boom and the body is 0 degrees and in the calculations made;

$F_y(\text{Lateral load}) = 90 \text{ t} + F_r$ (Wind load, 15 knot according to max. wind speed) = 2 t = 92 t

$F_w(\text{Boom} + \text{balance weight} + \text{top section} + \text{engine room} + \text{Swl}) = 500 \text{ t}$

$F_f = 100 \text{ t}$

$M_y = 1943 \text{ t.m}$

It is found as. The loading situation according to the 0 degree boom angle is shared below in Figure 3.

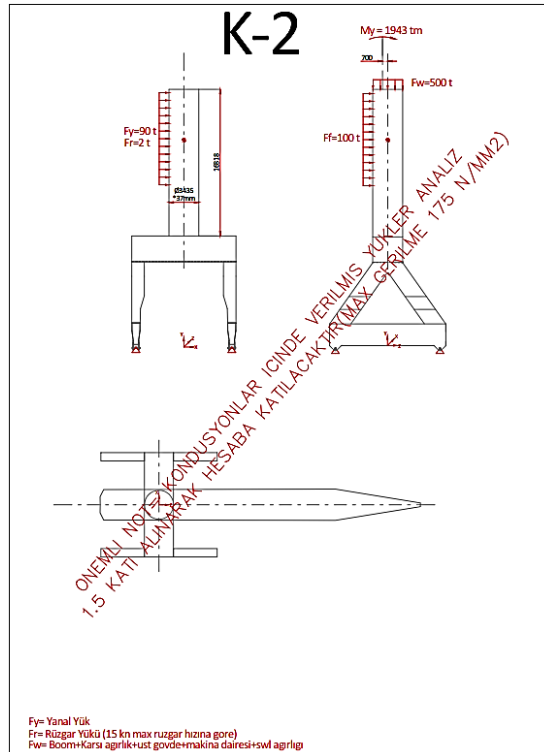


Figure 3. Second loading condition

Third Loading Condition

In the third loading condition, the angle between the boom and the body is 0 degrees and in the calculations made;

$$F_y(\text{Lateral load}) = 90 \text{ t} + F_r (\text{Wind load, 15 knot according to max. wind speed}) = 2 \text{ t} = 92 \text{ t}$$

$$F_w(\text{Boom} + \text{balance weight} + \text{top section} + \text{engine room} + \text{Swl}) = 500 \text{ t}$$

$$F_f = 100 \text{ t}$$

$$M_y = 1943 \text{ t.m}$$

It is found as. The loading situation according to the 0 degree boom angle is shared below in Figure 4.

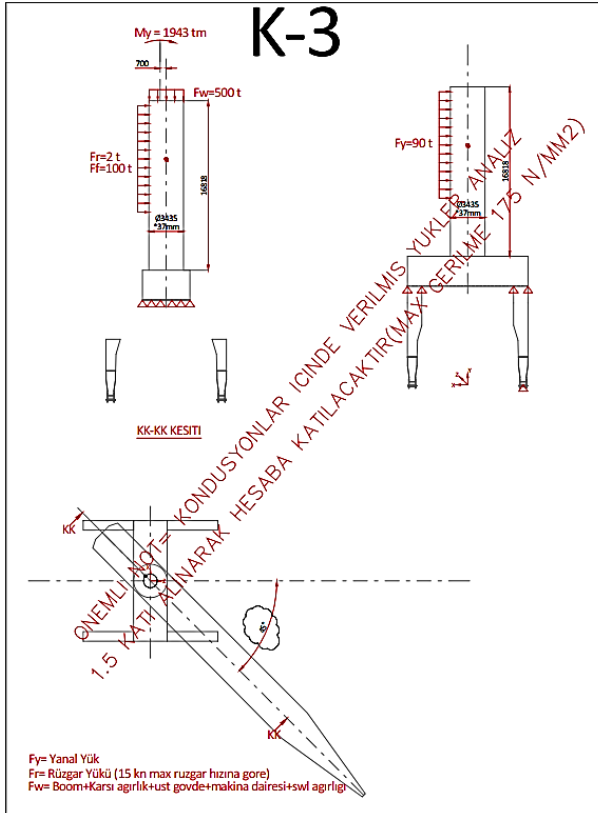


Figure 4. Third loading condition

3. DESIGN OPTIMIZATION AND RESULTS

Optimization is a concept used to optimize a system or process. In general, it ensures the most effective and efficient use of resources [5]. The purpose of the optimization in this study is to obtain a safe structure using the minimum amount of steel. In this context, analysis studies were started after the first model was created. Many analysis studies were carried out and the model was revised many times along with these analysis studies.

In Figure 5 below, the designs showing the initial and final model weight distributions are shared with their weights.

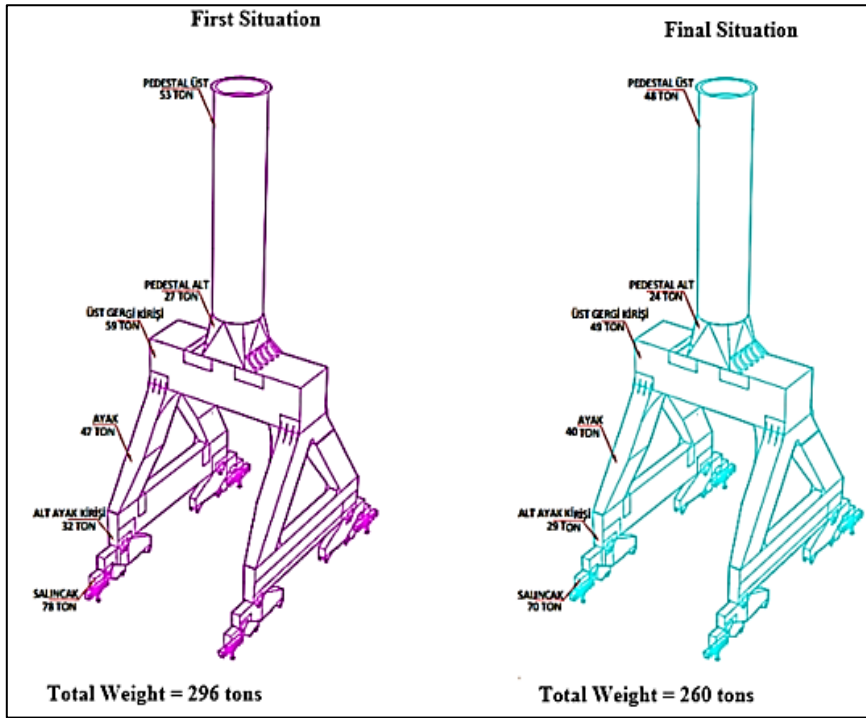


Figure 5. First and final model weight distribution

3.1. Structural Analysis

The basic idea of the finite element method (FEM) is to solve a complex problem by replacing it with an equivalent but simpler problem. The Finite Element Method allows simple solution and analysis of models with complex geometry by separating them into much smaller finite elements and defining boundary conditions. [6].

The static structural analysis for the jib crane designed with Rhinoceros was performed using MSC APEX Workbench to determine the displacements in our structure, stresses due to gravity and external loading. It should be noted that this process is an iterative process. In other words, the jib crane design was changed many times to meet the applied force requirements and the analysis was repeated until the applied forces were met. As the first stage of the analysis, the selected material, Grade A structural steel, was defined for the designed structure in the program. The next step is the mesh creation process. The geometry needs to be extracted to solve the mathematical model. The mesh creation tool divides the geometry into finite elements. The nodes in the structure are connected with lines to create a mesh structure of the complex geometry. In the next stage, the points where the structure will be fixed, the forces to be applied and the direction of the forces were selected and the analysis is run.

Table 2 below shows the mechanical properties of the material selected for the structure designed within the scope of the study.

Table 2. Mechanical properties of the material selected for the structure

Material used	A Grade structural steel
Density	7.8E-09 (<i>Mg/mm³</i>)
Poisson ratio	0.3
Tensile yield strength	241.68 (<i>MPa</i>)
Elastic modulus	200000 (<i>MPa</i>)

In this study, the forces in section-2 is applied to the designed structure with three different loading conditions and as a result, the maximum Von Mises Stress value and the maximum displacement value are reached [7]. As mentioned above, in order for the structure to be considered safe; 1.5 times the loads are taken into account in the analysis and the maximum stress is requested not to exceed 175 N/mm².

First Analysis Study

It is fixed in x, y and z directions and the forces of $F_x = 1.50E+006N$, $F_y = -1.38E+006N$, $F_z = -7.50E+006N$ and $M_x = 2.91E+010Nmm$ are applied to the structure, which is also included in gravity. The displacements and stresses in our structure are seen in Figure 6.

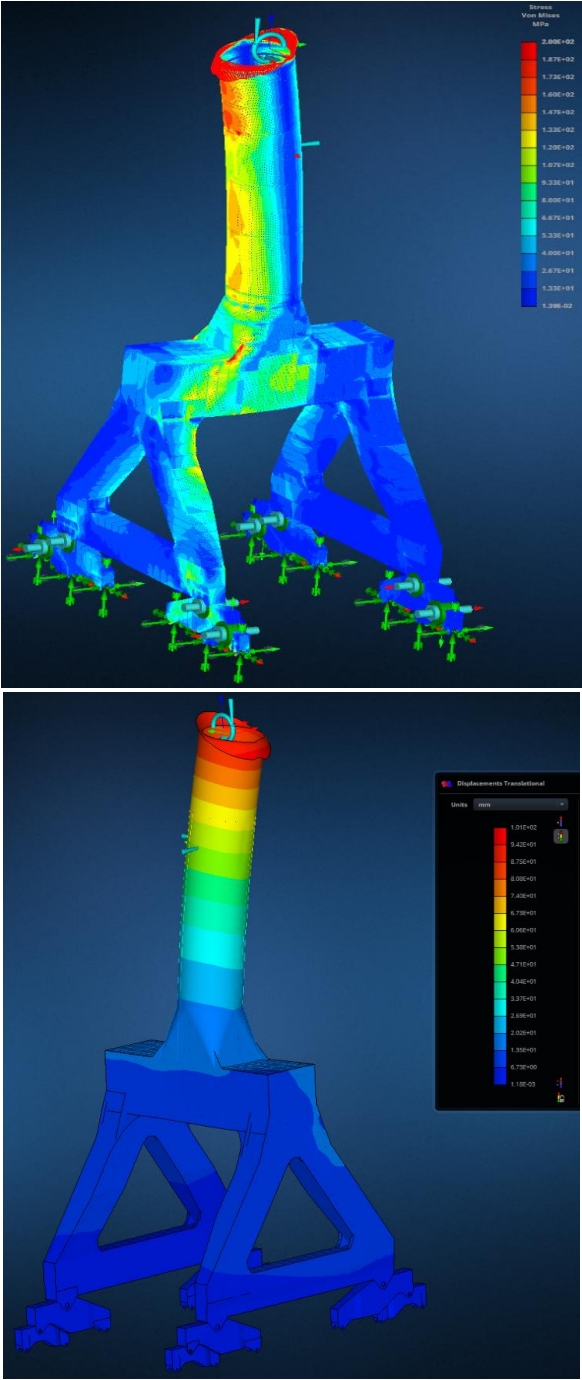


Figure 6. Displacement and stress conditions in the first analysis

Second Analysis Study

It is fixed in x, y and z directions and the forces of $F_x=1.50E+006N$, $F_y= -1.38E+006N$, $F_z= -7.50E+006N$ and $M_x= 2.91E+010Nmm$ are applied. The structure displacements and stresses are seen in Figure 7.

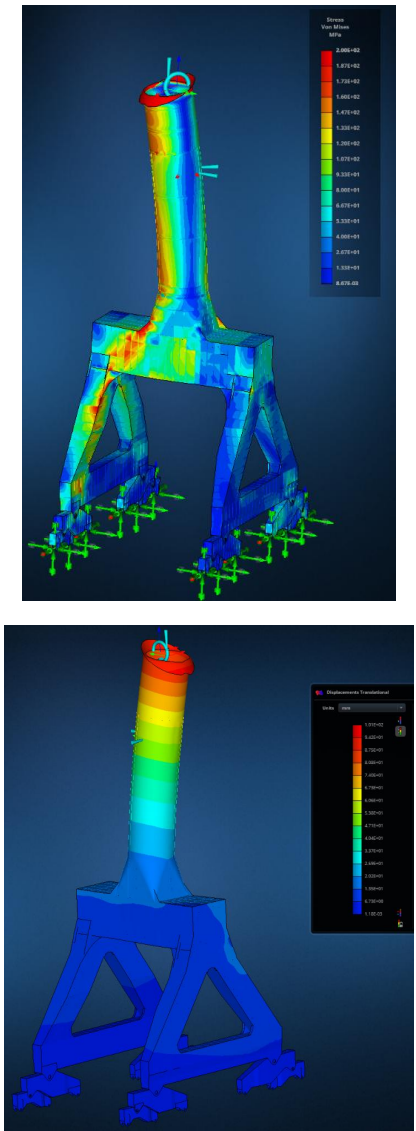


Figure 7. Displacement and stress conditions in the second analysis

Third Analysis Study

It is fixed in x, y and z directions and the forces of $F_x = -1.35E+006N$, $F_y = -1.35E+006N$, at a 45° angle $F_z = -7.50E+006N$ and $M_x = 2.91E+010Nmm$ are applied. The structure displacements and stresses are seen in Figure 8.

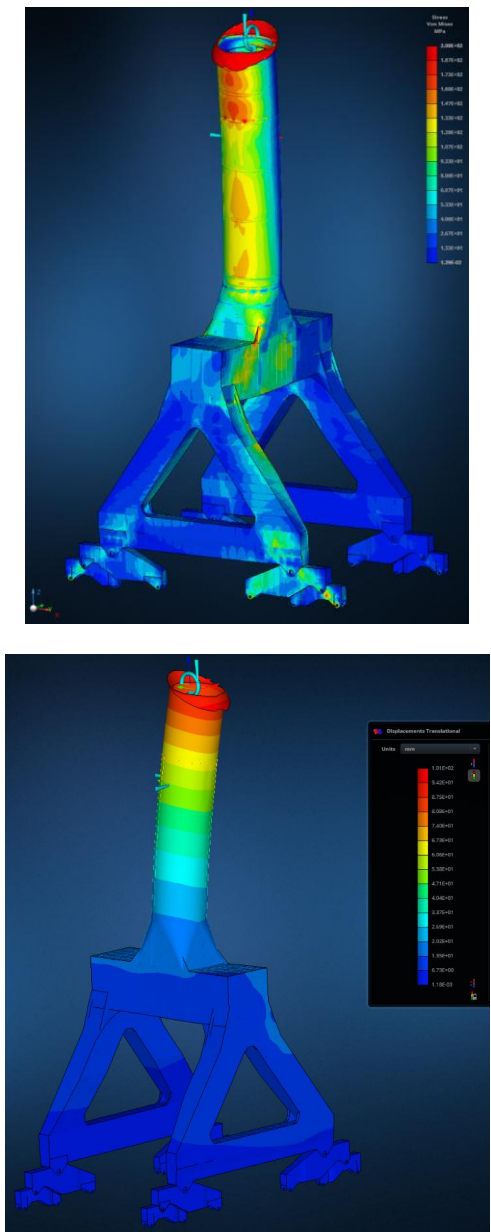


Figure 8. Displacement and stress conditions in the second analysis

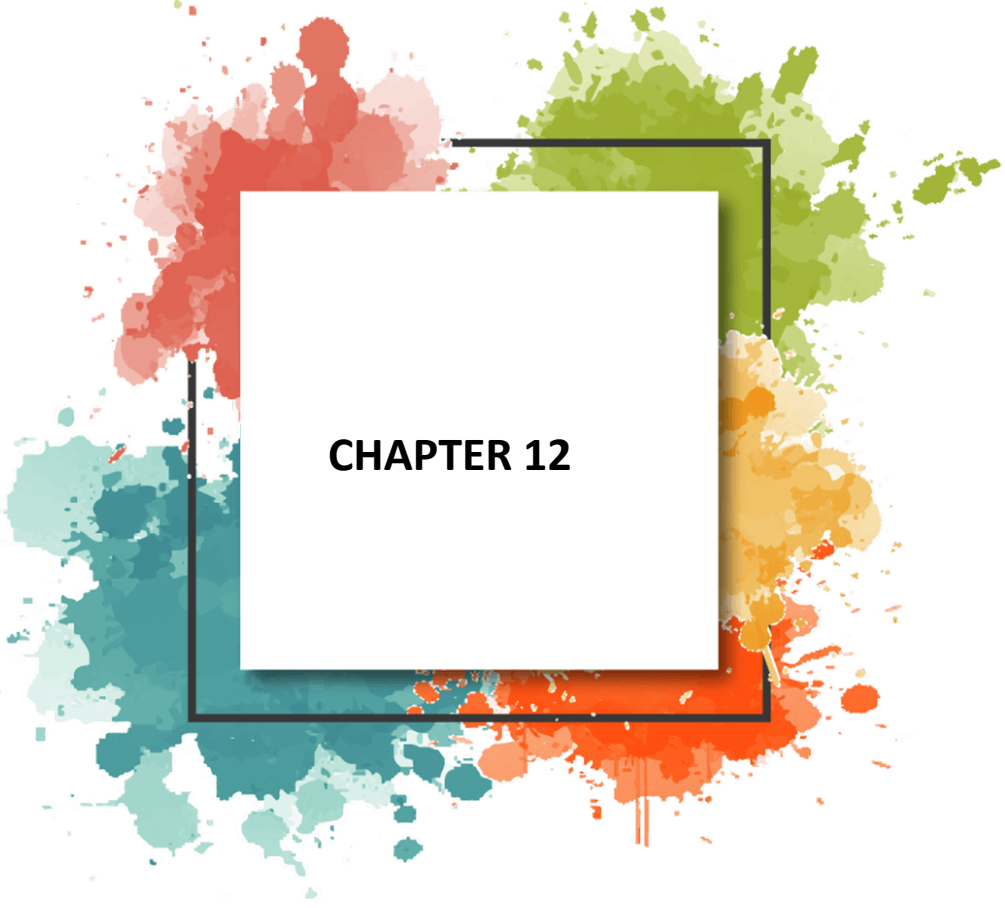
4. DISCUSSION OF RESULTS

As a result of these studies, the first model is 296 tons, while the weight of the final model is found to be 260 tons and 36 tons of steel is saved.

As a result of the analysis study, in order for our structure to be considered safe, the maximum stress should not exceed 175N/mm^2 . However, in the analysis review, which is the 3rd section, it is seen that in some parts of our structure, the desired maximum stress is exceeded in all 3 loading cases. In order to prevent this situation and to ensure the safety of our structure, AH-36 structural steel with a tensile yield strength value of 352MPa is used in places exceeding the desired maximum stress, and the safety of our structure is ensured.

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CHAPTER 12

E-Commerce Logistics Technologies

Serap Özhan Doğan¹ & Zafer Yıldırım²

1. INTRODUCTION

The e-commerce sector, which has developed after the pandemic, has also brought technological developments. While many automation systems and e-commerce applications are used for the service sector, they have also been incredibly developed by sector players who are open to development. When the growth in managed turnover is taken into account, it can be seen that there has been a significant increase in the share allocated to technological infrastructure.

The share of the e-commerce logistics sector in the global logistics market is increasing every year. The share of the logistics sector is expected to reach 12.68 billion dollars in 2023. However, the emergence of the pandemic caused interruptions in logistics processes and caused interruptions in the supply chain. As a result, it was accepted that digitalization is the only way to reduce inefficiencies and losses for sustainable logistics systems [1].

The application of digitalization technologies in logistics processes ensures that products are where they should be, when they should be, and in the amount that will meet the demand, thus reducing waste. In addition to all this, digitalization helps visualize logistics activities and provides connections to simulation and optimization tools for effective decision-making. Establishing such an environment allows for increased employee skills and innovation [1].

Due to the multi-component structure of the logistics sector, the coordinated realization of activities in the processes increases operational efficiency. Information and communication technologies make a great contribution to the digital transformation of logistics [2].

Digitalization provides a highly sensitive and dynamic ecosystem that can respond to customer needs while helping companies achieve environmental goals. A sustainable logistics management established with methods such as real-time traceability, smart storage applications and transportation planning can provide efficient supply chains that reduce delays, fuel consumption and costs.

¹ Mechanical Engineering Department, İstanbul Beykent University,
Orcid: 0000-0001-5210-1549

² İstanbul Beykent University, Orcid: 0000-0001-7284-7014

In the logistics sector and in particular in the rapidly developing e-commerce logistics, effective and major changes will be experienced in the workforce requirement, technology acceptance and decision support approaches, which started with the pandemic and will be felt more strongly in the coming years. It is inevitable for the logistics sector to fall into a situation where the need for qualified/qualified field personnel cannot be met in the destructive competitive environment. Realizing the transformation required by digital transformation and adapting to the new world is a must for the logistics sector. While adapting to this obligation; It has to meet increasingly complex customer needs, such as the internalization of automation technologies, the widespread use of big data technology and feeding into decision support systems, and the establishment of new business models with driverless vehicles.

The importance given to digital transformation will increase rapidly in order to be ready for new expectations and to solve the problem of insufficient qualified workforce. In summary, companies that correctly understand and internalize the requirements of the concept of Logistics 4.0, which has been defined more comprehensively in the last 10 years, and transform their existing technologies in the way they should be, will manage the future [3].

In this study, the expectations of companies in the sector from existing and emerging technologies are classified into three main groups as tactical, operational and strategic levels within the scope of logistics and specifically e-commerce logistics processes. On the other hand, advanced technologies that will dominate future processes in the logistics sector have been investigated and 10 emerging technologies to be examined within the scope of this study have been determined. Considering the process management models of the future, how emerging technologies will be positioned in logistics processes, their ability to respond to customer needs and expectations, the conceptual and potential of relevant technologies in logistics processes and their usage examples have been presented.

2. E- Commerce and Its Types

It is the ordering of the product that the consumer needs on the online platform and the shipment of the product to the consumer's address. In other words, it is the trading of goods and services over the internet, through marketplaces or company-specific web portals.

There are different business models in the e-commerce world depending on the relationship structure between the buyer-seller and partners, and these are;

B2C - Companies sell to end users. It is the most preferred business model.

B2B - Companies sell to other companies in the market. Most of the time, the buyer resells the products to the end consumer in the consumer market.

C2B - This is the model where end consumers sell to companies. C2B companies allow customers to sell to other companies in the market.

C2C - End consumers sell to different consumers who need the product. Companies create online marketplaces that connect end consumers and provide interaction [4].

We can define technology as systematic knowledge and actions within industrial processes, applicable to any activity/business model, closely related to science and engineering, and the name given to the body of knowledge that exists for the acquisition of all kinds of goods and benefits [5].

Here again, the issue that needs to be examined is the expectations of logistics companies and the place that this technology will take in these expectations should be well determined.

3. PLACE AND USE OF TECHNOLOGY IN E-COMMERCE LOGISTICS MANAGEMENT

The history of technology is the history of the invention of tools and techniques and is one of the categories of world history. Technology can refer to methods ranging from as simple as stone tools to complex genetic engineering and information technology that has emerged since the 1980s.

Since most technology is applied science, technical history is closely related to the history of science. Since technology uses resources, technique is closely tied to history and economics. At the same time, technological change affects and is affected by the cultural traditions of a society. It can be said that it is a force for economic growth and political, military power is a reason for developing social welfare.

When we come from the past to the present, we can see that technology has developed at a dizzying pace and that the technological developments presented are positioned in different sectors and industries. In this way, it can be observed that they have managed to transform both their own development and the industries.

The Hannover Fair in 2014 introduced the Industry 4.0 process, where all technological transformations meet on a common ground, and the robotic systems with increased self-management capabilities and self-learning. It is seen that it is increasingly strengthening its position in the industry in the supply chain, logistics management and production development processes every passing year. This actually expresses a period and era in which almost everything that exists in

the real world can be digitalized and found a place in the virtual environment. In this period, it is predicted that digitalized automatic systems will replace human presence in decision-making processes and will have the competence to produce more effective results. Therefore, digitalized processes and robots will take on more characteristic functions than their current potential in the near future [6].

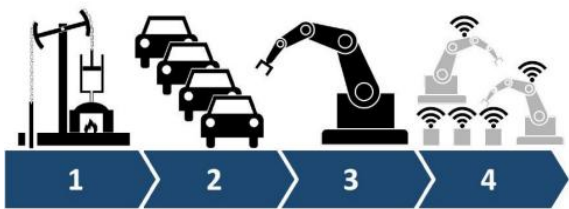


Figure 1. Four basicProcesses of the industry [6]

4. E- COMMERCE LOGISTICS TECHNOLOGIES

Industry 4.0 is defined as the integration of information and communication technologies with the activities of production processes. It has emerged as a result of the need for more automation and digitalization of operations and processes and the developments in the field of communication. Smart factories have automated processes and activities at all organizational levels, digital business operations and information support. When we say smart logistics; the digital environment includes business partners, suppliers, buyers, users and the entire market with which the smart factory communicates over the internet. The information technologies and systems used in smart logistics applications are visualized in Figure 2.

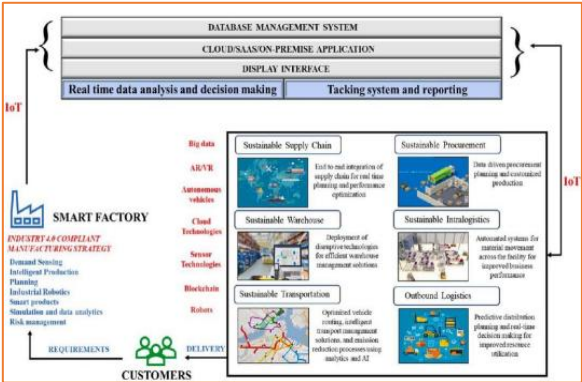


Figure 2. Sustainable Logistics Model [1]

customer loyalty, and bringing new business opportunities. In addition to this, data transparency, access problems, data quality, and the lack of appropriate data sciences can be mentioned.

4.3. Artificial Intelligence

Artificial Intelligence can be used in many different areas such as smart roads, autonomous vehicles, robotic assistants to improve logistics processes [2]. It is a comprehensive and complex field. Therefore, the field of study includes many ideas, theories, findings, technologies and methods from past to present. Cognitive computing, computer vision, machine learning, artificial neural networks, deep learning and natural language processing sub-technologies need to be examined in relation to each other. Cognitive computing; It is used to express the interaction experienced with people and other systems.

Deep learning; Machine learning (ML) is the use of mathematical models that help a computer learn what to do without needing explicit instructions from humans. In other words, we can position machine learning as a subset of artificial intelligence that is based on how humans learn, shapes patterns in data with algorithms, and thus creates a data model that can make predictions. Deep learning uses various tools to explore the complex structure and design how to establish a relationship between layers. Sub-tools such as image, video, speech, and audio processing play an important role in deep learning [9].

4.4. Autonomous Robots

Autonomous robot technology is a technology that aims to produce machines (robots) that resemble humans, copy human activities, and make decisions like humans. It is an important field of study in artificial intelligence technology. Autonomous robots are a technology field that perceives events and movements in a sensitive way to its environment, can make decisions according to the situation it perceives, and can be programmed to start or end a movement [10].

The flexibility of the logistics infrastructure provides advantages such as increasing efficiency, reducing stock levels and stock costs, and facilitating routine and tiring tasks. There are also deficiencies in fundamental issues such as ethics, legal restrictions and deficiencies in legislation.

4.5. Machine Learning

It can also be defined as the application of parsing and using algorithms with the obtained data, learning it and making predictions for a phenomenon or thing in daily life. Many processes and algorithms can be developed with Artificial Intelligence and machine learning in the logistics sector. Many topics such as customer loss tracking, demand forecasting, inventory management, minimum stock management, purchasing, supplier selection, vehicle routing, logistics

operation planning, logistics tracking, order picking algorithm development, quality control in the supply chain, equipment maintenance forecasting are open to development with artificial intelligence and machine learning technologies [9].

4.6. RFID

It is the communication of many components via radio frequency. It is a structure formed by the combination of three basic components: reader, tag and antenna. It enables the transmission of information about objects via radio waves with readers. Tags provide information. The antenna provides data communication between the tag and the reader. The reading distance can be increased with additional antennas [11].

Below, a diagram explaining the working principle of RFID is shared in Figure 4.

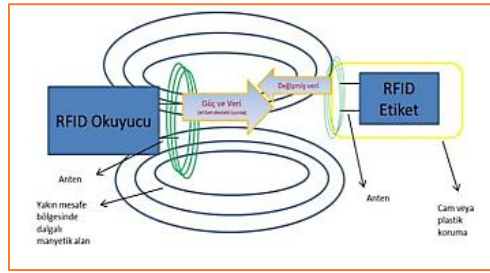


Figure 4. RFID Temel Çalışma Prensibi [11]

RFID tags (we can also call them invisible barcodes), which we can define more generally as digital identifiers, are used in different industries to identify objects and even people more precisely. By assigning an ID to each product in the logistics process, it is possible to track it, determine its transportation conditions, storage climate, and shipment location. Tracking parts and providing security information within the global supply chain is possible with RFID.

4.7. Augmented Reality (VR)

It provides better training for forklift operators and other personnel who will work in dangerous jobs in the logistics sector and reduces the factors that cause work accidents. Augmented Reality (VR) used through smart glasses has exceeded the initial future projection at the point we have reached today. Order preparation in logistics is used effectively and efficiently, hands-free.

4.8. Bionic Strengthening

Developments in smart sensors and nanotechnology have enabled the development of different technologies. Companies with strong future projections are investigating ways to develop products suitable for exoskeleton systems and to adopt them in the workplace. In the field of logistics, it is possible to use exoskeletons especially in manual transportation and ergonomically problematic work areas. Exoskeletons will also allow for the development of work safety in jobs with high stress and tiring routine movements. Bionic clothing can seriously prevent human injuries [3].

4.9. Drone (Unmanned Aerial Vehicle – UAV) Usage

As a new approach to the use of drone technology in warehouses and product deliveries; speed, time and labor savings are achieved by transferring product count results in the warehouse in an integrated manner to the Warehouse Management System [12].

The image of the Prime Air cargo drone model Amazon's book distribution project is shared in Figure 5 below.



Figure 5. Logistics Distribution with Drone [8]

We can list other benefits of drones as follows.

- Provides reduction in logistics, distribution and shipping costs,
- Provides faster delivery, Delivery can be made to hard-to-reach places,
- Minimizes logistics city traffic,
- Reduces CO2 emissions, provides a more livable environment,
- Provides warehouse stock and inventory tracking,
- Ability to work 24 hours a day, 365 days a year.

We can list four types of cargo drones according to their intended use [14].

Intralogistics Automation: All in-plant logistics activities and integration.

First and Last Miles Logistics: The distance that the transportation vehicle must travel for the last load to be taken to the delivery point.

Medical Cargo Logistics: The name given to the logistics processes in which medical products are included in the medical equipment industry.

Air Cargo Logistics: Transportation is carried out via air.

Some governments (Switzerland, Iceland, Australia and Singapore) have introduced regulations and developed encouraging policies regarding drone transportation [14].

4.10. Autonomous Vehicles

Driverless vehicles (autonomous) have a usage area that will contribute significantly to efficiency in the logistics sector, especially in warehouse operations and commercial transportation. The first generations of autonomous services, forklifts (e.g. Linde and Balyo) and in-warehouse vehicles are expected to bring great gains in efficiency and performance by being used in designated areas of the warehouse [3].

5. RESULTS AND DISCUSSIONS

E-commerce logistics can be defined as the totality of all planned work required for the delivery of the product to the final consumer (end user) from the shipping point (warehouse, transfer center, etc.) in accordance with the supply chain management rules, on the day and time interval requested by the consumer.

For companies that plan to make digital changes starting today and that will be reflected in the coming years, there will be major transformations in every field. Although companies aim to develop processes and technology, they are often unclear about what digital transformation will bring them and what kind of expectations they should have.

Within the scope of the study, it is obvious that there are expectations from the transformation in e-commerce logistics technologies for the classical management levels of companies and that technological developments will occur in line with these expectations. These expectations are examined under three headings.

5.1. Expectations at the Strategic Level

The uncertainty of the future drives companies to make high-risk strategic decisions. Companies' future projections and plans are determined by senior managers, administrators and other decision makers who have authority and roles at this level. Strategic level expectations are determined by considering the

desired benefits and gains from developing technologies in the long term in logistics and specifically in e-commerce logistics. The determined strategic level expectations are shared below with the short code symbols provided.

- Assistance and coordination in strategic decision making (S1)
- Risk management and scoring in the supply chain (S2)
- Increase in customer loyalty/customer retention measurement (S3)
- Secure and traceable business processes, control and monitoring (S4)
- Reducing dependence on people (S5)
- Ease of access to real-time data collection and accurate information (S6)

In addition, in recent periods; Establishing R&D departments, employing R&D engineers, and implementing innovation and digital transformation projects are mostly aimed at protecting companies from market changes, increasing operational efficiency, entering new markets, launching new products, providing new services, and complying with legal requirements.

5.2. Tactical Level Expectations

In companies, tactical level applications are mostly based on decisions made at strategic level. Works, activities, daily plans that are not in the routine of companies are carried out at this level to be executed. Expected gains and expectations are questioned together with what kind of facilitation is expected from technologies tactically. The determined tactical level expectations are shared below with their abbreviations.

- Demand and order (sometimes labor) forecasting (T1)
- Optimization of resource usage and planning (T2)
- Traceability within the supply chain process (T3)
- Fuel saving and efficiency (correct routing) (T4)
- Flexibility and ease of delivery (T5)

5.3. Expectations at the Operational Level

Changes in consumer behavior, receiving demands from marketplaces (internet environment) and web applications, and developments in technology have brought a new concept to the table instead of face-to-face retail sales. If there were no changes in the products and quantities ordered by consumers, there would be significant changes in product supply and distribution processes. Companies that wanted to adapt to this have redesigned their logistics business

processes. While the product flow in traditional supply chains classically occurs from retail stores to the end consumer, in today's online environment, businesses that deliver products to customers, produce logistics services, perform cargo transportation and collection (logistics and e-commerce companies) have also entered the process of receiving orders and delivering products [7].

The goods acceptance, stacking and shipping activities in warehouses are further enriched and the efficiency of warehouses is increased, and many different processes such as value-added transactions, consolidation (combining, creating sets), separation and finalizing the product are carried out by organizations established in warehouse areas to meet customer needs. These activities are supported by technology and robotic systems, becoming more productive, and characteristic processes specific to companies emerge.

The expectations of companies at the operational level are to implement the decisions made at the tactical level. At the operational level, it is questioned how the daily business practices of companies have changed thanks to these developing logistics technologies. The expectations at the determined operational level are shared below with their abbreviations.

- Increased productivity in in-warehouse activities (O1)
- Reducing failure rate (O2)
- Reducing cycle time of processes (O3)
- Increased traceability and auditability (O4)

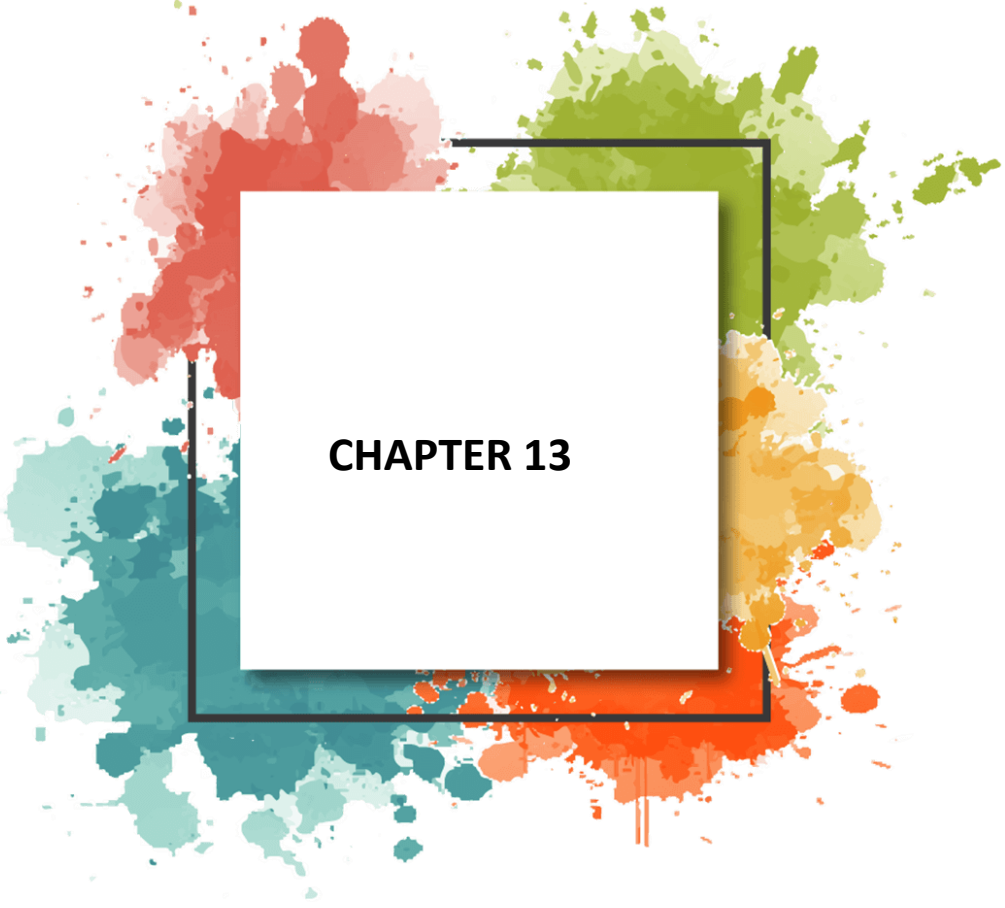
6. CONCLUSIONS

Logistics technologies will develop parallel to the changing technological age. Logistics technologies offered in accordance with the dynamics in e-commerce will be offered for use by being more specialized in order to carry the expectations of end consumers to a higher level. It is stated that new professions will enter our lives in the coming years with the logistics sector working in harmony with information technologies and Industry 4.0. Studies predict that many professions done today will no longer exist in 2030 and beyond. In today's commercial activity chain, where competition shows itself with two important criteria as speed and cost, technological approaches provide competitive advantage. Data production is much more valuable and costly in current process managements compared to the past. In order to develop processes, improve existing processes and solve problems, information production from the work results produced by the systems and their reporting are extremely valuable. It is emphasized in the study that automatic identification systems have a critical importance that is

based on process improvement studies due to their role in this detail. In general, the technological position of digitalization and its areas of use in the logistics sector are examined. The applications developed with digital technologies can be applied in many different areas, and the fact that they are still widely used in the logistics sector will be a guide for the sector in terms of developing many different projects on these applications. The world's digitalization adventure continues. Integration processes with automation are developing and adapting to the processes of businesses. Logistics and especially the e-commerce sector also receive their share of this adaptation and this share will increase even more in the near future. It can be said that the driving technology of automation is artificial intelligence technology. Technology continues to grow exponentially per unit of time. Although it is the Industry 4.0 era that we are experiencing, Industry 5.0 has become a popular topic in recent years. Industry 4.0 can be defined as the foundation of Industry 5.0 and it is absolutely necessary for the foundations established to be solid while moving to the future era. In an environment where there is destructive competition and many competitors that include Logistics 4.0 in their processing processes, yesterday's qualifications, experiences, knowledge accumulation and old technologies will not be sufficient for the future of companies. Companies are obliged to incorporate continuously developing technology into their business routines. The world's largest brands are conducting both external and internal technology development studies to manage their logistics business models. Future technologies such as the Internet of Things (IoT), Big Data Analytics and Cloud Computing will probably be adopted in the next 10 years in terms of the system level, operational level and real-time decision-making level of E-commerce logistics [8]. According to the pioneers of E-commerce such as UPS, DHL and Amazon, which are among the prominent logistics companies in the world today, the Internet of Things, robotic technologies, cloud computing and augmented reality technologies will shape the future more clearly. In addition, the scientific articles examined also include the practices of technologies such as big data and IoT in the logistics sector, thus drawing attention to the importance of these technologies. In this context, it is seen that the results of the study and the opinions, predictions and scientific studies of companies operating in Turkey and the world coincide with the logistics technology practices and concepts. It is essential to emphasize that digital transformation must continue in order for some of the technologies included in this study to be applied holistically in the logistics sector. This study will help logistics and in particular e-commerce logistics managers and researchers on the subject by providing a new model and providing information about the areas of use of logistics technologies with high future potential.

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CHAPTER 13

AI for Capital Markets: A Comparative Evaluation of Methods and Practices

Aytürk Keleş¹ & Ali Keleş²

1. Introduction

Capital markets are environments that operate with large volumes of data, are highly competitive, and are subject to strict regulations. These markets involve complex processes such as price discovery, liquidity provision, and risk transfer, which range from microsecond-level microstructure details to multi-year macro cycles. Artificial Intelligence (AI) significantly contributes to this ecosystem by learning from diverse and complex information sources, including time series, limit order books, news, filings, counterparty relationship graphs, and alternative data. This enhances prediction accuracy, improves trading quality, enables market monitoring, and increases administrative efficiency (Enke & Thawornwong, 2005; Kara, Boyacıoğlu, & Baykan, 2011; Chong, Han, & Park, 2017; Sezer, Özbayoğlu, & Doğdu, 2017).

However, decisions made by AI also affect the data that shapes the market. This means that AI's decisions are not only based on existing data but also influence and change data over time. Competitors can learn these strategies, and sudden changes in market conditions or shifts in data distribution can reduce the reliability of the models. Therefore, for AI to be used sustainably, it is very important to develop data models that consider the small details of markets, apply strong and reliable validation processes, be able to explain the reasons behind decisions, and establish effective governance systems (Jasic & Wood, 2004; Kaynar & Taştan, 2015).

2. AI Techniques for Use in Capital Markets

In this section, we briefly survey the principal categories of methods that can be employed in capital markets and synthesize prior applications into a comparative table. Specifically, we group approaches into supervised learning (SL), deep learning (DL), graph representation learning (GRL), reinforcement learning (RL), and probabilistic/Bayesian and causal frameworks; we also discuss representation/generative models and large language models (LLMs) for text. For each category, we collate representative studies that have implemented these

¹ Assoc. Prof. Dr., Ağrı İbrahim Çeçen University, Faculty of Education, Department of Computer and Education Technologies Education, ORCID: 0000-0001-9755-295X

² Assoc. Prof. Dr., Ağrı İbrahim Çeçen University, Faculty of Education, Department of Computer and Education Technologies Education, ORCID: 0000-0002-0785-9593

techniques on market data, noting the problem setting (e.g., return prediction, microstructure modeling, risk estimation), data sources and sampling schemes, evaluation design (including cost-aware metrics), and the main empirical findings. The resulting table provides a concise, structured overview of the literature, highlighting where each method has shown promise and the contexts in which it is most effective.

- Supervised learning: regularized linear models, tree-based ensembles, and support vector machines (SVMs) are widely used for return/factor prediction and risk metrics, balancing bias–variance under heteroskedasticity³ and regime shifts (Kara et al., 2011).

- Deep learning: Long short term memory (LSTM)/ gated recurrent unit (GRU), temporal convolutional neural networks (CNNs), and Transformers capture temporal dependence and fuse multi-modal signals; event-time limit order book (LOB) features (depth, order-flow imbalance, queue position) are particularly effective (Chen, Zhou, & Dai, 2015; Nelson, Pereira, & De Oliveira, 2017; Baek & Kim, 2018; Roondiwala, Patel, & Varma, 2015; Chong et al., 2017).

- Graph learning: graph neural networks extract topological motifs in transaction/counterparty networks for surveillance and multi-asset spillovers.

- Reinforcement learning: Policies for order slicing, timing, and quoting aim to reduce slippage while balancing fill probability and inventory risk under real-world constraints; safe deployment requires realistic simulation and off-policy evaluation (Sezer et al., 2017).

- Probabilistic/Bayesian & causal: uncertainty quantification (posterior intervals), regime-switching, and counterfactual evaluation improve risk communication and policy selection (Liao & Wang, 2010).

- LLMs and generative models: text extraction/labeling and synthetic stress scenarios accelerate operations and testing (Chong et al., 2017).

³ Heteroskedasticity, non-constant error variance in a regression

Table 1. Structured overview of the literature

AI Methods	Applications	Data Types	Notable Studies (Year)	Main Findings	Risks/ Caveats
Supervised Learning	Return/alpha prediction, feature/factor selection, credit/default risk, anomaly detection	Price–return panels, firm fundamentals, market microstructure data	Gu, Kelly & Xiu (2020); Kara et al. (2011); Jasic & Wood (2004)	Tree-based models and NNs outperform linear baselines; interactions matter	Data snooping, realistic costs, regime shifts
Deep Learning	Short-horizon direction/volatility from LOB, option pricing, risk management	Limit order books, high-frequency quotes/trades, option surfaces	Heaton et al. (2016); Sirignano & Cont (2019); Nelson et al. (2017); Baek & Kim (2018)	Evidence of universal price-formation patterns; captures nonlinear structures	Overfitting, leakage, explainability
Graph Representation Learning	Movement prediction via equity relations, portfolio network optimization	Correlation/weighted graphs, sector/supply-chain links, event/news graphs	Feng et al. (2019)	Time-varying graph embeddings can boost predictive power	Sensitive to graph construction; evolving relationships
Reinforcement Learning (RL)	Portfolio/trading policy, market making, inventory control	Time series, transaction costs & constraints, reward functions	Zhang, Zohren & Roberts (2019)	End-to-end policy learning; volatility-scaled rewards can help	Needs realistic simulation; stability/generalization issues
Probabilistic/Bayesian & Causal	Stochastic volatility, Bayesian VAR-SV; event impact, policy/product causality	Returns & realized measures, macro/corporate data, event times	Kim, Shephard & Chib (1998); Carriero et al. (2016); Athey & Imbens (2017)	Quantifies uncertainty; transparent inference; causal analysis improves explainability	Prior sensitivity, misspecification, identification assumptions
Representation / Generative Models	Synthetic data generation, anomaly detection, latent representation learning	High-frequency time series, multi-modal (price, news) data	Yoon, Jarrett & van der Schaar (2019) [TimeGAN]	Synthetic data aids augmentation and privacy; learned reps help	Distributional shift; overfitting to synthetic data

				downstream tasks	
Large Language Models (LLMs)	News/report sentiment, NER, Q&A, text-numeric signal integration	News, regulatory filings (SEC), analyst reports, social media	Araci (2019) [FinBERT]; Wu et al. (2023) [Bloomberg GPT]	Domain adaptation boosts performance; multi-task capabilities	Source transparency; hallucinations; data governance/IP

3. Implementation Principles in Capital-Market AI: A Comparative Evaluation

There is no single “best method” for artificial intelligence in capital markets. The appropriate choice depends on the structure of the data (such as high frequency order books, daily panels, and text), the decision horizon (from milliseconds to quarters), trading constraints (including liquidity, costs, and latency), and governance requirements (such as model risk, explainability, and regulation). This section compares common families of approaches, including SL, DL, GRL, RL, probabilistic and Bayesian methods, causal frameworks, representation learning and generative models, and LLMs, highlighting their respective strengths and weaknesses. The evaluation is grounded in both the literature and practical implementation principles, for example realistic treatment of costs and liquidity, prevention of data leakage, walk forward validation, rigorous versioning, and continuous monitoring (for example, Gu, Kelly and Xiu, 2020; Heaton, Polson and Witte, 2016; Sirignano and Cont, 2019; Kara, Boyacıoğlu and Baykan, 2011).

- *Supervised Learning (Trees, Ensembles, SVM, etc.)*

Strengths: Tree-based and ensemble methods capture interactions in high-dimensional spaces and often outperform linear baselines for asset-pricing/alpha prediction; they are relatively explainable via feature importance and partial-dependence tools (Gu, Kelly & Xiu, 2020). Empirical studies on Borsa İstanbul also report gains in direction classification (Kara et al., 2011; Jasic & Wood, 2004).

Weaknesses: In time series, leakage and improper validation can quickly create “illusory superiority”; sensitivity to regime shifts is notable. Robust walk-forward testing, net performance after costs/liquidity, and strong baselines are essential.

- *Deep Learning (CNN/RNN/LSTM/Transformer)*

Strengths: Effective at capturing nonlinear microstructure patterns in LOB and high-frequency data; evidence suggests “universal features of price formation” (Sirignano & Cont, 2019). Advantages extend to option surfaces, multi-modal data, and reduced manual feature engineering (Heaton et al., 2016; Nelson et al., 2017; Baek & Kim, 2018).

Weaknesses: Explainability and leakage risks are higher; performance can be latency-sensitive and degrade under regime shifts. Regularization, early stopping, time-consistent validation, and production-grade drift/latency monitoring are required.

- *Graph Representation Learning (GNN, etc.)*

Strength: Dynamically modeling inter-asset relations (correlation, supply chains, sectors, news/event graphs) can improve movement/volatility prediction and offers a natural representation for multi-asset portfolios (Feng et al., 2019).

Weaknesses: Performance depends heavily on graph construction assumptions; unstable/incorrect edges impair generalization. Updating time-varying relations and running stability/robustness checks are mandatory.

- *Reinforcement Learning (Trading/Portfolio Policies)*

Strengths: Can jointly optimize transaction costs, risk, and constraints inside the reward; useful for market making and inventory control (Zhang, Zohren & Roberts, 2019).

Weaknesses: The key obstacle is realistic simulation and stability: if market impact, partial fills, and latency are not modeled, paper gains evaporate in production. Safe exploration/exploitation, canary/shadow deployments, and rollback are operational prerequisites.

- *Probabilistic/Bayesian and Causal Frameworks*

Strengths: Provide uncertainty quantification (predictive distributions), transparent inference, and causal interpretation. SV/VAR-SV models are preferred for stress testing and policy/event-impact analysis (Kim, Shephard & Chib, 1998; Carriero, Clark & Marcellino, 2016; Athey & Imbens, 2017).

Weaknesses: Sensitive to priors and identification assumptions; computational cost rises in high-dimensional/multi-asset settings. Hierarchical/sparse priors and variational methods are practical mitigations.

- *Representation/Generative Models*

Strengths: Synthetic data enriches rare events, supports privacy and augmentation; latent representations can improve downstream tasks (Yoon, Jarrett & van der Schaar, 2019).

Weaknesses: Risk of distributional mismatch and overfitting to synthetics; faithfully reproducing financial tail behavior is hard. Generated data should be clearly labeled and validated against real data using diagnostic tests.

- *Large Language Models (LLMs)*

Strengths: Strong on signal extraction from text news, regulatory filings, analyst reports (NER), and institutional context understanding; domain adaptation materially boosts performance (Araci, 2019; Wu et al., 2023).

Weaknesses: Source transparency, legal data governance, and hallucination risks persist. Tight right-aligned time integration with numeric features and safe-use controls (prompt/output checks) are needed.

3.1. Comparative Summary of Methods

Short-horizon predictive power: DL generally performs best, followed by graph-based models, then conventional supervised methods. Deep networks excel on limit-order-book and other high-frequency data, while graph neural networks add value by capturing cross-asset relationships (Sirignano & Cont, 2019; Feng et al., 2019).

Explainability and auditability: Bayesian and causal approaches offer the strongest interpretability, next come standard supervised models, and after that deep and graph-based models. For capital allocation decisions and regulatory review, methods with clear explanatory pathways are preferable (Athey & Imbens, 2017; Gu et al., 2020).

Operational integration (cost/liquidity/latency): Supervised and Bayesian approaches are more predictable; RL is risky without realistic sim and controlled rollout (Zhang et al., 2019).

Data demand and robustness: Deep based methods are data-hungry and sensitive to regime change; supervised/Bayesian methods are more stable with smaller-to-medium data and disciplined feature engineering.

Text and multi-modal integration: LLMs plus numeric models are complementary; LLM risks and timing alignment must be handled carefully (Araci, 2019; Wu et al., 2023).

Risk/Governance: Bayesian-causal and well-documented supervised models had better satisfy MRM and independent validation; deep/RL demand extensive monitoring (drift, latency) and safe rollback.

4. Conclusion

There is no single perfect method for artificial intelligence in capital markets. The right choice depends on the nature of the data, the time horizon of decisions, trading costs and liquidity, and regulatory requirements. Data can range from second-level order book streams to daily prices or news articles. Decision horizons may vary from seconds to several months. In practice, factors such as commissions, bid-ask spreads, slippage, and partial fills all influence outcomes. Moreover, regulatory expectations and the need for transparency play a crucial role in determining which approach is most suitable.

Overview:

- Supervised learning and Bayesian/causal methods stand out when explain ability and auditability matter.
- Deep learning and graph-based learning are strong at capturing complex, nonlinear market patterns.
- Reinforcement learning (RL) is attractive for strategy/policy design, but it is risky without realistic simulation and controlled rollout.
- Large language models (LLMs) are valuable for turning text (news/reports) into signals, but need safeguards for temporal alignment and hallucination risk.

Three golden rules in practice:

- Handle time correctly. Record data now the event occurs (trade, price change, news). Prevent any misalignment that would accidentally incorporate future information.
- Evaluate realistically. Paper profits are not real profits. Always account for commissions, bid-ask spreads, slippage, partial fills, and latency. Use walk-forward testing that respects temporal order.
- Govern for production. Without clear model cards (purpose, data, limits), strict versioning, independent validation, drift and latency monitoring, and the ability to run canary releases with automatic rollback, systems will not be durable.

Why a hybrid approach?

No single tool fits all. At short horizons, deep nets capture order-book patterns, while graph models add cross-asset relations. Bayesian layers can make outputs more stable and interpretable. In text-heavy workflows, LLMs extract signals that supervised or probabilistic models can quantify. Where policy optimization is needed, RL should run on faithful simulators and be deployed cautiously.

Practical forward goals:

- Build models that are regime-robust and cost/latency-aware.
- Use causal analysis and counterfactual evaluation to better explain decisions.
- Generate privacy-preserving synthetic data, and regularly verify realism with diagnostic tests.
- Standardize model risk management so systems are auditable, versioned, and continuously monitored.

Accordingly, lasting success in capital markets is not achieved through any single algorithm. Rather, it depends on correct data representation, realistic performance measurement, and mature system governance. When these three are integrated, AI transitions from a laboratory result to a real-world value driver.

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