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EDITORIAL

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PREFACE

The present issue of *History of Science and Technology* (Vol. 15, Issue 2, 2025) brings together a wide-ranging collection of studies that illuminate the long-term dynamics of scientific knowledge, technological systems, and their social, cultural, and political entanglements. The contributions assembled here reflect the journal's enduring commitment to interdisciplinary scholarship and to the integration of diverse geographical, chronological, and methodological perspectives. Taken together, the articles demonstrate that science and technology are not isolated domains of technical ingenuity, but historically contingent processes shaped by imagination, institutions, power relations, material practices, and cultural values.

A unifying theme of this issue is the continuity between past and present: ancient myths and early mechanical devices resonate with contemporary debates on artificial intelligence; nineteenth-century academic networks prefigure modern systems of scientific communication; industrial technologies mature through decades of negotiation between laboratories, factories, and regulatory regimes; and cultural technologies such as music, cinema, and transport reveal deep interconnections between material innovation and human perception. By juxtaposing case studies from Europe, Asia, the Middle East, and Southeast Asia, this issue underscores the global character of scientific and technological development while remaining attentive to local contexts and specific historical trajectories.

The issue opens with Ahmed Shaker Alalaq's study *"Artificial Intelligence and Robotics in Ancient Times: Between Myth and Interpretation"*, which explores how ancient civilizations conceptualized artificial beings capable of thought and action. By examining myths such as Automata, the Golem, and other legendary constructs from Greek, Chinese, and Near Eastern traditions, the article demonstrates that the aspiration to create intelligent artifacts is not a product of the digital age alone. Rather, it is embedded in long-standing philosophical and cultural reflections on consciousness, creativity, and the boundaries of human agency. Alalaq's contribution situates contemporary debates on artificial intelligence within a longue durée perspective, showing how ethical concerns, fears of loss of control, and hopes for human enhancement were already articulated in mythological form. In doing so, the article provides a conceptual bridge between ancient imagination and modern technological realities, reminding readers that innovation is often guided by deeply rooted narratives and symbolic frameworks.

Several contributions in this issue focus on the nineteenth century as a formative period for modern scientific institutions and communication networks. Denys Buhor's article *"Development of Ukrainian Mechanics: Context of Scientific Publications by Kharkiv Scientists of the 19th Century"* offers a detailed historiographical and bibliometric analysis of the Kharkiv scientific milieu. By examining publications produced at Kharkiv University and the Kharkiv Institute of Technology, the study reveals how theoretical and applied mechanics developed in close institutional synergy. Figures such as Oleksandr Lyapunov and Volodymyr Steklov emerge not only as individual innovators but as representatives of scientific schools shaped by mentoring, academic heredity, and international exchange. Buhor's work highlights the transition from isolated scholarly efforts to systematic research cultures aligned with industrialization and European scientific standards.

Complementing this perspective, the article by Natalya Pasichnyk, Renat Rizhniak, and Hanna Deforzh, *"International Relations and Scientific Communication of the Imperial Novorossiya University in the Last Third of the 19th Century"*, examines the mechanisms through which Odesa scientists integrated into the European scientific space. Focusing on translations, academic mobility, participation in international congresses, and the role of the *Notes of the Novorossiya Society of Naturalists*, the authors demonstrate how multilingualism and institutional platforms facilitated knowledge circulation. This study underscores that scientific globalization in the nineteenth century was not a one-way transfer of ideas from Western Europe to the periphery, but a complex process of adaptation, negotiation, and mutual recognition.

The transition from scientific knowledge to industrial application is examined in Artemii Bernatskyi's article *"Hybrid Laser-Arc Welding of Low-Alloy Steels: From Scientific Concept to Industrial Technology (1970s–2020s)"*. This contribution traces the four-decade trajectory of hybrid welding from laboratory experiments to its selective stabilization in sectors such as shipbuilding, pipeline construction, wind-energy infrastructure, and offshore engineering. By emphasizing institutional conservatism, certification barriers, and capital intensity, Bernatskyi shows that technological diffusion of innovations is rarely linear or inevitable. The article also situates hybrid welding within contemporary sustainability debates, revealing how a technology originally developed for productivity gains later acquired environmental significance through reduced material consumption and extended service life of structures.

A cluster of articles addresses the socio-political dimensions of technology in architectural and infrastructural contexts. Bharoto Bharoto, Himasari Hanan, and Andry Widyowijatnoko, in *"Institutionalising Concrete Construction Technology: A Socio-Technical Formation of Modern Architecture in Indonesia"*, analyze how concrete became the dominant material of postcolonial Indonesian architecture. Drawing on social construction theory, the authors show that technological institutionalization unfolded differently under the Old Order and the New Order regimes, yet resulted in a durable socio-technical system that bridged ideological and economic transformations. This study contributes a valuable Global South perspective to Science and Technology Studies by demonstrating that modernity emerges through negotiated, context-specific processes rather than simple technological transfer.

Similarly, Hary Ganjar Budiman and colleagues explore colonial power relations in *"Colonial Technopolitics in the Dutch East Indies: A Study of Colonial Hydroelectric Power in Pamanoekan and Tjiasemlanden Plantation"*. By combining archival research with historical archaeology, the authors reveal how hydroelectric infrastructure functioned as an instrument of colonial technocracy. Hydropower stations are shown not merely as technical achievements, but as mechanisms for rendering nature calculable and for integrating local environments into global economic networks. The article foregrounds the concept of technopolitics, emphasizing that technology operates simultaneously as material infrastructure and as a means of governance.

Petra Hyklová's contribution, *"Negotiating a Great Telescope: The Case of Czechoslovakia"*, offers a detailed reconstruction of the political, institutional, and personal negotiations surrounding the construction of the Ondřejov 2-m telescope. The article demonstrates that large scientific instruments are products of complex collaborations involving scientists, manufacturers, state administrations, and international partners. By highlighting the parallel development of similar telescopes in Czechoslovakia and Azerbaijan, Hyklová reveals how scientific ambitions intersected with Cold War politics, economic constraints, and long-term planning. The continued operation of these instruments today underscores the durability of such negotiated technological systems.

The cultural dimensions of technology are explored in the article *"Pneumatics, Acoustics and Digital Sound: The Organ in the History of Science and Technology"* by Olena Spolska and co-authors. Treating the organ as a long-lived technological system, the study traces its evolution from the ancient *hydraulis* to contemporary digital and hybrid instruments. The article demonstrates how advances in pneumatics, acoustics, metallurgy, electrification, and computation were gradually absorbed into organ building without erasing earlier traditions.

Transport history and the culture of speed form the focus of the next article *"The*

History of the Emergence, Development and Improvement of High-Speed Railways". By combining technical, socio-economic, and cultural analysis, the authors show how high-speed rail transformed perceptions of space and time while serving as a tool of regional integration and economic development. From the Shinkansen and TGV to contemporary maglev and Hyperloop concepts, high-speed rail emerges as a key component of twenty-first-century energy-intelligent mobility.

The issue concludes with the article *"Silent Cinema as a Technological System: Infrastructure, Innovation, and Institutionalization (1890–1930)"* by Liudmyla Vaniuha and colleagues. Challenging the view of silent cinema as a primitive precursor to sound film, the authors demonstrate that this period established the foundational technological and institutional structures of modern cinema. Projection systems, permanent theaters, studio infrastructures, special effects, and genre formation collectively transformed film into a global medium of mass communication. This study highlights cinema as a paradigmatic example of how technology, industry, and culture co-evolve.

Together, the articles in this issue of *History of Science and Technology* illustrate the richness and diversity of contemporary scholarship in the field. They reaffirm that the history of science and technology is best understood through interdisciplinary approaches that connect technical detail with social context, institutional frameworks, and cultural meaning. By bringing ancient myths into dialogue with artificial intelligence, colonial infrastructures with postcolonial modernity, and nineteenth-century scientific schools with global knowledge networks, this issue invites readers to reflect on the enduring and evolving relationship between humanity and its technologies.

We hope that this collection will stimulate further research, foster international dialogue, and contribute to a deeper understanding of science and technology as historical processes that continue to shape our present and future.

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Artificial Intelligence and robotics in Ancient Times: Between myth and interpretation

Abstract. *This research examines the concept of artificial intelligence and robotics across ancient times, where philosophers and scientists in ancient civilizations such as Greece and China sought to imagine beings capable of thinking and interacting, thus embodying humanity's desire to transcend the limits of its biological capabilities. These ideas manifest in mythical figures such as the "Golem" and "Automata" indicating the human preoccupation with the idea of creating intelligent beings. The study is of significant importance by helping us understand the historical roots of the cultural visions that have shaped the concept of artificial intelligence today. It also raises issues regarding the boundaries between myth and reality and what can actually be achieved. These issues relate to human ambitions versus technological possibilities, raising questions about ethics and the necessity of setting limits on these innovations. Additionally, this topic contributes to the analysis of philosophical and cultural thought in human and machine interactions, that strengthens our comprehension of the complex interaction between humans and technology in the contemporary world. Thus, this topic represents a bridge between the past and the future, where ancient myths can help guide us toward a future of artificial intelligence and robotics with a human and ethical character. It is worth noting that the evocation of these ancient visions is not limited to the historical dimension alone, but also opens the way for us to understand how human imagination has always been the primary driving force behind scientific and technological progress. The myths crafted by ancient civilizations were not merely symbolic tales; rather, they constituted an initial framework for reflecting on issues that remain relevant today, such as the boundaries of consciousness, the possibility of simulating the human mind, and the question of what it means to be human. Re-reading these myths in light of current developments in artificial intelligence and robotics offers us* *an opportunity to reshape our relationship with technology – not merely as a useful tool, but as a cultural and ethical force that demands critical awareness and shared responsibility.*

Keywords: *ancient civilizations; robots; greeks; Artificial Intelligence; myths; eternal life*

Introduction.

The idea of Artificial Intelligence (AI) and robotics is one of the most engaging topics of discussion in the modern era, showing its increasing impact on various aspects of human life. However, if we look back to ancient times, we find that these ideas were not alien to early human thinkers. Many philosophers and scientists in ancient civilizations, such as the Greeks and Chinese, sought to imagine beings capable of thinking and interacting, reflecting humanity's desire to create beings that resemble it in intelligence and thought. These ideas were represented in myths and legendary figures such as the "Golem" in Jewish culture and the "Automata" in Greek mythology, showing the human preoccupation with the idea of intelligent machines since ancient times. These myths were not just stories but expressions of human ambition to overcome biological limitations and to regard intelligence as a trait that could be embedded in non-human beings. The significance of this topic lies in understanding the historical roots and cultural visions that contributed to the formation of the concept of artificial intelligence and robotics today. Exploring ancient times gives us deep insights into how these concepts evolved, and the role of philosophy and religion in shaping humanity's perception of these beings. However, these visions also raise several issues concerning the boundaries between myth and reality, and what can actually be achieved through technology.

The problem arises from the disparity between human ambitions and the available technological possibilities. Many seek to develop artificial intelligence inspired by these myths, but questions remain about ethics and the limits that should be set in this context. How are we to interpret the human-machine relationship through these early ideas? And what dangers of crossing natural boundaries are there?

We can say that the scope of this research goes beyond a mere historical study to include a philosophical and cultural analysis of human ambitions in creating artificial intelligence and how these ambitions have reflected across the ages. Thus, this topic forms a bridge between the past and the present, providing fertile ground for discussions on the future relationship between humans and machines, and how cultural and mythical heritage can influence our contemporary approaches to innovation and technological advancement.

In our research, we have relied on a variety of sources and studies that have discussed the history of artificial intelligence in historical narratives and ancient myths, including the following:

- Adrienne Mayor (2018a, 2018b, 2018c, 2023) study;
- Ekwere (2024) study;
- Gasparetto & Scalera (2018);

– Scalera, Gasparetto, Seriani, & Gallina (2024).

Such sources are extremely important for several reasons, especially if you are working on a study that addresses symbolism or futuristic concepts (such as artificial intelligence or utopian narratives) in literature, whether classical or modern. The key aspects of their importance include:

Mythological and intellectual roots of technology and symbolism:

– these sources provide insights into how ancient civilizations imagined concepts similar to artificial intelligence and machines, through myths like talos (the bronze automaton) and pandora;

– this reinforces the idea that technological symbolism is not a product of the modern era, but has deep roots in literature and mythology.

Expanding analytical horizons:

– by linking the past with the present, these studies allow for comparisons between ancient and modern symbolic representations, enriching the reader's or researcher's understanding of the topic;

– this is particularly useful when studying the symbolism in modern utopian novels that engage with artificial intelligence or technological utopian societies.

Theoretical support and contextual analysis:

– they provide a historical and theoretical foundation for understanding the development of ideas related to artificial intelligence and technology;

– this is crucial for framing and analyzing modern symbols in utopian novels, particularly when machines or artificial intelligence are presented as symbols or metaphors.

Supporting the interdisciplinary overlap between literature, philosophy, and technology:

– these sources represent multidisciplinary approaches, which enhances the scholarly value of any study that relies on them, especially when integrating literature, mythology, and technology.

These aspects collectively emphasize the importance of these sources in bridging the gap between ancient mythological concepts and modern technological explorations, offering both historical depth and interdisciplinary connections for studies on symbolism, artificial intelligence, and futuristic narratives in literature.

Originality of the Study.

Whereas earlier works had for the most part consisted of either the technical development of automata or the philosophizing and myth-constructing nature of man-made objects, the paper conducts an exhaustive treatment on ancient robotics and artificial intelligence situated between myths as well as analytical commentary. Exploring both fictional accounts (like Talos, Pandora, Chinese and Indian automata) and ancient mechanical inventions, it reveals the conceptual connection between early realization of technology and imagination. Provides a conceptual map, as described by the figures in the paper, which outlines the evolution of the mythological mode of imagining to the modern understanding of artificial intelligence, thereby offering a pictorial tool never before available in the literature. Under this paradigm, the present work completes the gap in the literature by interweaving so far unrelated elements of mythology, ethics, and mechanical engineering. It also situates itself in the history allowing for an intrinsic understanding of the evolution of artificial intelligence.

Study Methodology.

The historical approach in studying a topic like "Artificial Intelligence and Robots in Ancient Times: Between Myth and Interpretation" is fundamental because it allows the researcher to track the development of concepts and perceptions related to technology and artificial intelligence across different eras. The importance of this approach lies in:

1. Reconstructing historical and cultural contexts. Through this approach, we can understand how ancient civilizations perceived technology and artificial beings, like robots, within a mythical or philosophical framework. This helps in understanding how these ideas developed and transitioned to modern civilizations.
2. Tracking the evolution of perceptions. The historical approach helps track the perceptions of artificial intelligence that existed in ancient times, and how these ideas inspired modern thinkers and scientists. For example, studying myths like "Talos" or "Pandora" provides insight into the early origins of the idea of beings that mimic humans.
3. Connecting the past with the present. The historical approach allows for connecting ancient myths and philosophical ideas with contemporary concepts in artificial intelligence. This connection enhances a deeper understanding of how technology and our perceptions of it have evolved over time and how myths have contributed to shaping this perception.
4. Drawing lessons. Through this approach, we can derive lessons and insights from ancient human experiences in dealing with artificial beings and technology.

In short, the historical approach is an effective tool for understanding the cultural, philosophical, and historical roots that shaped modern perceptions of artificial intelligence. Through it, we don't just study the facts and developments of today, but also the origins of these concepts in ancient times, offering a broader and deeper perspective in AI studies.

Sources on artificial intelligence and robots in ancient times were gathered with a focus on studies that avoided the history of these ideas early in their development. Some of the sources were interpreted using a historical-analytical analysis, and all of them were peer-reviewed scholarly articles. The research also explains the criteria used to select references, whether ancient or existing studies on early mechanical machines.

Besides, a survey of recent literature found that there was increasing interest in research comparing myth and early technology, with increasing focus on the ethical and historical implications of artificial intelligence, and comparative research across cultures in determining the evolution of ideas about smart machines and artificial persons.

What is Artificial Intelligence?

Artificial intelligence (AI) is a field that aims to create systems capable of mimicking human cognitive functions. It involves developing technologies that can perform various tasks traditionally requiring human intelligence. (Jiang et al, 2017; Kovanov, 2024)

Key aspects and capabilities of AI include:

– Mimicking Human. Intelligence AI systems are designed to simulate human-like thought processes, reasoning, and learning abilities. (Jiang et al, 2017; Bubeck et al, 2023);

– Problem-Solving. AI can solve complex problems through methods like searching, logical reasoning, planning, and making decisions under uncertainty. (Sumadevi,2024);

– Learning. A significant component of AI is the ability to learn from observations and data, utilizing techniques such as machine learning, neural networks, and reinforcement learning. Modern AI models, like large language models, are trained on vast datasets and can exhibit general intelligence across diverse tasks such as mathematics, coding, and vision, often performing at or near human-level capabilities. (Negnevitsky, 2005);

– Applications. AI is applied across numerous domains, including healthcare for diagnosis, treatment recommendations, and patient engagement; service industries for automating tasks; and various scientific research ar eas (Alowais et al, 2023);

– Components and Techniques. The field encompasses methods such as rule-based expert systems, fuzzy expert systems, artificial neural networks, evolutionary computation, and natural language processing. Recent advancements include "foundation models" and "generalist medical AI" that can perform diverse tasks with minimal specific training data (Alowais et al, 2023).

The goal is to develop intelligent agents that can perceive their environment and take actions to maximize their chances of achieving goals.

Previously, specialists handled everything related to software and applications, from their creation to their updates, development, and final release on the internet. Now, AI performs all those tasks, often surpassing the ability and potential of some specialists in their respective fields. The goal behind this is to create systems and data that are available for self-learning without human intervention and with abilities that exceed human capabilities. This is achieved by feeding large and highly accurate amounts of data into the computer, enabling it to answer any question according to patterns and algorithms, eventually allowing it to work independently in the future, AI can save the time and effort spent by specialists in creating data or software related to a specific knowledge base. Instead of spending extensive time on these tasks, AI tools can generate such data in minutes or even seconds (Floridi, 2023).

The fields of AI are vast and varied. It is not limited to extracting educational knowledge data or creating visual, auditory, or written content. AI has advanced to perform practical tasks that substitute for human labor, such as programming factory machines, performing administrative tasks like archiving, writing programming code, developing websites, and others, with minimal errors, or with error rates significantly lower than those associated with human work (Renda & Engler, 2023).

The rapid and phenomenal rise of AI technology has finally rattled the confidence of many specialists in their respective fields and caused a widespread reluctance among programmers and electronics experts to venture into this domain. This is because, with the AI revolution, the need for many of these programmers has diminished, as the better and more efficient alternatives are now available for free (Alalaq, 2025; Ahmad et al., 2023).

With the rapid acceleration of the artificial intelligence revolution, intelligent robots have emerged as one of its most prominent achievements. These robots now possess advanced capabilities in self-learning, adapting to various environments, and making independent decisions without direct human intervention. Robotics as a field has witnessed remarkable development since its inception, contributing to profound transformations across numerous industries and societies–from manufacturing and healthcare to education and logistics (Trovato, Mavridis, Huerta-Mercado, & Chellali, 2021).

The field of robotics has witnessed significant advancement, driven by progress in artificial intelligence and machine learning technologies. These developments have enabled robots to learn autonomously and make independent decisions. Additionally, precise sensors and advanced actuators have enhanced robots' ability to interact with their environment, while innovations in materials science have improved their flexibility and durability (Wang & Siau, 2019).

This evolution has had a clear impact across various sectors. In industry, automation has boosted efficiency and reduced costs. In healthcare, robotic systems have improved surgical outcomes and opened new possibilities in medical procedures. Moreover, robots are playing an increasingly prominent role in everyday life, such as in autonomous vehicles and personal assistants (Raj & Kos, 2022).

Ancient Greek and Roman Myths.

People have been fascinated with the thought of building artificial beings that think and act like humans–or even gods–since ancient times. Long before anyone said "artificial intelligence" old myths were packed with these ideas. Take Greek mythology: Hephaestus, the god known for his craftsmanship, made things like the bronze giant Talos, who stood watch over Crete. He also built golden maidens to help him out in his workshop. This urge to create thinking machines runs deep (Ekwere, 2024). Hephaestus is also credited with creating other mechanisms, such as the golden maidens and the three-legged wheeled carriers, which served both practical and symbolic purposes. These creations were not only marvels of engineering but also reflected societal attitudes of the time, particularly the desire to replace human labor with artificial counterparts (Silverman, 2022; Marcinkowski & Wilgaux, 2004).

Centuries before the advent of robots, the ancient Greeks had already imagined technological beings and forms of artificial life. Both ancient and modern perspectives on technological entities offer us a way to think about the meaning of being human, raising questions about the boundaries between the natural and the artificial, between the human and the non-human, between slavery and freedom, and between mortality and immortality. The narratives about automatons (self-moving machines), such as those presented by Philo and Hero of Alexandria, show that such innovations were not mere products of imagination. Long before science fiction literature depicted dystopian worlds caused by technological human-like beings, the ancient Greeks and Romans expressed concerns about such entities. In ancient literature, robots vary from the beneficial, like the golden maids made by Hephaestus, to the destructive, like Pandora and Talos (see Figure 1). Furthermore, the statue of Pygmalion's Galatea, which closely resembles Pandora, inspired many contemporary works of art, such as the films *Ex Machina* and *Her*. Themes from the stories of Pandora and Galatea appear frequently in 20th and 21st-century literature, such as in the works of Isaac Asimov, Philip K. Dick, and the many films based on their writings (Donovan, 2023).

Figure 1. An imaginary image of the robot (Talos) (Markham, 2023).

The bronze robot Talos and the artificial woman Pandora pop up early in Greek stories, with Hesiod mentioning them way back around 700 BCE. Some old accounts even show the Trojan Horse as a sort of moving statue. Artists loved these ideas, so you'll find Talos, Pandora, and the Horse in vase paintings and other ancient art. Homer was the first to use the word "Automaton" which means something that acts on its own. He used it to talk about the wild inventions of Hephaestus–the god of blacksmiths, inventors, and tech. Hephaestus didn't hold back. He built self-walking tripod stands, automatic bellows, a chair that trapped whoever sat down, mechanical gates, robot guard dogs, and even a whole crew of golden robot servants. (Mayor, 2018a). The earliest artistic depictions of Talos and Pandora appear on Greek vases dating back to the 5th century BCE. The earliest artistic representation of the Trojan Horse is on an ancient vase dating back to around 670 BCE. The recording of this literary and artistic evidence, over two thousand years old, marks a significant milestone in the history of ancient technology (Mayor, 2023).

The construction of Talos and other bronze figures, and their ability to perform specific tasks, makes them one of the earliest ideas of a robot of ancient Greek philosophy (Christodoulou & Tsoucalas, 2023; Donovan, 2023), indicating the level of automation that was developed in the mythological era (Figure 2). Talos exemplifies the modern definition of a robot, containing an internal mechanism and its own source of energy. According to ancient texts, a vein or conduit extended from his head to his feet, a tube that pulsed with ‘ichor,’ the vital fluid that flowed through the veins of the immortal gods (Mayor, 2023). Talos was half machine and half human, walking around the island at high speed three times a day, searching for strangers. "Programmed" with something akin to artificial intelligence, he was capable of interpreting his surroundings and interacting with them. When he saw invaders approaching by sea, he threw rocks to sink their ships from a distance. Talos would heat his bronze body until it turned red and crush men to his chest, roasting them alive. Jason and his Argonauts, in the myth, defeated Talos with the help of sorceress Medea, who knew where Talos' weak spot was and she also understood that despite his metallic heart that is not powered by electricity but magic his body had its limits as he looked half-man/half-machine. Talos, on Medea's persuasion, allowed Jason to take out the bolt from his ankle, which let the ichor or life fluid pour out and made him hemorrhage to death (Mayor, 2023).

Figure 2. A silver coin depicting Talos with wings and rocks on each hand. 5th century BC (Lykiardopoulou, 2023).

Talos' role in mythology extends beyond his physical form; he symbolizes the power and potential of technology, where machines were designed to serve and protect human interests. His bronze body and mechanical movements also represent the fusion of natural and artificial elements, blurring the lines between living beings and machines (Liveley, 2023). This highlights how the evolution of modern artificial intelligence systems reflects humanity's ongoing fascination with creating machines that can think and act independently. While Talos was a product of mythical imagination, his conception laid the groundwork for the philosophical and technological explorations that would follow in the centuries to come (Duymaz & Şahin, 2023; Christodoulou & Tsoucalas, 2023).

We can say that the story of Talos shows that the ancient Greeks anticipated that artificial intelligence, similar to humans, should take a human form and have a similar bodily structure. However, it should be capable of accomplishing things that humans cannot. For instance, Talos was able to turn into fire and ward off enemies, something humans are incapable of doing.

Pandora: The First Artificial Human.

Pandora, another invention of Hephaestus, is often regarded as the first artificial human (see Figure 3). She was made from clay and gifted with life by the gods, sent to Earth as a punishment for humanity. Her story raises questions about the boundaries between natural and artificial life, as well as the ethical implications of creating sentient beings (Mayor, 2023; Domouzi & Bär, 2024; Koetsier, 2019).

Figure 3. A vessel depicting the creation of Pandora. In the upper row, Pandora stands in the center facing forward, a position typically used for inanimate beings. To her left stand Athena and Poseidon, and to her right stands Ares, looking at Hermes. In the lower row, there is a chorus of Panes. 5th century BC (Lykiardopoulou, 2023).

Pandora – a fascinating creature often referred to by Mayor as the "robotic female". Pandora was sent to Earth with a jar to be the wife of Epimetheus, the brother of Prometheus. Although Prometheus warned Epimetheus against accepting gifts from Zeus, Epimetheus took Pandora as his wife but forbade her from opening the jar. However, it was Zeus who had commanded (or perhaps programmed) her to open the jar. When she finally did, all the afflictions of humanity–diseases, aging, madness, famine, and all kinds of suffering and misery–were unleashed (Hurt, 2022).

Name In the history of Pandora, your future is titled "all gifts", a reference to all the gods that worked on her production after she was created in Hephaestus' forge. Hermes followed the seductive lady to Earth and Pandora was married as a bride to Epimetheus. As dowry, she came with the sealed, mysterious jar of ill haps that held additional "gifts" as well. Pandora was herself created as punishment for humanity accepting the gift of fire from Prometheus. In essence, she was a female robot with no parents or childhood memories and no feelings whatsoever and she would never age and die" She was made to do only one wicked act: to go into the world of men and open the jar. The ancient image of Pandora dancing with fear as an evil cloud comes forth out of the jar is new. Similarly, the sickening image of hope coming out of the jar to calm men's hearts is new too. In Greek representations, Pandora is also depicted as a clever trick: the most celebrated vase painting of her consists of a young woman standing boldly with a creeping smile (Mayor, 2018c).

Trojan Horse: A Marvel of Engineering.

The Trojan Horse, although not strictly a robot, is another example of Greek ingenuity in creating self-moving entities (see Figure 4). In some accounts, the Trojan Horse is depicted as a moving statue, focusing on the fusion of technology and art in ancient Greek thought (Mayor, 2023; Domouzi & Bär, 2024).

Furthermore, the ancient Greeks explored concepts of mind, intelligence, and consciousness through their philosophical research, especially in the works of philosophers such as Plato and Aristotle. Although their understanding of intelligence was based on human perception rather than mechanical computation, their ideas about the nature of intelligence and logic laid the foundation for future discussions on artificial intelligence (Andrion, 2023).

Many stories are also mentioned that the inventors created things called "automata", which were mechanical and moved independently of human intervention. The term "automatic" comes from ancient Greek, which means "plays of the will", and one of the first items of an automatic comes from about 400 BC, referring to a mechanical pigeon invented by a friend of philosopher Plato. Many years later, Leonardo da Vinci invented one of the most well – known slots around 1495 AD. (Tableau, n.d.).

Many of the crucial methodological issues surrounding artificial intelligence have echoed through the field of philosophy for millennia. Philosophers as diverse as Aristotle, Saint Thomas Aquinas, William of Ockham, René Descartes, Thomas Hobbes, and Gottfried W. Leibniz posed skeptical questions like the following ones:

"What are the basic processes of cognition?", "What must the formal language do in order to provide an adequate medium for accurately and uniquely describing the world?", and "Can thought be automated?" (Flasiński, 2016). All of these questions were of interest to scholars of ancient times and are, in themselves, hypotheses related to the possibility of developing machines that can think as humans do and perform their daily tasks and work.

Figure 4. The horse's hind leg is unfinished. On the wall behind of Athena, goddess of crafts and wisdom, creating a clay model of a realistic Trojan horse to be cast in bronze (Mayor, 2023).

Greek engineering also demonstrated these innovative ways of extending human elements to include machines and similar technologies. Shortly after the beginning of the Anno Domini era, an engineer named Ctesibius invented hundreds of machines using hydraulics and pneumatics, which were engines that worked automatically using compressed air. His other works included steam-powered military turbines. Around 400 BC, Before the end of the fifth century BC the polymath Archytas invented a mechanical bird powered by steam. Later, scientists invented moving figures capable of making sounds, opening doors, and even attacking. These methods of automation formed the primitive approaches to attributing human traits to machines (Ahistoryofai, n. d.).

Ancient Chinese Civilization.

The concept of robotics is rooted in ancient Chinese history, both in myth and early mechanical inventions. Historical accounts suggest that the idea of automata was not only prevalent in Western civilizations but also found expression in ancient China, where inventors like King-su Tse created mechanical devices around 500 BC. This reflects a broader human fascination with artificial beings designed to perform tasks traditionally carried out by humans.

There are references to "King-su Tse" in classical China, who invented a self-moving machine (automaton) around 500 BC. Archytas of Tarentum (circa 400 BC) is considered the father of mechanical engineering and one of the classical masters of Western robotics (Fron & Korn, 2019).

Ancient texts also describe Yan Shi, a craftsman who created automated machines capable of singing and dancing. Yan Shi used a system of gears and pulleys to move the machines, demonstrating his early understanding of mechanical engineering. King-su Tse is renowned for his creation of automata, showcasing early Chinese ingenuity in the field of robotics (Sánchez Martín et al., 2007). These inventions were often designed for entertainment or to demonstrate technological prowess, similar to their Western counterparts. The creation of robots in ancient China can be seen as a reflection of societal values, where technology was intertwined with myths and philosophy (Fron & Korn, 2019).

Chinese myths also highlight artificial intelligence. Yueying Huang, the wife of the famous Chinese historical advisor Zhuge Liang, was skilled in making "artificially intelligent machines". It is said that Zhuge Liang was so impressed by her intelligence that he decided to marry her. When he first visited Huang's home, he was greeted by two large dogs. The dogs rushed towards him aggressively, prompting two servants to strike their foreheads and stop them. Upon closer inspection, Zhuge Liang discovered that the dogs were, in fact, wooden machines. He laughed, showing his appreciation for Huang's wisdom. These mechanical dogs represent another form of artificial intelligence in ancient folklore. They suggest that humans should have the ability to start or stop artificial intelligence. When given a stop signal, the mechanical dogs immediately cease (Tian, 2017).

Ancient Indian Civilization.

In Hindu mythology, King Ravana had a flying chariot called *Pushpaka Vimana*, which was capable of moving independently and following his commands (Ekwere, 2024). Buddhist myths from the fourth and third centuries BC, focusing on northeastern India, tell of an army of machines guarding the relics of Buddha, created with knowledge smuggled from the Greek-speaking world. In one of them, where the robot killers as well as the robot guards coexist, there was a young man who disguised himself and went to the country of Yavana so as to learn the trade of constructing machines, the tightly kept secret of the Yantakāras (machine craftsmen). He then snatched the knowledge and made the first artificial guards. There exist accounts of robotic warriors who protected Buddha's relics in Chinese, Sanskrit, Hindu, as well as Tibetan literature (Truitt, 2021).

Between the second and fourth centuries, the Buddhist tale of an alluring female robot appeared in *Mahāvastu*. This lifelike girl, known as *Yantrāputrikā* ("the mechanical girl"), captivated an artist who was called by the robot's inventor. When the artist touched the robot, it broke into pieces. The artist took revenge on the inventor by creating a hanging corpse of himself. When the inventor woke up and believed the artist had died, he alerted the king. Upon the king's arrival with ministers and other citizens to witness the scene, the artist emerged from his hiding place and revealed that the corpse was a fake, showcasing the lifelike realism of both the robot and the corpse–illusions of self-control. The Buddhist saying "We are all robots" reflects the lack of spirit in all beings. Robotic guards appeared in Buddhist mythology during the reigns of Kings *Ajatashatru* and *Ashoka* in India. Ajatashatru designed robotic warriors to defend Buddha's relics using a powerful catapult and war chariot. The chariot was a robot with rotating clubs and swords. These robots were inspired by Greek-Roman machines, as King Ashoka communicated with Hellenistic rulers via ambassadors (Ahistoryofai, n. d.).

Since ancient times, human imagination has been preoccupied with the possibility of creating humanoid beings capable of movement, decision-making, and sometimes even thinking. These ideas clearly appeared in Greek mythology, such as in the tale of *Talos*. With the evolution of science fiction in the 19th and 20th centuries, these ideas became more aligned with science, as seen in works like Mary Shelley's novel *Frankenstein*, which can be considered the first literary depiction of creating an intelligent being through technology. This type of literature later inspired developers and scientists to dream of producing intelligence that could think and interact with humans (Shelley, 2020).

Moreover, the Roman civilization witnessed the production of a heritage that spoke of intelligent robots. It is said that the Roman poet Vergil has designed a series of wood sculptures, each representing a province of the Roman Empire, which plays a clock if the province was threatened with rebellion. A bronze rider pointed to danger. In Troy's book history we find six Golden Mechanical Devices, including four robot machines, which monitored the entire Trojan court for any deficiency in dress, behavior, speech or even in mind, while we also provided entertainment. (Trovato, Mavridis, Huerta-Mercado, & Chellali, 2021). Courtiers could relax, knowing they wouldn't make any unintentional mistakes, and neither would anyone else, while rulers could relax, knowing that no one in the Trojan court was spreading misinformation or conspiring against them. Philip II "the Good," Duke of Burgundy, used part of his vast wealth to install many automata, trick fountains, and other mechanical devices in his castle of Hesdin in Artois, where guests found themselves tested in a long corridor filled with automata and other devices that drenched them with water, covered them in dirt and flour, struck them with sticks, and cursed them with foul names, while the duke or his agents watched without being seen (Truitt, 2021).

Thus, the roots of artificial intelligence stem not only from modern technological developments but from a long history of myths and stories that have shaped human imagination around robots and artificial consciousness.

Ancient Egypt.

The ancient era witnessed remarkable achievements in the creation of automated devices and mechanical servants across multiple civilizations. From the priest-operated statues of ancient Egypt around 2500 BCE to the sophisticated automata described in Chinese texts and the mechanical marvels of Hellenistic engineers, ancient peoples demonstrated extraordinary creativity in designing self-operating machines. These early robots served various purposes: religious devices that inspired awe in temple visitors, entertainment automata that delighted royal courts, practical mechanisms for timekeeping and water distribution, and philosophical demonstrations of mechanical principles. The technological innovations of this period, including the use of hydraulics, pneumatics, cam mechanisms, and feedback systems, established fundamental principles that would influence automation and robotics for centuries to come (Al-Masry Al-Youm, 2022).

In ancient Egypt, early attempts emerged to create self-operating machines and mechanical devices that amazed people and served both religious and practical purposes. Around 2500 BCE, priests used hollow statues in which they could hide and manipulate movable parts to make the public believe the statues were alive, thereby reinforcing awe and religious devotion. By 2000 BCE, mechanical theatrical models appeared, such as a platform on which three dwarfs stood, moving through an interconnected system of rollers and strings to perform dances. In the sixteenth century BCE, the Egyptian official Amenemhat was credited with inventing the water clock, one of the earliest instruments for measuring time. Texts dating to around 1100 BCE also described moving statues built with relatively advanced mechanical techniques. During the Ptolemaic era in Alexandria, the inventor Ctesibius (285–250 BCE) distinguished himself by creating musical instruments such as the water organ, self-regulating water clocks, moving statues, and mechanisms based on compressed air and bronze springs. Engineers in Alexandria continued in the third century BCE to develop moving figures of humans, animals, and mythological beings, integrating them into royal ceremonies. Thus, it becomes clear that ancient Egypt was not only the cradle of religious and political civilization but also a pioneer in laying the earliest foundations of automata, which would later influence the course of mechanics and robotics throughout the ages (Colwell, 2025).

Ancient Myths as Intellectual Roots for Contemporary Artificial Intelligence.

Modern studies reveal that ancient myths were not merely symbolic tales but served as early frameworks for understanding the concept of "artificial intelligence" long before it evolved into a scientific and technological pursuit. Research published in various journals highlights this connection:

1. "The Journey of Artificial Intelligence Through Time: From Homeric Myths to Modern Algorithms" (Mohsen, 2025) – This recent article explores the evolution of the idea from myths such as Homer's *Talos* to Aristotelian philosophy and ultimately to contemporary algorithmic systems.
2. Recent academic research in philosophy and the history of technology indicates that myths like *Prometheus* and *Icarus* are being revisited today as symbolic frameworks for understanding the ethical risks of AI – such as excessive ambition and the defiance of natural limits.
3. The *Handbook of Geospatial Artificial Intelligence* (Couclelis, 2023) discusses the evolution of geospatial AI from its mythological roots, such as the legend of *Talos*, to its modern scientific manifestations from Turing to the present day. The work shows how general and specialized meanings of AI intersect, ranging from programming and neural networks to speculation and humanism, within a broader debate on the boundaries and potential of intelligence.
4. A study in the *European Journal of Therapeutics* titled *"From Ancient Mythology to Modern Technology: The Historical Evolution of Artificial Intelligence"* (Duymaz & Şahin, 2023) demonstrates that ancient myths – such as that of *Talos* and other intelligent autonomous beings–reflect humanity's early imagination of artificial intelligence. This symbolic heritage has persisted throughout history, finding tangible expression in modern innovations like robots and surgical systems, revealing a profound continuity between mythic past and technological present.
5. Digital anthropology studies show that modern societies continue to use mythological archetypes–such as the "obedient servant" and the "rebellious monster"– to interpret artificial intelligence, just as myths once served to explain natural phenomena.
6. An article published in *SAGE Journal* under the title *"Artificial Life"* (Belk, Humayun, & Gopaldas, 2020) emphasizes that attempts to create "artificial life" date back to ancient myths. Cultural symbols such as *Pygmalion*, *the Golem*, *Frankenstein*, and *Metropolis* continue to influence public perception of modern technologies. The study highlights that contemporary approaches to Artificial Life (AL) span biochemical, mechanical, and computational domains and extend into posthumanist thought–calling for ethical frameworks that balance scientific ambition with human dignity and safety.

Collectively, these and other studies demonstrate how mythological figures like *Prometheus* and *Talos* have been revived to interpret the aspirations and risks associated with artificial intelligence. Philosophical and historical research suggests that such myths functioned as an "imaginary laboratory," shaping early conceptions of non-human beings. This explains the deep historical continuity between mythic imagination and scientific innovation. Thus, analyzing these paradigms offers a deeper understanding of the intellectual roots of AI, revealing that today's technological reality is not a rupture with the past, but rather an extension of a long-standing dialogue between symbol and reality (see Figure 5).

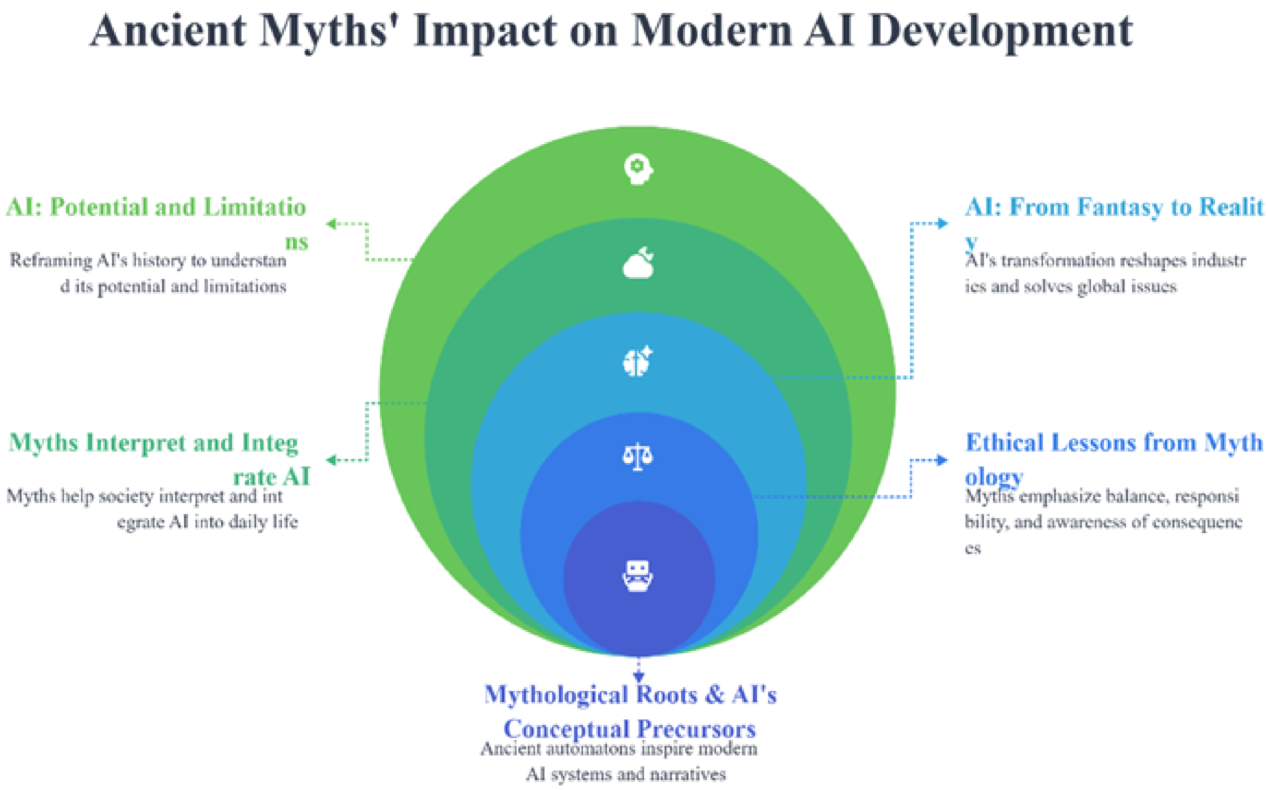

Figure 5. The influence of ancient myths on the development of modern Artificial Intelligence (Author' Source).

Let's take a look at this figure from a historical angle – It's not just a cluster of overlapping circles, but a map that links the mythic past to our tech-savvy present.

1. The mythical origins and the start of the concep. Right in the middle, we've got "mythical roots and the early beginnings of AI. Historically, since the earliest civilizations (Sumerian, Egyptian, Greek), people have always dreamed up or thought of artificial beings or gods giving them wisdom. The myth of Prometheus, who gave fire to humans, or Talos, the bronze man of Greek mythology, are early models of a non-human entity with extraordinary powers. This mythological idea was the first spark that led to the concept of making an "artificial mind.

2. Ethical lessons from myths .The second layer points to "ethical lessons." Myths weren't just random tales; they were cautionary tales, like the story of Icarus, who flew too close to the sun with his wax wings and ended up crashing. This symbolism is like

today's talks about the dangers of AI: pushing too far, being overconfident in science, and needing to be responsible.

3. From imagination to reality. The Industrial Revolution and the 20th century turned myths into legit science projects, what used to be in epic tales got turned into calculators, robots, and then smart systems Here we see how humanity's intellectual history shifted from "mythical dream" to "technological reality," just as myths about nature eventually became astronomy and medicine.

4. Myths as tools for interpreting modernity. Societies have always needed symbols to make sense of the new stuff. Just as people in the past turned to myths to understand the natural world, today we turn to them to describe artificial intelligence and technological developments:

– Is it a "loyal servant" like the enchanted gadgets in those old stories?
– Is it like a "threat" from those wild, mythical beasts that go against the norm?

This shows historical continuity: Humans deal with the unknown by telling stories that have deeper meanings.

5. Potentials and limits of artificial intelligence :the outer layer shows us that every progress has its boundaries. Modern history draws boundaries between humans and machines, just like myths did between humans and gods.

This historical dimension reminds us that every technological innovation is an extension of the ancient struggle between human ambition and natural or ethical constraints.

The figure illustrates that artificial intelligence is not merely a modern invention, but the continuation of a long trajectory beginning with ancient myths, passing through philosophy and ethics, and eventually transforming into science and technology. Myths acted as the *"first laboratory"* for humanity's ideas about non-human minds.

Ancient myths and early technological innovations formed a mirror reflecting humanity's conception of the idea of "artificial life" since the earliest ages. From the first civilizations, imagination was never separate from practical experience; rather, myth intertwined with early engineering attempts to embody the notion of manufactured beings or intelligent machines. This overlap between the symbolic and the scientific dimensions produced a rich legacy of examples that combine mythological imagination with mechanical innovation, making the study of these models a gateway to understanding the roots of thought on artificial intelligence and robotics throughout history.

In addition to what has been previously mentioned in the course of the research, Table 1 below presents analytical examples of the most prominent models introduced by the Egyptian, Indian, Chinese, Greek, and Roman civilizations, showing how they varied between myth and historical interpretation (Mayor, 2018b; Singh, G., Bhadauria, & Singh, S., 2025; Roy, 2021; Mingren, 2016; Truitt, 2021; LaGrandeur, 2012; Duymaz & Şahin, 2023).

Table 1. Analytical examples of the most prominent models (Author' Source).

Civilization	Time Period	Main Examples	Interpretation: Between Myth and Explanation
Ancient Egyptian	Around 3000 B.C. – 30 B.C.	Moving Shabti statues in tombs, and divine statues moving in temples using hydraulic or magical mechanisms, such as those that move or speak to serve the gods or the dead.	Mythically: Manufactured beings not born, reflecting a belief in divine artificial life. Historically: References to simple mechanisms such as statues moving by steam or pulleys, reflecting early engineering progress that influenced later civilizations.
Ancient Indian	Around 1500 B.C. – 500 B.C. (the Vedas and epics)	Yantra as mechanical devices or robots, such as Yantra-Purusha (human robots) in the Mahabharata and Ramayana; Pushpaka Vimana (intelligent flying craft); Buddha's guards as robots in myths.	Mythically: Artificial beings created by the god Vishwakarma or the sorcerer Maya, reflecting ideas of artificial intelligence that protects or serves. Historically: References to advanced engineering devices in Vedic texts, such as automated systems resembling modern robots, with philosophical links to intelligence.
Ancient Chinese	Around 2000 B.C. – 220 A.D. (Xia, Qin, and Han dynasties)	Mechanical dolls that dance or sing in the text *Liezi*; inventions of Zhang Heng such as the automatic seismograph; mechanical automata such as the South-Pointing Chariot.	Mythically: Stories of artificial living beings, such as a mechanical singer deceiving the king. Historically: Real advanced mechanical devices, such as water clocks and moving dolls, reflecting engineering progress resembling primitive robots.
Ancient Greek	Around 800 B.C. – 146 B.C.	Talos, the bronze guardian robot; Hephaestus' automata such as golden maidservants; Pandora as an artificial being; Hero of Alexandria's devices such as automatic doors and hydraulic machines.	Mythically: Beings created by the gods, expressing dreams of artificial life. Historically: Real engineering innovations such as steam and automatic machines, a prelude to artificial intelligence.
Ancient Roman	Around 753 B.C. – 476 A.D.	Continuation of Greek myths such as Vitruvius' automata; hydraulic and mechanical devices in theaters and temples; stories of moving statues and war machines.	Mythically: Repetition of Greek myths with a focus on control and danger. Historically: Practical applications of Greek devices, such as the hydraulic organ and automatic machines, with links to military engineering.

Conclusion and Future Trends.

The historical interest in artificial intelligence and robotics reveals a long journey of intellectual explorations and practical experiments. Perspectives on these modern technologies vary, ranging from concerns about losing control over what we have created, to great hopes for improving the quality of life and enhancing human capabilities.

The development of artificial intelligence from old myths to modern applications reflects the changes that occur in our understanding of the world around us. In this context, we see that a balanced and durable understanding of this technique gives us a challenge for us, which requires considerable thinking and insight into how it should be used to ensure progress without compromising human values.

In conclusion, drawing lessons from ancient myths and stories gives us keys to understanding the complex relationships between humans and technology. As we look toward the future, we must strive to create an open dialogue that includes all concerned parties, including scientists, philosophers, and communities, to ensure that the course of artificial intelligence serves humanity and achieves the necessary balance between innovation and responsibility. If used wisely, artificial intelligence and robotics can contribute to building a better, more harmonious, and cohesive world.

The near future of industrial robotics lies in the transition from the "automated machine" to the "intelligent partner", enhancing productivity and reshaping the relationship between humans and technology within a more ethically and environmentally conscious framework.

Historical studies on the development of industrial robots, from *Unimate* to the *Delta Robot*, indicate that the future is moving toward a new phase characterized by adaptive intelligence and human–robot collaboration. Robots are no longer merely mechanical tools for automation; rather, they are gradually evolving into intelligent systems capable of self-learning and interacting with dynamic work environments. The most prominent anticipated future directions Modern studies indicate that the future of industrial robotics is moving toward a new phase characterized by adaptive intelligence and close collaboration between humans and machines. In this context, several significant future directions emerge, most notably strengthening the role of collaborative robots (Cobots) that work side by side with humans in flexible and safe production environments, and integrating artificial intelligence and machine learning technologies to enable robots to make more autonomous decisions.

The future also points toward expanding into new applications beyond traditional industry–such as agriculture, healthcare, and logistics–alongside the development of smaller and more flexible robots capable of performing highly precise tasks in advanced fields such as microelectronics and medicine.

In line with global efforts toward sustainability and the green economy, robots are increasingly being employed to improve energy efficiency and reduce industrial waste (Gasparetto & Scalera, 2018). One of the most striking examples of how ancient mythological aspirations have been transformed into tangible technological achievements is the development of drawing robots. The academic study *History of Drawing Robots* (2024) documents the historical evolution of this technology, illustrating how the idea of a machine capable of imitating human creativity evolved from a philosophical dream into an advanced technological reality.

As drawing robots continue to evolve and their creative capacities expand, age-old philosophical questions persist with even greater force: Can a machine truly create? What distinguishes human art from machine-generated art? And is self-awareness a necessary condition for artistic creativity?

These questions, implicitly raised by ancient myths, find partial answers in contemporary practice, yet they remain open to philosophical and ethical debate. Thus, the dialogue between the mythological past and the technological present continues – affirming that the fundamental questions of creativity, consciousness, and humanity transcend both temporal and technological boundaries (Scalera, Gasparetto, Seriani, Gallina, 2024).

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Штучний інтелект і робототехніка в давні часи: Між міфом і тлумаченням

Анотація. *У цьому дослідженні розглядається концепція штучного інтелекту та робототехніки в контексті давніх часів, коли філософи й учені стародавніх цивілізацій, таких як Греція та Китай, намагалися уявити істот, здатних мислити й взаємодіяти, уособлюючи тим самим прагнення людства перевершити межі своїх біологічних можливостей. Ці ідеї проявляються в міфічних постатях, таких як Голем і Автомати, що свідчить про давнє людське захоплення ідеєю створення розумних істот. Дослідження має важливе значення, оскільки допомагає зрозуміти історичні корені культурних уявлень, які сформували сучасну концепцію штучного інтелекту. Воно також порушує питання щодо меж між міфом і реальністю та щодо того, що насправді можна досягти. Ці питання стосуються людських амбіцій у порівнянні з технологічними можливостями, порушуючи етичні аспекти та необхідність встановлення меж для таких інновацій. Крім того, дана тема сприяє аналізу філософської та культурної думки у взаємодії людини й машини, що поглиблює наше розуміння складної взаємодії між людиною та технологією в сучасному світі. Таким чином, ця тема є своєрідним мостом між минулим і майбутнім, де стародавні міфи можуть допомогти нам спрямувати розвиток штучного інтелекту та робототехніки у гуманістичному та етичному напрямі. Варто зазначити, що звернення до цих давніх уявлень не обмежується лише історичним* *виміром, а й відкриває шлях до розуміння того, як людська уява завжди була головною рушійною силою наукового та технологічного прогресу. Міфи, створені стародавніми цивілізаціями, не були просто символічними оповідями; вони становили початкову основу для роздумів над питаннями, що залишаються актуальними й сьогодні – такими як межі свідомості, можливість імітації людського розуму та сутність людської природи. Переосмислення цих міфів у світлі сучасних досягнень штучного інтелекту й робототехніки дає змогу по-новому осмислити наше ставлення до технологій – не лише як до корисного інструменту, а як до культурної та етичної сили, що вимагає критичної свідомості та спільної відповідальності.*

Ключові слова: *стародавні цивілізації; роботи; греки; штучний інтелект; міфи; вічне життя*

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Development of Ukrainian mechanics: Context of scientific publications by Kharkiv scientists of the 19th century

Abstract. *This study presents a comprehensive historiographical and content analysis of the development of Ukrainian mechanics in the 19th century, examining scientific publications by Kharkiv scientists through a historical lens. Special attention is paid to the institutional and intellectual contribution of Kharkiv University and Kharkiv Institute of Technology, which together created a unique scientific ecosystem that promotes both theoretical and applied research in the field of mechanics. The study uses an interdisciplinary methodology that combines a historical approach, a content analysis of primary sources, and bibliometric methods to track thematic trends, terminological evolution, and the dynamics of scientific communication. The results of the study indicate that during the 19th and early 20th centuries, Kharkiv emerged as a significant scientific center in the Russian Empire and Eastern Europe. Theoretical mechanics at Kharkiv University flourished thanks to the work of prominent scientists such as O. M. Lyapunov, V. A. Steklov, and I. D. Sokolov, who laid the foundations of modern stability theory, nonlinear dynamics, and mathematical modeling of mechanical systems. At the same time, Kharkiv Institute of Technology developed applied mechanics under the leadership of V. L. Kyrpychov and his colleagues, innovators in research in the field of strength of materials, structural engineering, machine design, and industrial technologies. The analysis highlights the notable synergy between the two institutions, reflected in inter-institutional training, joint research efforts, and the formation of powerful scientific schools. The publication activity of Kharkiv mechanical scientists showed a wave-like trend, reaching a peak between 1880 and 1905, driven by the demands of industrialization and international scientific integration. This period marked a paradigm shift from isolated intellectual efforts to systematic, collaborative scientific production. This article argues that the legacy of Kharkiv mechanical science lies not only in the creation of advanced theoretical constructs, but also in the institutionalization of technical education and research, which significantly contributed to the modernization of Ukrainian and Eastern European engineering sciences. The conclusions drawn from this study offer* *a deeper understanding of the processes of knowledge production, transfer, and adaptation in the context of scientific globalization of the 19th century. The results of the study show that institutional cooperation between Kharkiv University and the Technological Institute contributed to the creation of a unique scientific ecosystem, which ensured the effective development of mechanics as a scientific discipline. The article reveals the importance of this process for the further formation of Ukrainian technical thought in the 20th century and emphasizes the significance of the legacy of Kharkiv scientists in the global context of the history of science.*

Keywords: *history of mechanics; Kharkiv Scientific School; scientific publications; institutional history; theoretical and applied mechanics; scientific communication*

Introduction.

The development of natural sciences in the 19th century was of particular importance for the formation of scientific thought in Ukraine. Among the fundamental areas that determined the technical and engineering progress of the era, mechanics occupied a special place - both applied and theoretical. Kharkiv, as one of the leading scientific centers of Ukraine at that time, played a key role in the formation of the scientific school of mechanics, laying the institutional, methodological, and creative foundations for its further development. In the 19th century, prominent scientists were active in Kharkiv, whose research in the field of mechanics received recognition both within the Russian Empire and beyond. Scientific publications of Kharkiv scientists of this period reflect the processes of the formation of scientific approaches, the formation of terminology, the adaptation of Western European theories, and the creation of their conceptual models of mechanical phenomena. The study of these publications allows us to trace not only the substantive development of the discipline but also the functioning of the scientific environment, the formation of a network of communications between researchers, and the growing role of university education in the dissemination of scientific ideas.

The purpose of this article is to analyze the formation of the foundations of Ukrainian mechanics through the prism of scientific publications of Kharkiv scientists of the 19th century. The formulated objective is consistent with the ideas presented in relevant publications in international scholarly journals, where the historical development of applied mathematics and mechanics is analyzed in Italy (Martini, 1999), Spain (Martínez-Verdú, Massa-Esteve, & Linero-Bas, 2023), France (Darrigol, 2022), Germany, and the Netherlands (Jahnke, Jankvist, & Kjeldsen, 2022).

The study is based on a historical-scientific approach and content analysis of sources, which allows us to identify key topics, research areas, and the degree of their integration into the international scientific context. Special attention is paid to the role of Kharkiv University (KhU) and Kharkiv Institute of Technology (KhIT) as scientific centers that provided institutional support to scientists and facilitated their scientific and publishing activity.

Literature Review.

The study of the development of mechanics in Kharkiv in the 19th century is based on a broad historiographical background, which includes both classical sources of the early 20th century and modern analytical and biographical works.

The first systematic generalizations of the history of Kharkiv University were made in the works of D. I. Bagalei, I. P. Osypov, D. M. Sintsov, in particular in the publications dedicated to the anniversaries of the university (Bagalei, Sumtsov, & Buzeskul, 1906; Sintsov, 1908; Osipov & Bagalei, 1908), in the article by A. N. Krasnov (Krasnov, 1897). They provide a chronicle of the development of departments, the composition of the teaching staff, and a general overview of scientific activity. However, these works are mostly descriptive in nature and do not offer a deep analysis of the content of scientific publications.

In the biographical view, studies devoted to individual figures are of great importance, in particular, V. I. Albitsky (Gutnyk, 2018), V. G. Imshenetsky (Andreev, 1895), V. L. Kyrpychov (Gavrilyuk, 2007, p. 302), O. M. Lyapunov (Larin & Breslavskyi, 2007). These works allow to reconstruct individual scientific trajectories, explore the directions of mechanics that were developing in Kharkiv, and understand the connections between individual scientists and educational institutions.

Particular attention to the formation of natural sciences and technical education at Kharkiv University was paid by O. Ye. Tverytnykova, N. I. Posviatenko, T. V. Melnyk (Tverytnykova, Posviatenko, & Melnyk, 2015), A. G. Zhurylo, D. Yu. Zhurylo (Zhurylo, A. G. & Zhurylo, D. Yu., 2021), A. S. Lytvynko (Lytvynko, 2025), A. K. Sushkevych (Sushkevych, 1956). Their works indicate the growing role of applied mechanics and mechanical engineering in the late 19th and early 20th centuries. In these publications, the emphasis is on the institutional aspect without focusing on the analysis of the content of scientific publications.

Modern research expands historiography through an interdisciplinary approach. For example, N. O. Pasichnyk, R. Ya. Rizhniak, H. V. Deforzh (Pasichnyk, Rizhniak, & Deforzh, 2023) examine publications in specialized scientific publications (such as the “Bulletin of Experimental Physics and Elementary Mathematics”) as a source for the reconstruction of scientific communication. This approach is valuable for content analysis and can be adapted for the study of Kharkiv publications on mechanics.

Special attention in historiography is paid to the role of foreign professors (Greffe, 1999), who significantly influenced the methodological culture of teaching and research in Kharkiv. Their presence contributed to the transfer of Western European ideas into the scientific space of imperial Ukraine, in particular in the field of mechanics.

A significant group consists of sources related to the history of the departments of mechanics of Kharkiv University and the Institute of Technology (Kizilova & Popova, 2011; DTMSM, 2025), as well as memoir sources that provide an idea of the scientific environment of Kharkiv in the 19th century (Posokhov, 2008).

An important component of the historiographical part of the study also consists of articles by foreign authors that examine the particularities of the formation of mechanics in European science – such as the role in world mechanics of the German scholar of Dutch origin Richard von Mises (Siegmund-Schultze, 2018), Felix Klein's development of Galois theory (Heller, 2023), the use of mechanical models from the nineteenth century (Rowe, 2022), the achievements of algebraic research schools in Italy (Martini, 2004), as well as a comprehensive account of the history of European applied mathematics (Barrow-Green & Siegmund-Schultze, 2015).

In conclusion, it is worth noting that the historiography of the topic is quite broad in biographical, institutional, and chronological dimensions. At the same time, a comprehensive analysis of the scientific publications of Kharkiv mechanics of the 19th century, taking into account the context of their appearance, content, terminology, and influence on the further development of Ukrainian mechanics, has not yet been presented. This determines the relevance of the proposed study.

Methodology.

In the process of studying the formation of the foundations of Ukrainian mechanics through the prism of scientific publications of Kharkiv scientists of the 19th century, a complex of methods of historical and scientific analysis was applied, focused both on studying the content of primary sources and on identifying the socio-cultural and institutional context of their creation.

1. The historical and scientific approach became the basis for a general analysis of the formation of mechanics as a scientific discipline in Kharkiv. It allowed us to consider mechanics not only as a set of theoretical knowledge, but as part of the holistic scientific culture of the university environment.

2. Content analysis of historical scientific publications was used to study the thematic spectrum, structure, and terminology of publications by Kharkiv scientists-mechanics (Früh, 2015). The objects of analysis were works published in scientific journals and collections of the university, monographs and manuals of professors, dissertations presented during the 19th century, and individual publications in the professional press devoted to applied and theoretical mechanics.

3. Elements of the bibliometric approach were used to identify the frequency of mentions of individual topics, authors, and scientific schools, as well as to trace the dynamics of publication activity over the century. Although the full quantitative base is limited, the use of elements of this method allowed us to assess general trends.

In addition to the aforementioned methods, techniques for studying scientific processes (citation, collaboration, identification of trends) were applied, as described in the publications of European authors (Renn, 2015; Gibson & Ermus, 2019; Fortunato et al., 2018).

The source base of the study includes primary sources (works published by Kharkiv scientists in the 19th century), reference and biographical literature, memoirs, and archival documents, including anniversary collections, works on the history of university departments and faculties.

Main Research Results.

Kharkiv, as one of the leading scientific and educational centers of Ukraine, played a key role in the formation of domestic science and technology during the 19th and early 20th centuries. This period was characterized by the intensive development of higher education and the formation of scientific schools, in particular in the field of mechanics. The establishment and flourishing of both a classical university and a specialized technological institute in Kharkiv testify to targeted and strategic investments in scientific and technical education. This dual institutional structure allowed for the achievement of both fundamental theoretical achievements (University) and applied engineering solutions (Technological Institute), contributing to the creation of a comprehensive ecosystem for research in the field of mechanics. This approach ensured the multifaceted development of science and industry in the region.

Kharkiv University, founded in 1805, became one of the centers of fundamental scientific research in the Russian Empire, in particular in the fields of Mathematics and Physics. The Department of Physics and Mathematics, which by the 1870s had grown into a powerful faculty with three departments (mathematical, physical and chemical, and natural), played a key role in the development of mechanics. Its transformation into a powerful structure indicates significant institutional maturation. This growth indicates increased academic specialization, resource allocation, and the creation of a reliable intellectual environment conducive to advanced scientific research, which became a prerequisite for the emergence of influential scientific schools in mechanics.

One of the most prominent figures of Kharkiv University, who made a fundamental contribution to mechanics, was Oleksandr Mykhailovych Lyapunov. He worked at Kharkiv University from 1885 to 1902. O. M. Lyapunov developed a rigorous theory of stability of equilibrium and motion of mechanical systems with a finite number of parameters, as well as a general method for solving stability problems in his dissertations “On the stability of ellipsoidal equilibrium forms of a rotating fluid”, “The general problem of stability of motion” and the article “On the body of maximum potential”. His works laid the foundations of a mathematical apparatus adequate for the entire cycle of nonlinear oscillations, which was later used by the school of L. Mandelstam. This emphasizes the long-term, transformative impact of his work on the critical and complex field of mechanics, demonstrating the role of the University in the formation of fundamental theoretical mechanics with a stable global significance. He was also the first to prove the existence of equilibrium figures of homogeneous and weakly inhomogeneous fluids close to a sphere, as well as the existence of equilibrium figures of slowly rotating inhomogeneous fluids under very general assumptions.

Volodymyr Andriiovych Steklov, a student of O. M. Lyapunov, also made a significant contribution to the development of mechanics and related fields. His works were mainly concerned with mathematical physics, in particular, the solution of fundamental problems of potential theory, heat conduction theory, elasticity theory, and hydrodynamics (master's thesis “On the motion of a solid body in a fluid”, doctoral thesis "General methods for solving basic problems of mathematical physics" and article "On the equilibrium of elastic bodies of rotation"). V. A. Steklov provided a complete justification for the solutions of problems of heat propagation in an inhomogeneous rod and oscillations of an inhomogeneous string or rod. He also derived differential equations of motion of a solid in a fluid under general assumptions and solved a number of problems of the theory of elasticity. V. A. Steklov's specialization in "mathematical physics" and his doctoral degree in "applied mathematics" are examples of the significant interdisciplinary nature of research in mechanics at Kharkiv University. His work applied mathematical methods to solve complex problems in physical and mechanical phenomena (e.g., thermal conductivity, elasticity, hydrodynamics), demonstrating the bridging of the gap between theoretical mathematics and practical engineering challenges.

In addition to O. M. Lyapunov and V. A. Steklov, other scientists of Kharkiv University also made an important contribution to the field that is the foundation for mechanics. V. I. Imshenetsky developed methods for finding rational solutions of linear differential equations and methods for integrating partial differential equations of the second order, investigated canonical differential equations of a flexible inextensible thread and brachistochrone in the case of potential forces, and generalized the functions of Jacques Bernoulli. V. I. Albitsky, in addition to classical works on practical mechanics, dealt with the problems of solvability of second-degree equations with two variables. A. P. Shymkov combined mathematical physics with experiment, formed a teaching methodology, and created relevant textbooks ("On the compression of gases in connection with the mechanical theory of heat and hypotheses about the internal structure of bodies", "On the relationship between electricity and heat"). The main directions of scientific activity of I. D. Sokolov were writing the textbook "Dynamics" in 2 parts, researching the problems of the calculus of variations and Lagrange's analytical mechanics. The main works of M. A. Dyachenko belonged to the field of mathematical analysis and its application in other sections of mathematics and mechanics. The scientific works of D. M. Delariu related to mathematical analysis and algebra. And his monograph "General Theory of Algebraic Solving of Equations" was the first book on the foundations of the theory of E. Galois in the empire. V. I. Lapshyn, in addition to productive classes in practical physics, was one of the first to apply mathematical methods in teaching physics (the manual "Experience of Mathematical Teaching of Physics" in 2 parts). V. I. Gruzintsev in the articles "On the Geometry of the Propagation and Absorption of Electromagnetic Energy", "Mathematical Theory of the Phenomena of Reflection and Refraction of Polarized Light", "On the Refraction of Light Rays in Media Bounded by Any Surfaces" investigated geometric patterns in the study of physical phenomena. Although these scientists were not direct researchers of "mechanics," their contribution to fundamental mathematics (differential equations, geometry) provided the necessary analytical tools and theoretical foundations on which advanced research in mechanics could be built, in particular the works of such figures as O. M. Lyapunov and V. A. Steklov. One of the first professors of applied mathematics at Kharkiv University was T. F. Osypovsky, who at the beginning of the

19th century investigated mathematical models of the motion of bodies thrown from the surface of the earth and the patterns of astronomical refraction. The years of activity of mechanical scientists of Kharkiv University, the areas of their scientific research, and the list of key achievements are shown in Table 1.

Table 1. Key figures and their contribution to the development of mechanics at Kharkiv University (19th – early 20th centuries) (Author' Source).

Scientist's initials and surname	Years of activity at the KhU	Main areas of research	Key scientific achievements
O.M. Lyapunov	1885–1902	Theory of stability of motion, nonlinear oscillations, equilibrium figures of liquids	Development of a strict theory of stability, a general method for solving stability problems, proving the existence of equilibrium figures of liquids, the foundations of the theory of nonlinear oscillations.
V.A. Steklov	1891–1906	Mathematical Physics, potential theory, heat conduction, theory of elasticity, hydrodynamics	Substantiation of solutions to problems of heat conduction and oscillations, derivation of equations of motion of a solid in a liquid, solution of problems of the theory of elasticity, organization of science.
V.I. Imshenetsky	1872–1882	Linear differential equations	Method for finding rational solutions
A.P. Shymkov	1871–1904	Theoretical Physics	Development and publication of the first textbook on theoretical physics at Kharkiv University
D.M. Delariu	1861–1862 1866–1884	Analytical Mechanics (Statics, Kinematics, Dynamics of a point and Dynamics of systems of material points)	Solving first-order differential equations with two variables
I.D. Sokolov	1840–1866	Calculus of variations and analytical mechanics	Investigation of sufficient conditions for solving variational problems, generalization of variation of motion and the principle of least action
M.A. Dyachenko	1832–1835 1837–1839	Application of mathematical analysis in mechanics	Solving problems using definite integrals in mechanics
M.M. Arkhangelsky	1813–1837	Mathematical theory of fluids	Solving models of fluid motion
T.F. Osypovsky	1805–1820	Course of Mathematics, study of dynamic systems	Solving problems to determine the state of equilibrium under the action of forces on flexible bodies

It should be noted that the teaching of mechanics at Kharkiv University was closely connected with the activities of leading scientists who formed scientific schools. The fact that "scientific schools were formed" indicates a more structured, continuous, and collaborative research effort that went beyond individual scientific pursuits. This indicated a reliable model of mentorship, where leading scientists, such as O. M. Lyapunov, not only conducted groundbreaking research but also actively trained and influenced the next generation of scientists (e.g., V. A. Steklov), ensuring the preservation and growth of specific research areas and intellectual traditions in mechanics.

Kharkiv Practical Technological Institute (since 1898 – Kharkiv Technological Institute, KhTI) was founded in 1885. It played a crucial role in the training of engineering personnel and the development of technical sciences in Ukraine. Since its foundation, theoretical and analytical mechanics have been taught as fundamental disciplines. The very foundation of KhTI as a practical technological institute in 1885 testifies to changes in educational and scientific priorities towards applied sciences and industrial needs, which directly complemented the more theoretical orientation of Kharkiv University. Such institutional design inherently promoted research in applied mechanics, materials science, and various engineering disciplines, directly responding to the growing needs of industrialization of Ukrainian territories at the end of the 19th century. The creation of the scientific school of mechanics at KhTI began in 1885–1893 and was associated with the scientific interests of the first director of the institute, Volodymyr Lvovych Kyrpychov, Professor of Mechanics, who was an outstanding scientist and a founder of higher technical education in Ukraine. His scientific school is one of the most famous in the field of technical sciences at KhTI. He developed the theory of similarity, widely used the reciprocity theorem in the resistance of materials (a famous speech at the general meeting of Kharkiv Department of Imperial Russian Technical Cooperation "New investigations on strength of metal, steel and copper''), and significantly simplified the method of calculating various statically indeterminate structures. V. L. Kyrpychov worked productively in the field of structural mechanics, resistance of materials (monograph "Resistance of Materials"), and the theory of mechanisms. His active participation in the establishment of the scientific school of mechanics at KhTI and the invitation of other prominent mechanics demonstrate conscious efforts to create a critical mass of expertise and promote a common research environment. Scientific and practical contributions of V. L. Kyrpychov (similarity theory, resistance of materials, structural mechanics, theory of mechanisms) clearly emphasize the applied, engineering-oriented nature of research in mechanics at KhTI, which directly corresponds to the mission of the institute and provides a strong contrast to the more theoretical emphasis of Kharkiv University.

A number of other scientists at KhTI also made a significant contribution to the development of applied aspects of mechanics. Kharlampii Sergiovych Golovin was one of the professors invited by V. L. Kyrpychov, an outstanding mechanic who was teaching the results of research into the problems of solid mechanics in the books "On Internal Tensions in the Walls of Metal Cylinders" and "One of the Problems of Solid

Statics". The teaching staff of the institute included such famous professors as D. S. Zernov (researched the problems of strength of materials), V. I. Albitsky (created drawings of machine parts and design), O. V. Grechaninov (dealt with the hydrodynamic theory of friction), A. I. Predtechensky (dealt with the mechanics of foundry production), P. M. Mukhachov (dealt with steam locomotive construction), A. P. Lidov (investigated chemical technologies), K. O. Zvorykin (founder of the theory of metal cutting), O. K. Pogorelko (studied the deformations of solid bodies under the influence of electrical pressures). The diverse and specialized contributions of these scientists (foundry production, metal cutting, steam locomotive construction, radio-controlled mechanisms) illustrate the wide and interdisciplinary scope of applied research in mechanics at KhTI. This indicates that mechanics was considered not as an isolated branch, but as a fundamental discipline underlying various industrial and technological achievements.

Since 1885, theoretical mechanics has been studied at KhTI as a separate discipline of the curriculum for training engineers. Famous scientists were invited to teach it, in particular O. M. Lyapunov and V. A. Steklov (in addition to the above-mentioned scientists, other professors of Kharkiv University were invited to teach various courses – M. D. Pylchykov (author of works on optics, terrestrial magnetism, electrical and radio engineering, electrochemistry), M. M. Beketov (author of physicochemical research), D. O. Grave (researched systems of differential equations of the three-body problem), K. A. Andreev (researcher of problems of projective geometry and mathematical analysis), M. A. Dyachenko (researcher of the functionality of hydraulic wheels)). The fact that theoretical mechanics has been taught as a separate discipline since the foundation of KhTI (1885), and that prominent figures such as O. M. Lyapunov and V. A. Steklov were invited to teach, reveals the importance of scientific relations and the depth of intellectual cooperation between the two institutions. This indicates that KhTI, despite its applied orientation, recognized the fundamental importance of theoretical mechanics and actively used the experience available at the University. The years of creative activity of mechanical scientists of the Kharkiv Institute of Technology, the main areas of scientific research and a list of their key achievements are shown in Table 2.

Thus, Kharkiv University, as a classical institution of higher education, focused on fundamental theoretical research in mechanics and mathematical physics, as evidenced by the works of O. M. Lyapunov (theory of stability, nonlinear oscillations) and V. A. Steklov (potential theory, hydrodynamics). In contrast, Kharkiv Institute of Technology, as a technical university, focused on applied mechanics, the strength of materials, structural mechanics, and engineering applications, as reflected in the works of V. L. Kyrpychov and other mechanical scientists. This clear division of labor in research in mechanics – fundamental theory at the university and applied engineering at the technological institute – is a complex and effective model of scientific development within the boundaries of one city. Such specialization allowed each institution to achieve success in its respective field, while collectively contributing to the broader development of mechanics. This indicates a mature and strategically developed scientific ecosystem in Kharkiv, which optimized the allocation of resources and intellectual focus. Despite their differences, both institutions were centers of formation of scientific schools and played a key role in training highly qualified personnel. There was a noticeable interconnection between the two institutions, in particular through the exchange of personnel and knowledge. An example is the invitation of O. M. Lyapunov and V. A. Steklov, leading scientists of Kharkiv University, to teach theoretical mechanics at KhTI. This indicates that the institutions, despite their different missions, understood the need for a strong theoretical foundation even in a practical engineering context, contributing to a holistic approach to education and research in mechanics in Kharkiv. This spirit of cooperation probably accelerated the overall scientific progress in the city.

Table 2. Key figures and their contribution to the development of mechanics at Kharkiv Institute of Technology (19th – early 20th centuries) (Author' Source).

Scientist's name and initials	Years of activity at KhTI	Main areas of research	Key scientific achievements
V. L. Kyrpychov	1885–1898	Similarity theory, resistance of materials, structural mechanics, theory of mechanisms	Development of the similarity theory, use of the reciprocity theorem, simplification of the calculation of statically indeterminate structures.
H. S. Golovin	1885–1893	Mechanics of solids	Solving the problem of bending curved rods using methods of the theory of elasticity
D. S. Zernov	1891–1902	Mechanics of strength of materials	Development of the theory of resistance of materials
A. I. Predtechensky	1889–1900	Mechanics of foundry production	Initiator of systematic research in foundry production
K. O. Zvorykin	1889–1898	Mechanics of metal cutting	He laid the foundations of the science of metal cutting
P. M. Mukhachov	1887–1917	Steam power generation, forging technology	Development of problems of steam power generation and forging technology.
M. D. Pylchykov	1898–1908	Wireless telegraphy, radio communication, radio-controlled mechanisms	Development of ideas of radio-controlled mechanisms.
O. K. Pogorelko	1885–1898	Mechanics of solids and fluids	Solving problems of fluid motion

The substantive (content) analysis (Früh, 2015) of the main publications of Kharkiv mechanical scientists of the 19th and early 20th centuries, which allowed to identify the leading directions of scientific research that developed in Kharkiv during this period. The main scientific directions of research were as follows.

1. Theoretical mechanics – this direction covered the fundamental problems of motion, equilibrium of bodies, flexible systems, calculus of variations and stability.

The key topics of this direction were the calculus of variations, equations of motion of a rigid body, stability of mechanical systems, and analytical mechanics. This direction was represented by O. M. Lyapunov, I. D. Sokolov, V. A. Steklov, V. G. Imshenetsky, T. F. Osypovsky. The publications of this direction were characterized by a high level of mathematization of research, the influence of the works of the luminaries of mathematics Lagrange and Euler, and the development of the ideas of classical dynamics.

2. Mechanics of deformed bodies and resistance of materials - this direction was associated with applied mechanics, in particular with the determination of the strength of materials, stresses, and the influence of external forces. The key topics of this group of publications were the study of the regularities of stresses in the walls of cylinders, the calculation of beams and joints, and the study of the properties of metals. Representatives of this direction were the publications of H. S. Golovin, V. L. Kyrpychov, D. S. Zernov. The scientific works of scientists of this direction of research were oriented towards industrial engineering and were important for the development of construction, mechanical engineering, and military equipment.

3. Hydraulics and fluid mechanics – the subject of research in this direction was the phenomena of fluid motion, pressure, hydraulic wheels, lubrication. The key research topics were the principles of operation of hydraulic machines, the definition and consideration of friction in a liquid medium, and the modeling of the motion of bodies in liquids. This direction of research is represented by the publications of M. A. Dyachenko, O. V. Grechaninov, V. A. Steklov, V. I. Albitsky. This direction of publications was closely related to engineering practice, the construction of mills, pumps, and water intakes.

4. Mechanical engineering and gear transmissions – this applied direction demonstrates the development of mechanical engineering culture in Kharkiv, associated with the design of mechanical connections, gear wheels, and steam locomotives. The key research topics in this direction were the methodology of using graphical calculation methods, the features of designing screws, bolts, gears, designing and building steam engines, and locomotives. This direction was represented by scientific and practical research by V. I. Albitsky, A. I. Predtechensky, P. M. Mukhachov. This group of publications was focused on the practical training of engineers and the development of the industrial potential of Kharkiv and the region.

5. Mathematical foundations of mechanics and physics – the works of this direction were interdisciplinary in nature, related to mathematical physics, electromagnetism, and thermodynamics. The key research topics of scientists were the theory of refraction and polarization of light, the properties of gases and heat, the mathematical substantiation of physical laws. The main publications of this direction were the results of research by A. P. Shymkov, O. P. Gruzintsev, V. I. Lapshin. Research in this area was aimed at the formation of a physical and mathematical school at the junction of mechanics, thermodynamics and optics.

Thus, in Kharkiv in the 19th and early 20th centuries, a wide range of research in the field of mechanics was formed, from fundamental dynamics to applied mechanical engineering. The scientific tradition was interdisciplinary, with active use of mathematical apparatus to describe physical and technical processes. Practical publications by V. I. Albitsky, V. L. Kyrpychov, A. I. Predtechensky became the basis of technical education in engineering universities. Theoretical research by O. M. Lyapunov, V. A. Steklov, and I. D. Sokolov placed Kharkiv School in the pan-European context of mathematical mechanics. To determine the trends in the publication activity of scientists-mechanics of Kharkiv University and Kharkiv Institute of Technology during 1805–1905, a time series with indicators of scientists' publications for 5-year periods of the specified time period was constructed. This made it possible to identify periods of changes in publication activity, which can be characterized as follows.

1. Initial period (1800–1830): isolated publications – in the first third of the 19th century, the publication activity of Kharkiv mechanical scientists was low and was limited mainly to the works of T. F. Osypovsky and M. M. Arkhangelsky. This is explained by the formation of the university, the absence of stable scientific schools, and a limited publishing base.

2. Growth period (1850–1870): the emergence of a stable academic environment – in the second half of the 19th century, a gradual increase in the number of publications is noticeable. New authors appear (I. D. Sokolov, A. P. Shymkov), and university education begins to actively produce research on applied and theoretical mechanics. The first departments appear, the number of students increases.

3. Peak of activity (1876–1900): institutionalization of science – this period became the peak of scientific productivity. It was at this time that O. M. Lyapunov, V. G. Imshenetsky, V. A. Steklov, V. I. Albitsky, V. L. Kyrpychov actively published. Publications were concentrated around the Kharkiv Mathematical Society, university departments, and technical schools. This surge was explained by stable institutional support for science (university, technical society, polytechnic institute), international integration (the influence of German and French engineering schools), and the demand for engineering personnel in the conditions of industrialization.

4. Stabilization at the turn of the century, when activity remains high, but the growth rate slows down. The number of applied research (mechanical engineering, steam boilers, gear transmissions) is increasing, which reflects a shift in emphasis from theoretical to technical and applied science.

Thus, during the 19th and early 20th centuries, publication activity had a wave-like character, with a distinct peak in 1880–1905 (see Fig. 1). The transition from individual creativity to systemic science took place in the last third of the 19th century. Theoretical mechanics developed in parallel with engineering education, which was oriented towards the needs of the railway, machine-building and military sectors. Kharkiv during this period became the leading scientific center of mechanics in Ukraine and within the Russian Empire.

Discussion.

The formation of mechanics in Kharkiv in the nineteenth century took place in close dialogue with the European scientific tradition, yet it also had its own specific features. Kharkiv University, oriented toward fundamental research, embodied an approach close to the German model, with its emphasis on the mathematization of mechanics and the development of analytical methods. At the same time, the Kharkiv Technological Institute, focused on applied tasks, resembled the French grandes écoles system, where the emphasis was placed on engineering education and practical calculations. The Spanish context demonstrated a slower assimilation of new mechanical theories, shaped by a long-standing reliance on translations and the local adaptation of Western works, whereas in Kharkiv a more dynamic integration of Western European ideas was evident.

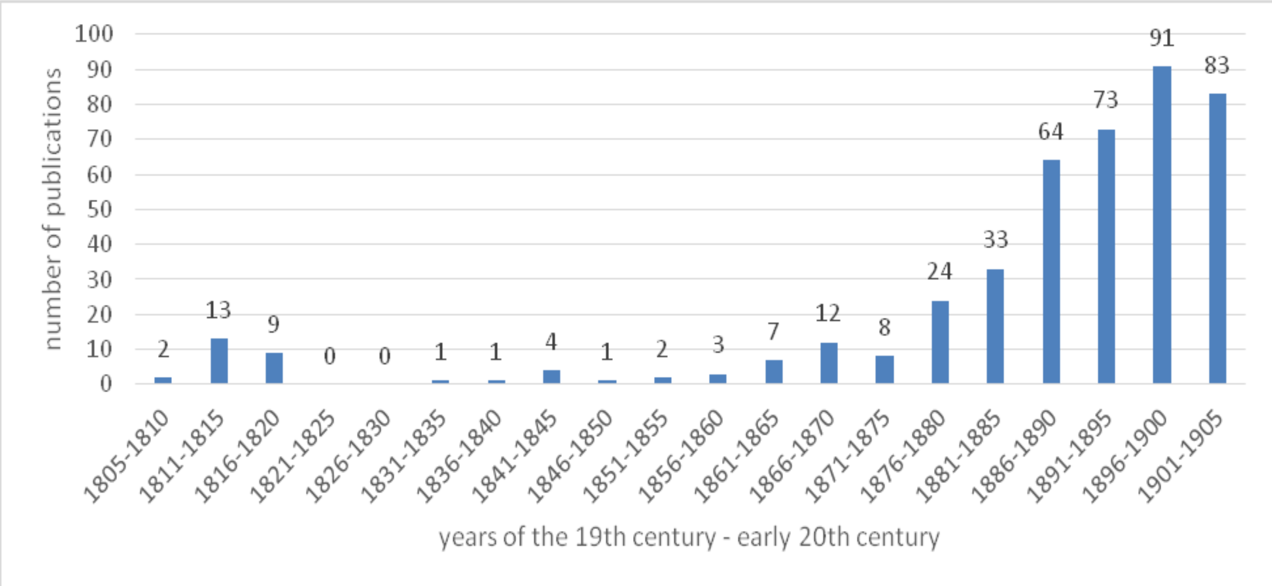

Figure 1. Dynamics of publication activity of mechanical scientists of Kharkiv (1805–1905) (Author' Source).

Significantly, German universities – most notably Göttingen – formed scientific schools around figures such as Klein or Helmholtz, whereas in Kharkiv the corresponding centers were Lyapunov and Steklov, whose research secured entry into the broader European scientific arena (Barrow-Green & Siegmund-Schultze, 2015; Jahnke, Jankvist, U. T., & Kjeldsen, 2022; Heller, 2023). In France, an important factor was the institutional synthesis of the École Polytechnique and the universities, which combined theoretical training with engineering applications—analogous to the dual structure of Kharkiv University and the Technological Institute (Darrigol, 2003). In Spain, despite the smaller number of specialized centers, the development of mechanics was supported through educational reforms and the gradual introduction of applied disciplines in technical schools, which resonates with Kharkiv’s efforts in engineering training (Navarro-Loidi & Llombart, 2008).

Unlike many European centers, where the specialization between fundamental and applied mechanics emerged gradually, in Kharkiv this division was clearly formalized thanks to the existence of two separate institutions. Such a structure ensured broad interdisciplinarity and complementarity, reflected in joint publications and in the invitation of university scholars to teach at the Technological Institute. Compared to France or Germany, the Kharkiv model reveals a more explicit example of coordination between theory and practice at the local level.

Thus, it can be argued that in the nineteenth century Kharkiv created its own "miniature Europe", combining the German tradition of fundamental science, the French orientation toward engineering, and the Spanish attention to the gradual adaptation of knowledge. This synthesis made Kharkiv one of the leading centers of mechanics in Eastern Europe and ensured the continuity of a scientific school that had a lasting influence in the twentieth century.

Conclusions.

As a result of the study, it was established that Kharkiv in the 19th and early 20th centuries became the leading scientific center for the development of mechanics in Ukraine and within the Russian Empire. The formation of two institutional centers – Kharkiv University and Kharkiv Institute of Technology – ensured the integration of fundamental and applied research areas, which contributed to the development of both theoretical mechanics and engineering education.

1. Fundamental research at Kharkiv University, embodied in the works of O. M. Lyapunov, V. A. Steklov and others, laid the foundations of the theory of stability, mathematical analysis of mechanical systems, which ensured the emergence of the Kharkiv school at the pan-European level.

2. Applied research carried out at the Kharkiv Institute of Technology under the leadership of V. L. Kyrpychov and his followers became the basis for the development of technical sciences and the training of engineering personnel for the needs of industrialization.

3. Scientific publications of Kharkiv scientists indicate a high level of interdisciplinarity, as they combined mathematical apparatus with applied engineering tasks (hydrodynamics, resistance of materials, mechanical engineering, theory of mechanisms).

4. Analysis of publications has shown the transition from isolated scientific initiatives to the formation of a stable scientific tradition and schools based on mentoring, academic heredity and interinstitutional cooperation.

5. The dynamics of publication activity in the 19th century confirmed the wave-like nature of the development of science with a peak of productivity in the last third of the century. This surge was due to institutional support, the influence of Western European science, and the urgent needs of the region's technical development.

Thus, a unique scientific ecosystem was formed in Kharkiv, combining fundamental and applied research, contributing to the development of mechanics as a science and creating the basis for further achievements of Ukrainian technical thought in the 20th century.

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Розвиток української механіки: Контекст наукових публікацій харківських вчених XIX століття

Анотація. *Це дослідження пропонує комплексний історіографічний та контент-аналіз розвитку української механіки у XIX столітті крізь призму наукових публікацій харківських вчених. Особлива увага приділяється інституційному та інтелектуальному внеску Харківського університету та Харківського технологічного інституту, які разом утворили унікальну наукову екосистему, що сприяє як теоретичним, так і прикладним дослідженням у галузі механіки. У дослідженні використовується міждисциплінарна методологія, що поєднує історичний підхід, контент-аналіз першоджерел та бібліометричні методи для відстеження тематичних тенденцій, термінологічної еволюції та динаміки наукової комунікації. Результати дослідження показують, що протягом XIX та початку XX століть Харків став важливим науковим центром Російської імперії та Східної Європи. У Харківському університеті теоретична механіка процвітала завдяки роботам видатних вчених, таких як О. М. Ляпунов, В. А. Стєклов та І. Д. Соколов, які заклали основи сучасної теорії стійкості, нелінійної динаміки та математичного моделювання механічних систем. Одночасно Харківський технологічний інститут розвивав прикладну механіку під керівництвом В. Л. Кирпичова та його колеги, новатори досліджень у галузі міцності* *матеріалів, конструкційної інженерії, проектування машин та промислових технологій. Аналіз підкреслює помітну синергію між двома установами, що відображається в міжінституційному навчанні, спільних дослідницьких зусиллях та формуванні потужних наукових шкіл. Публікаційна активність харківських вчених-механіків демонструвала хвилеподібну тенденцію, досягши піку між 1880 і 1905 роками, зумовлену вимогами індустріалізації та міжнародної наукової інтеграції. Цей період ознаменував зміну парадигми від ізольованих інтелектуальних зусиль до системного, спільного наукового виробництва. У цій статті стверджується, що спадщина харківської механічної науки полягає не лише у створенні передових теоретичних конструкцій, але й в інституціоналізації технічної освіти та досліджень, що значною мірою сприяло модернізації українських та східноєвропейських інженерних наук. Висновки, отримані в результаті цього дослідження, пропонують глибше розуміння процесів виробництва, передачі та адаптації знань у контексті наукової глобалізації 19-го століття. Результати дослідження засвідчують, що інституційна співпраця між Харківським університетом і Технологічним інститутом сприяла створенню унікальної наукової екосистеми, яка забезпечила ефективний розвиток механіки як наукової дисципліни. Стаття розкриває важливість цього процесу для подальшого формування української технічної думки у XX столітті та підкреслює значущість спадщини харківських учених у глобальному контексті історії науки.*

Ключові слова: *історія механіки; харківська наукова школа; наукові публікації; інституційна історія; теоретична та прикладна механіка; наукова комунікація*

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International relations and scientific communication of the Imperial Novorossiya University in the last third of the 19th century: The context of the development of Natural Science

Abstract. *The article is devoted to the study of international relations and forms of scientific communication of natural scientists of the Imperial Novorossiya University in the last third of the 19th century. The work traces how scientists and teachers gradually integrated into the European research and academic space, using a number of channels – from translations of Western European literature and adaptation of methodologies to participation in international congresses and academic mobility programs. The authors analyze the role of the "Notes of the Novorossiya Society of Natural Scientists" as an institutional platform for the dissemination of scientific results, which combined the publication of local research with an orientation to the needs of the European scientific community. The publication regularly published articles with summaries in foreign languages, which facilitated interaction with foreign colleagues. The practice of exchanging copies with foreign libraries was also revealed,* *which made the "Notes" an important channel of scientific communication between Odesa and leading centers in Europe. Special attention was paid to the participation of Odesa scientists in international congresses on Biology, Medicine, and Zoology in Berlin, Paris, and Geneva. Their reports reflected the results of research on the Black Sea, as well as cooperation with German and French scientific schools. This contributed to increasing the prestige of the university, recognition of Odesa scientists in the European academic community, and transformation of the university into an important center of science in the region. The authors studied the processes of academic mobility of teachers and students. Teachers trained in laboratories in Berlin and Paris, mastering new experimental methods, which were later used in Odesa. Students had the opportunity to undergo internships at European zoological stations and in scientific clinics, which contributed to raising the level of their future dissertation research. At the same time, the university hosted foreign scientists, whose lectures and seminars broadened the worldview of the academic community and contributed to integration into international intellectual processes. A special place in the work is occupied by the analysis of translation activities and the influence of Western European methodologies. It is shown that the translations of the works of Ch. Darwin, E. Haeckel, R. Virchow, C. Bernard, and J. Charcot, carried out in particular by the Odesa publishing house "Mathesis", contributed to the spread of modern concepts and the formation of academic terminology. This not only improved the quality of the educational process but also formed multilingualism as a feature of the university's scientific culture. The conclusions emphasize that international relations and scientific communication were key factors in the formation of the Imperial Novorossiya University as a regional center of natural sciences with European characteristics. The experience of Odesa in the last third of the 19th century showed that integration into the international scientific space was ensured by combining local research practices with global trends and the wide use of channels of intellectual exchange.*

Keywords: *Imperial Novorossiya University; international scientific space; scientific cooperation; natural science; Novorossiya Society of Naturalists; international congresses; Western European methodologie*

Introduction.

The second half of the 19th century was a time of intensive transformation of scientific life in Europe and the world. This period is characterized by the growth of the role of universities as centers of not only educational but also research activities, the formation of scientific societies, the active development of specialized journals, and the wide involvement of scientists in international forms of cooperation. In the European context, it was then that the foundations of modern science were formed, in particular in the field of natural sciences, where comparative studies, experimental methods, and interdisciplinary approaches became significant. In this general process, an increasingly prominent place is occupied by Southern Ukraine, namely Odesa, which in the second half of the 19th century is turning into an important scientific and cultural center. The foundation of the Imperial Novorossiya University in 1865 created the prerequisites for the formation of a powerful scientific school that developed in close contact with the European intellectual tradition. A special role here was played by natural science disciplines, which had not only academic but also applied significance – in the development of agriculture, navigation, medicine, and trade. Odesa, as a port city with a developed network of international contacts, provided special conditions for scientific communication: new ideas, literature, technical means and methodological approaches arrived here through maritime and trade ties. This contributed to the rapid introduction of Western European scientific models into the local educational and research process.

The relevance of the study of international relations and scientific communication of the Imperial Novorossiya University in the last third of the 19th century is determined by the fact that it was through the mechanisms of academic mobility, publishing activities, and participation in international forums that the conditions for the integration of Odesa science into the world scientific space were formed. At the same time, this process was not one-sided: Odesa scientists contributed to the development of natural science at the level of the Russian Empire and in the international context, disseminating the results of their research through specialized publications, translations, and scientific correspondence.

The purpose of this article is to analyze how the international ties between the Imperial Novorossiya University and the Odesa scientific community of the last third of the 19th century were manifested in publishing activity, academic mobility, participation in international congresses, and translation activities. The study aims to identify how actively Odesa scientists participated in the European scientific discourse, as well as to trace the mechanisms of knowledge transfer in the field of natural science. To achieve this goal, a number of tasks are planned to be performed. First, it is important to show the role of the "Notes of the Novorossiya Society of Naturalists" as one of the leading platforms for the dissemination of scientific knowledge in the region. This publication played a dual function: on the one hand, it popularized the achievements of Odesa researchers, and on the other, it ensured the inclusion of local scientific practices in a broader international context. Secondly, it is necessary to characterize the participation of Odesa scientists in international scientific events – congresses, symposia, and conventions, which at the end of the 19th century become one of the key tools of international scientific communication. This will allow us to assess the level of integration of Novorossiya University into the network of European scientific institutions. Thirdly, the tasks of the article include tracing the channels of academic exchanges – internships, business trips, and invited lectures, which ensured the dissemination of modern research methods. Such exchanges contributed not only to the professional growth of individual scientists but also to the general improvement of the quality of scientific research at the Imperial Novorossiya University. Finally, the fourth task is to identify the influence of Western European methodologies on natural science in Odesa. Here, it is important to analyze which scientific paradigms – Darwinism, experimental physiology, new approaches in geology or chemistry – most actively penetrated the Odesa scientific space and how they transformed local research practices.

Thus, the study will allow not only to reconstruct the mechanisms of international scientific communication at the Imperial Novorossiya University, but also to gain a deeper understanding of the peculiarities of the development of natural science in Southern Ukraine in the last third of the 19th century. The study of these processes is important for the history of science in general, as it shows how peripheral (at first glance) centers gradually integrated into the world scientific system, becoming important centers of knowledge generation and dissemination.

Literature Review.

The issue of the development of university science in Odesa in the last third of the 19th century has repeatedly become a subject of interest for historians of science. However, the level of elaboration of various aspects of this topic is uneven: the general history of the Imperial Novorossiya University and its scientific schools has been studied quite actively, while the issue of international relations and the communication dimension of scientific life remains rather peripheral in research.

The first stage in the development of the topic was the works dedicated to the anniversary dates of the university. At the end of the 19th century and the beginning of the 20th century, chronicles and collections of materials were published, which emphasized the role of the university as an educational and cultural center of Southern Ukraine (Markevich, 1890). Such publications were mainly descriptive in nature, but they laid the foundation for further research. In the Soviet period, the attention of researchers was focused on the analysis of university science in the context of the socio-economic development of the region and state policy in the field of education (see, e.g., (Kryvets, 2013)). Although the international aspect of scientific life was mentioned, it was mainly considered as an auxiliary factor.

From the second half of the 20th century, works began to appear that covered the history of individual faculties and scientific schools of the Imperial Novorossiya University. A fairly significant layer of research concerned natural sciences – biology, medicine, geology, and chemistry. Authors, in particular Brauner (1997) and Muzychko (2014), focused on the contribution of Odesa scientists to the development of general imperial science, emphasizing their innovative activity. At the same time, the issues of sources of new ideas, contacts with European colleagues, and the influence of these connections on research were largely ignored.

At the end of the 20th and beginning of the 21st centuries, historians' interest in the cultural and communication aspects of the development of science increased. In the works of Ukrainian and foreign authors (in particular, Barbarich & Pogrebnyak, 1979; Yurzhenko, 1968), more attention is paid to the transfer of knowledge, institutional forms of scientific exchange, and academic mobility. In this context, Odesa is considered an important communicative center, where unique conditions for the development of science were formed at the intersection of trade, political, and cultural ties. At the same time, most of these studies are focused on individual personalities – leading university professors, or on the history of societies, leaving the overall picture of international interaction incomplete.

Separately, it is necessary to highlight scientific works devoted to the activities of the Novorossiya Society of Naturalists. Among modern authors, the most systematic analysis of the issue of its role was Savchuk (1994), Demuz (2014), and Koval (Koval, 2015), who emphasized the importance of the "Notes" for the exchange of knowledge between the scientific centers of the empire. However, the international dimension of the society's activities – to what extent the "Notes" were known outside the Russian Empire and how international contacts were built through publications – remained open.

An important direction of modern historiography is the study of academic mobility of scientists of the second half of the 19th century. For example, the work (Ivanenko, 2013) examines the training and internship of professors in European universities, their participation in congresses and meetings. For the Odesa context, this issue is only beginning to be worked out: there are biographical investigations of individual scientists (see, for example, the work (Karpov, Semik, & Gladky, 2013)), which lack a systematic analysis of academic exchanges.

A general analysis of the coverage of the results of congresses and meetings of natural scientists on the pages of the journal "Proceedings of Experimental Physics and Elementary Mathematics" (with a description of the features of the participation of scientists from Kharkiv, Kyiv, and Odesa) was made in the work (Pasichnyk, Rizhniak, & Deforzh, 2023). Among foreign studies that investigate the phenomenon of international scientific congresses of the 19th century, the work (Schroeder-Gudehus, 2023) and the work (Feuerhahn & Rabault-Feuerhahn, 2010) stand out. Also important is the analysis of international forums on natural science (Kaeser, 2010). In addition to the above-mentioned studies by foreign scientists, it is also appropriate to highlight works that studied the general patterns of establishing international scientific cooperation (Dusdal & Powell, 2021), the processes of synthesizing cross-border ties between universities through the exchange of natural history collections (Müller-Wille & Charmantier, 2012), the formation of the German model of the "research university" and its role in the formation of national science networks (Dusdal, Powell, Baker, Shamekhi, Stock, 2020; McClelland, 2019), the development of British academic networks and imperial integration (Pietsch, 2013; Simon, 2019), the material and institutional conditions for the development and dissemination of French physics, chemistry, and astronomy methods (Lequeux, 2015), the Italian university evolution of natural sciences (Padua) with strong international ties (Bittante et al., 2022), the emergence and evolution of innovation networks in Spain (Barbosa, Sáiz, & Zofío, 2024).

Thus, previous studies have laid a solid foundation for studying the history of the Imperial Novorossiya University as a scientific center. At the same time, international ties and channels of scientific communication remain insufficiently covered. There is a need for a comprehensive analysis of how publishing activities, participation in international events, translations, and academic contacts contributed to the integration of the Odesa scientific community into the European space of knowledge. It is this gap in modern historiography that determines the relevance of further studies, to which this article belongs.

Methodology.

The study used diverse sources that allowed for a comprehensive consideration of the international relations of the Imperial Novorossiya University – archival materials and printed sources, as well as modern studies by historians of science of Ukraine and foreign works on international scientific congresses. Among the methodological approaches used were the historical-genetic method (which allowed us to trace the evolution of the university's scientific contacts, from the first translations and publications to active participation in international congresses); the comparative-historical method (used to compare the practices of the Imperial Novorossiya University with the experience of leading European centers (Berlin, Paris, Geneva)); content analysis of publications (a selective analysis of articles in the "Notes of the Novorossiya Society of Naturalists" was conducted to identify international channels for the dissemination of knowledge) (Atteslander, 2003); prosopographic approach (in the study of biographies of Odesa scientists (I. Mechnikov, O. Kovalevsky, V. Pidvysotsky), which allowed to personalize the plot and trace their participation in European scientific events); measurement and comparison of parameters of the organization of international cooperation (when constructing tables of scientific communication of university scientists) (Van Eck, Waltman, Dekker, & Van den Berg, 2010; Glänzel, 2001); features of the application of source research technologies (Grebtsova & Kovalska, 2021). The logic of the study is built on the problem-chronological principle: the formation of university publications as a communication tool is analyzed; the participation of scientists in international congresses and scientific exchanges is highlighted; the academic mobility of teachers and students is considered; the influence of Western European translations and methodologies on the development of natural science disciplines is investigated.

Main Research Results.

"Notes of the Novorossiya Society of Naturalists" as a platform for international scientific communication.

The activities of the Novorossiya Society of Naturalists, established within the walls of the Imperial Novorossiya University in Odesa in 1869, organically fit into the European trends of self-organization of scientific corporations. Already at an early stage of the society's existence, a need arose for its own printed organ, which would perform not only the function of recording the results of scientific studies, but also a tool for communication with wider academic circles. The response to this need was the launch in 1873 of the "Notes of the Novorossiya Society of Naturalists" (hereinafter referred to as "Notes"), which were published regularly and quickly acquired the status of an authoritative regional scientific journal (Markevich, 1890).

The editorial policy of "Notes" had a distinct duality. On the one hand, the editors sought to represent local research – primarily the results of expeditions to the Black Sea (Rishawi, 1879), fieldwork in the steppe zone of Southern Ukraine, and research on natural resources that had applied value for the economy (Prendel, 1879). On the other hand, due to its orientation towards European scientific standards – the structure of articles, systematic references to foreign literature, and the involvement of foreign reviewers – the publication sought to integrate Odesa studies into the broader scientific discourse (Koval, 2015, p. 104).

An equally important element of the editorial policy was the desire to make the publication understandable for European colleagues. Already in the first volumes, there are articles with summaries in French and German, which significantly increased their "circulation" outside the Russian Empire. The society also initiated the exchange of copies with university libraries in Berlin, Leipzig, Paris, and Geneva, as evidenced by archival documents (SAOR, 2, pp. 35–37).

One of the leading directions presented in the "Notes" was the study of the flora and fauna of the Black Sea. In the publications, we find the results of the expeditions of Professors M. Nikiforov and O. Kovalevsky, who systematically studied marine invertebrates and algae (Markevich, 1890, pp. 122–124). A series of articles devoted to the dynamics of the ichthyofauna of the northwestern coast of the sea had a significant resonance. Odesa biologists actively collaborated with German and French oceanographers, sending materials for comparison with the Atlantic and Mediterranean Seas. It was thanks to the "Notes" that the results of these studies became available to foreign colleagues.

The second thematic block concerned geological and paleontological research. The publication published works on the structure of soils, mineral deposits, and fossil remains found in the steppe zone of Kherson and Katerynoslav regions. Publications by Professor K. F. Meyer on the stratigraphy of the Black Sea region were of international importance, as they allowed comparing the geological horizons of Southern Ukraine with similar layers of Central Europe (Koval, 2015, p. 187). Such studies made "Notes" a significant source for comparative geological studies, which were actively discussed at European congresses.

The third important block was made up of articles on medicine and human biology. In Odesa, where port life contributed to the rapid spread of cholera and plague epidemics, medical and biological experiments were of particular practical importance. The "Notes" published the results of microbiological research that preceded the establishment of bacteriology as a science, in particular articles on the nature of pathogens and methods of their detection (Koval, 2015, pp. 76–78). These materials were sent to libraries in Paris and Vienna, where they were cited during discussions in the field of hygiene and sanitation.

"Notes" became a key means of communication between Odesa scientists and the scientific world outside the city. The publication not only ensured internal academic continuity, but also became a kind of "window" into European science. First, the international significance dictated the use of foreign languages. Although most articles were printed in Russian, some materials were published with summaries in French and German. This was an important step in bringing the publication closer to the standards of leading European journals and facilitated the integration of the results into the pan-European discourse (SAOR, 3). Second, the active practice of exchanging copies with libraries of universities and scientific societies in Germany, France, Austria-Hungary, and Switzerland contributed to the fact that the works of Odesa scientists came into the field of view of European researchers. Archival documents confirm the regular sending of sets of the journal to the University of Berlin and the Paris National Library (SAOR, 3, pp. 14–15). Third, thanks to the "Notes", scientific results became part of discussions at international forums. For example, reports on the biology of the Black Sea published in the journal were cited at the International Zoological Congress in Paris in 1889, which indicates the real influence of the Odesa scientific community on the development of European science (Vincent & Bastos, 2022). Thus, the "Notes" can be considered as an institutional channel of international scientific communication. They ensured the circulation of knowledge between Odesa and European centers, contributed to the academic reputation of the Imperial Novorossiya University, and to the integration of Odesa research into the global scientific context.

Participation of Odesa Scientists in International Congresses.

The last third of the 19th century was characterized by the intensification of international scientific life, in particular, due to the organization of regular international congresses in the fields of biology, zoology, medicine and geography. Participation in these forums opened up opportunities for scientists to integrate into the world academic environment, and for universities – the way to form an international authority. Odesa scientists, representing the Imperial Novorossiya University, joined this process since the 1870s. The most significant were their speeches at international congresses in Berlin, Paris and Geneva. Medical and natural science forums were held in Berlin, where representatives of the university center of the Dniper region presented the results of research in the field of epidemiology and bacteriology. Paris, as the center of European science, attracted biologists and zoologists, especially within the framework of the International Zoological Congresses of the 1880s. In Geneva, scientific meetings were held devoted to the geography and biology of mountainous and marine regions, which was close to the subject of Black Sea research. The first speeches of Odesa scientists at these forums can be seen as steps of integration into the global academic community. Despite the relatively modest representation, their presence meant the emergence of local studies beyond the boundaries of the imperial scientific space (Vincent & Bastos, 2022).

The most important contribution of Odesa scientists to the work of international congresses was the results of research on the Black Sea. Issues of marine biology and oceanography attracted the attention of European scientists, since the Black Sea, due to its geographical location and unique ecological conditions, was considered a natural laboratory (Mechnikova, 1879). The reports of Odesa researchers at the congresses in Paris (1889) and Berlin (1890) discussed new species of marine organisms, the conditions of their existence, and the problems of water pollution, which were important for the development of fishing and trade (SAOR, 4, pp. 45–47). The reports devoted to the ichthyofauna and invertebrate zoology of the Black Sea received special recognition. They were in harmony with the research of French marine biologists (for example, the laboratory in Villefranche) and German naturalists who studied the Baltic Sea. Thanks to these contacts, cooperation with scientific schools in France and Germany was initiated (Ivanenko, 2013, pp. 112–113).

No less important was the medical unit. Odesa doctors and microbiologists presented the results of research on cholera and plague, which periodically arose in Odesa as a large port city. Their speeches at international medical congresses in Berlin were noticed by leading European bacteriologists, including Robert Koch, who was interested in Black Sea observations. Thus, Odesa scientists not only informed about local problems, but also contributed to the development of global approaches to combating infectious diseases (SAOR, 6, pp. 22–25).

In general, the participation of scientists from the Imperial Novorossiya University in international congresses had several important consequences for the development of science in Odesa. First, it contributed to raising the status of the university as a scientific center. The presence of Odesa representatives at European forums indicated that the university was not limited to regional topics, but claimed a place in the global scientific space. Regular references to "Odesa studies" in foreign publications contributed to the establishment of the university as an authoritative institution (Yurzhenko, 1968, p. 243). Second, the recognition of individual scientists in the international arena strengthened their academic reputation and opened up opportunities for further cooperation. Thus, contacts with French and German colleagues led to invitations to joint expeditions, exchanges of students and literature.

It is known that some of the materials from the "Notes" were sent to the Paris National Library and the Berlin University Library as part of academic exchanges (SAOR, 3, pp. 14–15). Thirdly, international contacts contributed to the methodological renewal of science in Odesa. Thanks to direct acquaintance with new approaches in France and Germany, Odesa scientists introduced modern research methods in the field of marine biology, geology, and medicine. This allowed the university not only to establish itself on the map of scientific centers of the Russian Empire, but also to gradually approach European standards of academic culture.

Thus, the research of the famous zoologist and evolutionist, professor of the Imperial Novorossiya University Alexander Onufriyovich Kovalevsky (1840–1901) on the embryology of invertebrates and vertebrates laid the foundations of comparative embryology in the Russian Empire (SAOR, 4). In Odesa, O. O. Kovalevsky actively worked within the framework of the Novorossiya Society of Naturalists, published materials on the marine fauna of the Black Sea in "Notes" (Koval, 2015). In 1889, O. O. Kovalevsky presented the results of Odesa research at the International Zoological Congress in Paris, where his reports aroused the interest of French biologists, in particular scientists from the Laboratory of Marine Biology in Villefranche (Vincent & Bastos, 2022). His speeches became an important element in the integration of the Odesa school of zoology into the international scientific community. The future Nobel Prize laureate, one of the most famous graduates of the Imperial Novorossiya University, professor of the Department of Zoology and Comparative Anatomy, Ilya Ilyich Mechnikov (1845–1916) conducted research on immunity in Odesa and founded his own scientific school (SAOR, 6). At international medical and biological congresses in Berlin and Paris, he presented the results of his experiments on phagocytosis, which influenced the development of immunology (Mechnikov, 1879). His works caused widespread discussion among European scientists, and contacts with German bacteriologists (in particular Robert Koch) became an important step in his further scientific career (Ivanenko, 2013, pp. 127–130). I. I. Mechnikov's speeches contributed to the international recognition of Odesa science already in the last third of the 19th century. (Markevich, 1890, pp. 273–275). Less well-known today, but influential in his time, Professor of Botany and Microbiology at the Imperial Novorossiya University, Nikolai Yakovlevich Nikiforov (1836–1894), was actively involved in the study of the marine flora of the Black Sea, conducting research on algae and their impact on the ecology of coastal zones (SAOR, 3). N. Ya. Nikiforov presented the results of his work at congresses in Geneva and Berlin. His reports concerned ecological changes in the Black Sea associated with economic activity, which met the interests of European naturalists studying the issue of anthropogenic impact on marine ecosystems. His contacts with German botanists contributed to the publication of some of his works in German-language journals (Yurzhenko, 1968; Koval, 2015). More detailed information on the participation of scientists from the Imperial Novorossiya University in international scientific congresses is shown in Table 1.

Thus, the participation of Odesa scientists in international congresses in the last third of the 19th century was an important stage in the integration of the Imperial Novorossiya University into the world scientific space. It ensured the recognition of both individual researchers and the university as a whole, securing Odesa the status of one of the leading centers of natural science in Eastern Europe.

Table 1. Participation of Odesa scientists in international congresses (last third of the 19th century) (Authors' source).

Scientist	Specialization	Topic of the speech / research	City, year of congress	Significance of participation
Alexander Onufrievich Kovalevsky (1840–1901)	Zoology, Embryology	Comparative embryology of invertebrates; fauna of the Black Sea	Paris, 1889 (International Zoological Congress)	Integration of Odesa School of Zoology into the European academic space
Ilya Ilyich Mechnikov (1845–1916)	Zoology, Microbiology, Immunology	Theory of phagocytosis; experiments on immunity	Berlin, 1880s; Paris, 1889 (International Medical Congress)	Recognition of Odesa research in the field of medicine; establishment of cooperation with Robert Koch and French biologists
Nikolai Yakovlevich Nikiforov (1836–1894)	Botany, Marine Flora	Algae of the Black Sea; impact of anthropogenic factors on marine ecosystems	Geneva, 1882; Berlin, 1884 (botanical sections of congresses)	Dissemination of Odesa ecological research; publications in German journals
Alexei Pavlovich Fedchenko (1844–1897)	Ethnography, Natural History	Data from expeditions to Southern Ukraine, geography and climate observations	Paris, 1875 (Geographical Congress)	Demonstration of the potential of regional research at the international level

Academic Mobility and Exchanges of Natural Scientists and Students.

In the second half of the 19th century, the academic mobility of professors and associate professors of the Imperial Novorossiya University became one of the main factors in the integration of Odesa science into the European scientific space. Teaching trips to leading universities in Berlin, Paris, and Vienna allowed not only to deepen individual research competencies, but also to ensure the transfer of the latest methods to the walls of the university. Thus, archival documents record the internship of Professor of Zoology O. O. Kovalevsky at the University of Berlin in 1878–1879, where he worked in the laboratory of Rudolf Leykart, one of the most authoritative parasitologists of his time (SAOR, 4, p. 46). The influence of the German methodological school affected the further scientific activity of O. O. Kovalevsky: in his lectures on zoology in Odesa, a comparative-morphological approach was systematically used, which corresponded to European trends. No less important were medical and biological trips. Professor of physiology V. V. Pidvysotsky in the 1880s worked for several months in the laboratory of Claude Bernard in Paris, where he mastered experimental methods for studying the activity of glands and the nervous system. Returning to Odesa, he introduced the practice of independent physiological experiments by students into the educational process, which significantly increased the level of training (Markevich, 1890, pp. 289–292). Thus, teaching trips served as "channels of knowledge transfer": they made it possible to promptly introduce the latest techniques and laboratory equipment at the Imperial Novorossiya University, which made Odesa science competitive against the background of other universities in the empire.

An important aspect of international communication was the invitation of foreign scientists to Odesa. The university administration sought to provide students with contact with the bearers of the Western European scientific tradition. Archival data indicate that in 1884 a series of lectures by the French hydrobiologist J. Apschel was held in Odesa, dedicated to the methods of researching marine organisms (SAOR, 7, pp. 19–20). Such speeches not only expanded students' ideas about the current state of science but also contributed to the establishment of cooperation between Odesa and French researchers. In the 1890s, German geologists who participated in the research of the Black Sea coast gave reports at the university. In particular, Professor F. Schmidt (University of Berlin) presented the results of mapping geological formations in Crimea, which sparked a lively discussion among Odesa geologists and became the impetus for the creation of its own cartographic school at the university (Koval, 2015, pp. 128–130). For students and young researchers, these contacts were of strategic importance: they became acquainted with the latest publications, methods and approaches, which integrated them into the international academic space even without going abroad.

An equally important component of academic mobility was foreign internships for students and postgraduates. Already in the 1870s and 1880s, talented university graduates were allowed to work in laboratories at European universities, often on scholarships from the Ministry of Public Education or private patrons. One of the first was the case of the medical student G. M. Minh's secondment to Louis Pasteur's laboratory in Paris in 1886 (SAOR, 5, pp. 33–34). Upon his return, he introduced microbiological analysis methods in his dissertation that were not yet widespread in the Russian Empire. Such internships not only increased the level of training of young scientists, but also consolidated Odesa's status as a university center open to innovations. Another example is the secondment of natural science students for summer internships to zoological stations in Naples and Villefranche-sur-Mer (France). These internships provided an opportunity to work directly with the latest methods of studying marine organisms, which had a direct connection with the study of the Black Sea (Protocols, 1870). As a result, the dissertation research of Odesa graduates included comparative materials that correlated local observations with the results of Mediterranean research (Yurzhenko, 1968, pp. 111–112). Thus, students became "agents of innovation," returning from European centers of science with new knowledge and methods, laying the foundations for the development of local schools in the fields of biology, medicine, and geology.

In general, academic mobility at the Imperial Novorossiya University in the last third of the 19th century was complex. Teaching trips contributed to the modernization of curricula and methodology. The arrival of foreign scientists broadened the educational horizons of students and integrated the university into world science. Student internships ensured the formation of a generation of young researchers capable of critically perceiving and adapting European methods. All these practices together formed the international image of the Imperial Novorossiya University as a center of science open to dialogue and capable of being a full-fledged partner in the system of European academic communication.

Translations and the Influence of Western European Methodologies.

One of the key mechanisms for the integration of the Imperial Novorossiya University into the European scientific space was the translations of textbooks, monographs and articles coming from university centers in Germany, France, and Great Britain. Since the 1870s, a specialized collection of foreign literature on natural science and medicine has been formed in the university library (SAOR, 1, pp. 9–11). An important direction was the adaptation of German and French textbooks to the needs of the student audience. For example, in the lecture courses of Professor I. I. Mechnikov, translations of the works of Karl Baer and Ernst Haeckel were used, which spread the latest evolutionary concepts. Students had the opportunity to get acquainted with primary sources not only in Russian but also in the form of translated excerpts, which were reproduced for educational purposes. Similar processes can be traced in medicine: Professor V. V. Pidvysotsky actively used adapted translations of Claude Bernard's works on experimental physiology in his courses. This made it possible to popularize among students advanced theories of the functioning of the organism, which at that time determined the development of world science. Translated literature served as a channel through which Odesa joined the scientific discussions relevant at that time, which were conducted on the pages of European journals (La Revue Scientifique, Archiv für Anatomie und Physiologie, etc.). The most important translations that were actively used by Odesa scientists in teaching practice and scientific research are listed in Table 2.

In addition, the publishing house "Mathesis", which operated in Odesa in the late 19th and early 20th centuries, was of particular importance for the dissemination of European scientific achievements in the southern Ukrainian intellectual environment.

Its translation activities became one of the key mechanisms for including the local academic and student community in the context of modern Western European science. Many German, French, and English books and articles on natural science were published in languages that were not widely known among students and novice scientists in Odesa. Translations of "Mathesis" opened access to the works of leading authors – from Ch. Darwin and E. Haeckel to R. Virchow and C. Bernard (Pasichnyk, Rizhniak, & Deforzh, 2024). This allowed young scientists to familiarize themselves with current concepts without remaining in a provincial isolation from the scientific world. Translated publications were not limited to the literal reproduction of texts. The publishing house often accompanied them with explanations, notes, and glossaries of terms.

Table 2. Examples of translated and adapted works used at the Imperial Novorossiya University (Authors' source).

Author	Title of work (original)	Subjects	Use in Odesa and influence
Ernst Haeckel (Germany)	*Generelle Morphologie der Organismen* (1866)	Evolutionary Biology, Morphology	Used by I. Mechnikov in lectures; spread of ideas of evolutionary morphology among students
Karl Ernst von Baer (Germany)	*Über Entwicklungsgeschichte der Tiere* (1828)	Embryology	Translated fragments were used in embryology courses; contributed to consolidation of the experimental approach
Claude Bernard (France)	*Leçons sur les phénomènes de la vie communs aux animaux et aux végétaux* (1878)	Physiology, Experimental Medicine	Adapted texts were included in V. Pidvysotsky's lectures; popularized the experimental approach in medicine
Rudolf Virchow (Germany)	*Die Cellularpathologie* (1858)	Cell Pathology, Medicine	Influenced pathology courses and medical practice of the university clinic; confirmed the cell theory
Charles Darwin (Great Britain)	*On the Origin of Species* (1859)	Evolutionary Theory	Read in translations and notes; stimulated the development of discussions in the student environment and academic circles
Jean-Martin Charcot (France)	*Leçons sur les maladies du système nerveux* (1872–1873)	Neurology	Used at the Department of Medicine; introduced French clinical approaches in Odesa

This led to the development of academic terminology in Russian (and partly Ukrainian) languages, which was important for the establishment of a single scientific language in university courses (Table 3).

"Mathesis" is also known for its desire to distribute not only specialized texts, but also popular scientific translations. This contributed to the formation of interest in natural sciences among high school students, junior students, and even the general urban public. Odesa, as a cosmopolitan city, had access to translated literature in public libraries and bookstores. The publishing house's translations were actively used in the educational process of the Imperial Novorossiya University. They filled the gap in modern textbooks in biology, physiology, medicine, and geology, which made teaching more modern and competitive compared to the leading universities of the empire. Through the translations of "Mathesis", Odesa scientists actually joined international discussions: they were able to refer to the works of European colleagues, discuss new theories and methods. This contributed to the development of international scientific communication and raised the prestige of the university (Kryvets, 2013).

Table 3. Examples of translated books and series of "Mathesis" in the field of natural sciences (Authors' source).

Author / Series	**Title (original/translation)**	**Subjects**	**Uses and Impact**
Svante Arrhenius	Physics of the sky (translated from German)	Astronomy, Atmospheric Physics	Opened up a new field of astrophysics to students; spread ideas about planetary and space physics
F. Auerbach	The Queen of Peace and Her Shadow	Energy, Entropy, Thermodynamics	Popularized concepts of energy in the Russian Empire
G. Weber, J. Wellstein	Encyclopedia of Elementary Mathematics	Mathematics, Natural Science	Used as a universal introductory course
Series "Successes in Physics"	Collections of translations of contemporary articles from Western journals (Annalen der Physik, Comptes rendus)	Physics, Electricity, Optics	Provided access to the latest research; used by university professors as additional literature
Series "Successes in Biology"	Translations of works from Archiv für Entwicklungsmechanik, La Revue Scientifique, etc.	Biology, Zoology, Embryology	Popularized evolutionary and embryological research; important for natural science students
Series "Successes in Chemistry"	Collections from German and French journals (Berichte der Deutschen Chemischen Gesellschaft)	Chemistry, Organic Reactions	Allowed rapid acquisition of the latest advances in European laboratories

The second important level of influence of European science was the assimilation and adaptation of specific methodological approaches. In Biology, the German experimental tradition, formed by the school of K. Ludwig, J. Müller and G. Trautschold (Sintsov, 1879), was of particular importance. Professors of the Imperial Novorossiya University, visiting German laboratories during business trips, brought not only new devices, but also methodological standards of research. As a result, laboratory classes in Odesa increasingly acquired the features of a systematic experiment with control of variables, which distinguished them from the previous descriptive naturalistic tradition. The medical departments of the university, in turn, were under the strong influence of the French school. The practice of clinical teaching, initiated in Paris in the late 18th - early 19th centuries, was adapted to the conditions of the Odesa University Clinic. Resident physicians, familiar with the works of René Laennec, Gabriel Andrall, and Jean-Martin Charcot, introduced methods of clinical diagnosis, which significantly improved the quality of medical student training (Pavlenko, Ruda, Khorosheva, & Khramov, 2001, pp. 301–304). Thus, the university became a laboratory for adapting Western methodologies to the local context, combining experimental models with the specifics of research in the southern region of the empire (for example, the zoology of the Black Sea or pathologies common in the steppe zone) (Pavlenko, Ruda, Khorosheva, & Khramov, 2001).

Another important consequence of the influence of European science was the formation of a new academic language in Odesa. In lectures and publications of the late 19th century. active tracing and adaptation of foreign language concepts can be traced. Terminology in the field of embryology, histology, bacteriology mostly came from German, while in medicine, French terms played a significant role. University professors often required students to know at least one European language, and in some cases (for example, at the Department of Botany) allowed the defense of coursework in German. This contributed to the formation of multilingualism as a characteristic feature of the university's scientific culture. Archival protocols of faculty meetings of the 1890s. contain mentions of student reports in French (SAOR, 8, pp. 14–15). Multilingualism allowed Odesa scientists not only to get acquainted with the latest publications but also to actively participate in international discussions. Articles with summaries in French and German were published in Notes, which made them accessible to foreign colleagues (Sintsov, 1890; Levchenko, 2017). This became an institutional norm that contributed to the establishment of the Imperial Novorossiya University as an academic center that was European in spirit.

In general, translations, methodological borrowings and multilingualism constituted a triune mechanism for the integration of the Imperial Novorossiya University into the international scientific space. Translated literature spread European theories among students, the methods of Western schools formed new research practices, and the academic language was transformed in accordance with the standards of world science. Thus, Odesa in the last third of the 19th century. emerged as a laboratory for the synthesis of local scientific tasks with global trends in the development of natural science.

Discussion.

The development of international relations of the Imperial Novorossiya University in the last third of the 19th century organically fit into the broader European trends in the formation of scientific communication networks. Similar to the universities of Berlin or Heidelberg (Dusdal, Powell, Baker, Shamekhi, Stock, 2020), Odesa scientists actively used publishing as a channel of integration into the academic space of Europe. The "Notes of the Novorossiya Society of Naturalists" played a similar function to the French Comptes rendus (Simon, 2019) or the British Proceedings of the Royal Society (Pietsch, 2013), ensuring the circulation of local results at the international level. The participation of Odesa scientists in international congresses in Berlin, Paris, and Geneva was in line with the practices of universities in Germany and France, where such forums became a key tool for knowledge transfer (Dusdal & Powell, 2021). At the same time, unlike British and German universities, which acted as "donors" of methodologies, the Imperial Novorossiya University mainly absorbed and adapted Western European traditions. A comparison with Italian centers (Naples, Padua) shows the closeness of Odesa's experience in the field of marine biological research and the role of zoological stations as platforms for international cooperation (Bittante et al., 2022). In Spain, academic networks were similarly formed through the exchange of collections and participation in congresses, which allows Odesa to be considered as part of a broader European trend of integration of peripheral universities (Barbosa, Sáiz, & Zofío, 2024). The academic mobility of professors and students of the Imperial Novorossiya University correlated with processes in Germany and France, where internships and laboratory practice became an integral part of the training of scientific personnel. Translations of works by Darwin, Haeckel, Bernard, or Charcot in Odesa mirror similar translation initiatives in Italy and Spain, which were used to modernize the educational process. The multilingualism of Odesa's academic environment echoes the practices of European universities, where knowledge of French, German, and Latin was mandatory for integration into the international debate. An important aspect is that, unlike established universities in Western Europe, the Imperial Novorossiya University combined the functions of an educational center and a regional laboratory for the adaptation of scientific methodologies. Thus, the Odesa experience demonstrates that a peripheral university could play an active role in knowledge transfer and act as a partner in the European system of scientific communications.

Conclusions.

A meaningful analysis of the international relations of the Imperial Novorossiya University and the Odesa scientific community in the field of natural sciences in the last third of the 19th century allowed us to draw the following conclusions.

1. The Imperial Novorossiya University in the last third of the 19th century became an important center for the development of natural science disciplines in Southern Ukraine. Its formation took place in close connection with European

academic traditions, which was due to both the geographical location of Odesa and the presence of active channels of international communication.

2. “Notes of the Novorossiya Society of Naturalists” played a key role in the dissemination of scientific knowledge and communication with the European scientific community. The publication combined local research with an orientation to international standards of scientific journalism, and also ensured the circulation of research results through summaries in foreign languages and the exchange of copies with libraries in Europe.

3. The participation of Odesa scientists in international congresses (Berlin, Paris, Geneva) became an important stage in the integration of the university into world science. Their reports on marine biology, medicine, and geology received a positive response among European researchers and contributed to the establishment of the university's international reputation.

4. Academic mobility of professors and students (business trips, internships, summer internships) ensured the transfer of the latest knowledge and research methods from leading centers in Germany and France. The arrival of foreign scientists with lectures and seminars broadened the worldview of the Odesa academic community and stimulated the development of new scientific directions.

5. Translations of European textbooks and works (Darwin, Haeckel, Virchow, Bernard, Charcot, etc.) and the activities of the Odesa publishing house “Mathesis” contributed to the dissemination of modern scientific concepts, the formation of academic terminology, and the inclusion of local research in the international scientific discourse.

6. Western European methodologies (German experimental tradition in biology, French clinical school in medicine) were actively adapted in Odesa. This ensured a qualitative transformation of the educational process and research practices, bringing the university closer to European standards.

7. The formation of multilingualism as a feature of the university's scientific culture became an important factor in integration into the global academic space. Knowledge of foreign languages, summaries in other languages, and publications in foreign journals increased the visibility of Odesa scientists in the world.

Thus, the international ties and scientific communication of the Imperial Novorossiya University in the last third of the 19th century ensured its transition beyond the boundaries of a regional educational center and transformation into a significant center of natural science research in Eastern Europe.

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Міжнародні зв’язки та наукова комунікація Імператорського Новоросійського університету в останній третині XIX століття: Контекст розвитку природознавства

Анотація. *Стаття присвячена дослідженню міжнародних зв'язків та форм наукової комунікації вчених-природознавців Імператорського Новоросійського університету в останній третині XIX століття У роботі простежено, як науковці та викладачі поступово інтегрувалася у європейський дослідницький та академічний простір, використовуючи низку каналів – від перекладів західноєвропейської літератури та адаптації методологій до участі у міжнародних конгресах і програм академічної мобільності. Автори аналізують роль "Записок Новоросійського товариства дослідників природи" як інституційного майданчика поширення наукових результатів, що поєднував публікацію локальних досліджень із орієнтацією на потреби європейської наукової спільноти. У виданні регулярно публікувалися статті з резюме іноземними мовами, що полегшувало взаємодію з зарубіжними колегами. Також виявлено практику обміну примірниками із зарубіжними бібліотеками, що робило "Записки" важливим каналом наукової комунікації між Одесою та провідними центрами Європи. Окрему увагу приділено участі одеських учених у міжнародних конгресах з біології, медицини та зоології в Берліні, Парижі та Женеві. У їхніх доповідях відображалися результати досліджень Чорного моря, а також співпраця з німецькими й французькими науковими школами. Це сприяло підвищенню престижу університету, визнанню одеських учених у європейській академічній спільноті та перетворенню університету на важливий центр науки в регіоні. Авторами досліджені процеси академічної мобільності викладачів і студентів. Викладачі стажувалися в лабораторіях Берліна й Парижа, засвоюючи нові експериментальні методи, які згодом застосовувалися в Одесі. Студенти мали можливість проходити практику на європейських зоологічних станціях та в наукових клініках, що сприяло підвищенню рівня їхніх майбутніх дисертаційних досліджень. Водночас університет приймав закордонних учених, чиї лекції й семінари розширювали світогляд академічної спільноти та сприяли інтеграції в міжнародні інтелектуальні процеси. Особливе місце в роботі займає аналіз перекладацької діяльності та впливу західноєвропейських методологій. Показано, що переклади творів Ч. Дарвіна, Е. Геккеля, Р. Вірхова, К. Бернара та Ж. Шарко, здійснені зокрема одеським видавництвом "Матезіс", сприяли поширенню сучасних концепцій і становленню академічної термінології. Це не лише підвищувало якість навчального процесу, але й формувало багатомовність як ознаку наукової культури університету. Методологічну основу статті становлять історико-генетичний, порівняльно-історичний, контент-аналіз та просопографічний підхід. Джерельна база включає архівні документи, університетські звіти, публікації "Записок Новоросійського товариства дослідників природи", а також сучасні українські й зарубіжні дослідження з історії науки. У висновках наголошено, що міжнародні зв'язки й наукова комунікація були ключовими факторами становлення Імператорського Новоросійського університету як* *регіонального осередку природознавства з європейськими характеристиками. Досвід Одеси останньої третини XIX ст. засвідчив, що інтеграція в міжнародний науковий простір забезпечувалася поєднанням локальних дослідницьких практик із глобальними тенденціями та широким використанням каналів інтелектуального обміну.*

Ключові слова: *Імператорський Новоросійський університет; міжнародний науковий простір; наукова співпраця; природознавство; Новоросійське товариство дослідників природи; міжнародні конгреси; західноєвропейські методології*

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Hybrid laser-arc welding of low-alloy steels: From scientific concept to industrial technology (1970s–2020s)

Abstract. *The article examines the historical development of hybrid laser-arc welding of low-alloy steels from the formulation of the hybrid concept in the late 1970s to its emergence as an industrial technology in the early 21st century. Two interrelated but historically non-synchronous trajectories are identified: the evolution of fundamental and applied scientific research on laser-arc interaction and the subsequent formation of sustainable industrial applications in shipbuilding, pipeline welding, wind turbine tower manufacturing, and energy structures. Based on scientific publications, institutional reports, and documented industrial implementations in Germany, Denmark, Finland, USA and China, the path of hybrid welding transition from laboratory experiments to serial production in sectors with complex design requirements is reconstructed. Particular attention is paid to the role of leading research centers, as well as technology transfer processes. It is shown that the significant time lag between scientific justification and industrial implementation was due not only to the level of development of laser equipment, but also to institutional conservatism, certification barriers and high capital intensity of laser-oriented production systems. The sectoral nature of the technology's spread is separately analyzed, which explains why hybrid laser-arc welding first became established in European shipbuilding, later in selected pipeline projects in North America, then in the production of wind energy towers in Germany, and to the greatest extent in offshore and energy structures in China. The fundamentally important rethinking of this technology in the context of the United Nations Sustainable Development Goals is also considered, with an emphasis on reducing heat input, reducing welding consumables, reducing deformations and extending the service life of large steel structures. It is proven that hybrid laser-arc welding did not emerge as a universal alternative to* *traditional arc or submerged arc processes, but as a highly productive targeted solution determined by the interaction of scientific knowledge, industrial demand, institutional networks, and long-term structural changes in steel-intensive industries.*

Keywords: *hybrid laser-arc welding; low-alloy steels; history of welding technologies; laser materials processing; science-industry interaction; sustainable development*

Introduction.

Low-alloy steels have long been among the most widely used structural materials in heavy industry, transport, infrastructure and energy systems. Their widespread use stems from a balance of mechanical strength, weldability, cost-effectiveness, and material availability.

In the late 20th century, the growing scale and technical demands of welded steel structures (thicker plates, longer weld seams, higher production rates) highlighted the limitations of conventional arc-based welding. In particular, for thick-section joints, conventional arc welding often required multiple passes, produced wide heat-affected zones, and introduced significant distortion and residual stress (Lobanov, Poznyakov, Pivtorak, Mikhodui, & Orlovs'kyi, 2009; Paton, 2003; Poznyakov, Kasatkin, Zhdanov, & Strizhak, 2005). At the same time, the effort to use laser welding methods offered high energy density and deep penetration but encountered limitations related to joint fit-up tolerances, gap sensitivity, and cost of high-power laser equipment (Krivtsun & Seyffarth, 2002; Piekarska & Kubiak, 2013; Shelyagin et al., 2005b).

The concept of combining a laser beam with an electric arc, now known as hybrid laser-arc welding (HLAW), emerged in this context (Figure 1). According to technical histories, the first demonstrations of what later became called HLAW date to the late 1970s under the term "arc-augmented laser welding" (Eboo, Steen, & Clarke, 1978; Steen & Eboo, 1979; Steen, 1980).

Over the following decades, hybrid welding developed at the intersection of several disciplines: laser physics, arc plasma physics, metallurgical science, welding engineering, and later automation and control engineering. It was not a one-time invention but rather a slow convergence of multiple lines of research and development. By the 1990s, researchers in welding institutes and laser-technology centers began to treat HLAW as a distinct subject. In parallel, industrial demand (especially from sectors working with thick low-alloy steel plates, such as shipbuilding, pipelines, heavy machinery, railway manufacturing and energy) created pressure for a welding process combining depth, speed, and tolerance to joint imperfections.

Despite a growing technical literature (on thermal behaviour (Gu, Li, H., & Li, L. J., 2013;Piekarska & Kubiak, 2013; Wei, Li, Yang, Gao, & Ding, 2015), weld pool dynamics (Krivtsun, Reisgen, Semenov, & Zabirov, 2016; Üstündağ, Fritzsche, Avilov, Gumenyuk, & Rethmeier, 2018a; Yang et al., 2020), metallurgical effects (Berdnikova, Poznyakov, Bernatskyi, Alekseienko, & Sydorets, 2019; Bunaziv, Akselsen, Frostevarg, & Kaplan, 2018a; Górka & Stano, 2018), weld quality (Kim, Hirohata, & Inose, 2014; Liu et al., 2024; Norman, Karlsson, & Kaplan, 2011), process stability (Gu, Li, H., & Li, L. J., 2013; Liu et al., 2023; Moradi, Ghoreishi, Frostevarg, & Kaplan, 2013)) the historical development of hybrid laser-arc welding of low-alloy steels, considered as a coherent technological trajectory, has rarely been treated as an independent subject in history-of-technology or history-of-science studies. Most publications remain firmly within engineering and materials science disciplines, focusing on process parameters and mechanical outcomes, not on institutional developments, national research traditions, or the broader industrial and socio-economic context.

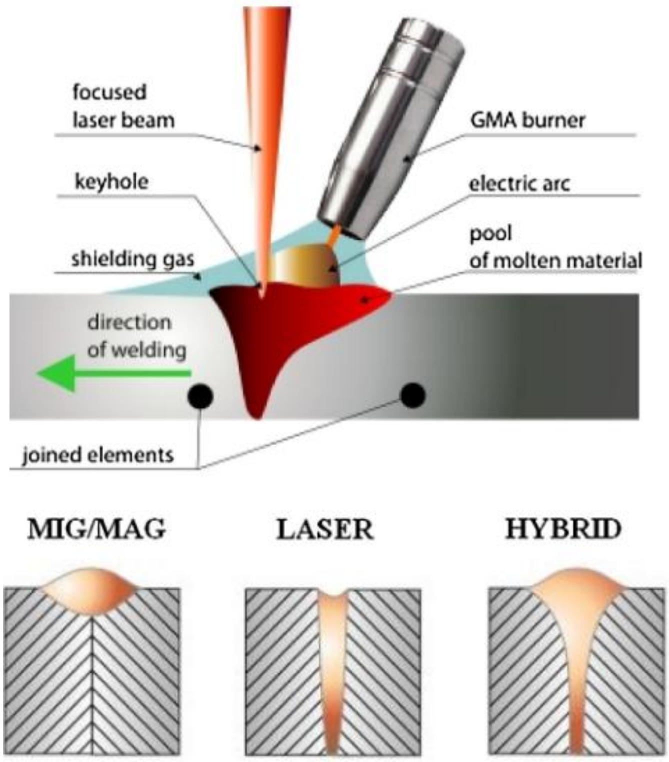


Figure 1. Scheme of hybrid laser arc welding process and patterns of formation of weld beads during arc welding, laser welding and hybrid laser arc welding (Acherjee, 2018a).

This article takes that broader historical view. It aims to reconstruct the evolution of HLAW for low-alloy steels, from its scientific origins to its industrial applications, with specific attention to dates, institutional actors, quantitative milestones where available, and the interplay between research, technology, and industrial demand. The article treats this evolution as a two-level process: first, the development of fundamental and applied research; second, the diffusion into stable industrial practice. It also considers the role of HLAW in longer-term trends in industrial modernization and sustainable use of steel structures.

Methodology.

This study applies a historical-analytical methodology combined with comparative and contextual analysis, which are often used in similar studies (Strelko, 2021; Strelko & Pylypchuk, 2021; Strelko, Pylypchuk, & Berdnychenko, 2019). The central task is to reconstruct the long-term formation of HLAW of low-alloy steels as a scientific field and as an industrial technology, with clear chronological markers and institutional attribution. The core empirical basis of the study consists of three major groups of sources.

First, peer-reviewed scientific literature on laser welding, arc welding, and hybrid processes published's between 1978 and 2025. The earliest technical descriptions of arc-assisted laser welding appear in the late 1970s, while systematic hybrid welding studies became visible in international journals from the early 1990s.

Second, international patent documentation on hybrid laser-arc welding systems and process control was examined. A targeted search of Espacenet and Google Patents for the period 1980–2025 yields more than 1,200 patent families directly related to hybrid laser-arc welding heads, laser-arc coupling methods, and adaptive control systems.

Third, reports and technical papers from major welding and laser research institutions were analyzed. These include publications from the Fraunhofer Institute for Laser Technology, RWTH Aachen University, Fraunhofer Institute for Production Systems and Design Techology and Federal Institute for Materials Research and Testing (Germany), Edison Welding Institute and Pennsylvania State University (USA), Osaka University (Japan), Harbin Institute of Technology and Tianjin University (China), Lappeenranta University of Technology and Aalto University (Finland), SINTEF and Norwegian University of Science and Technology (Norway), Luleå University of Technology (Sweden), Silesian University of Technology and the Welding Institute in Gliwice, Częstochowa University of Technology (Poland) and the E. O. Paton Electric Welding Institute (Ukraine).

The methodological separation between fundamental research, applied engineering research, and industrial implementation is a key principle of this study. Fundamental research includes laser-metal interaction physics, arc plasma behavior, and thermophysical modeling. Applied research includes hybrid process stability, metallurgical phase transformations in low-alloy steels, and weld quality optimization. Industrial implementation is traced through pilot plants, serial production lines, and certified welding procedures.

Comparative national analysis is used to identify differences in scientific traditions, industrial incentives, and technological policy. The study focuses primarily on Germany, the United States, Japan, China, and Eastern Europe, where continuous research trajectories in hybrid welding can be documented from the 1990s onward.

Finally, contextual interpretation is applied to relate hybrid laser-arc welding to broader processes of industrial modernization, energy efficiency, and sustainability.

This allows a historical connection to be drawn between welding technology development and long-term transformations of industrial production systems rather than treating HLAW solely as an isolated technical process.

Early Priority and the "First Publication" on Hybrid Welding.

The question of which work should be regarded as the "first" publication on hybrid laser-arc welding cannot be answered unambiguously, because different communities have fixed priority at different points in Steen's early work. Chronologically, the conference paper "Arc Augmented Laser Welding", presented at *the 4th International Conference on Advances in Welding Processes* in Harrogate in May 1978, is the earliest public description of a laser weld augmented by an electric arc (Eboo, Steen, & Clarke, 1978). Recent overview articles and handbooks explicitly treat this *Harrogate paper* as the initial disclosure of the hybrid concept and cite it as such when describing the late-1970s origins of hybrid welding.

In the welding-technology literature, however, the 1979 journal article by Steen and Eboo, "Arc Augmented Laser Welding", published in *Metal Construction*, is often treated as the first "real" hybrid welding publication (Steen & Eboo, 1979). Educational reviews and technical reports refer to this paper as the point at which hybrid welding was "originally invented" for combined laser-TIG welding, and European reviews on hybrid laser-arc processes routinely cite this 1979 article as the starting reference in their historical sections.

A third group of authors, especially in physics-oriented and numerical-simulation work, takes the 1980 article "Arc Augmented Laser Processing of Materials" in *Journal of Applied Physics* as the primary reference (Steen, 1980). In reviews of hybrid welding physics and numerical modelling, the hybrid concept is often said to have been "introduced around 1980" and directly linked to this paper, which formulates arc-augmented laser processing as a general materials-processing idea rather than as a specific welding procedure.

Thus, there is no single universally accepted "first" publication. In this article we therefore distinguish explicitly between three levels of priority: the 1978 *Harrogate conference paper* as the first public disclosure of hybrid welding, the 1979 *Metal Construction* article as the first archival welding-journal paper on the process, and the 1980 *Journal of Applied Physics* article as the first broad physical formulation of arc-augmented laser processing. This distinction helps to clarify the apparent confusion in the literature, where different authors label different members of this trio as the "first" depending on whether their focus is conference precedence, welding practice, or general process physics.

Results.

1. Periodization: Historical Development of Scientific Research (Fundamental and Applied).

The historical development of scientific research on hybrid laser-arc welding of low-alloy steels can be divided into four main stages. These stages reflect changes in laser technology, arc power sources, diagnostic tools, and computational modeling, as well as shifts in the balance between fundamental and applied research.

1.1. Stage I (1970s–1980s): Physical Foundations of Hybrid Interaction.

The first stage is associated with the formation of the physical foundations of laser-metal and arc-plasma interaction, prior to the establishment of hybrid welding as an independent applied field. During the 1970s, laser welding research was focused primarily on the keyhole mechanism, laser absorption in metals, and melt pool dynamics. Industrial CO_2 lasers with power levels of 1–3 kW became available by the mid-1970s, enabling systematic penetration studies in carbon and low-alloy steels with thicknesses up to 5–8 mm in a single pass.

During this first stage, research was focused less on specific industrial steels and more on understanding the basic mechanisms of interaction between the laser-induced keyhole, the arc plasma and the molten pool. Early experiments examined how arc polarity, current, and shielding gas composition affect the shape and stability of the keyhole, the absorption of laser radiation, and the distribution of heat input in the joint. The central questions were whether the arc could increase effective energy coupling into the material, stabilize the keyhole against collapse, and extend the permissible range of joint fit-up and surface conditions compared with pure laser welding.

In parallel, the first analytical and semi-empirical models of hybrid interaction began to appear. Researchers attempted to describe the temperature field, the shape of the molten pool, and the vapor-plasma plume when an arc is present above the laser spot. These models were still simplified, but they introduced a conceptual framework that distinguished hybrid processes from both conventional arc welding and classical laser welding. By the end of the 1980s, the main physical features of arc-augmented laser processing had been identified: the possibility of deeper penetration at a given total power, the redistribution of heat between the arc and the laser, and a potential increase in process robustness. At the same time, this work remained predominantly experimental and conceptual.

1.2. Stage II (Early–Mid 1990s): Formation of Hybrid Welding as an Applied Research Field.

The second stage begins in the early 1990s, when laser technology, numerical control systems, and arc power sources reached a level that allowed synchronized hybrid operation to be studied systematically. During this decade, continuous-wave lasers with power levels of 3–6 kW became increasingly available to research laboratories and industrial development centers. By the end of the 1990s, experimental hybrid welding of low-alloy steels with thicknesses of 8–12 mm in a single pass had already been repeatedly demonstrated in laboratory settings.

During this period, the first numerical models of hybrid heat sources also appeared, combining Gaussian laser distributions with distributed arc heat input. These models represented a methodological shift from descriptive experimentation toward predictive simulation.

1.3. Stage III (2000s): Expansion of Applied Metallurgical and Process Control Research.

The 2000s represent a phase of rapid expansion of applied scientific research. Several structural factors contributed to this acceleration. First, industrial fiber and disk lasers with power levels exceeding 8–10 kW became commercially available after approximately 2005–2010, significantly improving efficiency and beam quality. Second, real-time vision systems and digital synchronization tools enabled precise coordination of laser and arc heat sources.

During this decade, hybrid welding research focused on: thermal field distribution; weld pool hydrodynamics; phase transformations in low-alloy steels; defect formation mechanisms (porosity, hot cracking); mechanical performance of hybrid welds under static and cyclic loading.

By the late 2000s, hybrid welding was no longer regarded as an exotic process. Scientific publications documented stable welding of low-alloy steels with thicknesses of 12–20 mm in a single pass, with welding speeds exceeding those of multi-pass arc welding by factors of 2–4.

1.4. Stage IV (2010s–2020s): Digitalization, Fiber Lasers, and Process Optimization.

The most recent stage, beginning in the early 2010s, is characterized by the integration of digital monitoring, computational control, and artificial intelligence methods into hybrid welding systems. Fiber lasers with output powers of 15–30 kW became industrially widespread after 2012–2017, enabling single-pass welding of steel plates exceeding 20–25 mm thickness under controlled conditions.

Research during this period increasingly focused on: real-time process monitoring using high-speed cameras and optical sensors; adaptive control of laser-arc coupling; numerical "digital twin" models of hybrid weld pools; residual stress minimization and fatigue-life prediction.

At this stage, fundamental plasma–laser interaction studies became tightly integrated with industrially oriented optimization. The boundary between fundamental and applied research became increasingly blurred, reflecting the maturity of hybrid laser-arc welding as a scientific and technological field.

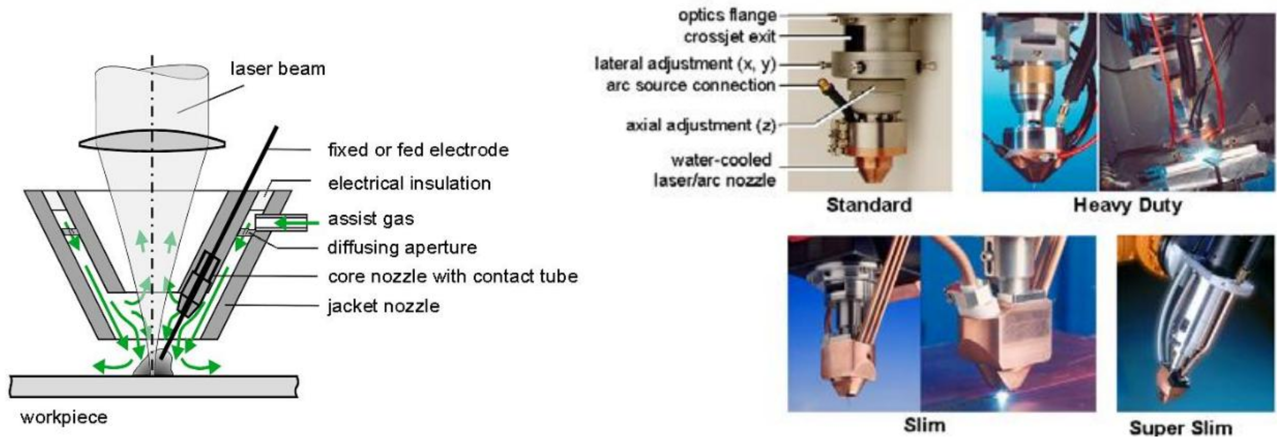
2. Leading Countries and Scientific Centers.

The development of hybrid laser-arc welding of low-alloy steels has been shaped by a relatively small group of countries with strong welding science, advanced laser technology, and intensive industrial use of thick steel structures. Their leading role is visible in three dimensions: early entry into hybrid research, systematic work on thick low-alloy steels, and documented transfer of hybrid technologies into shipbuilding, pipelines, heavy machinery, rail, and energy infrastructure.

2.1. Germany: Fraunhofer ILT, RWTH, Fraunhofer IPK, BAM and the Engineering of Hybrid Laser–Arc Welding for Thick Steels.

Germany occupies a central position in the historical development of hybrid laser-arc welding, particularly in relation to thick-section and high-strength structural steels. From the late 1990s onward, German research institutions played a decisive role in transforming hybrid welding from a laboratory concept into a robust engineering process suitable for heavy steel fabrication. Among these institutions, the Fraunhofer Institute for Laser Technology (Fraunhofer ILT) in Aachen emerged as one of the most influential centers for applied hybrid welding research.

At the turn of the millennium, researchers at Fraunhofer ILT introduced one of the most consequential technical innovations in the field: the integrated hybrid welding head, often referred to as the "integrated nozzle", which combined laser optics and a MAG welding torch into a single system (Figure 2).



a b

Figure 2. Integrated hybrid welding nozzle: *(a)* principle of the integrated hybrid welding nozzle; *(b)* standard and customized hybridwelding heads with the integrated nozzle design (Petring & Fuhrman, 2004).

This design significantly improved process stability and industrial usability. In a series of papers presented at ICALEO and related conferences (Petring, Fuhrmann, Wolf, & Poprawe, 2003; Petring & Fuhrmann, 2004; Petring, Fuhrmann, Wolf, & Poprawe, 2007). Dirk Petring and co-authors documented industrial applications of this concept beginning around 2000, including hybrid laser-MAG welding of structural and low-alloy steels with thicknesses of approximately 20–30 mm in single- or double-sided configurations. These studies are notable because they go beyond penetration depth and welding speed, reporting also on weld quality, defect sensitivity, and fatigue performance in steels used for tanks, ship structures, and heavy machinery.

Fraunhofer ILT's contribution was not limited to hardware development. Throughout the 2000s and early 2010s, ILT researchers conducted systematic investigations into process windows for hybrid laser-MAG welding of steels, addressing joint preparation, laser-arc positioning, filler wire selection, and shielding gas composition. These studies established quantitative tolerances for gap width and misalignment and clarified how hybrid welding parameters influence weld bead geometry and microstructural evolution in low-alloy steels. Results were published in international journals and proceedings and formed the technical basis for transferring hybrid welding into shipbuilding and heavy-structure production (Kaierle, Bongard, Dahmen, & Poprawe, 2000; Petring, 2013; Webster, Kristensen, & Petring, 2008).

Parallel to the work at ILT, German university groups (particularly at RWTH Aachen University) contributed numerical modeling and advanced diagnostics (Olschok, Reisgen, & Dilthey, 2007; Reisgen, Olschok, Jakobs, & Engels, 2016; Wieschemann, Kelle, & Dilthey, 2003). Their studies addressed heat source interaction, molten pool dynamics, and solidification behavior in laser-MAG hybrid welding of steels, linking process parameters with microstructure and mechanical properties. This modeling work complemented ILT's applied research by providing mechanistic explanations for observed stability limits and defect formation, thereby refining process design for low-alloy structural steels.

In the 2010s, hybrid laser-arc welding of thick steels became part of a broader German research agenda focused on energy infrastructure and large welded components. A representative example is the works of Fraunhofer Institute for Production Systems and Design Techology (Fraunhofer IPK in German) and Federal Institute for Materials Research and Testing (BAM in German) in Berlin. These research extended the German thick-steel agenda by focusing on electromagnetic support of the weld pool in hybrid laser-arc welding (Üstündag, Avilov, Gumenyuk, & Rethmeier, 2018; Üstündağ, Fritzsche, Avilov, Gumenyuk, & Rethmeier, 2018a, 2018b). A series of studies demonstrated that applying an oscillating magnetic field beneath the joint can suppress root sagging and enable single-pass welding of ferromagnetic steels up to approximately 28 mm in thickness, while maintaining acceptable mechanical properties. These concepts were subsequently applied to wind-tower fabrication and energy-transition structures, where BAM and associated projects proposed hybrid laser-arc welding as an alternative to multi-layer submerged arc welding for circumferential welds in 20–30 mm thick tower shells (Brunner-Schwer, Üstündağ, Bakir, Gumenyuk, & Rethmeier, 2023). This work reflects a shift from experimental feasibility toward system-level production strategies for large cylindrical steel structures.

BAM also became a central actor in pipeline-oriented hybrid welding, often in close cooperation with Fraunhofer IPK. Studies (Gook, Gumenyuk, & Rethmeier, 2014; Üstündağ, Gook, Gumenyuk, & Rethmeier, 2020) examined hybrid welding of high-strength pipeline steels such as X80 and X120, including orbital hybrid welding of large-diameter pipes. These works defined realistic process windows in terms of welding speed, penetration, and defect control and are now widely cited in reviews and design recommendations for hybrid welding of linepipe steels.

Taken together, German research on hybrid laser-arc welding of low-alloy steels is characterized by the integration of equipment development (Fraunhofer ILT), process modeling (RWTH), materials performance assessment (BAM, Fraunhofer IPK), and sector-specific application (shipbuilding, energy, pipelines, offshore structures). This multi-institutional framework has made Germany one of the key reference points for hybrid welding of thick structural steels and has strongly influenced both European and global development trajectories in this field.

2.2. United States: DebRoy's Group and the Pipeline-Structure Focus.

In the United States, leadership in hybrid laser-arc welding is shared between academic groups (DebRoy's and others) and the Edison Welding Institute (EWI).

The applied pillar is EWI. From the early 2000s, EWI worked on hybrid laser-arc welding for pipelines and structural components under sponsorship from US regulators and industry (Harris & Norfolk, 2008; Victor, Nagy, Ream, & Farson, 2009; Victor, 2011). EWI and associated studies focused on transition from laboratory demonstrations to field-suitable procedures, including discussions of weld procedure qualification, toughness requirements, and defect acceptance criteria. These efforts helped define the place of hybrid welding within North American pipeline and structural standards.

Researchers from Tarasankar DebRoy's group (Pennsylvania State University) are often cited in hybrid laser-arc welding because they treated the process as a coupled heat transfer + fluid flow + arc/plasma interaction problem, and then used that framework to explain the practical behavior that production engineers care about (penetration, pool shape, gap tolerance, and stability). A key example is Ribic, Rai and DebRoy's paper (2008) on GTA/laser hybrid welding, which combines modeling with experimental comparison and shows (among other points) that hybrid welding can broaden the weld pool and improve gap-bridging relative to laser-only welding, and that penetration can peak at an optimal separation distance between the laser beam and arc electrode. Although the paper is not restricted to a single low-alloy grade, it is widely used as a foundational reference for hybrid welding of structural steels because the governing mechanisms (convection forces, heat-source coupling, pool geometry control) carry directly into low-alloy steel procedure development.

In parallel, DebRoy's group produced one of the most cited "map" papers in the field (Ribic, Palmer, & DebRoy, 2009). This article is commonly used as a starting point because it organizes the field around recurring technical barriers (process stability, defect mechanisms, and transferability of parameters) rather than presenting a single application case. They also pushed into diagnostics, for example by applying optical emission spectroscopy to hybrid welding plasmas and showing how arc current and heat-source separation influence measurable plasma properties that correlate with weld quality and stability (Ribic, Burgardt, & DebRoy, 2011).

U.S. contributions to hybrid laser-arc welding of low-alloy steels are distinguished by the tight coupling between scientific modeling and industrial qualification. University-based research, particularly from DebRoy's group, supplied a rigorous physical and numerical understanding of hybrid interaction, while EWI translated these insights into procedures suitable for pipelines and heavy structural components operating under strict regulatory constraints. This dual structure has shaped a distinctly American trajectory for hybrid welding research, in which the technology is evaluated primarily through its ability to meet qualification standards and service requirements in large-scale steel infrastructure.

2.3. Japan: Osaka University and High-Strength Bridge and Ship Steels.

Japan's contribution to the development of hybrid laser-arc welding is closely connected with national requirements in bridge construction, shipbuilding, and the fabrication of large steel structures, where low-alloy and high-strength steels are extensively employed. One of the most prominent research centers in this field is the Joining and Welding Research Institute (JWRI) of Osaka University, which has long combined experimental welding research with process modelling and structural performance evaluation. Earlier JWRI work from the 2000s and early 2010s concentrated on hybrid laser-MAG welding of structural steels with thicknesses of approximately 10–24 mm, using high-power disk or fiber lasers (Ohnishi, Kawahito, Mizutani, & Katayama, 2013; Pan, Mizutani, Kawahito, & Katayama, 2015; Pan, Mizutani, Kawahito, & Katayama, 2016). These studies examined penetration mechanisms, weld bead geometry, and porosity formation, often in connection with the weldability of high-tensile steels for shipbuilding and offshore structures. Productivity improvement and distortion reduction were recurrent themes, reflecting the needs of Japanese shipyards and heavy-fabrication industries.

Japanese researchers have also made contributions to the physical modelling of hybrid heat sources and to the analysis of arc behavior under hybrid conditions (Chen, et al., 2023; Kim, Hirohata, & Inose, 2014; Hirohata et al., 2019). Experimental and numerical studies have quantified changes in arc characteristics, metal transfer modes, and molten pool dynamics when an arc operates in the presence of a laser beam. Such work has clarified how the interaction between laser radiation and arc plasma affects penetration efficiency and melting behavior in steels, providing a scientific basis for process optimization.

Japanese contributions to hybrid laser-arc welding research demonstrate a consistent coupling between fundamental process understanding and application-oriented studies tailored to bridges, ships, and high-strength structural steel fabrication.

This alignment between scientific analysis and national infrastructure needs has been a defining feature of Japan's role in the historical development of hybrid welding technologies.

2.4. China: Harbin, Tianjin and the Rapid Expansion of Hybrid Laser-Arc Welding Research.

Over the past two decades, China has emerged as one of the most active centers of research on hybrid laser-arc welding, including extensive work on low-alloy and structural steels used in shipbuilding, pipelines, offshore platforms, and energy infrastructure. This rapid expansion reflects both the scale of domestic demand for steel-intensive structures and sustained investment in laser manufacturing and welding research. As a result, Chinese research in this field spans fundamental studies of laser-arc interaction, applied investigations of joint performance, and large-scale industrial implementation.

A central role in fundamental research belongs to the State Key Laboratory of Advanced Welding and Joining at Harbin Institute of Technology. Numerous studies from this laboratory address weld pool dynamics, keyhole stability, and defect formation in hybrid laser-arc welding of steels. Experimental and numerical work has examined arc characteristics, metal transfer behavior, and their combined influence on penetration depth and weld bead geometry in thick steel plates (Liu et al., 2020; Yang et al., 2020; Zhenglong, Caiwang, Yanbin, & Zhongshao, 2013). These studies have clarified how the arc modifies laser energy absorption and molten pool flow, providing a physical basis for improving process stability and reducing defects such as porosity and lack of fusion.

Another important academic center is Tianjin University. Research conducted there has focused on laser and laser-arc hybrid welding of steels and other structural alloys, with strong emphasis on numerical modelling and process control (Gu, Li, H., & Li, L. J., 2013; Wei, Li, Yang, Gao, & Ding, 2015; Wu, Luo, & Ao, 2023). Tianjin-based studies have developed coupled thermal-fluid models to describe heat source interaction, molten pool behavior, and solidification dynamics under hybrid conditions. These models are frequently validated against experimental welds in low-alloy steels and are intended to support transfer of hybrid welding to complex structural applications.

Beyond laboratory-scale studies, Chinese publications and technical reports increasingly document industrial-scale integration of high-power hybrid laser-arc welding systems (Liu et al., 2024; Zhang, Li, Gao, & Zeng, 2017; Zhang et al., 2023). Examples include hybrid welding of thick steel plates for offshore wind towers, ship hull structures, and heavy components for energy infrastructure. These implementations demonstrate a level of scale that remains uncommon in many other countries and is facilitated by the availability of domestically produced high-power fiber and disk lasers.

The breadth of Chinese activity is reflected in recent international reviews (Ma, Cheng, Ning, Zhang, & Na, 2021; Liu et al., 2023; Liu et al., 2024). In particular, the comprehensive review by He et al. (2025) in *Metals* summarizes global progress in laser-arc hybrid welding and highlights the high volume of Chinese publications and projects. The review identifies joint design, microstructure evolution, mechanical property evaluation, and laser-arc interaction mechanisms in steels as key ongoing research directions in China, and emphasizes the strong linkage between academic research and industrial deployment.

Chinese research on hybrid laser-arc welding of low-alloy steels is characterized by the close coupling of fundamental process studies, numerical modelling, and large-scale industrial application. This combination, supported by strong domestic demand and advanced laser manufacturing capabilities, positions China as one of the principal drivers of current and future developments in hybrid welding technologies for structural steels.

2.5. Northern and Eastern Europe: Finland, Norway, Sweden and Poland.

Northern and Eastern Europe have also contributed significantly to hybrid welding research, particularly through high-quality reviews and detailed process investigations.

Research on hybrid laser-arc welding of low-alloy and structural steels in Finland has developed along two closely connected but methodologically distinct lines. The first is associated with process-parameterization and process-physics studies carried out at Lappeenranta University of Technology (now LUT University). The second line is linked to application-oriented investigations focused on shipbuilding and structural integrity, conducted within VTT and the ship mechanics community of Helsinki University of Technology (later Aalto University).

Representative of the LUT approach is the study by Kah, Salminen, and Martikainen on the role of shielding gases in hybrid laser-arc welding of steels, which treats gas composition as a primary control variable influencing plasma behavior, process stability, penetration depth, and the reproducibility of welding procedures. Their work (Kah, Salminen & Martikainen, 2011), is significant because it contributed to transforming hybrid laser-arc welding from an experimental combination of heat sources into a process that can be systematically parameterized and transferred to industrial practice. Rather than presenting isolated demonstration welds, this line of research emphasizes conditions and boundaries directly relevant to procedure development for structural steels.

More application-oriented Finnish studies addressed hybrid welding in the context of real ship structures at an early stage. A widely cited example is the work by Jokinen, Vihervä, Riikonen, and Kujanpää (2000) on hybrid Nd:YAG laser-GMAW welding of ship structural steel A36. This study reports butt-joint trials under shipbuilding-relevant conditions, including gap tolerance, macrostructural features, and hardness distributions, situating the results explicitly within a framing and fabrication context. The article provides experimental data and weld quality assessments that are directly comparable to conventional techniques.

A related but distinct contribution emerged from the mechanics and fatigue research tradition at Aalto University, represented by the work of Remes and Värstä (2010). Their study on weld geometry variability in laser-hybrid butt joints, examines how geometric scatter affects notch stresses and fatigue-life prediction, an issue of particular importance when hybrid welding is incorporated into classification rules and design standards for structural steels.

Finnish contributions form an important link between process definition and structural performance assessment: LUT-based research primarily formalizes how hybrid welding processes should be executed, while VTT- and Aalto-linked studies address how the resulting joints should be evaluated when applied to ships and other long-life steel structures.

Norwegian research on hybrid laser-arc welding of low-alloy and structural steels is closely associated with SINTEF and Norwegian University of Science and Technology and is characterized by a strong focus on thick-section steels and offshore-related applications. Within this research landscape, the works of Ivan Bunaziv and his colleagues occupies a central position, as it consistently addresses industrially relevant questions such as achievable penetration depth, process efficiency, defect formation, and mechanical performance under demanding service conditions (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2018a; Bunaziv, Akselsen, Frostevarg, & Kaplan, 2018b Bunaziv, Akselsen, Frostevarg, & Kaplan, 2020; Bunaziv, Ren, & Olden, 2023).

One of the most frequently cited contributions is the study on deep-penetration fiber laser-arc hybrid welding of thick HSLA steel (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2018a). This paper systematically analyzes penetration behavior, process stability, and weld quality for thick plates, providing quantitative guidance for parameter selection rather than isolated demonstration results. Closely related work on the penetration efficiency of thick plate hybrid welding (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2018b), examines the influence of joint preparation and process variables on effective penetration, which is critical for reducing the number of welding passes in heavy fabrication.

Subsequent studies extended this approach to application-specific contexts. In 2019, Bunaziv and co-authors investigated hybrid laser-arc welding of steels intended for low-temperature service (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2019), linking welding parameters to toughness and suitability for shipbuilding and offshore structures operating in cold environments. Later work addressed single-pass hybrid welding of 12–15 mm structural steel, focusing on process stability and typical imperfections relevant to industrial production (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2020).

Norwegian contributions frame hybrid laser-arc welding as a realistic alternative to multi-pass arc welding for thick structural steels, provided that process windows are rigorously defined and quality-limiting defects are well understood. This combination of experimental depth and application relevance explains the prominent position of Norwegian research in the international literature on hybrid welding of low-alloy steels.

Swedish research on hybrid laser-arc welding of low-alloy and structural steels is strongly associated with Luleå University of Technology, especially the long-running line led by Alexander Kaplan. A recurring theme in this body of work is that the key barrier to industrial transfer is not penetration alone but repeatable process stability at production speeds, particularly the control of surface shape and defects that become critical in structural steel fabrication. That emphasis is clear in the parameter-guideline paper by Eriksson, Powell, and Kaplan (2013), which explicitly aims to turn hybrid welding into usable rules for setup and operation rather than case-by-case trials. It is also visible in the stability study by Moradi, Ghoreishi, Frostevarg, and Kaplan (2013), which treats the hybrid process as a coupled system where stability depends on how laser-arc interaction affects transfer behavior and weld-surface dynamics.

A second distinct Swedish contribution is Luleå University of Technology's detailed work on undercut formation and suppression, which matters in structural steels because undercuts are treated as imperfections with direct fatigue implications and often become limiting acceptance criteria. This mechanism-based approach is illustrated by Norman, Karlsson, and Kaplan (2011), who analyzed how undercuts form during laser hybrid arc welding and linked the phenomenon to surface condition and melt-flow behavior. Building on this, Frostevarg and Kaplan published an extensive classification and mapping of undercut types in laser-arc hybrid welding, including practical guidance on how positioning and melt-flow "tailoring" can extend the critical welding speed without undercuts (Frostevarg & Kaplan, 2014).

Together, these Swedish contributions are useful historically because they reflect a mature phase of the field: hybrid laser-arc welding is treated less as a novel combination of heat sources and more as a production process whose industrial value depends on defect mechanisms, stability margins, and parameter rules that can be transferred across shops and steel grades.

Research on hybrid laser-arc welding of low-alloy and structural steels in Poland has been concentrated primarily within the scientific and industrial network formed around Gliwice, notably the Silesian University of Technology and the Welding Institute in Gliwice. A representative example of this line of work is the study by Górka and Stano, which investigates hybrid laser-MAG welding of TMCP S700MC steel with a thickness of 10 mm (2018). This paper analyzes weld microstructure and mechanical properties and explicitly positions hybrid welding as a technologically viable method for joining high-strength structural steels used in load-bearing applications.

Closely related research addresses even higher-strength grades, such as S960QL, which are relevant for crane structures and other heavy-duty components. For instance, Urbańczyk and Adamiec report on hybrid laser-MAG welding of S960QL steel (5–7 mm), linking process parameters to resulting microstructures and mechanical performance in Materials (2021). This work reflects a broader Polish research focus on transferring hybrid welding procedures to steels with limited weldability margins.

Complementary procedure-oriented studies from the Welding Institute in Gliwice, published in the Bulletin of the Institute of Welding, further illustrate how hybrid laser-arc welding parameters are adapted for industrial practice, particularly for high-strength structural steels (Urbańczyk, Banasik, Stano, & Adamiec, 2018).

Alongside this application-driven strand, Polish researchers have also contributed significantly to the modelling and analytical description of hybrid welding processes. Work associated with Częstochowa University of Technology, such as the study by Piekarska and Kubiak, compares thermal phenomena in laser welding and laser-arc hybrid welding of S355 structural steel sheets using numerical modelling (Piekarska & Kubiak, 2013). This paper provides insight into heat-flow redistribution and thermal-cycle modification introduced by the arc component, offering a transferable framework for process optimisation across different steel grades.

Taken together, Polish contributions form a coherent body of work that combines experimentally validated procedures for high- and ultra-high-strength structural steels with modelling approaches that link process parameters to thermal and mechanical outcomes.

2.6. The Kyiv School of Hybrid Laser-arc Welding of Steels.

The development of HLAW of low-alloy and high-strength steels is closely tied to the E. O. Paton Electric Welding Institute (PWI) of the National Academy of Sciences of Ukraine in Kyiv. Since the late Soviet period, PWI has been the main national center for welding science, with a large staff and a clear focus on new process combinations for structural steels. In Ukraine and the broader Eastern European context, the PWI remains a reference institution. Historically, Paton’s work focused on arc (Paton, 2003; Paton, Akhonin, Prilutsky, 2011), electron beam (Paton et al., 2004; Paton et al., 2019) and electroslag welding (Paton, 1980), but in the 2000s, Paton-related publications also began to address laser and hybrid laser-arc processes (Krivtsun, 2001; Paton, Gvozdetskij, Krivtsun, & Zagrebel'nyj, Shulym, Dzheppa, 2002; Shelyagin et al., 2005a, 2005b).

Under Borys Paton’s leadership, the institute systematically explored the combination of laser radiation with electric arcs and plasma sources, extending earlier ideas proposed by W. M. Steen and others into industrially oriented hybrid processes. In this context, a group of researchers that we can call the “Kyiv School” formed around several key figures: Ihor Krivtsun, Volodymyr Shelyagin, Vladyslav Khaskin, Valeriy Poznyakov, Volodymyr Korzhyk, Volodymyr Sydorets, Liudmyla Markashova, Olena Berdnikova and their colleagues.

A first line of work is linked to Ihor Krivtsun, who played an important role in formalizing laser-arc and laser-plasma hybrid processes (Krivtsun, 2001). Together with German colleague Peter Seyffarth he co-authored the monograph *Laser-Arc Processes and Their Applications in Welding and Material Treatment* (2002), which systematized laser-arc interactions, energy balance and process windows for hybrid applications, including steels. In parallel, Krivtsun and co-authors published a number of articles on laser-arc and laser-microplasma welding (Paton, Gvozdetskij, Krivtsun, & Zagrebel'nyj, Shulym, Dzheppa, 2002). His group's theoretical and experimental work is repeatedly cited in later reviews on hybrid laser-plasma welding as providing the basic understanding of synergic effects and energy efficiency.

A second, an important contribution to the development of hybrid laser-arc welding of low-alloy steels has also been made by the group led by Volodymyr Shelyagin. While much of the Kyiv school's work is widely known for fundamental welding science, Shelyagin's group played a distinctive role in advancing process-oriented and equipment-focused studies aimed at practical hybrid welding applications. Their research by Volodymyr Shelyagin, Vladyslav Khaskin and their co-authors addressed the integration of laser and arc heat sources, stability of hybrid processes, control of weld formation, and adaptation of hybrid technologies to structural and pipeline steels under industrial conditions (Shelyagin et al., 2005a, 2005b, 2018). A characteristic feature of this work is its close coupling of experimental welding trials with the development of specialized technological solutions, including welding heads, process layouts, and control strategies suited to hybrid operation.

A third, very extensive line of research is associated with Valeriy Poznyakov and his colleagues, who focused on the weldability, structure and service properties of welded joints in low-alloy and high-strength steels. Since the mid-2000s, Poznyakov's group has published a series of studies on structural steels with yield strengths from 350 to 490 MPa and higher, used in bridges, storage tanks, stadium roofs and other large structures (Poznyakov, Kasatkin, Zhdanov, & Strizhak, 2005). From about 2015, part of this work shifted specifically to hybrid laser-arc welding of high-strength steel's 14KhGN2MDAFB and N-A-XTRA-70 (Berdnikova, Pozniakov, & Bushma, 2016; Poznyakov, Markashova, Berdnikova, Alekseienko, & Zhdanov, 2018; Poznyakov et al., 2019). Poznyakov and co-authors analyzed the structure and crack resistance of hybrid-welded high-strength steel's joints, showing that, with proper thermal cycles, the critical stress intensity factor approaches that of base metal. It showed that, under selected HLAW regimes, the impact toughness of the heat-affected zone and weld metal can reach levels sufficient for heavy-duty service, while also reducing joint width and heat input. An important feature of the Kyiv School is the close link between process development and detailed microstructural analysis (Berdnikova, Poznyakov, Bernatskyi, Alekseienko, & Sydorets, 2019; Markashova, Berdnikova, Alekseienko, Bernatskyi, & Sydorets, 2019; Berdnikova et al., 2020).

A fourthly line is associated with Volodymyr Korzhyk, Vladyslav Khaskin and their co-authors developed a separate but related direction: hybrid laser-plasma welding of steels and other alloys. A 2017 conference paper by Korzhyk and co-authors presented a brief retrospective of hybrid laser-plasma welding, formulated key objectives for the process and analyzed its industrial prospects (Korzhyk, Bushma, Khaskin, Dong, & Sydorets, 2017). In 2024, Korzhyk and co-authors published a comprehensive review, introducing quantitative criteria for the synergic effect and reporting process efficiencies in the range 1.5–2.4 for steels (Korzhyk et al., 2024). This work also described a coaxial head for laser-plasma welding developed at PWI, designed to reduce laser power requirements and relax edge-preparation tolerances in welding of thin-walled steel products such as pipes and profiles (Figure 3).

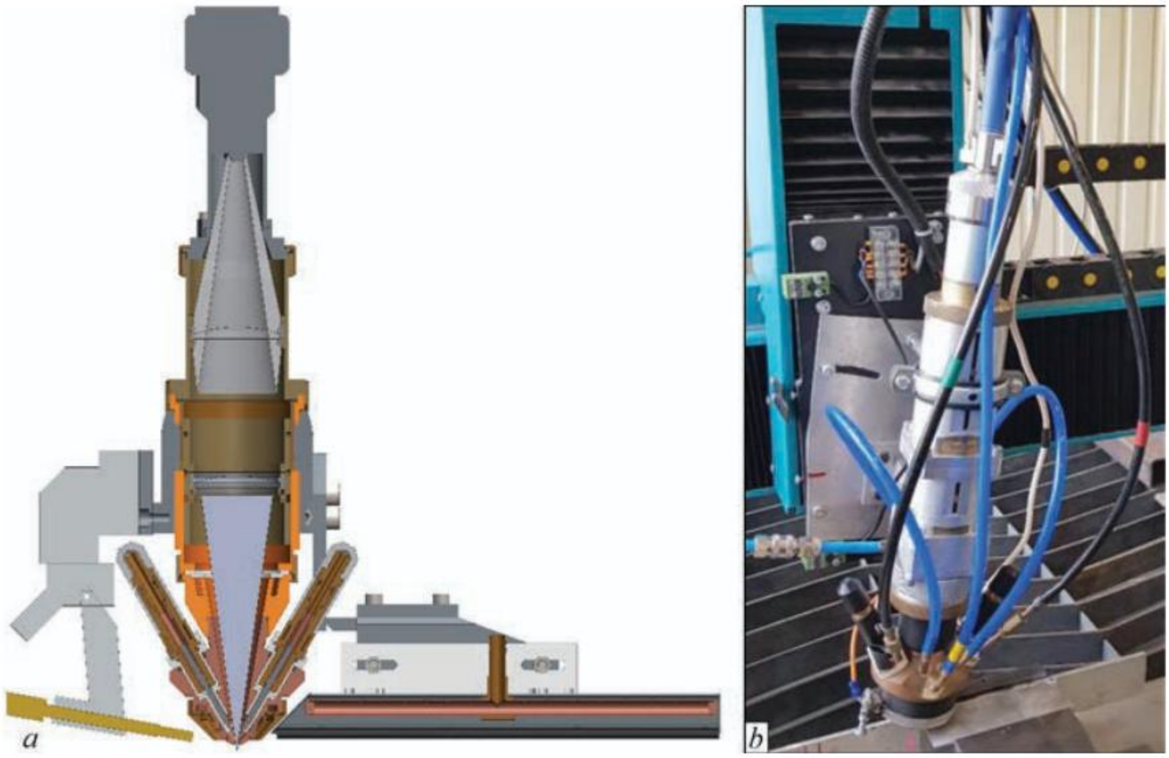


Figure 3. 3D-model *(a)* and appearance *(b)* of the head for laser and laser-plasma welding, developed at PWI (Korzhyk et al., 2024).

Taken together, the work of Paton, Krivtsun, Shelyagin, Khaskin, Poznyakov, Korzhyk, Sydorets, Markashova, Berdnikova and their colleagues forms a coherent Kyiv School of hybrid welding. It combines process physics, power-source engineering, detailed metallography and long-term service considerations, and it is embedded in international networks, especially with partners in China, Germany (Krivtsun, Reisgen, Semenov, & Zabirov, 2016; Reisgen, Krivtsun, Gerhards, &

Zabirov, 2016; Reisgen, Zabirov, Krivtsun, Demchenko, & Krikent, 2015) and other European countries. For the purposes of this article, this school can be seen as one of the central actors in the global historical development of hybrid laser-arc and related hybrid laser–plasma welding of low-alloy and high-strength steels.

3. Main Scientific Directions in Hybrid Welding of Low-Alloy Steels.

From the moment hybrid laser-arc welding moved beyond proof-of-concept experiments in the early 1990s, research on low-alloy steels developed along several stable scientific directions. These directions reflect the internal logic of the process itself: the interaction of two heat sources, the behavior of the molten pool, metallurgical transformations in the steel, and the formation of defects and mechanical properties. By the late 2000s, these directions had largely stabilized and continue to structure hybrid welding research today.

One of the earliest and most persistent research directions concerns the thermal field and hybrid heat-source modeling. In the 1990s, numerical descriptions of hybrid welding were still rudimentary and typically combined a Gaussian laser heat source with a distributed arc heat input. These early models were developed to explain why hybrid welding produces deeper penetration at comparable or even lower total heat input than pure arc welding. By the early 2000s, three-dimensional transient models were already being used to predict melt pool shape and cooling rates for laser-arc hybrid welding of carbon and low-alloy steels (Krivtsun, 2001; Krivtsun & Seyffarth, 2002; Ribic, Rai, & DebRoy, 2008).

A key methodological synthesis of hybrid heat-source modeling and fluid-flow behavior is given in the review by Ribic, Palmer and DebRoy (2009), which summarized how laser power, arc current, torch-beam distance and travel speed control penetration depth, weld width and thermal gradients in steels.

Subsequent computational studies in the 2010s introduced fully coupled thermal–fluid models that included Marangoni flow, electromagnetic stirring by the arc, and vaporization recoil pressure from the laser keyhole (Krivtsun, Reisgen, Semenov, & Zabirov, 2016; Piekarska & Kubiak, 2013; Ribic, Burgardt, & DebRoy, 2011). These models showed that in low-alloy steels the hybrid weld pool is dominated by forced convection rather than pure thermal diffusion, which explains the deeper and narrower penetration profile compared to arc welding.

A second major research direction concerns weld pool dynamics and arc-laser interaction mechanisms. Experimental high-speed imaging work carried out in the 2000s and 2010s, especially in China, Germany, Sweden and Ukraine, demonstrated that the arc plays a stabilizing role for the laser keyhole by preheating the steel surface and reducing reflectivity (Eriksson, Powell, & Kaplan, 2013; Gu, X. Y., Li, H., & Li, L. J. 2013; Reisgen, Zabirov, Krivtsun, Demchenko, & Krikent, 2015). Conversely, the laser acts as a constrictor of the arc column. Studies from the Tianjin University and Luleå University of Technology quantified oscillation frequencies of the molten pool and showed that hybrid interaction suppresses irregular droplet transfer typical for conventional MAG welding of low-alloy steels.

Closely connected to weld pool dynamics is the research direction devoted to defect formation mechanisms, especially porosity, lack of fusion and hot cracking. For low-alloy steels, porosity became a key issue in the early industrial adoption phase, particularly in the 2000s. It was shown that hydrogen content, laser-induced metal vapor, and unstable keyhole behavior were the main contributors (Petring & Fuhrmann, 2004; Shelyagin et al., 2005a; Victor, Nagy, Ream, & Farson, 2009). Studies demonstrated that adjusting the arc mode (pulsed MAG, CMT variants) and the laser-arc distance could significantly reduce pore density. By the late 2000s, stable pore-free hybrid welds in 12–20 mm thick low-alloy steels were already reported under laboratory and pilot-industrial conditions.

Another central research direction is metallurgical phase transformation and microstructure evolution in hybrid welds. Unlike pure laser welding, which often produces extremely high cooling rates and brittle martensitic zones in low-alloy steels, hybrid welding offers a broader thermal cycle. Studies from the 2000s showed that hybrid weld metal and heat-affected zones typically exhibit a mixture of bainitic and martensitic structures with improved toughness compared to pure laser welds (Harris & Norfolk, 2008; Jokinen, Vihervä, Riikonen, & Kujanpää, 2000; Katayama, Naito, Uchiumi, & Mizutani, 2007). The microstructural investigations were closely linked with mechanical performance studies. Tensile strength, impact toughness and fatigue life of hybrid welds in low-alloy steels became one of the most important applied research directions after 2005. German shipbuilding-related studies showed that fatigue strength of hybrid welds was comparable to or higher than that of conventional multi-pass arc welds, provided that weld toe geometry was properly controlled (Mahrle & Beyer, 2006; Petring, Fuhrmann, Wolf, & Poprawe, 2007; Wieschemann, Kelle, & Dilthey, 2003). In pipeline-oriented studies in the United States, attention focused on root pass integrity and resistance to hydrogen-assisted cracking in hybrid welded girth welds (Harris & Norfolk, 2008; Victor, Nagy, Ream, & Farson, 2009).

Since approximately 2010, a distinct new research direction has been the digitalization and real-time monitoring of hybrid welding processes. Fiber lasers with output powers of 15–30 kW, together with high-speed cameras, photodiodes and spectroscopic sensors, enabled real-time observation of keyhole behavior, arc stability and plume formation. Research groups in Germany and China introduced closed-loop control systems that automatically adjusted laser power and arc current in response to signal fluctuations (Gu, Li, H., & Li, L. J., 2013; Petring, 2013; Reisgen, Olschok, Jakobs, & Engels, 2016). By the early 2020s, this logic evolved into the concept of a "digital twin" of the hybrid weld pool, in which numerical models are continuously corrected by live sensor data.

A further applied research direction concerns hybrid welding in combination with additive and narrow-gap technologies. In the late 2010s, hybrid laser-arc heat sources began to be investigated for directed energy deposition of steel and for narrow-gap hybrid welding of thick low-alloy plates above 20–40 mm (Shelyagin et al., 2018; Üstündağ, Fritzsche, Avilov, Gumenyuk, & Rethmeier, 2018a; Zhang, Li, Gao, & Zeng, 2017). These studies aim at further reducing the number of passes and lowering total heat input in massive steel structures for energy and offshore applications.

Taken together, these scientific directions show that research on hybrid welding of low-alloy steels developed in a coherent manner: from physical heat-source interaction and thermal modeling in the 1990s, through metallurgy and defect control in the 2000s, to digital monitoring, control and integration with advanced manufacturing systems in the 2010s–2020s. This body of research formed the scientific foundation for the large-scale industrial applications that will be examined in the following section.

4. Industrial Development and Practical Applications of Hybrid Laser-Arc Welding of Low-Alloy Steels.

The transition of hybrid laser-arc welding from experimental technology to an industrial method for low-alloy steels unfolded unevenly and over a long period. Although the physical principle had been demonstrated in the late 1970s, nearly twenty years passed before hybrid welding entered stable production environments. This delay was not accidental. It reflected the slow maturation of high-power laser sources, the conservatism of heavy industries, and the high economic risks associated with introducing laser-based systems into serial steel fabrication.

In the early 1990s, the introduction of laser and hybrid welding in shipbuilding was primarily constrained by the strict regulatory framework imposed by classification societies, notably Lloyd’s Register, whose construction rules were based on conventional welding technologies (Gerritsen & Howarth, 2005). A 1992 European feasibility study identified regulatory acceptance as the main barrier, since laser welding had been applied industrially only in very limited, non-structural ship components. To address this, a second collaborative project was launched with the direct involvement of classification societies, focusing on butt and fillet welds on panel lines and aiming to demonstrate reduced distortion and rework despite high equipment costs. By 1996, this effort resulted in the first formal approval guidelines for CO_2 laser welding in ship construction, later adopted by Lloyd’s Register. Subsequent EU-funded projects further extended this framework to quality assurance and non-destructive testing, enabling cautious but structured regulatory acceptance of advanced welding processes.

The development of hybrid laser-arc welding in European shipbuilding was driven by a sequence of EU-funded research and development programmes initiated in the early 1990s and consolidated within the 6th and 7th EU Framework Programmes (FP6 and FP7), including projects such as L-SHIP, TRANSLAS, SANDWICH, DOCKLASER, InterSHIP, and BESST. A decisive breakthrough occurred in the late

1990s with the introduction of laser-arc hybrid welding, which overcame the gap-tolerance and robustness limitations of purely laser-based processes.

Meyer Werft (Germany) became a flagship industrial implementer, replacing its conventional panel line with a hybrid laser welding facility in 2000, resulting in substantial improvements in weld quality, process stability, and productivity (Acherjee, 2018a; Gerritsen & Howarth, 2005; Reisgen, Olschok, & Turner, 2014). These panels, often exceeding 20 m in length, required strict geometric tolerances for automated block assembly (Figure 4). Hybrid welding made it possible to maintain these tolerances without extensive post-weld thermal correction. By the end of the 2000s, hybrid laser-arc welding had become a routine production option for selected structural joints at Meyer Werft.

Figure 4. Laser arc hybrid welded steel panels and stiffeners used for fabrication of ships at Meyer-Werft GmbH (Acherjee, 2018b, p. 225).

Outside Germany, Denmark and Finland followed slightly later (Acherjee, 2018a; Kah, Salminen & Martikainen, 2011). At the Odense Steel Shipyard, hybrid laser-arc welding was tested and introduced between 2005 and 2008 for container ship and offshore vessel panels made of 8–10 mm structural steel. The hybrid welding offered a way to compensate for rising labor costs by shortening production cycles in panel fabrication. In Aker Yards (Finland), hybrid welding entered ship production in Turku after 2006. There it was applied to low-alloy steels in the 8–12 mm range, particularly for ice-class structures. Finnish studies stressed improved fatigue performance at welded stiffener joints, which was critical for ships operating under cyclic ice loads.

At nearly the same time, a different industrial logic shaped the introduction of hybrid laser-arc welding in the United States (Harris & Norfolk, 2008; Victor, Nagy, Ream, & Farson, 2009). There, the focus was not on plate panels but on pipeline girth welding. Between 2004 and 2006, the Edison Welding Institute carried out large-scale hybrid welding trials for transmission pipelines made of low-alloy steels of grades API X65-X70. These trials, supported by U.S. federal safety authorities, used fiber lasers of 8–10 kW combined with MAG arcs to weld pipes with wall thicknesses of 9–14 mm. The hybrid root pass replaced several conventional arc passes. Field data showed that total welding time per joint dropped by roughly one third while low-temperature impact toughness remained within qualification limits for gas transmission. Despite its technical success, hybrid welding did not become standard in U.S. pipeline construction because of conservative certification rules and the high investment cost of laser systems.

After 2010, hybrid laser-arc welding entered a new phase associated with thick low-alloy steels for energy and offshore applications. This shift became possible only after the widespread industrial availability of fiber and disk lasers in the 15–30 kW range. One of the most important new fields was the fabrication of wind-energy towers in Germany (Brunner-Schwer, Üstündağ, Bakir, Gumenyuk, & Rethmeier, 2023). At the research led by Michael Rethmeier and Andrey Gumenyuk began around 2012 and focused on hybrid laser-MAG welding of steels with thicknesses of 20–30 mm, typical for wind-tower shells. Between 2012 and 2020, these researchers demonstrated stable single- and double-sided hybrid welding of 25 mm plates using laser powers of 16–24 kW. Their work showed that groove volume could be drastically reduced and that the number of welding passes could be lowered from eight to ten with submerged arc welding to only two or three hybrid passes. At the same time, residual stress and fatigue behavior under cyclic loading were carefully investigated, as these factors determine the lifetime of wind-energy structures.

The largest scale of hybrid laser-arc welding of low-alloy steels developed in China after approximately 2013–2015. Unlike Europe, where hybrid welding remained concentrated in selected niches, China introduced it directly into heavy offshore and energy structures (Acherjee, 2018b; Liu et al., 2024; Ma, Cheng, Ning, Zhang, & Na, 2021). At fabrication yards in Nantong and Yantai, hybrid welding systems were installed for offshore wind monopiles, transition pieces, and large tower sections made of 30–40 mm low-alloy steels. These systems combined fiber lasers with optical powers of 25–32 kW and high-current MAG arcs. In these applications, more than ten submerged arc welding passes were replaced by two or three hybrid passes. This reduced production time for a single circumferential joint from several hours to well below one hour and significantly lowered energy consumption and distortion in massive steel shells.

By the early 2020s, hybrid laser-arc welding of low-alloy steels had become a stable industrial technology in several high-performance sectors: European ship panel production, selected pipeline projects in North America, wind-energy tower fabrication in Germany, and large offshore and energy structures in China. At the same time, it did not replace classical arc or submerged arc welding on a universal scale. Instead, it occupies a clearly defined technological niche where thick sections, cyclic loading, strict geometric tolerances, and productivity requirements make the economic advantages of hybrid welding decisive.

5. Hybrid Laser-Arc Welding and Sustainable Development.

The connection between hybrid laser-arc welding of low-alloy steels and sustainable development did not exist at the moment when the technology first emerged in 1970s–1980s. For the first two decades, hybrid welding developed almost entirely within a framework of productivity, penetration depth, and process stability. The sustainability dimension became explicit only much later, after the adoption of the United Nations Sustainable Development Goals (SDGs) in 2015, when industrial technologies began to be evaluated not only by economic efficiency but also by energy use, material efficiency, and environmental impact.

From a historical perspective, the sustainability relevance of hybrid laser-arc welding rests primarily on three factors: reduced heat input, reduced material consumption, and extended service life of welded steel structures. These factors appeared as practical engineering advantages long before they were framed in sustainability language, but after 2015 they began to be interpreted within the SDG framework.

The reduction of heat input is one of the oldest documented advantages of hybrid welding. Already in the early shipbuilding applications in Germany in the mid-2000s, hybrid welding allowed three- or four-pass MAG joints to be replaced by a single hybrid pass in low-alloy steels of 10–12 mm thickness. This directly meant lower electrical energy consumption per meter of weld and narrower heat-affected zones. In historical terms, this corresponds most closely to SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production), even though these categories were defined only later.

Material savings became especially visible after hybrid welding moved into thick-section energy structures in the 2010s. In wind-tower fabrication in Germany, as demonstrated by the research of Michael Rethmeier and Andrey Gumenyuk at the reduction of groove volume when welding 20–30 mm low-alloy steels led to a drastic decrease in deposited filler metal. In traditional submerged arc welding, the wide V-groove geometry required large volumes of wire and flux. Hybrid laser-arc welding allowed narrow grooves and two- or three-pass joints instead of eight to ten passes. In sustainability terms, this translates directly into lower consumption of consumables and lower embodied energy in the welded joint.

A similar effect appeared on a much larger scale in Chinese offshore wind and energy structures after 2015. At fabrication yards in Nantong and Yantai, hybrid welding of 30–40 mm low-alloy steels reduced the number of welding passes by a factor of four to five compared with submerged arc welding. This led not only to shorter production times but also to substantial reductions in total electrical energy used per circumferential joint. In sustainability language, this fits directly into SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action), since lower energy consumption per unit of welded structure contributes to reduced indirect greenhouse gas emissions.

The third sustainability dimension is service life. Hybrid laser-arc welding produces narrower heat-affected zones and more controlled microstructures than many conventional multi-pass arc procedures. This has direct consequences for fatigue resistance. In shipbuilding and wind-energy applications, where low-alloy steels are exposed to long-term cyclic loading, fatigue life is one of the main determinants of structural longevity. German and Finnish shipbuilding studies from the late 2000s already showed that hybrid welds at stiffener joints exhibit comparable or higher fatigue strength than conventional arc welds. In wind-energy towers, the work conducted in Berlin after 2012 explicitly addressed fatigue performance under realistic cyclic loading conditions. From a sustainability perspective, extending the service life of large steel structures reduces the need for early replacement and lowers the long-term material footprint of infrastructure.

Historically, it is important to underline that hybrid laser-arc welding was not developed as a "green" technology in the modern sense. Its sustainability effects are mostly a secondary result of engineering optimization aimed at productivity and quality. Only after the global diffusion of the SDG framework did these technological advantages begin to be interpreted in environmental and resource-oriented terms. In this sense, hybrid welding represents a typical case of a technology whose sustainability significance became visible only retrospectively, through changing societal and policy frameworks.

Today, hybrid laser-arc welding of low-alloy steels can be seen as a mature industrial technology that aligns well with several core SDGs without having been explicitly created for that purpose. Its historical trajectory shows how industrial efficiency, once pursued mainly for economic reasons, can later acquire a broader environmental and social meaning.

6. Interaction Between Scientific Research and Industrial Implementation.

The historical development of hybrid laser-arc welding of low-alloy steels shows a clear and persistent gap between scientific research and industrial implementation. Although the physical principle of hybrid interaction was formulated in 1980, stable industrial deployment did not begin until nearly twenty years later. This delay reflects not only technical barriers but also institutional, economic, and regulatory constraints.

In the early phase, research on hybrid processes was concentrated almost entirely in university laboratories and national research institutes. Experimental work required expensive laser systems, which in the 1980s and early 1990s were available only at a limited number of sites. Even when laboratory experiments demonstrated deeper penetration and improved stability, industry remained cautious. For manufacturers of heavy steel structures, hybrid welding represented a high-risk investment with uncertain economic return. Conventional arc welding, by contrast, was already deeply integrated into production systems, standards, and worker qualification frameworks.

A more systematic interaction between research and industry began to form only in the late 1990s, when institutes such as the Fraunhofer Institute for Laser Technology and the Edison Welding Institute began to act as intermediaries between laboratory science and production. In Germany, Fraunhofer ILT developed hybrid laser-arc welding not only as a research topic but as an industrial service technology. This institutional model, in which research institutes operate hybrid systems directly on industrial sites, was a decisive factor in building trust in the new technology.

In the United States, the transfer mechanism followed a different logic. At Edison Welding Institute, hybrid welding was introduced through industry-funded projects aimed at solving concrete production problems, particularly in pipeline construction. The hybrid process was tested under field conditions, not only under laboratory constraints. However, even technically successful demonstrations did not guarantee rapid diffusion. Pipeline welding in the United States is governed by strict regulatory frameworks, and the adoption of a new welding process requires long and costly qualification campaigns. As a result, hybrid welding remained confined to selected projects rather than becoming a universal pipeline standard.

The wind-energy case in Germany illustrates a third pattern of science–industry interaction. Here, hybrid laser-arc welding entered industrial production not through incremental panel fabrication but through a new energy sector that was expanding rapidly after 2010. Research at under the leadership of Michael Rethmeier and Andrey Gumenyuk addressed problems that were directly relevant for wind-tower manufacturers: reduction of groove volume, control of residual stresses, and fatigue resistance in thick low-alloy shells. In this case, the growth of a new industrial sector created a window in which a new welding technology could be adopted without displacing deeply entrenched older production routines.

In China, the interaction between science and industry has followed yet another trajectory. Since the mid-2010s, hybrid laser-arc welding has been integrated into massive offshore and energy-structure fabrication almost simultaneously with its scientific development. Large state-supported enterprises, together with university laboratories such as the Harbin Institute of Technology, have treated hybrid welding as a strategic manufacturing technology. The scale of Chinese industrial deployment allowed rapid feedback between production problems and scientific optimization, shortening the traditional gap between research and implementation.

Across all these cases, one structural feature remains constant. Hybrid laser-arc welding did not move into industry simply because it was technically superior in isolated experiments. It required a specific institutional setting in which research organizations, equipment suppliers, and manufacturing companies could operate within shared development projects over several years. Where such structures were absent, hybrid welding diffused slowly or remained confined to niche applications.

From a historical perspective, the interaction between science and industry in the field of hybrid welding demonstrates that technological feasibility alone is not sufficient for industrial adoption. Long-term cooperation, regulatory acceptance, capital investment capacity, and the emergence of new industrial demand all played decisive roles in determining when and where hybrid laser-arc welding of low-alloy steels became a stable production technology.

7. Discussion.

The historical trajectory of hybrid laser-arc welding of low-alloy steels shows a pattern that differs from many classical welding technologies. It did not emerge as a direct response to a shortage of welding methods but as a result of cumulative limitations that became visible only after both laser welding and arc welding had independently reached high levels of maturity. By the late 1970s, laser welding offered penetration and speed but lacked tolerance to joint imperfections. Arc welding offered adaptability but was constrained by heat input and productivity in thick sections. Hybrid welding emerged precisely at the intersection of these unresolved limitations.

What is particularly notable is the long temporal gap between scientific formulation and industrial stabilization. The physical foundation of hybrid welding was clearly articulated by 1980 (Steen, 1980), yet stable industrial deployment began only around the early 2000s (He et al., 2025; Petring, 2013).). This delay cannot be explained by technological immaturity alone. It reflects the high capital cost of laser systems, the conservative nature of steel-intensive industries, and the rigid structure of welding standards and certification systems. Hybrid welding had to prove not only its technical capability but also its reliability under long production cycles, variable joint conditions, and strict quality regulations.

Another important feature of its historical development is the dependence on sector-specific demand. Hybrid welding did not spread uniformly across manufacturing. It became established first in ship panel production, where distortion control and dimensional accuracy are decisive (Jokinen, Vihervä, Riikonen, & Kujanpää, 2000; Olschok, Reisgen, & Dilthey, 2007; Wieschemann, Kelle, & Dilthey, 2003). It then entered pipeline welding under regulatory pressure for productivity gains (Gook, Gumenyuk, & Rethmeier, 2014; Harris & Norfolk, 2008; Zhenglong, Caiwang, Yanbin, & Zhongshao, 2013), and later moved into wind-energy (Brunner-Schwer, Üstündağ, Bakir, Gumenyuk, & Rethmeier, 2023) and offshore structures when thick-wall shells and high cyclic loading created new performance requirements that conventional submerged arc welding could not satisfy economically (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2019; Bunaziv, Ren, & Olden, 2023; Liu et al., 2024).

In this sense, hybrid laser-arc welding developed not as a universal replacement for arc welding but as a targeted solution for structurally demanding applications of low-alloy steels.

The national patterns also reveal different models of technological diffusion. In Germany and Northern Europe, hybrid welding grew through close cooperation between research institutes and shipyards or wind-tower manufacturers (Bunaziv, Akselsen, Frostevarg, & Kaplan, 2019; Gook, Gumenyuk, & Rethmeier, 2014; Petring, 2013). In the United States, it was tested through regulatory-driven pipeline projects but remained limited by certification barriers. In China, it was integrated rapidly into large-scale offshore and energy fabrication, supported by state-backed industry and research institutions. These different pathways show that hybrid welding is shaped as much by industrial organization and policy as by technical parameters.

From a longer historical perspective, hybrid laser-arc welding can be seen as a transitional technology. It stands at the boundary between classical fusion welding and digitally controlled, sensor-driven manufacturing systems. Its development in the 2010s and 2020s, with the integration of real-time monitoring and adaptive control, suggests that hybrid welding is no longer just a combination of two heat sources but part of a broader transformation of steel fabrication toward data-driven production.

Conclusions.

The historical development of hybrid laser-arc welding of low-alloy steels began with the scientific formulation of arc-augmented laser processing in the late 1970s and unfolded over more than four decades. During the first two decades, hybrid welding remained primarily a research topic, shaped by advances in laser physics, arc plasma modeling, and numerical simulation. Only with the maturation of high-power industrial lasers, digital control systems, and sensor technologies did it become a viable industrial welding method.

Its industrial stabilization occurred unevenly across sectors and countries. In European shipbuilding, hybrid welding became a practical solution for reducing distortion and increasing panel-line productivity. In North American pipelines, it demonstrated technical feasibility but remained constrained by regulatory and economic factors. In German wind-energy manufacturing, it provided a response to the challenge of welding thick low-alloy shells under cyclic loading. In China, it reached the largest scale of industrial deployment in offshore wind and energy structures, supported by large fabrication yards.

Hybrid laser-arc welding did not replace conventional arc or submerged arc welding as universal methods. Instead, it established itself as a high-performance technology for demanding applications where thick sections, fatigue resistance, geometric precision, and productivity requirements converge. Its historical trajectory shows that the success of a welding technology depends not only on physical principles and equipment performance but also on institutional networks, industrial structure, and sector-specific demand.

From the perspective of sustainable development, the significance of hybrid welding became visible only retrospectively. By reducing heat input, consumable use, and distortion, and by extending the service life of large steel structures, it aligns with contemporary sustainability goals even though it was not created with environmental objectives in mind.

In historical terms, hybrid laser-arc welding of low-alloy steels represents a mature example of how late twentieth-century laser science, classical welding engineering, and twenty-first-century digital manufacturing converged into a stable industrial technology shaped equally by science, industry, and long-term structural change.

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Гібридне лазерно-дугове зварювання низьколегованих сталей: Від наукової концепції до промислової технології (1970-ті – 2020-ті роки)

Анотація. *У статті досліджено історичний розвиток гібридного лазерно-дугового зварювання низьколегованих сталей від формулювання гібридної концепції наприкінці 1970-х років до її становлення як промислової технології на початку XXI ст. Виділено дві взаємопов'язані, але історично не синхронні траєкторії: еволюцію фундаментальних і прикладних наукових досліджень лазерно-дугової взаємодії та подальше формування сталих промислових застосувань у суднобудуванні, трубопровідному зварюванні, виготовленні* *вітроенергетичних веж, а також енергетичних конструкцій. На основі наукових публікацій, інституційних звітів і задокументованих промислових впроваджень у Німеччині, Данії, Фінляндії, США та Китаї реконструйовано шлях переходу гібридного зварювання від лабораторних експериментів до серійного виробництва у секторах зі складними конструктивними вимогами. Особливу увагу приділено ролі провідних наукових центрів, а також процесам трансферу технологій. Показано, що істотна часова затримка між науковим обґрунтуванням і промисловим впровадженням зумовлювалася не лише рівнем розвитку лазерного обладнання, а й інституційним консерватизмом, бар'єрами сертифікації та високою капіталомісткістю лазерно-орієнтованих виробничих систем. Окремо проаналізовано секторальний характер поширення технології, що пояснює, чому гібридне лазерно-дугове зварювання спочатку закріпилося у європейському суднобудуванні, згодом – у вибраних трубопровідних проєктах Північної Америки, далі – у виробництві вітроенергетичних веж у Німеччині, а найбільшою мірою – в офшорних та енергетичних конструкціях у Китаї. Також розглянуто принципово важливе переосмислення цієї технології в контексті Цілей сталого розвитку Організація Об'єднаних Націй, із акцентом на зниження тепловкладення, скорочення витрат зварювальних матеріалів, зменшення деформацій та подовження ресурсу експлуатації великих сталевих конструкцій. Доведено, що гібридне лазерно-дугове зварювання не сформувалося як універсальна альтернатива традиційним дуговим або підфлюсовим процесам, а як високопродуктивне цільове рішення, детерміноване взаємодією наукових знань, промислового попиту, інституційних мереж і довготривалих структурних змін у сталемістких галузях виробництва.*

Ключові слова: *гібридне лазерно-дугове зварювання; низьколеговані сталі; історія зварювальних технологій; лазерна обробка матеріалів; взаємодія науки та промисловості; сталий розвиток*

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Institutionalising concrete construction technology: A socio-technical formation of modern architecture in Indonesia

Abstract. *The institutionalisation of construction technology in postcolonial architecture has seldom been studied through Science and Technology Studies, particularly in developing countries where political agendas often shaped modernisation more than industrial growth. This article addresses this gap by analysing the socio-technical process of institutionalising concrete construction technology in Indonesian architecture between 1959 and 1981. Drawing on Berger and Luckmann's social construction theory, especially externalisation and objectivation, the study frames the Old Order and the New Order as successive regimes that produced and stabilised technological meanings within their respective national development narratives. The research investigates presidential speeches, governmental policies, and practitioners' writings to trace historical discourses* *linking technology and national development. Findings indicate that these discourses were initially divergent: the Old Order focused on nation building through monumental projects, whereas the New Order emphasised social welfare through economic growth. Gradually, these contrasting discourses interacted and contributed to the objectivation of concrete as the dominant material and construction method in post-independence Indonesian architecture. Developmental discontinuity under the Old Order (1959–1966) generated modernity arising from economic constraints but marked by innovation through unprecedented concrete applications. In contrast, the New Order (1966–1981) produced modernity characterised by efficiency, utilisation of local materials, and social empathy amid economic surplus. Despite these differences, concrete construction technology persisted architecturally, bridging both regimes. The institutionalisation process thus represents a negotiated socio-technical transition rather than a linear diffusion of modern technology. This Indonesian case contributes to global Science and Technology Studies debates by offering a Southern perspective on how modern architecture materialises through historically and contextually contingent technological constructions.*

Keywords: *developmental policy; externalisation; Indonesian modern architecture; objectivation; socio-technical institutionalisation*

Introduction.

This article examines the institutionalisation of concrete construction technology in Indonesian architectural practice as a socio-technical process that unfolded across political regimes. It originated under the Old Order (1945–1966) through the deployment of concrete in monumental state projects and became systematised during the New Order (1966–1998) through large-scale, standardised, and professionally integrated construction practices aligned with national development agendas. Although architectural expressions from these two regimes may appear formally distinct, the continuity of construction technology reveals a deeper structural linkage between them. Investigating this process of institutionalisation is therefore essential to reconstruct historical trajectories and challenge interpretations that view regional architecture merely as stylistic refelections of global trends.

The term New Order refers to the Indonesian government under President Soeharto (1921–2008), which spanned from 1966 to 1998 (Boediono, 2016; Taylor, 2012). This regime represented a decisive departure from the preceding Old Order (1945–1966), whose central policies emphasised decolonisation and national consolidation, typical of a newly independent state (Fakih, 2020; Mustopadidjaja et al., 2012). A pivotal shift during this earlier period, particularly from 1959 onwards, involved the nationalisation of foreign assets and the withdrawal from Western-bloc investments (Bandyopadhyaya, 1977; MacDougall, 1976; Uzair, 1970). The Old Order government rejected the free-market model associated with capitalism and liberalism, opting instead to transfer control of economic activity to the Indonesian people (Fakih, 2020; Zanden & Marks, 2012). These policies, however, led to severe economic decline and ultimately contributed to the collapse of the regime. The New Order sought to reverse this trajectory. In a speech before the Provisional People's Consultative Assembly (DPR-GR) on August 16, 1970, Soeharto articulated the New Order's principal role as rectifying past deviations across all sectors (Mustopadidjaja et al., 2012). One major manifestation of this corrective agenda was the implementation of state-led development policies oriented towards economic growth and modernisation (Bazbauers, 2018; Booth, 2016; Liddle, 1991). Under this regime, national development in Indonesia began to unfold in a more structured and sustained manner (Fuady, 2012, p. 375).

The discussion of concrete construction technology during the Old Order begins in 1959, a year interpreted as marking a disjunction in state policy (Siahaan, 2000; Sopandi, 2017a; Widodo, 2009). In contrast, the analysis of technological developments in New Order architecture concentrates on the period from 1966 to 1981, which encompasses two contrasting phases in Indonesia's economic trajectory. Australian economist Hal Hill (2001, p. 15) identifies the first phase (1966−1972) as a period of economic rehabilitation, characterised by efforts to stabilise and recover from the preceding crisis, while the second phase (1973−1981) is marked by rapid economic growth, driven largely by the surge in global oil prices. The year 1981 serves as a terminus for this study, as it signifies the end of the oil price surge and the consequent shift in the direction and capacity of national development policies.

Scholarly investigations of Indonesian architecture during the Old Order period remain more prominent than those addressing the New Order era. This imbalance is surprising, given that architectural production under the New Order was significantly greater in quantity and displayed characteristics distinct from other periods. Seminal works by Akihary (1990), Passchier (2016), and Norbruis (2020) explore Indonesian architecture primarily up to the 1960s and 1970s, aligning with the Old Order period. Similarly, Kusno (2012), Eryudhawan (2012), and Subijono (2012) emphasise President Sukarno's instrumental role in promoting architectural modernity, in line with Sopandi's (2017b) study on Friedrich Silaban, a key architect active during that time. In contrast, scholarship on New Order architecture remains thematically fragmented, despite notable contributions by Hidayat & Sjarief (2019a, 2019b, 2021), Khudori (2001), Moersid (2015), Odang (1992), Rahardjo & Soerasno (2010), Sukada (2011), and Tjahjono & Agustiananda (2002), who have examined the ideas and works of Indonesian architects during the New Order government. Further enrichment comes from the recent volume edited by Henning and Kögel (2023), which highlights Indonesian architects trained in Germany who were professionally active throughout the New Order period. Nevertheless, most of these studies have yet to adequately engage with the role of construction technology, particularly reinforced concrete technology, and its institutionalisation within New Order architectural practice. Critical assessments of architecture from this era–such as Wiryomartono's (2012, p. 216) appraisal that it lacks monumentality, innovation, and tends toward conventionalism– often overlook the material and technological frameworks that underpinned it. This gap is further evidenced by the lack of analysis on the continuity between the Old and New Orders, despite both periods exhibiting sustained patterns in the adoption and institutionalisation of concrete construction technologies, which unfolded beyond the logic of formal state policy.

The imbalance in scholarship between Old Order and New Order architecture reveals a lack of attention to construction technology as an integral aspect of the institutional dynamics of modern architecture in Indonesia. This study thus investigates how concrete construction technology became institutionalised within two distinct politico-economic contexts. The analysis employs the perspective of social construction theory to interpret technological practices as products of historically situated negotiations between actors and institutions, legitimised through developmental narratives.

Research Methods.

This study draws upon twentieth-century architectural historiography and Science and Technology Studies (STS) to reconceptualise modern architecture not as a stylistic category but as a socio-technical process of modernisation. It situates the discourse of modern architecture within the epistemological interplay between design practice, construction technology, and developmental governance. Accordingly, the investigation focuses on how the institutionalisation of concrete construction technology mediated the modernisation of architectural practice in Indonesia, positioning architectural modernity as a historically contingent outcome shaped by the political and economic objectives of the state.

Earlier historiography of modern architecture tended to privilege *episteme* - the aesthetic and compositional logic of form (Hirst, 1993), while marginalising *techne*, the procedural intelligence of making (Schatzberg, 2012; Wang, 2013; Miller, 2023). Yet *techne* constitutes the epistemic foundation of technology: whereas *techne* embodies the situated and embodied practices of making, technology denotes an organised assemblage integrating theoretical knowledge, technical mastery, and productive systems oriented toward specific ends (Li-Hua, 2009). The dialectical relationship between these two dimensions, *episteme* and *techne*, underpins the historical process through which architecture becomes modernised, not merely in its formal expression but through the systemic reorganisation of its production and institutional logics.

Guided by Berger and Luckmann's Social Construction of Reality (1966), this study interprets technology as a socially constructed reality produced through dialectical interactions between actors and institutions. Through the processes of externalisation and objectivation, technological meanings are generated, materialised, and legitimised within broader socio-political frameworks. Within this theoretical lens, the adoption of concrete construction technology in Indonesian architecture is treated as the outcome of historically situated negotiations whose collective actions shaped its legitimacy as an agent of modernisation.

Methodologically, this study employs a qualitative content analysis structured within the conceptual categories of externalisation and objectivation. The primary and secondary historical sources comprise government records, professional monographs, biographies, and national media archives, all publicly accessible materials. These documents provide not only factual evidence but also discursive traces through which actors' intentions, institutional logics, and the socio-technical meanings of modernisation can be discerned. The analysis proceeded through five iterative stages: (1) extracting textual evidence that reveals actors' intentions or institutional narratives; (2) coding these excerpts according to their thematic relevance to externalisation or objectivation; (3) reconstructing, in chronological sequence–the socio-technical trajectories spanning the Old and New Order regimes; (4) interpreting the actions of individual and collective actors who advanced the institutionalisation of concrete construction technology; and (5) relating the institutionalisation of technology to broader patterns of architectural modernisation in Indonesia. The analytical framework moves from Berger and Luckmann's Social Construction of Reality (SCOR) toward the Social Construction of Technology (SCOT), thereby extending the analysis beyond discursive interpretation to the material mediation of technology in architectural practice. Analytical reliability was strengthened through iterative triangulation among textual evidence, theoretical interpretation, and historical context, ensuring that each analytical claim remained reflexively grounded in both empirical and conceptual coherence.

Institutionalisation, in this study, is defined as the convergence of externalised actions and their material objectivation, when technological practices become embedded within the mechanisms of developmental governance. The analysis deliberately excludes the stage of internalisation, focusing instead on how institutionalisation differentiated across political regimes. By mapping both discursive and material transformations, architectural works employing concrete construction are interpreted as tangible objectivations of these social processes. Comparative interpretation between the two regimes reveals how technology functioned as a constitutive agent of architectural modernity under distinct political economies. In doing so, the study extends global historiographical debates by shifting attention from stylistic or regional interpretations toward the institutionalisation of construction technology as a socio-technical process. Accordingly, this study conceptualises architectural modernisation through concrete construction as a non-linear process shaped by contextual contingencies and external influences (Bijker, 1997, 2010; Sismondo, 2011). It thereby challenges centre-periphery narratives and demonstrates how material governance structured the uneven, non-Western trajectories of modernisation.

Results and Discussion.

The modernisation of architecture in Indonesia unfolded differently from other non-Western contexts. Earlier studies rarely employed a socio-technical lens. Nevertheless, the dissemination of modernism in architecture can be understood as a socially constructed process shaped by three major trajectories. The first involved professional collaborations between Western and local architects that embedded modernist ideas directly in design and construction (Lima, 2014; Kapur, 1998). The second was institutional, through organisations such as the *Congrès Internationaux d'Architecture Moderne* (1928–1959) and the Modern Architectural Research Group (1933–1957), which standardised modernist principles across scales of design and planning (Frampton, 1970; Roux, 2004; Uduku, 2006). The third consisted of political-economic exchanges among non-Western nations, exemplified by the People's Republic of China's technical assistance to Africa and Latin America since the 1950s (Chang & Xue, 2019; Ding & Xue, 2015; Sun, 2023). In contrast, Indonesia's architectural modernisation was propelled by internally driven forces rooted in its domestic political economy rather than by external professional, institutional, or geopolitical mechanisms.

Building upon this internally driven trajectory, the institutionalisation of concrete construction technology in Indonesia demonstrates how socio-technical networks consolidated across successive regimes. Spanning the Guided Democracy and early New Order periods (1959–1981), this process unfolded as a continuous yet rapid transition shaped by the 1966 political shift and the subsequent five-year development plans initiated in 1969. Rather than arising abruptly from changing socio-economic conditions, the discourse on appropriate technology evolved gradually, underscoring the need to situate institutionalisation within the distinct temporal dynamics of both regimes.

The Institutionalisation of Concrete Construction Technology in Architecture during the Guided Democracy (Old Order) Era (1959–1966).

The Economic Context.

The institutionalisation of concrete construction technology during the Old Order was inseparable from Indonesia's fragile postcolonial economy and the complexities of decolonisation under Sukarno's leadership. This economic fragility not only delineated the nation's developmental constraints but also prompted the externalisation of technological rationality as an instrument of national autonomy. Emerging from the economic and political repercussions of the 1949 Round Table Conference, the early discourse on industrial self-reliance became intertwined with the search for appropriate construction technology. Three controversial provisions of the agreement subsequently constrained Indonesia's economy: the unresolved status of Papua, the obligation to assume Dutch East Indies debts totalling US$1.13 billion at 3% interest, and the guarantee of continued Dutch business operations within Indonesia

(Siahaan, 2000; Thee, 2012). Collectively, these conditions curtailed the state's fiscal capacity and industrial autonomy, shaping the early developmental context in which concrete construction technology began to be institutionalised.

The Round Table Conference Agreement left Indonesia's economy largely under foreign control, posing major obstacles for the new government. Dutch corporations and East Asian business communities continued to dominate key sectors, from agriculture and mining to manufacturing and trade, thereby limiting Indonesians' participation in productive enterprises (Siahaan, 2000; Al-Rahab, 2014). Monetary policy was also constrained, as *De Javasche Bank*, the colonial-era circulation bank, remained under Dutch authority until its nationalisation on July 1, 1953. Before this transfer, the bank primarily served Dutch economic interests, including profit repatriation (Thee, 2012). These structural continuities of colonial capitalism undermined Indonesia's fiscal sovereignty, further complicating the state's capacity to direct industrial and technological modernisation.

The dominance of foreign corporations and entrepreneurs across Indonesia's economy in the 1950s extended deeply into the construction sector, where local professionals faced structural barriers inherited from the colonial economy. Roosseno (1908−1996)–engineer, academic, bureaucrat, and later celebrated as the "Father of Indonesian Concrete"–became a critical observer of this continuity. His testimony reveals how post-independence construction practices remained stratified along colonial social lines: Dutch elites controlled the upper tier, Chinese Indonesians occupied the middle, and native Indonesians remained confined to the lowest stratum. This hierarchy curtailed indigenous participation in architectural planning and hindered the formation of a national technological agency. Roosseno (1974, p. 23) described the situation at that time as follows:

> The planning sector was in an even worse state. Major projects were monopolised by Dutch engineering and architectural firms such as *Bureau Ingenegeren-Vrijburg* and *NV. Architecten-Ingenieursbureau Fermont en Ed. Cuypers*. At the middle level operated a few local bureaus, including Liem Bwan Tjie's office in Semarang. Only one indigenous firm existed–the Sukarno-Roosseno engineering bureau in Banceuy, Bandung–whose commissions were limited to drawings for houses, offices, and prayer rooms for Indonesian clients and friends.

During the latter half of the Guided Democracy era (1959−1966), the cement industry became a strategic sector closely tied to the institutionalisation of concrete construction technology. Despite persistent political and economic instability, this industry emerged as one of the few capable of supporting the state's externalisation of technological self-reliance, linking material production to ideological autonomy. Indonesia's first cement plant, the Indarung Factory in Padang–a colonial legacy–was nationalised in 1957, yet its planned expansion under Sukarno's administration was never realised (Zed, Chaniago, & Jasmi, 2001). The country's second plant, NV. Pabrik Semen Gresik, was inaugurated in 1957 and expanded rapidly with technical assistance from the American firm Morrison Knudsen International Co. Inc. Although these two plants marked the foundation of Indonesia's cement industry, domestic production still met only about 36% of national demand by the early 1960s (Siahaan, 2000). To reduce dependence on imports, the government launched an ambitious plan to construct new cement factories across the archipelago, financed partly through socialist and Western bloc aid. However, most projects stalled due to financial and political turbulence, with only PT. Semen Tonasa materialising by 1967. Consequently, limited cement supply hindered the institutional consolidation of concrete construction during the Sukarno era.

Mobilising Technology for Development during the Old Order Era.

Sukarno (1901–1970) recognised the inseparable relationship between Indonesia's political and economic challenges and sought to address them through an integration of ideology, governance, and technological vision. His Presidential Decree of July 5, 1959, which reinstated the presidential system and introduced the principles of Guided Democracy and Guided Economy, reflected not only a political reconfiguration but also the externalisation of a techno-nationalist worldview in which technological advancement embodied the state's developmental will.

Beginning with his honorary Doctorate in Law acceptance speech at Gadjah Mada University on September 19, 1951, Sukarno articulated national self-reliance as the intellectual foundation of development (Sukarno, 1986). He framed the practical application of knowledge as an ethical duty to transform science into collective welfare, positioning technological utilisation as central to the nation's emancipatory project. This vision of science and technology as instruments of self-determination recurred throughout his subsequent honorary addresses, forming a consistent epistemic trajectory in his discourse on modern nationhood.

In his September 13, 1962 speech "*Engineering Science Must Serve a Just and Prosperous Society*" upon receiving an honorary doctorate from the Bandung Institute of Technology, Sukarno urged the practical application of knowledge to serve social welfare (Sukarno, 1986, p. 21). This statement was not merely an ethical exhortation but a discursive externalisation of technology as praxis–framing engineering as a moral and creative act grounded in the nation's material conditions. Although he did not explicitly invoke the notion of *techne* or technology, his articulation of engineering as both practical mastery and moral instrument resonates with the classical conception of *techne*. When extended toward innovation and collective welfare, this conception anticipated the modern understanding of technology as the transformative realisation of *techne* in social praxis.

Another part of Sukarno's 1962 speech emphasised that technological knowledge fostering prosperity must arise from self-reliant intellectual effort rooted in Indonesia's material and social realities, framing authenticity as both reflection and invention. Far from rhetorical idealism amid economic instability, Sukarno's appeal targeted the mental development necessary for creative praxis. Although he did not employ the term bricolage–Lévi-Strauss's (1962) concept describing how inventors or engineers transform available means into novel configurations (Johnson, 2012, p. 368)–his vision resonated with its logic: technology as a constructive rearticulation of the given toward innovation. Sukarno (1986, pp. 23–24) expressed it as follows:

> Similarly, my friends, I say, if we truly want to become a great nation, strong, prosperous, safe, peaceful, just, and wealthy, in which there is no *exploitation de l'homme par l'homme*, we must seek by ourselves. And in this search, number one, as I have said earlier, is creation, ideas. Once we have that creation, we look for technical means, science, to realise this idea."

In the same address, Sukarno's reflections on concrete technology exemplified this externalisation of authentic reasoning in material practice. Recalling his studies at the Technische Hogeschool Bandoeng (1921–1926), he critiqued his professor's prohibition against concrete spans exceeding twenty metres–a rule derived from European climatic assumptions (Sukarno, 1986, p. 27). By reframing this constraint through Indonesia's stable temperature range, Sukarno redefined the epistemic authority of colonial engineering, transforming local rationality into a national technological consciousness.

Concrete was not a novel construction technology in Indonesia at the time, yet its application lacked innovation. The Netherlands did not lead in concrete development around the turn of the 20th century, as its use remained confined to civil engineering projects (Heinemann, 2013, p. 42). Although concrete was employed in public buildings, it was often concealed behind arcades and load-bearing walls, in accordance with tropical design principles (Meijling, 1953; Norbruis, 2020; Sumalyo, 2021). Early 20th-century architectural preferences still prioritised historical stylistic standards over the structural potentials of concrete (Roosmalen, 2008).

Roosseno was among the earliest advocates of reinforced concrete in the Dutch East Indies. In his 1940 article "*Het gewapend beton in den bruggenbouw in Indië*" (*De Ingenieur in Ned. Indië*, no. 8, pp. I.143–I.155), he argued that despite higher initial foundation costs, reinforced concrete offered superior durability and lower maintenance compared to timber or steel (Wangsadinata, 2008, pp. 68–69). Drawing on his experience in the *Department van Burgelijke Openbare Werke* (Department of Public Works) (1935–1943), Roosseno further underscored the economic and social potential of using locally available materials–cement, sand, crushed stone, and timber for formwork–to advance community welfare and technological self-sufficiency (Salam, 1987).

Roosseno played a pivotal role in institutionalising concrete construction knowledge in Indonesia. He sustained its teaching through the Japanese occupation (1944–1945) and into the post-independence era, ensuring the continuity of engineering education amid political upheaval (Salam, 1987; Wangsadinata, 2008). Between 1950 and 1965, he founded several private universities across Java and produced key monographs and articles on mechanics and reinforced concrete. As both scholar and practitioner involved in major architectural works of the Old Order, Roosseno acted as a knowledge broker who translated colonial engineering principles into a modern national epistemology. Through this dual role, concrete engineering evolved from a technical craft into a systematic and autonomous field of national expertise.

Objectifying Concrete Construction Technology in Indonesian Architecture during the Old Order Era.

The objectivation of reinforced concrete technology during the Old Order marked the translation of Sukarno's ideological and pedagogical vision into institutional and material form. Long before 1959, he had laid the groundwork for this transformation by framing technological advancement as both civic education and a vehicle for national development.

Sukarno's inauguration of the Architecture Department at the Bandung Institute of Technology (ITB) on October 24, 1950 marked a decisive institutional moment in shaping Indonesia's architectural modernity (Atmadi, 1997; Hutahean, 2021; Saidi & Warsidi, 2021). Prior to this, architectural instruction existed only as a subdivision within civil engineering, a colonial legacy of the *Technische Hogeschool Bandoeng* founded in 1920. The formal establishment of architecture as an autonomous discipline not only redefined the epistemic boundaries between design and engineering but also positioned ITB as the nucleus for architectural education nationwide, as most subsequent schools were founded by its alumni.

Following the preparation of architectural professionals, the institutional consolidation of the construction sector became imperative. This process was accelerated by deteriorating Indonesia-Netherlands relations, culminating in the nationalisation of Dutch enterprises in 1959 (Siahaan, 2000; Thee, 2012). Government Regulation No. 2/1960 enabled the state to assume control over all Dutch-owned architectural and construction firms, facilitating the transfer of managerial expertise and technological competence, particularly in reinforced concrete. Notably, *De Kondor NV.* and *Naamloze Vennootschap Hollandsche Beton Maatschappij*, each with more than half a century of experience, became instrumental in embedding advanced concrete practices within Indonesia's public works. Yet, the establishment of NV. Pembangunan Perumahan in 1953 as a subsidiary of the state-owned *Bank Industri Niaga* demonstrates that the state's effort to indigenise the construction industry had already begun prior to nationalisation (Konstruksi, 1979b, p. 29).

Sukarno's final modernisation initiative materialised through large-scale construction projects that operated beyond the scope of the Guided National Development Plan. These state-led works pursued not economic rationality but the symbolic construction of national sovereignty, Nation Character Building. Financed largely through foreign loans and Japanese war reparations (Pasaribu, 2014; Sopandi, 2017a), they functioned as experimental arenas where reinforced concrete technologies were transferred, adapted, and institutionalised. Thus, these projects embodied both a political performance of independence and a techno-material process of nation-building during the Old Order.

Within this framework, the Nation Character Building programme materialised through two principal typologies of reinforced-concrete construction. The first comprised high-rise buildings, hotels, department stores, and office towers, that marked Indonesia's entry into vertical construction. The Hotel Indonesia (1959), designed by American architect Abel Sorensen, pioneered this transition. Its 14-storey reinforced concrete frame with shear walls along the broad façades introduced modern construction methods and spatial standards unprecedented in the country (Kwee, 2002, p. 121). Although structurally modest, it became the prototype for subsequent locally designed projects, the Bali Beach (1962), Samudera Beach (1962), and Ambarukmo Palace Hotels (1963), signifying the early localisation of high-rise concrete technology.

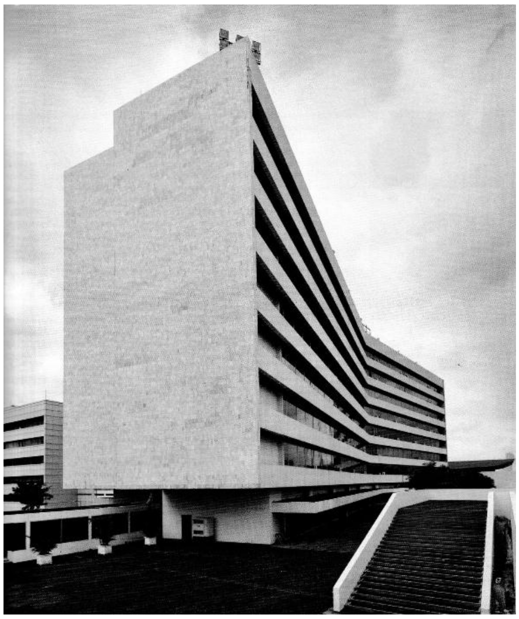
The second typology comprised long-span concrete structures, epitomised by the Sports Complex built for the 4th Asian Games in 1962. Initiated in 1959 and realised through Soviet technical assistance, the project introduced Indonesia to advanced structural engineering concepts such as the ultimate strength theory and the ring-beam system, applied for the first time in the country (Direktorat Sejarah, 2018). Beyond meeting the event's infrastructural demands, the complex served as a pedagogical site where reinforced concrete design shifted from empirical practice toward a scientifically modelled understanding of structural behaviour.

The Conference of New Emerging Forces (Conefo) complex, initiated in March 1965, represented the apex of Sukarno's Nation Character Building policy and the culmination of Old Order experimentation with reinforced concrete. Designed by Soejoedi Wirjoatmodjo (1928–1981), a graduate of the Bandung Institute of Technology and *Technische Universität* Berlin, the project advanced long-span construction through a synthesis of architectural form and structural innovation. Its main assembly hall (fig. 1a) employed a prestressed concrete shell supported by paired 120-metre arch beams, designed under the Ultimate Strength Theory introduced from Soviet engineering (Sukada, 2011; Syatria, 1995; Varia, 1965). By integrating modern analytical calculation with expressive structural form, Conefo transformed concrete into both a material and symbolic medium of technological sovereignty, positioning Indonesia within the global discourse of modern construction.

The adjoining banquet and secretariat buildings further extended this rationality into everyday structural practice. The banquet hall's 15-metre column spacing and 7.5-metre cantilevers (Fig. 1b), along with the secretariat's 11-storey frame spanning 7–10 metres, demonstrated a new confidence in the plastic behaviour of reinforced concrete (Fig. 1c). Under Soetami's direction, structural analyses adopted a limit-state approach that redefined engineering pedagogy from empirical calculation to analytical reasoning. As observed by Wiratman Wangsadinata, this shift signified not merely technical progress but the internalisation of scientific modernity within Indonesian civil engineering (Syatria, 1995; Varia, 1965; Akmal & Faiz, 2010).

(a) main assembly hall

(b) banquet hall



(c) secretariat building

Figure 1. The Conference of New Emerging Forces (Conefo) complex, now the Indonesian parliament building (sources: (1a) photograph by Davidelit, https://commons.wikimedia.org/wiki/File:MPRDPRBuilding.jpg; (1b-c) (Sukada, 2011, p. 65, 74–75).

Soejoedi extended the technological rationality of the Conefo complex by translating the Bauhaus *Ein Einheit: Kultur und Techniek* principle–the unity of art, technology, and social harmony–into an Indonesian context (Bredendieck, 1962; Smith, 1987). His design philosophy sought not only formal ingenuity but also constructability through collective labour. The shell of the main assembly hall, though conceptually and structurally advanced, was executed through a simplified Cartesian formwork that allowed unskilled workers to pour and cast the concrete with precision. Likewise, the Secretariat façade, composed of repetitive horisontal modules, enabled efficient production without artisanal specialisation. Through these strategies, Soejoedi transformed modernist aesthetics into a labour technology: the rationalisation of construction as a social process. By delineating the boundary between professional design and manual execution, he materialised Sukarno's ideal of a technology that rejects *l'exploitation de l'homme par l'homme*, a synthesis of technological modernity and human emancipation. In this culmination, concrete construction was fully objectified as both the medium and message of national modernity–an institutional reality through which the state's developmental imagination attained material permanence.

The Institutionalisation of Concrete Construction Technology in Architecture during the New Order Era (1966–1981).

The Economic Context.

As in the preceding regime, the institutionalisation of concrete construction technology during the New Order was inseparable from its economic foundations. Unlike the Old Order's ideologically driven developmentalism, however, the New Order's economic framework was grounded in technocratic rationality that subordinated political vision to managerial control. In this context, technology became explicitly instrumental to the state's macroeconomic strategy. Between 1966 and 1981, Indonesia underwent a dramatic economic reconfiguration: initial stabilisation policies gave way to rapid growth following the 1973 oil price surge, producing sharp fluctuations in development expenditure (Hill, 2001, pp. 65–67). These oscillations compelled the state to consolidate construction as a developmental apparatus, aligning technological standardisation, fiscal planning, and labour absorption into a unified framework of state-led modernisation. Despite fiscal volatility, the New Order sustained a consistent commitment to growth-oriented infrastructure, positioning concrete construction technology not merely as a technical medium but as a stabilising instrument of economic governance.

The New Order government adopted a dual strategy to stabilise and expand the post-crisis economy (Paauw, 1963, in Booth & McCawley, 1985), combining fiscal discipline with foreign capital liberalisation as instruments of controlled growth. Unlike the Old Order, which failed to institutionalise these mechanisms, the New Order translated them into an integrated technocratic apparatus. Policy formulation was delegated to university-trained economists who organised development within a two-tier framework: long-term plans of 20–25 years and short-term Five-Year Development Plans (REPELITA), first launched in 1969. Guided by the Broad Outlines of State Policy (GBHN), the New Order prioritised the fulfilment of basic human needs as a corrective to colonial economic disparities and the politicised growth agenda of the preceding regime (Indonesia, 1968, p. 11). Grounded in economic rationality and administrative discipline, the government embedded technology–particularly reinforced concrete construction–not only as an infrastructural instrument and a symbol of technocratic order but also as a medium of calculative governance, through which architectural practice was redefined as a function of developmental planning.

During the early New Order, economic policy and technological institutionalisation were tightly interwoven. In the First Five-Year Development Plan (REPELITA I), the state prioritised basic needs–food, clothing, shelter, employment, and spiritual welfare–through the optimal use of domestic resources (Indonesia, 1968, p. 16). Agriculture served as the developmental nucleus, yet its advancement depended on the parallel growth of supportive industries such as fertiliser, cement, and chemicals. Among these, cement manufacturing was regarded as particularly strategic, linking agricultural productivity with infrastructural expansion in dams, irrigation, and roads. The Second Plan (REPELITA II, 1974–1979) retained agriculture as a central concern but reframed economic growth as the nation's primary objective (Indonesia, 1974, p. 24). By prioritising productivity in agriculture, mining, transportation, and construction (Indonesia, 1974, p. 46), it reoriented the developmental logic from agrarian reinforcement to infrastructural modernisation–marking the construction sector's rise as a principal instrument of national progress. Through these policy shifts, reinforced concrete emerged as both infrastructural medium and epistemic apparatus, the material locus where the state's developmental rationality was externalised into built form. This constitutive ambiguity–between imported technocratic rationality and the local pursuit of technological authenticity–defined the New Order's modernisation project and underpinned the institutionalisation of concrete construction technology in Indonesia.

Indonesia's economy expanded rapidly under the New Order, sustaining one of the strongest growth trajectories in Southeast Asia despite recessions in 1975 and 1983 (Lewis, 2007; Sjahrir, 1990; Zanden & Marks, 2012). Between 1969 and 1982, GDP grew by about 8% annually (Liddle, 1991, p. 403), driven in part by the construction sector's strategic role in state-led development. Construction consistently contributed around 4% to real GDP and maintained an average annual growth rate of 8.3% between 1967 and 1981 (Fig. 2), revealing its structural importance within Indonesia's industrialisation framework and its function as a mechanism translating policy into infrastructural modernisation. This quantitative expansion mirrored the institutional consolidation of concrete technology as a material expression of the state's developmental order.

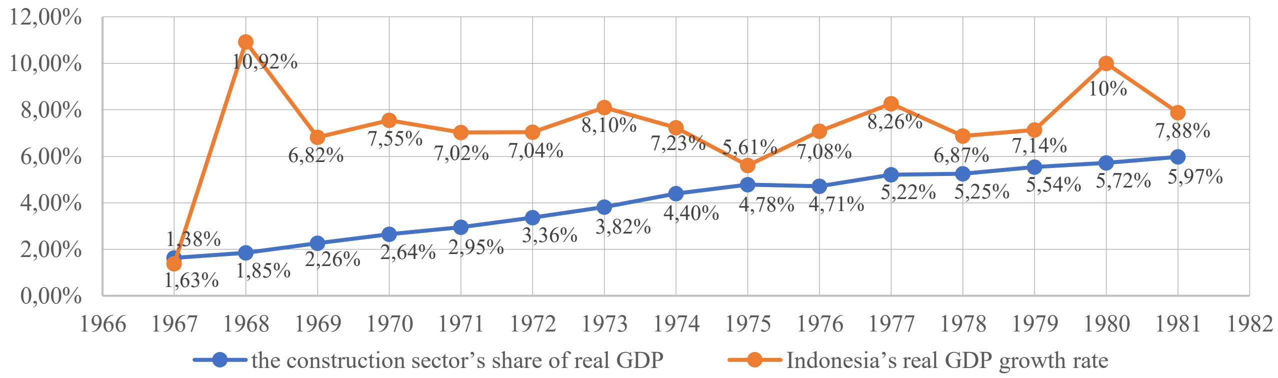


Figure 2. Indonesia's Real GDP Growth and the Construction Sector's Share of Real GDP, 1967–1981 (sources: Statistical Yearbook of Indonesia 1968–1982).

Initially positioned as an auxiliary industry to agriculture, cement manufacturing was subject to conservative production targets. During REPELITA I (1969–1974) through the early years of REPELITA III (1979–1981), government planning projected only a 24% increase in national capacity, equivalent to an annual growth rate of less than 2%. Actual expansion, however, far exceeded projections, reaching over 30% with an average annual growth rate of 25%. The commissioning of PT. Semen Tonasa in 1971, followed by the joint establishment of PT. Semen Baturaja by PT. Semen Padang and PT Semen Gresik in 1974, and the founding of the private PT. Distinct Indo Cement Enterprise (DICE) in Citereup in 1975, reflected progressive diversification in ownership and regional distribution. Although domestic output had met internal demand, selective imports continued under bilateral trade arrangements until 1976, when national production first surpassed imports. By 1979, Indonesia achieved self-sufficiency and entered the export market, marking the redefinition of cement from a supporting industry to a driver of national industrial capability. This industrial maturation embodied the objectivation of technological capacity–cement no longer functioned merely as a resource but as a manifestation of state rationality and industrial self-reliance.

Despite endorsing industrial intensification and extensification, the government's development policy maintained a paradoxical position by restricting technological advancement largely to the educational sphere (Indonesia, 1968, pp. 49–50). Rather than promoting applied innovation within emerging industries, technology was construed as a cognitive and pedagogical pursuit, justified by the perception that Indonesian society was not yet predisposed toward technological utilisation. This rationale reflected structural realities: in the early 1960s, agriculture employed 73% of the labour force in 1961 and 65.8% in 1971 (Hill, 2001), while educational attainment remained low, on the eve of REPELITA I, 76% of Jakarta's labour force and 72.7% in other urban centers had completed only primary education or less (Booth & Sundrum, 1985). These demographic and educational constraints explain the state's cautious stance toward integrating technology into industrial practice, situating it within a discourse of developmental pragmatism rather than industrial modernity.

Development Policies and the Discourse on Technology in the New Order Era.

During the First Five-Year Development Plan (REPELITA I), technology was positioned within two interlinked domains–education -labour and research-statistics–as instruments of developmental rationalisation. It was expected to foster a rational and democratic social consciousness (Indonesia, 1968, p. 18). At the same time, the government sought to strengthen the nation's weak scientific capacity through institutional rehabilitation, human resource development, and improved access to technical infrastructure (Indonesia, 1968, pp. 131–132). These initiatives marked the embryonic stage of Indonesia's technoscientific institutionalisation. Here, technology was no longer conceived as an ethical vocation, as in the Old Order, but as a cognitive mechanism for social rationalisation.

Under the Second Plan (REPELITA II), this orientation matured into a coherent science and technology policy framework. Technology was redefined as the application of scientific knowledge to national development (Indonesia, 1974, p. 188). Its coordination between state agencies and universities directed research toward key productive sectors–agriculture, mining, and industry–through objectives of job creation, labour productivity, and domestic tool utilisation (Indonesia, 1974, p. 194, 196). By this stage, technology had become an institutionalised driver of socio-economic transformation, embedding scientific rationality within the technocratic apparatus of the state.

Although each Five-Year Development Plan articulated systematic strategies for technological advancement, the government never clearly defined the conceptual meaning of "technology." This ambiguity arose from the normative criteria guiding its development, alignment with fiscal capacity, suitability to national conditions, and reliance on domestic materials, which collectively functioned as pragmatic filters for selecting and adapting foreign technologies while fostering limited indigenous innovation. Between 1972 and 1981, this conceptual indeterminacy generated sustained debate among bureaucrats, academics, and professionals, reflecting a broader epistemic struggle to reconcile imported technological rationality with the imperatives of national development. This indeterminacy was not merely semantic but epistemic, reflecting the unresolved tension between imported rationality and the local search for technological authenticity.

From these debates, at least three technological paradigms emerged. The first stressed the alignment of technology with ecological conditions and the everyday realities of its users. Advocating the gradual refinement of existing technological traditions, it sought to expand societal participation in development while sustaining environmental balance and utilising local resources. This approach, later termed ***teknologi madya*** (intermediate technology), was shaped by E. F. Schumacher's human-centered vision of technology articulated in his 1971 lecture at the Teilhard Centre for the Future of Man and popularized through *Small is Beautiful: A Study of Economics as if People Mattered* (1973). Schumacher's ethical emphasis on inclusive and context-sensitive development found particular resonance among Indonesian academics, who regarded it as a normative counterpoint to industrial models of technological modernisation.

In 1972, economist Sarbini Sumawinata (1918–2007) articulated a humanistic conception of development aimed at securing safety and well-being while integrating both material and immaterial dimensions of life. Acknowledging Indonesia's predominantly agrarian economy and traditional labour practices, he argued for a gradualist trajectory that balanced democratic aspirations for rapid progress with the population's technological readiness. To mediate these tensions, Sumawinata proposed intermediate technology as an equitable mode of modernisation–one enabling broad social participation without alienating users from unfamiliar work practices (Sumawinata, 1972, p. 12–13). Far from a mere revival of traditional tools, this paradigm represented the initial modernisation of vernacular systems, fostering a transformative disposition toward sustained, human-centered development.

In 1976, economist and statesman Sumitro Djojohadikusumo (1917–2001) refined the notion of intermediate technology into a more pragmatic framework rooted in economic rationality and environmental prudence (Djojohadikusumo, 1976). He argued that Indonesia's industrial policy should prioritise employment creation, the utilisation of domestic materials, and the protection of the balance of payments (Djojohadikoesoemo, 1976, p. 78). Defining appropriate or intermediate technology as adaptive technology, Sumitro proposed the selective assimilation of innovations from advanced economies through contextual reconfiguration to local socio-economic conditions. This process, he maintained, required ecological sensitivity, as sustainable resource use became integral to technological adaptation. Although epistemically distinct from earlier humanistic interpretations, Sumitro's conception retained a normative commitment to the human dimension as the ultimate measure of technological development.

As state planning deepened, this humanistic orientation gradually yielded to a bureaucratic interpretation of technology. The second technological paradigm, ***teknologi tepat guna*** (appropriate technology), evolved from the notion of intermediate technology but assumed a more instrumental orientation. While both share a concern for contextual adaptation, appropriate technology emphasised economic feasibility, functional utility, labour absorption, and the use of local materials–priorities often dictated by bureaucratic or project-specific agendas. In contrast to the holistic and ethical vision of intermediate technology, it became a pragmatic framework in which certain values were selectively amplified according to institutional and policy imperatives.

In Indonesian architectural discourse, appropriate technology was frequently conflated with existing technology, emphasising pragmatic adaptation over innovation. Among construction professionals, this view grounded technological validity in local material availability and technical feasibility. Hartono Purbosaputro (1931–?), for instance, identified reinforced concrete as Indonesia's most suitable construction technology due to the accessibility and workability of its raw materials (Purbosaputro, 1979, p. 83). Similarly, civil engineer Sedijatmo (1909–1984) regarded his invention, the floorplate foundation, as an exemplar of appropriate technology, precisely because it relied on locally available resources and the competencies of domestic labour (Konstruksi, 1979a, p. 7). Extending this pragmatism into architectural theory, Adhi Moersid (1937–2019), national architect, defined appropriate architecture as the synthesis of functional efficiency and human adaptability, where form arises from performative logic and the capacity for transformation (Moersid, 1983, p. 35). Collectively, these positions reoriented technological discourse from innovation as invention toward innovation as contextual optimisation.

The concept of teknologi tepat guna (appropriate technology) entered Indonesia's formal development agenda in REPELITA III (1979–1984), reflecting Djojohadikoesoemo's earlier assertion that technology must be economically viable, environmentally appropriate, and socially inclusive. Initially rooted in grassroots and intellectual discourse, it was institutionalised as an adaptive form of advanced technology suited to local resources and community capacities (Indonesia, 1979, p. 56). Expanding prior aspirations from REPELITA II, the state framed it as a strategic model for equitable, context-sensitive modernisation across basic needs, resource management, industrial, defense, and socio-cultural sectors. Through this translation, the ethical language of intermediate technology was transformed into an administrative logic of appropriate technology–marking the objectivation of technological rationality within the developmental state.

The discourse on technology culminated in the articulation of a value-added technology paradigm introduced by B. J. Habibie (1936–2019), then Minister of Research and Technology. Habibie conceived technology as an instrument for enhancing added value while minimising incremental costs (Konstruksi, 1978, p. 6). He defined it as an appropriate and adequate solution, contextually embedded yet functionally efficient (Habibie, 1995, p. 21). Distinct from the moderate ethos of intermediate technology, his notion emphasised technologically advanced processes capable of transforming identical materials into higher-performance outputs through refined engineering. To realise this, Habibie underscored research on end-stage technologies and the strategic integration of technological innovation with economic policy (Habibie, 1995, pp. 73–74). Ultimately, his paradigm reframed appropriate technology as an instrument of industrial modernisation, privileging systemic innovation over incremental adaptation. In doing so, Habibie's paradigm completed the institutionalisation cycle of technological discourse: from moral reasoning and contextual adaptation to industrial instrumentalism and systemic innovation.

Objectifying Concrete Construction Technology in Indonesian Architecture during the New Order Era.

The proliferation of state-driven building projects during the New Order's developmental surge embodied the regime's projection of construction success while redefining the objectivation of reinforced concrete technology. In the recovery phase (1966–1972), the government prioritised completing unfinished projects from the previous regime–such as the Parliament Complex, Istiqlal Mosque, and the National Monument–thereby consolidating modern construction practices through relative professional autonomy. However, during the oil price surge (1973–1981), as the state assumed multiple roles as investor, initiator, and regulator, technocratic control progressively curtailed such autonomy. From 1979 onward, tighter regulations emphasising efficiency, transparency, domestic material use, labour absorption, and professional expertise culminated in the 1981 height restriction on public buildings.

This regulatory shift marked the end of monumental state projects and redirected architectural production toward functional public facilities and an increasingly privatised construction sector driven by domestic and foreign investment.

The advancement of concrete construction technology during the early New Order was driven by three key initiatives: establishing national standards, supervising construction practices, and promoting concrete as the core material of national development. The initiative was first led by Roosseno and later carried forward by his students in key institutional positions. This generational continuity reveals the operation of epistemic patronage within Indonesia's civil engineering community. Such networks operated as both conduits of technical knowledge and socio-political instruments for institutionalising reinforced concrete. Consequently, the New Order's technological modernity emerged not solely from formal state apparatuses but from a hybrid governance model grounded in expertise and inherited authority.

The codification of reinforced concrete standards marked a decisive stage in the objectivation of technological rationality, transforming engineering knowledge into an institutionalised framework of governance. When the Department of Public Works and Power issued the Indonesian Reinforced Concrete Code (PBI 1971) on October 1, 1971, chaired by Wiratman Wangsadinata, it was conceived not merely as a revision of PBI 1955 but as an effort to formalize national expertise while aligning with international norms. The drafting committee selectively adapted references from FIP-CEB 1970 (France), ACI 318-70 (US), the Unified British Standard Codes (1970), and the draft *Voorschriften Beton* (VB 1974) (Dutch), translating them into standards suited to Indonesia's material conditions and construction practices. Through this process, the epistemic authority of global engineering was domesticated into a national normative system. The code introduced elastic and ultimate strength design methods, seismic provisions, and specifications based on characteristic compressive strength, though it did not yet include rules for prestressed concrete (Yustono, 1989, p. 11). As a result, reinforced concrete technology was no longer a matter of professional discretion but a codified expression of state-endorsed modernity.

The issuance of this guideline marked an early stage in the institutional diffusion of concrete construction knowledge in Indonesia. Its practical orientation reflected the committee's intent to transform expert codification into a normative consensus applicable to everyday engineering practice. Framing this expertise within an official state document was not merely an act of legitimation, but a strategic move to reposition the state from a regulator to a mediator of technological access. Through its dissemination, the guideline consolidated existing knowledge of reinforced concrete and reinforced the institutionalisation of technological rationality within the broader agenda of national development.

During the early New Order, construction activities were heavily centralised in Java–particularly Jakarta–producing spatial disparities yet enabling the concentration of expertise necessary for the institutionalisation of reinforced concrete technology.

The capital's density of state and private projects facilitated not only the consolidation of technical standards but also their spatial embodiment within a unified regulatory framework. High-rise construction expanded rapidly during the First Five-Year Development Plan (REPELITA I) (Zoelverdi, 1974). In response, the Jakarta Provincial Government established the Building Construction Advisory Team (TPKB) on June 30, 1972 to oversee structural assessment and permit issuance under PBI 1971 (Wangsadinata, 1992, p. 21). Chaired by Roosseno with Wiratman Wangsadinata as vice-chair (1972–1982), TPKB filtered foreign projects that lacked collaboration with local professionals. Its subsequent merger with the Architectural and Urban Advisory Team (TPAK) created an integrated system of professional oversight that transformed Jakarta into a spatial apparatus of technological governance. This institutional configuration reinforced the authority of the concrete code and positioned the capital as a national laboratory for the objectivation of modern building technology.

Ambivalence in the use of reinforced concrete during the New Order was most evident in architecture, where its democratisation expanded the field of design participation yet generated epistemic tension within professional reasoning. Three overlapping paradigms–intermediate, appropriate, and value-added technology–embodied competing logics of practice: the first drew on local traditions and climatic adaptation; the second aligned technical efficiency with the state's developmental agenda; and the third pursued structural sophistication and economic optimisation. Despite their shared reliance on concrete, these frameworks produced limited innovation, as the pursuit of modernity became constrained by technical standardisation, bureaucratic procedures, and socio-economic uncertainty.

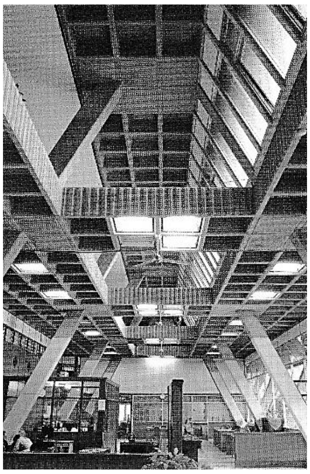
These technological modes evolved not in a linear sequence but concurrently across public architecture of varying scales, reflecting the heterogeneous conditions of state-led development. Rather than being shaped by abstract discourse, architectural practice generated its own empirical logic through everyday routines of design and construction. In the early phase of the New Order, architecture itself became a prefigurative agent of technological meaning, where the material discipline of reinforced concrete preceded and informed its conceptual articulation. Reinforced concrete thus functioned less as a differentiating marker of style than as an integrative substratum through which modern construction was institutionalised–not by discursive coherence, but through its adaptive incorporation into professional practice. This adaptive incorporation materialised in diverse architectural modes that reflected distinct technological rationalities. These variations reveal how the objectivation of concrete technology unfolded not merely through discourse, but through its physical articulation within the built environment.

These tendencies are most evident in public low- to mid-rise buildings employing appropriate (*madya*) concrete technology. Such works reveal a synthesis of modern construction and vernacular sensibility, emphasising tropical climatic adaptation. This is particularly expressed in building envelopes where traditional roof typologies are reinterpreted and façades integrated with the structural grid of columns and beams (Fig. 3a). Climatic responsiveness is reinforced through horisontally cantilevered concrete slabs as sunshades, porous walls for cross-ventilation, and precast concrete lattice blocks. Surfaces are finished with cement plaster, and open-frame systems with short spans predominate, reflecting a pragmatic rather than experimental structural logic.

(a) Central Kalimantan Provincial Government Office, 1978–1980

(c) State Treasury Building, Denpasar, 1975–1978

(b) PT Unilever Indonesia Office, Jakarta, 1981



(d) interior of State Treasury Building

Figure 3. Architectural works in Indonesia exemplifying three distinct technological paradigms (sources: (3a-b) (Ikatan Arsitek Indonesia, 1983, p. 49, 68); (3c-d) (Rahardjo & Soerasno, 2010, p. 110, 112).

Architectural works employing appropriate (*tepat guna*) concrete technology display significant formal diversity shaped by differing design priorities. When contextual responsiveness dominates, they resemble buildings constructed with intermediate (*madya*) concrete technology. Conversely, when efficiency, particularly the use of local materials, is prioritised, the architecture assumes simple geometric forms, open-frame structures, and painted or ceramic-clad walls (Fig. 3b). In some cases, efficiency extends to construction practicality, where large-scale components facilitate both cost management and labor absorption. Genuine appropriate technology applications include prefabricated structural elements, floor slabs, and wall panels. Spanning varied heights and functions, these works embody not merely technical rationality but institutional adaptation to the developmental agenda of the New Order.

Architectural works employing value-added (*nilai tambah*) concrete technology foregrounded structural inventiveness as a vehicle of modernisation. Emerging during the recovery period (1966–1972), these works, shaped by the lingering ethos of Nation Character Building and the influx of foreign investment, pursued aesthetic and tectonic refinement through modified open-frame systems, long-span structures, and double-skin façades (Fig. 3c-d). By the oil price surge era (1973–1981), such experimentation became increasingly aligned with foreign architects and clients. These shifts demonstrate that architectural creativity and technological innovation were both enabled and delimited by the institutionalisation of concrete construction under state-led developmentalism.

Conclusion.

This study establishes that the modernisation of architecture in Indonesia constituted a distinct, non-Western trajectory–one materially grounded in the ongoing institutionalisation of concrete construction technology across two contrasting political regimes. Rather than emerging from stylistic transformation or epistemic rupture, it evolved through the social construction of concrete technology as both a material and institutional medium of modernisation. Drawing on Berger and Luckmann's Social Construction of Reality, the study conceptualises modernisation as a dialectical process of externalisation and objectivation, in which knowledge, practices, and material forms were continually negotiated among state authorities, professional organisations, and construction actors. In this sense, technology was not merely transferred but continually produced and legitimised as a developmental instrument within changing political contexts.

During the Old Order, technological externalisation was articulated through the rhetoric of national autonomy and scientific advancement under economic austerity. Objectivation materialised in state-sponsored monumental projects–most notably the Conefo complex–that embodied political modernisation yet remained institutionally centralised. The institutionalisation of technology during this phase was prefigurative and exclusive: architects and constructors acted as agents of state ideology rather than autonomous negotiators of technological practice, rendering modernisation more symbolic than material.

The New Order redirected this trajectory from ideological representation toward managerial and technical rationalisation. Technological externalisation shifted into professional and academic domains, where architects and engineers sought to adapt imported methods to local capacities, labour structures, and regulatory standards. Objectivation expanded through the civil engineering field, transforming supervision and standardisation–exemplified by PBI 1971 and the Jakarta TPKB–into instruments of knowledge production. This marked a reproductive phase in the ongoing institutionalisation of concrete construction technology between 1966 and 1981, during which technological practices became increasingly integrated within bureaucratic and professional systems, though still shaped by administrative control.

By linking externalisation and objectivation to the unfolding phases of technological institutionalisation, this study advances an analytical framework for interpreting architectural modernisation as a socio-technical process rather than a stylistic evolution. It extends global historiography by demonstrating that Indonesian architectural modernity emerged through the materialisation of technology within non-Western developmental regimes. Bridging Social Construction of Reality (SCOR) and Social Construction of Technology (SCOT), this framework elucidates how material governance and actor configurations structured uneven, context-specific trajectories of modernisation. In doing so, it reconceptualises modernity as a negotiated socio- material construct–continuously sustained through technology, labour, and institutional order.

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Conflict of Interest.

The authors declare no conflict of interest.

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Інституціоналізація технології бетонного будівництва: Соціотехнічне формування сучасної архітектури в Індонезії

Анотація. *Інституціоналізація технології будівництва в постколоніальній архітектурі рідко досліджується з позицій досліджень науки і технологій, особливо в країнах, що розвиваються, де процес модернізації частіше визначався політичними програмами, ніж індустріальним зростанням. Ця стаття заповнює зазначену прогалину, аналізуючи соціотехнічний процес інституціоналізації технології бетонного будівництва в індонезійській архітектурі в період з 1959 по 1981 роки. Спираючись на теорію соціального конструювання Бергера та Лукмана, зокрема на поняття екстерналізації та об'єктивації, дослідження розглядає періоди Старого порядку та Нового порядку як послідовні режими, що формували й закріплювали технологічні значення у межах власних національних наративів розвитку. У дослідженні аналізуються президентські промови, урядові політики та публікації практиків з метою простежити історичні дискурси, які пов'язували технологію з національним розвитком. Результати свідчать, що ці дискурси спочатку були різноспрямованими: Старий порядок зосереджувався на розбудові нації через монументальні проєкти, тоді як Новий порядок наголошував на соціальному добробуті через економічне зростання. Згодом ці протилежні дискурси взаємодіяли й сприяли об'єктивації бетону як домінуючого матеріалу та методу будівництва в архітектурі після здобуття незалежності. Розрив у розвитку під час Старого порядку (1959–1966) породив модерність, що виникла з економічних обмежень, але вирізнялася інноваційністю через безпрецедентне використання бетону. Натомість період Нового порядку (1966–1981) характеризувався модерністю, заснованою на ефективності, використанні місцевих матеріалів і соціальній емпатії в умовах економічного піднесення. Попри відмінності, технологія бетонного будівництва зберегла архітектурну тяглість, поєднавши обидва режими. Таким чином, процес інституціоналізації є узгодженим соціотехнічним переходом, а не лінійним поширенням сучасної технології. Індонезійський досвід робить внесок у глобальні дискусії з досліджень науки і технологій, пропонуючи Південну перспективу на те, як сучасна архітектура матеріалізується через історично та контекстуально зумовлені технологічні конструкції.*

Ключові слова: *політика розвитку; екстерналізація; індонезійська сучасна архітектура; об'єктивація; соціотехнічна інституціоналізація*

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Colonial technopolitics in the Dutch East Indies: A study of hydroelectric power in Pamanoekan and Tjiasemlanden Plantation

Abstract*. This study aims to explore the historical development of hydroelectric power technology in the Dutch East Indies during the early 20th century, with a* *particular focus on the Pamanoekan and Tjiasemlanden plantation, currently managed by PTPN VIII Tambaksari-Ciater Plantation area in Subang, West Java. It seeks to investigate the transformation of water engineering technology from indigenous vernacular irrigation systems to modern irrigation and eventually to hydroelectric power plants. The study also examines the process of technological adaptation, the role of colonial engineers, the origin of technical components, and the operational mechanisms of hydroelectric stations within the broader context of Ethical Policy and colonial technocracy. The study integrates textual archives, and material remains into an interpretive narrative using a historical archaeology method. Private colonial plantations are treated as sites where domination over natural resources was enacted. Fieldwork focused on three hydroelectric stations – Cijambe, Gunungtua, and Cinangling – and was complemented by diverse textual sources, including newspapers, engineering journals, speeches and proceedings of Dutch engineers, colonial water regulations, company booklets, geological surveys, and plantation maps. This study's analysis applies the concept of technopolitics, framing technology not as a neutral instrument but as integral to the political-economic agendas of colonial rule. Findings indicate that the three hydroelectric stations expanded the colonial infrastructure regime following the implementation of irrigation projects in Pamanoekan and Tjiasemlanden. The Ethical Policy provided a civilizing narrative that legitimized technical rationalization. Through water flow engineering, colonial authorities and private enterprises – mediated by engineers – rendered rivers calculable and measurable, sustaining plantation-based industrial production while maintaining indigenous subsistence rice cultivation. Thus, the development of hydroelectric technology in Pamanoekan and Tjiasemlanden was not merely a technical achievement but a technopolitical project that mobilized water resources to consolidate economic productivity through networks of private enterprises, technocratic agencies, and international equipment distributors.*

Keywords: *hydroelectric power station; technopolitics; technocracy; ethical policy; colonialism; Pamanoekan and Tjiasemlanden*

Introduction.

Hydropower emerged as a key technology during the industrialization and modernization of the early 20th century. In the aftermath of World War I, amid growing competition in technological innovation, industrial expansion, and modern imperialism, countries such as Germany, Britain, and Switzerland developed hydropower as an alternative energy source (Cramer, 1914, p. 27) Beyond supplying electricity for urban lighting, it powered tram networks and stimulated new industries in electrochemistry and electrometallurgy (Floud, 1980). For imperial powers like the Netherlands, the rapid advancement of water engineering – through irrigation and hydropower – was strategically deployed to reinforce liberal economic policies (1870) and to legitimize the so-called civilizing mission of the Ethical Policy in the Dutch East Indies (Indonesia) (Bruno, 2023; Ravesteijn, 2007).

The modernization projects and the introduction of new technologies in the Dutch East Indies during the first decade of the 20th century were largely driven by the Ethical Policy – an initiative aimed at improving the welfare of the indigenous population. The Ethical Policy emphasized three main pillars: immigration, education, and irrigation. Yet in practice, irrigation projects often benefited private investors who had already established large-scale plantation industries in the colony (Moon, 2007). For the colonial government, the development of irrigation technology served a dual purpose: strengthening the agricultural sector that sustained the indigenous population's livelihood, while supporting foreign investment in plantation enterprises. Java became the center of these initiatives, as its population had historically been an agrarian society skilled in managing water circulation for farming (Christie, 2007). Moreover, Dutch imperial profits in the 19th century heavily depended on agricultural cultivation – coffee, rubber, cinchona, tea, rice, and sugar – making irrigation a vital factor in boosting production. The technical execution of these projects was entrusted to engineers trained at the Delft Institute of Technology, a leading institution renowned for its expertise in hydraulic engineering (*waterstaat*) (Oud-Alblas, 2012).

The development of irrigation engineering in the Dutch East Indies laid the foundation for more advanced technological applications, particularly hydropower, which played a crucial role in supporting the expansion of plantation industries, railway networks, and urban electricity systems. Before 1900, the Dutch engineer J. C. Melchior introduced the Melchior Method, a hydrological and technical design approach for calculating the optimal capacity of water in colonial hydropower projects. Recognizing the potential of water power, the colonial government established the *Waterkrachtbureau* (Water Power Bureau) in 1910, followed by the *Dienst voor Waterkracht en Electriciteit* (Government Service for Water Power and Electricity) in 1917 (Stibbe, 1939). The use of electricity was part of the colonial rationalization project, in which modern technology was deployed to strengthen control and increase production efficiency, in line with the logic of colonial capitalism, which is rooted in the exploitation of natural resources. In the Javanese sugar industry, for example, electric motors replaced steam engines powered by bagasse, reducing operational costs while enhancing production capacity (Knight, 2014). Similarly, in the tea plantations of the West Javanese highlands, small-scale hydropower was employed to operate factory machinery, provide lighting for administrative offices, and supply electricity to nearby urban areas (Stibbe, 1939). The geographical conditions of West Java – with its abundance of rivers, springs, and fertile volcanic soils in the uplands – provided the ecological basis for the successful development of hydroelectric power technology in the region (Bemmelen, 1934).

Notably, the hydropower infrastructure built by the colonial government and private companies continued to operate after Indonesian independence and remains in use today, particularly in West Java. Several large-scale hydropower plants, such as Dago, Lamajan, and Ubrug, are now managed by the state-owned company

Perusahaan Listrik Negara (PLN) to support electricity supply in urban areas. Meanwhile, smaller hydroelectric stations such as Cijambe, Gunungtua, and Cinangling, located on former Pamanoekan and Tjiasemlanden plantation lands, are still utilized by PT Perkebunan Nusantara to provide electricity for estate offices and, to a limited extent, nearby settlements. Yet despite their persistence, colonial hydropower systems remain understudied, often approached as heritage sites rather than as technopolitical instruments of domination. Examining these infrastructures is crucial for understanding how colonial engineering materialized power relations through the control of water, labor, and energy, leaving a tangible legacy of governance embedded within Indonesia's postcolonial physical landscape.

This study examines the development of hydroelectric technology on former colonial private plantations, where both natural and human resources were simultaneously exploited and controlled. The analysis focuses on the Pamanoekan and Tjiasemlanden Plantation in Subang, Indonesia, one of the largest private plantations in West Java during the 19th and 20th centuries. It explores the technological transformation of hydroelectric power, the processes of technological transmission, and the actors involved in its implementation. Rather than treating hydroelectric plants as neutral technical instruments, this study frames them as integral components of the political-economic objectives of colonial governance (Hecht, 2010; Mitchell, 2002). Timothy Mitchell (2002) demonstrates that technologies embody particular ways of organizing visibility, calculability, and control – what he terms colonial rationality. We argue that the modernization and rationalization of water engineering, both in irrigation and hydropower, in the Pamanoekan and Tjiasemlanden Plantation displaced vernacular systems of water management grounded in the empirical experience of local communities, which James Scott (1998) refers to as "metis."

The implementation of modern technologies in the colony depended on the technocratic role of engineers (Mrazek, 2002; Ravesteijn, 2007) as well as on global hardware networks that transmitted hydropower infrastructures into the colonial sphere. Components such as intakes, penstocks, and turbines can be read as material expressions of colonial governance. Their design carried assumptions of efficiency and order, projecting colonial ideals of modernity and discipline onto the landscape. Thus, we position hydroelectric technology not merely as a technical project but as a colonial instrument of control – by both state and private actors – over natural resources that sustained economic productivity, legitimized through narratives of civilization and claims of improving indigenous welfare.

This study represents an initial attempt to examine hydroelectric technology in colonial private plantations through a science, technology, and society (STS) lens. Historical studies that employ STS approaches – or STS studies focusing on Indonesia – remain limited. Previous study has examined electrification (McCawley, 1971), irrigation within the framework of the Ethical Policy (Moon, 2007), colonial public works (Nispen & Ravesteijn, 2009; Ravesteijn & Kop, 2008), technology and national imagination (Mrazek, 2002), post-independence modernization (Fakih, 2020), and the technocratic visions of the New Order regime (Amir, 2012). In contrast, research on hydropower in Indonesia has largely treated it as colonial material heritage, whether from archaeological (Fadlurrahman, 2023; Hermawan, 2016) or historical (Kholis Sofiah & Hakim, 2020) perspectives, without engaging critically with its colonial political-economic context. To our knowledge, no study has addressed hydropower technology in colonial private plantations through an STS framework. This study seeks to fill that gap.

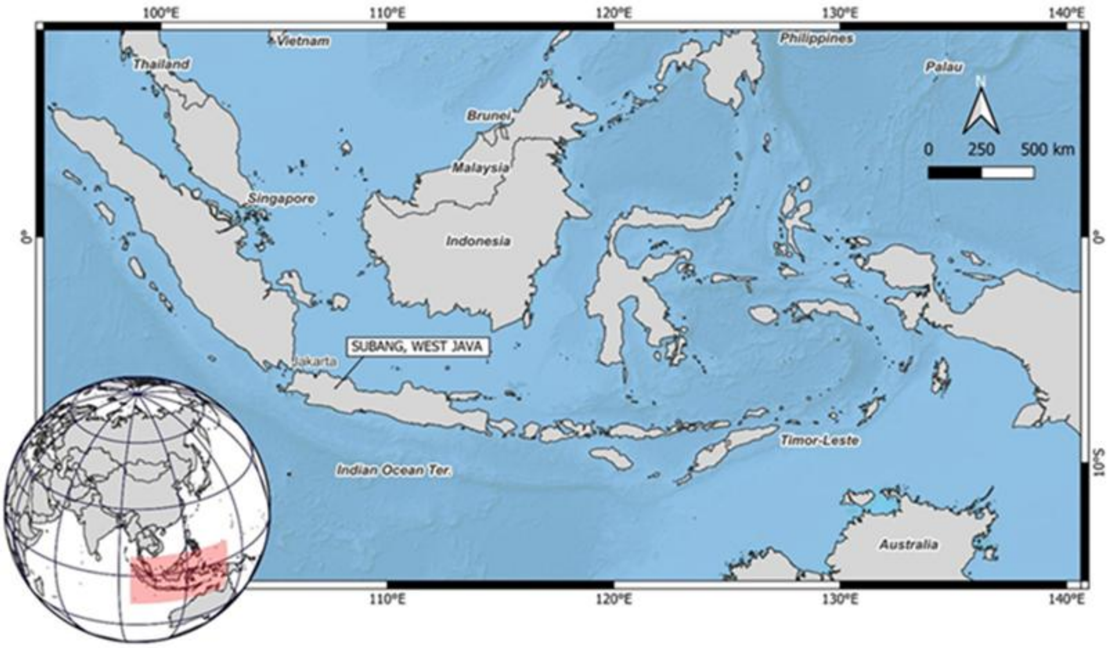

Figure 1. Research location in Subang, West Java, Indonesia (Author's Source).

Research Location.

We conducted this study in a former plantation area known as Pamanoekan and Tjiasemlanden, located in present-day Subang, West Java (Figure 1), which is now operated by PTPN VIII as the Tambaksari-Ciater Estate. Pamanoekan and Tjiasemlanden were the largest privately owned plantations in Java during the 19th and 20th centuries, cultivating a variety of estate crops (Imadudin, 2014). British entrepreneurs Muntinghe and Shrapnell, affiliated with Skelton and Co., established the estate in 1812. Shrapnell acquired approximately 212,900 hectares of land defined by specific geographical features: the Java Sea to the north, the Cilamaya River to the west, part of the Cipunagara River and the Cirebon prefecture to the east, and Mount Tangkuban Parahu to the south (P & T Land, 1954, pp. 5–6). In 1840, Dutch brothers Peter Willem Hofland and Thomas Hofland acquired the P&T Land. In 1853, they divided the land into eight administrative units: Tjiasem, Pamanoekan, Malang, Pagaden, Soebang, Kalidjati, Sagalaherang, and Batoe Sirap (P & T Land, 1954).

The Hofland brothers established *N. V. Maatschappij tot Exploitatie der Pamanoekan en Tjiasemlanden* in 1886. However, the company lasted only briefly due to poor financial conditions and the decline in coffee prices in the international market during the 1880s. All Hofland shares, valued at 2,300,000 guilders, were sold to *N. I. Landbouw* in 1905 (Broersma, 1938). Subsequently, *N. I. Landbouw* resold the shares to The Anglo-Dutch Plantation of Java Ltd in 1910 (Broersma, 1938). Since then, the 212,900 hectares of land have been managed by the Anglo-Dutch Plantation, becoming the largest private estate in Java (Imadudin, 2014). By 1940, before the outbreak of World War II, the Pamanoekan and Tjiasem estate produced various commodities such as tea, rubber, cassava, sisal, kapok, pepper, cocoa, cinchona, coffee, rice, teak, balsa wood, Chinese tung oil tree (*Aleurites Montana*), derris root, and cashew nuts (P & T Land, 1954).

The establishment of the Pamanoekan and Tjiasemlanden plantation industry stimulated the development of infrastructure, settlements, and urban facilities that laid the foundation for the town of Subang, West Java (Pranata & Akbar, 2022). Within the Tambaksari-Ciater Estate area, three hydroelectric power stations (*waterkrachtwerk*) remain (Figure 2): Cijambe Hydroelectric Power Station (established in 1912), Gunung Tua (established in 1922), and Cinangling (established in 1936). Currently, two of the three stations – Cijambe and Gunung Tua – are still operational, supplying electricity to the Tambaksari-Ciater Plantation industry, which comprises four plantation sites inherited from Pamanoekan and Tjiasemlanden: Kasomalang, Tambakan, Sarireja, and Bukanagara.

Figure 2. Photographs of the Cijambe, Gunung Tua, and Cinangling Hydroelectric Power Plants (Authors' Source).

Research Methods.

To achieve the objectives of this study, we employ the method of historical archaeology, which integrates oral accounts, textual sources, and material remains into an interpretive narrative (Wilkie, 2006). This approach is particularly appropriate given that the objects of our investigation are closely tied to material elements such as power stations, generators, transformers, pipelines, and cable networks. We consider colonial private plantations ideal for examining how domination and authority operated over natural resources and human labor. In this context, colonialism is a material phenomenon in which power was embedded in material culture and practices associated with symbolic centers (Lawrence & Shepherd, 2006).

Our archaeological data were collected from three hydroelectric power stations – Cijambe, Gunung Tua, and Cinangling – including generators, turbines, penstock pipes, sluice gates, and surrounding geomorphological features such as rivers and artificial lakes. Textual sources were drawn from newspapers such as *Bataviaasch Nieuwsblad*, *De Koerir*, and *Sumatera Post*; magazines such as *Nederlandsch-Indië Oud & Nieuw*; civil engineering journals such as *De Ingenieur*; proceedings and speeches published in *De Ingenieur in Nederlandsch-Indië op Etechnisch en Sociaal Gebied*; water management laws and regulations compiled in *Agrarische Regelingen voor het Gouvernementsgebied*; technical papers authored by Dutch engineers; company profiles of the Pamanoekan and Tjiasemlanden plantation; geological reports on Java (*Geologische Kaart van Java*); and historical maps including *Kaart van de Afdeeling Krawang*, *Kaart Pamanoekan en Tjiasem*, as well as maps of power stations and distribution networks.

Our research followed four stages. (1) Data collection and classification: this stage involved surface surveys focusing on the three hydroelectric power stations and their environmental settings, a review of relevant literature, tracing of historical maps, and identification of early 20th-century printed sources. (2) Sorting, selection, and verification of data. (3) Contextualization and analysis: verified data were analyzed by cross-checking historical information with visible material culture, including spatial analysis of power stations, penstocks, sluice gates, and adjacent waterways. (4) Interpretation: In this stage, material elements were read as autonomous texts containing diverse kinds of information (Ferguson, 2011; Hicks & Beaudry, 2006). The material evidence was then compared with textual sources to identify connections, gaps, and tensions between them. We produced a critical interpretation from this process, which was subsequently organized into a historical narrative.

Results and Discussion.

Governing through Water and the Transition from Vernacular Irrigation to Colonial Hydropower.

Since the 19th century, colonial maps – ranging from the *Kaart van de Afdeeling Krawang* (1853) and the *Map of Krawang* (1914) to the specialized map of

Pamanoekan and Tjiasemlanden (1955) – depicted Subang primarily through its waters: river networks, hydrological forests, and toponyms beginning with "Tji" or "chai," meaning water in Sundanese (Carnbee et al., 1853; Oudemans, 1914; *Pamanoekan en Tjiasemlanden*, 1955; Rigg, 1862). The Sundanese, the largest ethnic group in West Java, have historically grounded their spatial orientation and cultural practices in water. Place names such as Tjiherang ("clear water") were not merely geographical designations but cultural markers, underscoring water as the center of Sundanese cosmology. From the outset, therefore, this landscape was envisioned both by indigenous communities and colonial authorities as one that was articulated through water.

The abundance of Subang's water resources is evident in the presence of numerous springs – Cimutan, Cileuleuy, and Cipabeasan – as well as three major rivers, the Cipunagara, Ciasem, and Cilamaya, which originate in West Java's volcanic mountains. Geologically, this abundance is linked to Quaternary volcanic deposits and the topography that shapes the southern Subang plain (Silitonga, 1973; Bemmelen, 1934). These conditions rendered Subang a "hydrological enclave," where nature provided fertile ecological resources while simultaneously offering colonial administrators and plantation entrepreneurs a strategic reserve of water and potential energy.

For the Sundanese communities, the hydrological landscape had long been managed through a combination of cosmological and ecological practices. Spatial divisions – upstream areas as sacred sites, midstream areas as centers of agriculture and settlement, and downstream zones for ponds and sanitation – reflected a circulation system in harmony with the environment (Kus, 2019; Prestasi & Kim, 2020). Before the 16th century, Sundanese communities practiced swidden cultivation alongside vernacular forms of water use, while also maintaining cosmological notions of sacred springs and ecological order. The expansion of Mataram's influence in West Java during the 16th century further introduced and consolidated irrigated rice cultivation, transforming shifting fields into more permanent wet-rice systems supported by traditional irrigation (Wertheim, 1956). Technologies such as the *pantjoeran* (bamboo water spout) and communal irrigation channels thus represented a vernacular water management system that was adaptive and sustainable. This embodied a logic of water use distinct from colonial technical calculation: one rooted in sacredness and ecological balance rather than exploitation and efficiency.

Thus, Subang's geographic, geological, and cultural landscape should not be read merely as a descriptive backdrop but as a historical arena where two knowledge regimes intersected: the traditional Sundanese system that integrated water into everyday life, and the colonial regime that regarded water as a resource to be mobilized for plantation production and energy. This contrast set the stage for the emergence of colonial technopolitical projects in the late 19th century, when Subang's water potential was redirected from local systems to modern irrigation schemes.

In the 19th century, the Subang region – later incorporated into the private plantation domain of Pamanoekan and Tjiasemlanden – underwent a gradual transformation in water engineering. During the first half of the century, the plantation relied on a relatively simple irrigation system known as *slokkan bezaar* or *sorotan*. Constructed with locally available materials, including bamboo, coconut trunks, and stones, this small-scale system diverted water from rivers or springs. Its construction was carried out through communal labor or forced labor under the supervision of the village head (Lekkerkerker, 1938). Such arrangements reflected a vernacular mode of water management: low-tech, adaptive, and embedded in local social obligations and responsibilities.

Archaeological evidence substantiates this practice, most notably a commemorative monument dated 1861 in Purwadidi Village, which records the construction of a major canal in Curugagung (Figure 3). The inscription attributes the project to Mas Tjakra Pradja, a local official, who carried it out under the order of Mr. Hofland, the European administrator of the plantation (Nuralia, 2016). While the monument rhetorically portrays the canal as serving "the benefit of the common people," (*boeat orang ketjiel*), its location reveals its primary function: supporting plantation expansion and strengthening colonial administration. Indigenous elites, such as Mas Tjakra Pradja, thus operated as intermediaries who lent local legitimacy to projects that, in practice, subordinated vernacular irrigation systems to the priorities of estate agriculture. This shift illustrates the early displacement of vernacular water management by colonial rationalities. What had once been communal practices rooted in ecological adaptation was reconfigured into projects framed as public works but materially aligned with plantation needs.

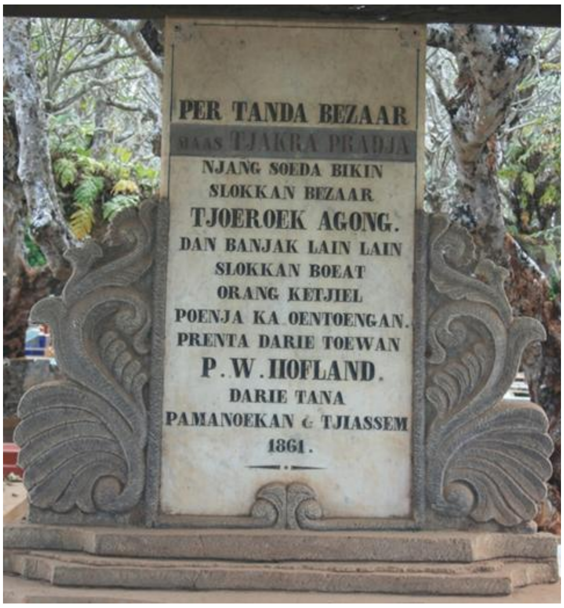

Figure 3. Commemorative monument of the irrigation canal construction, inscribed with the year 1861 (Nuralia, 2016).

In the 19th century, alongside irrigation channels, a rudimentary dam was constructed at Curugagung to regulate the flow of the Ciasem River ("Opening Der Tjoeroegagoeng-Werken," 1933; "Pembukaan Tjoeroegagoeng," 1932). Early structures, such as the Curugagung dam, built from stacked stones, reflected the limitations of colonial water control: they were fragile against floods and insufficient for the growing needs of plantations (Numans, 1918). By the 1870s, however, the colonial state, through the *Burgerlijk Openbare Werken* (Department of Public Works), introduced reinforced concrete dams, precisely mapped irrigation channels, and engineered intakes calibrated through hydrological measurements (Figure 4) (Numans, 1918; Nispen & Ravesteijn, 2009). By the late colonial period, such systems irrigated nearly 1.5 million hectares across Java (Ravesteijn, 2007).

Figure 4. Modern irrigation system with concrete framework in Java, early 20th century (Numans, 1918).

Yet these developments were never neutral technical improvements. The expansion of irrigation was embedded in the Dutch Ethical Policy, a reform agenda framed as a moral obligation to improve indigenous welfare while in practice reinforcing colonial control (Kartodirdjo, 1990). Irrigation, along with migration and education, was promoted as evidence of benevolent governance. Still, it was equally indispensable for the plantation economy, particularly the expanding sugar industry at the end of the nineteenth century. Irrigation thus served a dual role: stabilizing subsistence production to secure labor and legitimacy, while simultaneously guaranteeing the water supply required for colonial agribusiness. Irrigation became more than an agricultural aid; it functioned as a technopolitical infrastructure that translated Ethical Policy rhetoric into material control over land and people. Standardized dams and intakes transformed water into a calculable, governable resource, subordinating vernacular practices to colonial priorities. This shift also laid the groundwork for subsequent hydropower development. By reconfiguring rivers into rationalized flows and measurable discharges, the colonial irrigation regime established the technical and institutional foundations upon which hydroelectric power plants would later be constructed.

The modernization of irrigation in Subang laid the foundation for hydroelectric development in the Pamanoekan and Tjiasemlanden estates. In 1912, the Cijambe Hydroelectric Power Station was established under a government concession, making it one of the earliest plants in the Netherlands East Indies (Broersma, 1938; Stibbe, 1939). Managed by engineer Van Leeuwen and supported by C. W. Weys's broader modernization program, Cijambe powered rice mills, factory machines, and electric lighting – an achievement that marked a milestone in plantation electrification at a time when petroleum-based generation was still rare (Editor N. v. d. D. v. N. I., 1912; "Rechtzaken," 1917; "Soebang," 1930).

Following the estate's transfer to Anglo-Dutch ownership, additional hydroelectric stations were built: Gunungtua in 1922 and Cinangling in 1932, both relying on water regulated by the Curugagung Dam ("Opening Der Tjoeroegagoeng-Werken," 1933). These run-of-river facilities, together, produced under 5,000 kW – far less than larger hydro plants such as Lamadjan or Ubrug – and were dwarfed by steam power stations at Weltevreden and Sukamandi (Table 1) (Stibbe, 1939; Allied Geographical Section, 1945). Despite their modest scale, they supplied electricity across Subang, Ciater, Kasomalang, and surrounding districts, reinforcing plantation productivity and extending colonial infrastructure into the rural landscape (Figure 5).

The construction of irrigation infrastructure, both vernacular and modern, including hydroelectric power stations in Pamanoekan and Tjiasemlanden, relied heavily on the labor of local peasants and communities. Colonial private plantations that obtained state concessions (*erfpacht* rights) drew upon existing patron–client structures between peasants, workers, and indigenous elites. These elites mobilized local labor for plantation infrastructure projects, while those with professional education occupied higher-ranking positions within the plantation hierarchy, serving as intermediaries between plantation managers and workers. In daily operations, indigenous foremen (*mandor*) supervised laborers and peasants, whereas Dutch engineers held senior positions as technical heads or factory chiefs, ensuring that irrigation and hydropower electrification functioned effectively to sustain plantation production. This layered organization of labor illustrates how colonial rationality operated through infrastructures of water and power – not only to organize the flow of rivers, but also to discipline and control the workers whose labor sustained the plantation economy.

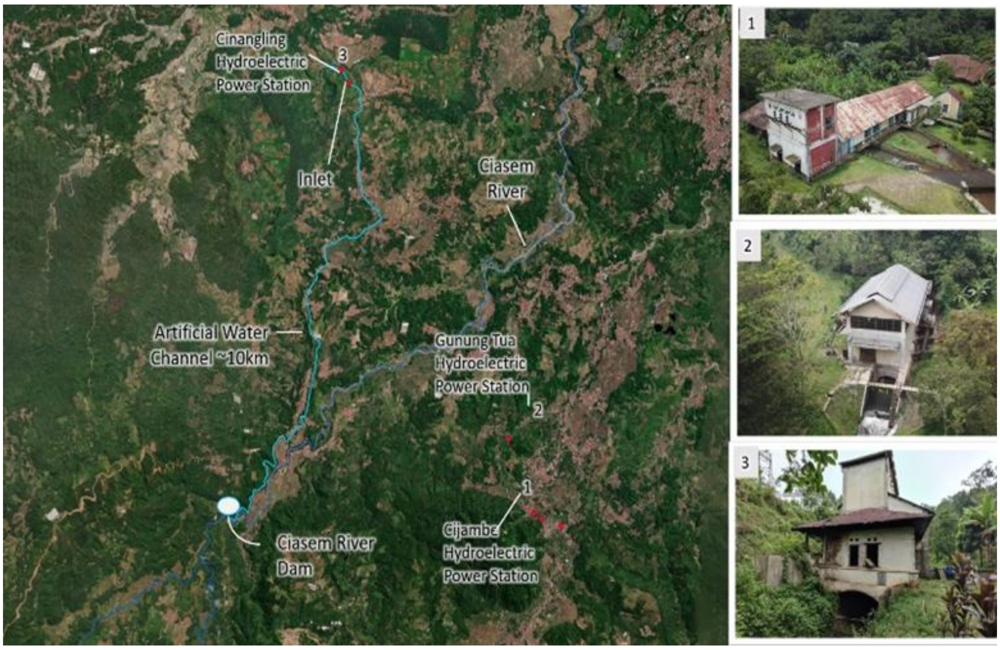

Figure 5. Water supply from the Ciasem River and the locations of three hydroelectric power stations: (1) Cijambe [6°37'53.24"S; 107°43'17.35"E], (2) Gunungtua [6°36'56.29"S; 107°43'19.93"E], (3) Cinangling [6°33'42.91"S; 107°41'8.38"E] (Authors' Source).

Table 1. Electricity Supply in West Java, Dutch East Indies (Source: Allied Geographical Section (1945)).

Types of Power Plants	Location of power stations	Power
Thermal power plant	Weltevreden	5.000 – 10.000 kW
	Soekamandi	5.000 – 10.000 kW
	Pamanoekan	5.000 – 10.000 kW
Hydroelectric power plant	Kratjak	10.000 – 25.000 kW
	Oebroeg	10.000 – 25.000 kW
	Lamadjan	10.000 – 25.000 kW
	Tjiandjoer	Below 5.000 kW
	Tjinangling	Below 5.000 kW
	Goenoengtoea	Below 5.000 kW
	Tjidjambe	Below 5.000 kW

Materializing Colonial Control: Hydropower Engineering in Cijambe, Gunungtua, and Cinangling.

Hydropower development in West Java illustrates how water was reorganized from a vernacular resource into a calculable force embedded in colonial governance. Rivers that had long sustained agrarian livelihoods were reframed as measurable flows, with their volume and pressure translated into horsepower; their channels were diverted into pipes and turbines. This transformation displaced local practices rooted in empirical adaptation with a rationality that privileged visibility, order, and efficiency. West Java, with its abundant water resources, became the foremost site for this transformation (Groothoff, 1921, p. 496). Private enterprises and state-related projects alike established hydroelectric plants, often using them for industrial and lighting purposes. Mountainous plantations, such as Pamanoekan and Tjiasem, had distinct geographical advantages, enabling electricity generation with relatively limited capital investment.

The Cijambe Hydroelectric Power Station, inaugurated in 1912, was among the earliest examples (Stibbe & Spat, 1927, p. 309). Located on the Cileuleuy River, a tributary of the Cipunagara, it produced 1000 HP and supplied energy for the estate's rice mills, machinery, and lighting. Its design diverted water through a bifurcated canal into a receiving basin, before channeling it via buried Mannesmann steel pipes that created a 30-meter head for two Francis turbines directly coupled with generators (Maassen & Hens, 1934, p. 952).

Like other private plants in West Java, Cijambe employed turbine models originally developed in mid-19th-century Europe (Groothoff, 1921, p. 496). These Francis turbines, oriented horizontally and connected to compact generators (Figure 6), exemplified efficient small-scale hydropower installations suited for plantation contexts (Slikkerveer, 1937, p. 241; Viollet, 2017, pp. 572–577). The adoption of such systems underscored how colonial engineers selectively adapted European technology to local conditions, embedding imported standards of efficiency into the everyday operations of the plantation economy.

To understand the operational logic of hydroelectric power in the Pamanoekan and Tjiasemlanden estate, we examined the surviving structures of three power stations. Hydropower plants in this region followed a standardized design that translated natural water flows into energy systems. Water captured at an intake was channeled through penstocks to drive turbines, which were directly coupled with generators to produce electricity. Transformers then elevated the voltage for distribution to plantations and surrounding facilities. These components – intake, penstock, turbine, generator, transformer, and transmission line – were not merely technical devices but material infrastructures that converted rivers into sources of industrial energy, embedding colonial ideals of efficiency and order into the landscape.

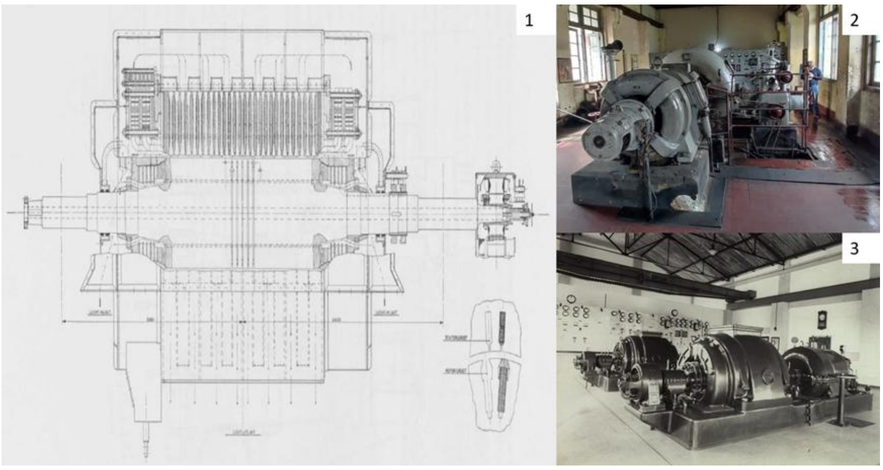

Figure 6. Generator design and examples used in the Dutch East Indies: (1) Horizontal generator design by Willem & Smit Co.; (2) generator unit at the Cijambe hydroelectric power station, Subang, West Java; (3) generator at the Durian hydroelectric power station, Sawahlunto, West Sumatra, in 1915 (Slikkerveer, 1937; Authors' documentation (2023); KITLV A1187).

The hydroelectric plants of Cijambe, Gunungtua, and Cinangling relied on run-of-river systems, using modest intake gates rather than large dams. At the Cijambe power station (Figure 7), water from the Cileuleuy River was diverted through two successive intakes near Pintu Village, with part of the flow channeled to rice fields while the rest entered the penstock. Gravity carried the water to the turbines, which powered a generator that supplied electricity to the plantation headquarters at Ciater, Subang. The Cijambe station remains operational today, providing energy to the Tambaksari–Ciater plantation under PTPN VIII, illustrating the persistence of colonial-era infrastructure.

Figure 7. Schematic of Water Supply from the Cileuleuy River to the Cijambe Hydroelectric Power Plant (Authors' Source).

The Gunungtua hydroelectric station (Figure 8), built in 1922, expanded this network. Drawing water from the Cibulakan River and the artificial Lake Sentiong, situated higher than the plant itself, ensured a regulated and powerful flow to drive its turbines. The Cinangling power station (built in 1932) relied on river diversions from the Cikopi and Pasir Nangka Rivers but is no longer operational due to a failed generator and intake system. Nevertheless, the remnants of its Dutch East Indies–era engineering remain visible, enabling us to reconstruct its former operations and revealing how colonial hydro-infrastructures reshaped landscapes to serve plantation needs.

Figure 8. Water supply from Lake Sentiong to the Gunungtua Hydroelectric Power Station (Authors' Source).

The Cinangling hydroelectric power station (Figure 9) harnessed kinetic energy from the Cikopi River, which originates at Curugagung and flows into the Ciasem River. According to *De Koerir* ("Pembukaan Tjoeroegagoeng," 1932), its construction was closely tied to the completion of the Curugagung Dam in 1931, which not only irrigated rice fields and plantations but also provided surplus flow for power generation. The report even claimed that Cinangling could produce more electricity than the combined output of Cijambe and Gunungtua.

Remains of the Cinangling station – three intake gates, a filtering gate, a penstock, a powerhouse, and a damaged generator – still reveal its operation. Water descended from 231 meters above sea level through the penstock to the powerhouse at 139 meters, where turbines and generators supplied electricity to Wangunreja and Jalupang plantations as well as the Cijambe station.

Field surveys show that even today, water overflow from Cinangling continues to irrigate local rice fields, confirming the dual function of these infrastructures as both industrial energy sources and irrigation providers. This duality was formalized in the 1919 land lease agreement between the Anglo-Dutch Plantations of Java Limited and the colonial state, which restricted hydropower use to prevent disruption of indigenous irrigation rights (Departement van Gouvernementsbedrijven, 1924, p. 46). Ultimately, the Three hydroelectric power station illustrates how colonial hydropower embodied both the rationalized order of plantation modernity and the negotiated persistence of local needs. While framed as advancing productivity and welfare, its design reveals a technopolitical compromise: transforming rivers into engines of colonial industry while maintaining just enough flow to sustain the subsistence agriculture of surrounding communities.

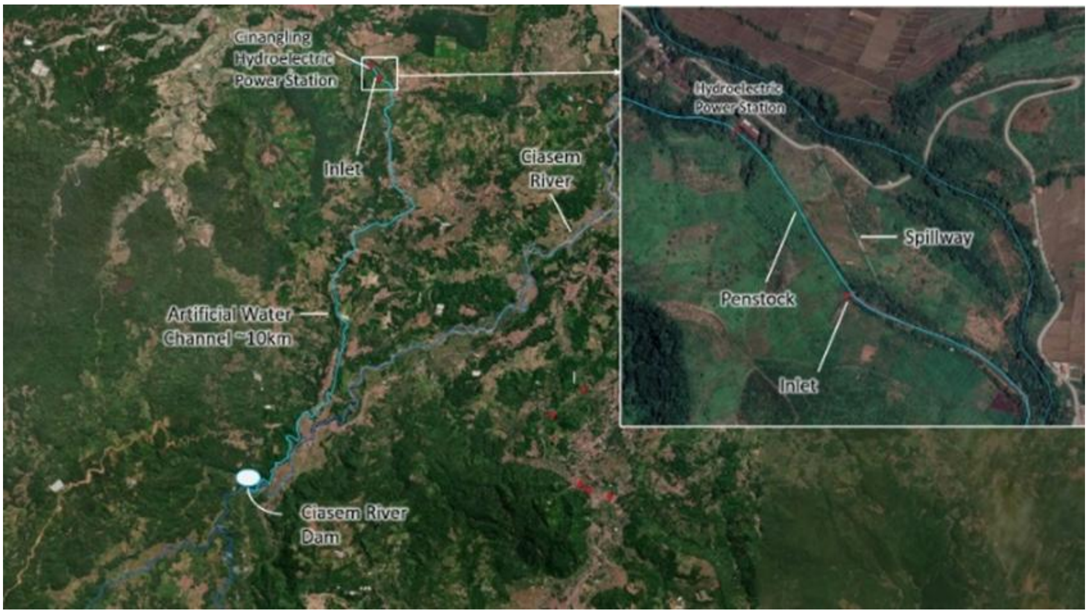

Figure 9. Water supply from the Cileuleuy River to the Cinangling Hydroelectric Station. Overflow water is channeled to local peasants' rice fields (Authors' Source).

Technological Circulation, Industrial Networks, and the Role of Engineers.

Based on field observations, the Cijambe hydroelectric power station utilizes a generator manufactured by Bell Maschinenfabrik AG of Kriens, Switzerland, a company established in 1855. The generator currently in use was installed in 1952 as part of post-war rehabilitation efforts following damage sustained during the Indonesian National Revolution (1945–1949) (Indie West-Java's Rijstpellerijen," 1947). Although the transformer and switchboard at Cijambe have not been definitively identified, archival sources and technical records (Hermsen & Ahlers, 2008; Hermsen, 2015) suggest that these components were manufactured by *Willem Smit & Co. Slikkerveer* (Figure 10). Similar equipment was employed at the power plants in Tanjungpriok (1894) and Lamajan, Pangalengan (1923), reflecting the dominance of

Dutch electrical firms in colonial infrastructure (Hermsen, 2014). It is therefore plausible that the original Cijambe generator, before wartime destruction, was also a product of *Willem Smit & Co.*

Figure 10. Switchboard at the Cijambe hydroelectric power station (Authors' Source).

Further archival evidence indicates that the *Heemaf Agency* in Surabaya, with branches in Bandung and Batavia, distributed *Willem Smit & Co.* transformers and generators throughout the Dutch East Indies ("Agentschap Heemaf Soerabaia," 1922; "Het Droogdok Voor Soerabaja," 1913). The agency imported electrical components from Nijmegen and supplied port illumination systems in Surabaya. Its catalog included a range of European electrical products – cables from Delft, mechanical parts from Hengelo, *Philips* lamps from Eindhoven, and wire materials from Amsterdam (Figure 11) ("Agentschap Heemaf Soerabaia," 1920). Registered in the *Handboek voor Cultuur en Handelsondernemingen in Nederlands-Indië* (Bussy, 1925), *Heemaf* – founded in 1909 as the *Hengelosche Electrische en Mechanische Apparaten Fabriek* – served as the exclusive colonial representative for *Willem Smit & Co.* transformers. To ensure optimal performance in tropical climates, the agency established testing facilities, oil-drying units, and climate-controlled warehouses, and employed Dutch engineers to oversee installation and maintenance ("Uitbreiding Hollandsche Electrische Zaken in Indië.," 1920).

Together, these findings reveal a complex network of technological circulation that linked Europe and the Indies through colonial trade and expertise. Electrical innovation emerged in the Netherlands as early as 1886, when Willem Benjamin Smit established the first Dutch power plant at Kinderdijk, utilizing an 80 HP steam engine to drive two 7.5 kW dynamos (Hermsen, 2011). In contrast, electricity generation in the Dutch East Indies only began in 1897 with the government-approved power plant at Koningsplein, Batavia (Stibbe, 1939, p. 1924), followed by installations in Medan (1899), Solo (1902), and Bandung (1906). The eleven-year delay underscores not merely logistical or technical constraints, but the colonial hierarchy of innovation, where the periphery selectively and strategically absorbed metropolitan technologies according to the empire's economic priorities.

Figure 11. Advertisement of Heemaf, distributor of electrical equipment for industry in the Dutch East Indies (Het Nieuws van den Dag voor Nederlandsch Indie, 21 August 1920).

Ideological and administrative factors also contributed to the temporal and spatial lag in electrification. The turn of the 20th century saw the Dutch government adopt the Ethical Policy, rooted in the notion of *Eereschuld* – a "debt of honor" owed to the Javanese population (Furnivall, 2010). While framed as a moral obligation to improve indigenous welfare through education, irrigation, and migration, its implementation largely served economic and political objectives: maximizing productivity, expanding markets, and ensuring a disciplined labor supply. In this sense, technological adaptation in the Indies reflected not only material modernization but also the rationalization of colonial governance through the development of infrastructure.

Engineers were the key agents of colonial technocracy. Archival sources, such as *Bataviaasch Nieuwsblad* ("Rechtzaken," 1917), *Encyclopaedie van Nederlandsch Indie* (Stibbe & Spat, 1927, p. 309), and *De Ingenieur* (Groothoff, 1921), record that Engineer C. W. Weys and his assistant, F. A. Janssen van Raay, led major water-engineering projects at Pamanoekan and Tjiasemlanden. Their work included the construction of sluice gates, irrigation channels, and pipelines for the hydroelectric power station, culminating in the establishment of the Cijambe facility in 1912. As head engineer of the estate, Weys oversaw not only electrification but also the modernization of plantation operations. In 1911, he established a rice mill on the slopes of Mount Tangkuban Parahu equipped with mechanized processing units and electric lighting powered by a 15,000-volt dynamo (Editor N. v. d. D. v. N. I., 1912). He further initiated agricultural experiments, such as sugarcane cultivation near Pagaden, and proposed transport improvements, including a tramway line from Subang to Pamanukan, to overcome the poor road access.

Weys led the Pamanoekan and Tjiasemlanden plantation until 1912 before continuing his career as Chief Engineer at the *Burgerlijk Openbare Werken* (Department of Public Works) (Sandick, 1920). Trained at Delft, he represented a generation of engineers who bridged the gap between metropolitan expertise and colonial governance. His later role on the Education Committee for the establishment of the *Technische Hoogeschool* (Technical College) in Bandung in 1920 ("De Opening van de Indische Technische Hoogeschool," 1920). illustrates how the colonial state institutionalized this technical rationality through higher education. Weys's appointment as professor of Hydraulic Engineering at the Delft Institute of Technology further attests to his prominence within transnational engineering networks linking the Netherlands and its colonies. Alongside his academic and governmental roles, he also served as director of the private company *N. V. Rystlanden Michiels-Aroold* ("De Opening van de Indische Technische Hoogeschool," 1920), reflecting the fluid boundaries between public service, private enterprise, and colonial exploitation.

His multiple positions – as plantation engineer, state technocrat, and educator – exemplify the technopolitical nexus that underpinned Dutch colonial modernization. Professional organizations, such as the Koninklijk Instituut van Ingenieurs and the Vereniging van Delftse Ingenieurs, actively promoted this nexus through a civilizing mission aligned with Calvinist ethics and imperial ambitions. These associations framed technological advancement as a moral endeavor, preparing Delft-trained engineers to engage with "native" societies as agents of both progress and control (Cramer, 1914). The professional ethos they cultivated made technical competence inseparable from the ideological responsibility to govern and "improve" colonial subjects.

This ideological outlook was reinforced by figures such as R. A. van Sandick and Henri van Kol, who infused Dutch engineering with moral and social dimensions through *De Ingenieur* and Delft's student circles (Oud-Alblas, 2012). Their socialist and activist perspectives recast engineering not merely as a mechanical profession, but as an ethical vocation that addresses the tension between technological progress and human welfare. Van Kol, a socialist parliamentarian, even argued in the *Tweede Kamer* that colonial governance must first ensure indigenous welfare before pursuing profit (Moon, 2007). These debates gave moral legitimacy to colonial technocracy, enabling engineers to view their interventions – such as irrigation, electrification, and industrial modernization – as acts of both technical mastery and humanitarian duty. Viewed through this lens, Weys embodied the intersection of knowledge, power, and ideology within colonial technocracy. His irrigation and hydroelectric projects in Pamanoekan and Tjiasemlanden were not merely feats of engineering but tangible expressions of colonial rationality: systems designed to discipline nature and labor under the guise of welfare and modernization. Through his work, the technical, economic, and moral imperatives of the Dutch colonial project converged, materializing the belief that technological order equated to social progress.

Hydropower Beyond Alternative Energy.

Three hydroelectric power stations in the Pamanoekan and Tjiasemlanden region illustrate how technology extended the colonial infrastructure regime following the successful implementation of irrigation projects in Java. The Ethical Policy provided a moral narrative for continuing a more modern and "civilized" form of colonialism, in which rational technical projects and designs were mobilized by state and private institutions – through the work of engineers – to control nature and resources (Ertsen, 2007). Technical rationalization, such as water flow engineering, made water resources calculable and measurable, thereby sustaining industrial production while maintaining the cultivation of local rice fields. The science-based technologies that emerged alongside the Ethical Policy played a crucial role in shaping the transformed Dutch East Indies (Furnivall, 2010; Ravesteijn, 2007).

This transformation shifted the colony from a politically dominated territory into an imperial state oriented toward free trade and industrial development. The shift also affected local populations, particularly indigenous communities, who moved from harmonizing technology with nature through local knowledge to adopting technologies aimed at controlling and manipulating nature. The adoption of these new technologies by local populations was most likely mediated through mechanisms of control and domination commonly practiced in plantation industries, particularly through the functions of the *Administratuur* leader and the authority of the local elites (Nuralia, Sulistiyono, Imadudin, Budiman, & Marzuki, 2025).

The rationalization and modernization of water infrastructure in the Dutch East Indies unfolded through two critical conjunctures: first, the industrialization and the rise of modern science and technology stimulated by the Liberal Policy of 1870; and second, the formulation of the Ethical Policy in 1901 (Moon, 2007). While the liberal phase initially opened space for the expansion of private capital, the Ethical Policy introduced a civilizing mission framed as a "moral obligation" toward colonial subjects. One of its central programs was the development of peasant agriculture through modern irrigation systems, which subsequently became both a prerequisite and a technical foundation for the advancement of hydroelectric power in the Dutch East Indies.

In the history of electrification in the Dutch East Indies, hydroelectric power plants emerged in the early 20th century (Stibbe, 1939), following the initial reliance on steam power. Remarkably, as early as the 1890s, entrepreneurs in the colony had already established local electricity networks in various parts of Java and actively lobbied the government for concessions to advance electrical infrastructure. Formal regulations on electricity were introduced through *Staatsblad* No. 190 of 1890 (Stibbe, 1939). Surabaya, Semarang, and Batavia were among the first cities to benefit from electricity (Stibbe, 1939). The pioneering use of hydropower began with the *Bandung Waterkrachtwerk Pakar aan de Tjikapoendoeng bij Dago* in 1906, followed by another *waterkrachtwerk* in Tutang, Semarang, in 1911 (Groothoff, 1918).

Initially, hydroelectric power plants served as a backup energy source during failures of steam power. Greater attention to hydropower emerged around 1910 with the establishment of the *Waterkrachtbureau* (Hydropower Bureau), tasked with conducting systematic research on water potential throughout the Dutch East Indies. From then on, the government began to rationally consider the utilization of hydropower, engaging in exploration while granting electricity concessions to private companies. These concessions imposed a fee of 4 guilders per horsepower (745.7 watts), effective from the sixth year after the company's establishment (Groothoff, 1918, p. 28). Through early explorations and electricity management policies, the Dutch East Indies had produced 2,500 kW of electricity by 1910, of which 800 kW came from hydroelectric plants (Stibbe, 1939).

In the early 20th century, electricity in the Dutch East Indies was primarily developed to serve industrial needs. Companies relied on electricity – mostly generated from steam power – to support production activities, such as coal mining in Ombilin, tin mining in Bangka, gold and silver extraction in Rejang Lebong, and sugar factories in East Java that utilized steam from bagasse combustion (Stibbe, 1939). In West Java, however, electrification was the most advanced in the colony, mainly due to the extensive development of hydroelectric power plants by the *Landswaterkrachtbedrijf* and private enterprises. Major hydroelectric plants operated in Bogor (Ubrog, Kracak), Batavia (Weltevreden), Bandung and its surroundings (Bengkok, Dago, Plengan, Lamajang), extending further to Garut, Tasikmalaya, Sumedang, and Banten. Electricity from these facilities supported various needs, including the electrification of major cities and railway lines, private plantation industries, manufacturing, and the Malabar Radio Station in Bandung. The Pamanoekan and Tjiasemlanden region played a significant role, as it managed its own network of private hydroelectric stations (Cijambe, Gunungtua, and Cinangling), supplying power to plantations and local distribution networks in Subang, Segalaherang, and Kalijati (Stibbe, 1939).

The global political-economic context also shaped the development of hydroelectric power in the Dutch East Indies before and during World War I. Rising energy demands drove significant growth in hydroelectric technology, particularly during the war (Ley, 1924). Countries facing coal shortages, such as France and Switzerland, have returned to hydropower to meet their industrial and transportation energy needs. The scarcity of fossil fuels accelerated large-scale investments in hydroelectric plants as a more sustainable and economically efficient alternative (Ley, 1924). This global shift also influenced energy strategies in the Dutch East Indies, which began to adopt similar approaches in expanding electrification.

In the Dutch East Indies, although not directly affected by World War I, figures such as Ir. P. A. Roelofsen had already recognized the importance of hydropower before the war. He advocated for establishing a water and electricity authority in 1917 to systematically explore the potential of this energy source. Despite post-war budget constraints slowing development, the government and the private sector began to show a gradual commitment to advancing hydroelectric power stations (Ley, 1924, p. 2). Ley (1924) estimated that the Dutch East Indies possessed a hydropower potential of 6,600,000 horsepower – equivalent to approximately 4,848 megawatts (MW) – or nearly one-fifth of global hydropower capacity. The island of Java contributed about 600,000 horsepower (±441 MW), significantly less than other islands, despite having a population of nearly 40 million. The availability of hydropower per capita in Java was only around 70 horsepower (±51 kW), far lower than that of industrialized nations. Until the 1920s, the use of hydropower in Java remained extremely limited, with approximately 1/2000 horsepower per person, and was primarily concentrated in major cities. At the same time, the rest of the island still relied on steam-based (thermal) power plants. Nevertheless, from an industrial perspective, hydropower was seen as an efficient means to continue productive land exploitation, even amid difficult economic conditions (Roelofsen, 1916).

According to Stibbe (1939), tea-producing companies in mountainous areas were among the earliest adopters of electricity, primarily sourced from hydropower. In the Pamanoekan and Tjiasemlanden region, the Cijambe, Gunungtua, and Cinangling hydroelectric stations played a crucial role in supplying electricity to support the plantation industry operated by *N. V. Maatschappij tot Exploitatie der Pamanoekan en Tjiasemlanden*. By 1945, hydroelectric power had become the dominant energy source in West Java, surpassing thermal energy. West Java had ten hydroelectric power stations – three generating between 10,000 and 25,000 kW, while the remaining seven produced less than 5,000 kW. In contrast, thermal power plants comprised only three major stations, each with an output of 5,000–10,000 kW (Allied Geographical Section, 1945).

Dutch engineers viewed hydroelectric power stations (*waterkrachtwerk*) in the early 20th century as having the potential to drive the development of both large and small-scale industries in the Dutch East Indies. Ir. A. Groothoff, in his article *"Eenige mededeelingen over de waterkrachtindustrie in Scandinavië en over het waterkrachtvraagstuk in Nederlandsch-Indië"* ("Some Notes on the Hydropower Industry in Scandinavia and the Hydropower Issue in the Dutch East Indies"), emphasized that water resources, unlike mineral resources, were virtually inexhaustible, making their exploitation a rational and sustainable choice. Groothoff stressed that hydroelectric stations could serve dual purposes: electricity generation and irrigation, citing a planned project for the Bengawan Solo River. He believed that realizing such projects would promote the growth of Dutch engineering and industry while enhancing the prosperity of the Dutch East Indies (Groothoff, 1918, p. 29).

Conclusion.

This study reveals that the transformation of water engineering technology at the Pamanoekan and Tjiasemlanden Plantation was characterized by a shift from vernacular irrigation systems to modern technical irrigation. The modernization of irrigation and the application of more scientific methods of water management enabled the construction of three hydroelectric power stations: Cijambe (1912), Gunungtua (1922), and Cinangling (1936). This technological evolution occurred alongside the rationalization and modernization of the colonial plantation system. It formed part of the broader infrastructure development driven by colonial technocratic interests in the early 20th century.

The construction of hydroelectric power plants in Subang exemplifies how colonial authority was materialized through water engineering. The three hydroelectric stations – Cijambe, Gunungtua, and Cinangling – operated as run-of-river systems, converting natural flows into quantifiable energy without the need for large dams. Their relatively small scale and reliance on the region's hydrological stability reflected a technical rationality grounded in efficiency, predictability, and control – principles that mirrored the administrative logic of colonial technocracy. Through these infrastructures, water was transformed from a communal and ecological resource into a regulated force serving the economic interests of the plantation regime.

This technological reorganization of water did not occur in isolation but was embedded within the broader economic and institutional structures of Dutch colonialism. The political-economic context of the Dutch East Indies – characterized by the convergence of liberal economic policies, private enterprise, and the colonial state's drive for modernization – facilitated the circulation of technology and expertise across the empire. Technology transfer occurred, as formal distribution channels, such as Heemaf in Surabaya, underscored the dependence on European standards. Meanwhile, the introduction of Francis turbines, Bell Maschinenfabrik generators, and Willem Smit & Co. transformers highlighted the colony's integration into international supply chains. The resulting electrical infrastructure supported the expansion of the plantation industry, while the Ethical Policy provided moral legitimacy by framing electrification and irrigation as part of a colonial welfare project. Yet, behind this narrative, hydroelectric power plants – such as those in Pamanoekan and Tjiasemlanden – ultimately functioned as instruments of colonial control over natural resources.

Colonial engineers drove the construction of hydropower plants in Pamanoekan and Tjiasem, led by C. W. Weys and his assistant, F. A. Janssen van Raay, was tasked with modernizing the plantation lands. Weys, a graduate of the Technische

Hoogeschool Delft, played a key role in the modernization of Pamanoekan and Tjiasemlanden. He was actively involved in developing dams, tramlines, factories, and irrigation systems. His role illustrates the involvement of engineers in ethical and technocratic colonial projects. It highlights the strong influence of the colonial engineering community in shaping private industrial development in the Indies.

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Conflicts of interest.

The authors declare no conflict of interest.

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Колоніальна технополітика в Нідерландській Ост-Індії: Дослідження колоніальної гідроелектроенергетики на плантації Паманоекан та Чіасемланден

Анотація. *Це дослідження присвячене історичному розвитку технологій гідроелектроенергетики в Нідерландській Ост-Індії на початку XX століття, з* *особливим акцентом на плантацію Паманоекан та Чіасемланден, нині частини плантацій регіону VIII Тамбаксарі-Сіатер у Субанзі, Західна Ява. Метою є дослідження трансформації водної інженерії – від традиційних місцевих зрошувальних систем до сучасних зрошувальних мереж і, зрештою, до гідроелектростанцій. Дослідження також розглядає процес технологічної адаптації, роль колоніальних інженерів, походження технічних компонентів та механізми роботи гідроелектростанцій у ширшому контексті політики етичності та колоніальної технократії. Використано метод історичної археології, поєднуючи текстові архіви та матеріальні залишки для інтерпретативного наративу. Приватні колоніальні плантації розглядаються як простори, де реалізовувалось домінування над природними ресурсами. Польові дослідження охоплювали три гідроелектростанції – Чіямбе, Ґунунгтуа та Чінанглінг, доповнені різноманітними текстовими джерелами: газетами, інженерними журналами, промовами та протоколами нідерландських інженерів, колоніальними водними нормативами, буклетами компаній, геологічними дослідженнями та картами плантацій. Аналіз застосовує концепцію технополітики, розглядаючи технологію не як нейтральний інструмент, а як невід'ємну частину політико-економічних стратегій колоніального правління. Виявлено, що три гідроелектростанції розширили колоніальну інфраструктурну мережу після реалізації зрошувальних проектів на Паманоекан ен Чіасемланден. Політика Етичності забезпечила «цивілізаційний» наратив, що легітимізував технічну раціоналізацію. Через інженерне регулювання водних потоків колоніальні адміністрації та приватні підприємства, за посередництвом інженерів, зробили річки вимірюваними та контрольованими, підтримуючи промислове виробництво на базі плантацій, одночасно зберігаючи традиційне місцеве вирощування рису для самозабезпечення. Отже, розвиток гідроелектричних технологій на Паманоекан ен Чіасемланден був не лише технічним досягненням, а й технополітичним проєктом, який мобілізував водні ресурси для консолідації економічної продуктивності через мережі приватних підприємств, технократичних агентств та міжнародних постачальників обладнання.*

Ключові слова: *гідроелектростанція; технополітика; технократія; політика етичності; колоніалізм; Паманоекан ен Чіасемланден*

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Negotiating a great telescope: The case of Czechoslovakia

Abstract. *In the late 1950s and early 1960s, the Astronomical Institute of the Czechoslovak Academy of Sciences undertook a long, complicated journey towards obtaining a 2-m refractor comparable to the largest instruments in the world, inaugurating it during the XIIIth General Assembly of the International Astronomical Union held on August 22–31, 1967 in Prague. The journey can be reconstructed from archival materials and recorded memories of the witnesses. What made this situation unique is the fact that two very similar telescopes were ordered at roughly the same time for the Czechoslovak Socialist Republic and the Azerbaijan SSR; those telescopes were developed in parallel to reduce costs, becoming the second and third in the Zeiss series of 2-m universal telescopes. The astronomical institutes of CSSR and AzSSR had to negotiate and compromise their requirements, and in addition, because constructing a large telescope and bringing it into service takes many years, anticipate future developments in the relevant fields as well as requirements for equipment and configuration. Successful completion of this international project required a high number of negotiations between astronomers from both institutions, the instrument manufacturer VEB Zeiss Jena, the highest levels of the state administrations, the Czechoslovak foreign trade company KOVO, and multiple other corporations from CSSR and the GDR involved in the construction and delivery of the telescope, its dome, and associated equipment. The project understandably experienced issues such as misunderstandings and delays, which all those actors had to deal with. The outcome of this early effort is a telescope that, following numerous modernisations, is still used for research in today's Czech Republic. This paper explores this early history of this telescope – from the first suggestions to the delivery and construction in the observatory of the Astronomical Institute of the CSAS in Ondřejov – with particular attention to the negotiations among key actors and to their personal reflections and memories of the process.*

Keywords: *2-m telescope; stellar astronomy; VEB Zeiss Jena; Ondřejov; Astronomical Institute of the Czechoslovak Academy of Sciences*

Introduction.

Constructing a large telescope is a painstaking and costly process that can last many years. Therefore, in order to facilitate this process, from the early 1950s, Carl Zeiss Jena had been developing the project of a universal, mass-produced 2-m reflecting telescope. The series's first telescope, named the Alfred Jensch Telescope since 1992, was constructed for the Karl Schwarzschild Observatory of the German Academy of Sciences at Berlin near Tautenburg in 1960. The second was for the Shamakhy Observatory in the Azerbaijan Soviet Socialist Republic. The third was built for the Astronomical Observatory of the Czechoslovak Academy of Sciences (CSAS), located in Ondřejov.

The purpose of this publication is the case study of the process of procuring the Ondřejov 2-m telescope, combining thorough archival research in archives of the CSAS, and Zeiss; retrospective narrations from witnesses (Perek, 1998; Zicha, 1998); contemporary articles and papers from Czechoslovak astronomers (Bumba et al., 1964; Guth, 1956, p. 19; Kohoutek, 1963; 'Ondřejovská observatoř', 1959; Perek, 1961); interviews with Luboš Perek (Autumn 2017, Winter 2017); publication about the generation of astronomers that was involved in building the telescope, and also about the 1967 General Assembly of the IAU in Prague (Pavlíček, Hyklová, & Šolc, 2024); and descriptions of history and technical background from experts on the 2-m telescopes (Jensch, 1961, 1967; Jensch, 1966; Pitoňák, 2023; Šlechta, n.d.-b, 2020).

Research Methods.

The text is based on archival research in the Zeiss Archive; Masaryk Institute and Archives of the CSAS; Archive of the Astronomical Observatory of the CAS; a survey of primary and secondary literature; and oral history interviews, which were based on methodologies of T. S. Kuhn and M. Vaněk (Kuhn, Heilbron, Forman, & Allen, 1967; Vaněk, 2003).

Results and Discussion.

The Astronomical Observatory in Ondřejov was founded in 1898 by Czech factory owner and amateur astronomer Josef Jan Frič (1861–1945) and built in cooperation with astronomer František Nušl (1867–1951) (later professor of astronomy at Charles University). This oldest part of the observatory was continuously built at the beginning of the 20th century. In 1928, on the 10th anniversary of the establishment of the First Czechoslovak Republic, Frič donated the observatory to the state for the purposes of Charles University.

In the postwar period, Czechoslovak academia as a whole underwent a transformation. The Czechoslovak Academy of Sciences (CSAS) was formed in the early 1950s, modelled after the Soviet Academy of Sciences, and Ondřejov Observatory became part of its Central Astronomical Institute (Ústřední ústav astronomický). From 1950, the institute was divided into two parts, the CSAS

Astrophysical Observatory and the CSAS Chronometry Laboratory, which were merged in 1954 into CSAS Astronomical Institute.

In the first years of its existence, CSAS underwent a period of enthusiasm and expansion. Moreover, space research, which has already played a key role in the Cold War science rivalry, entered a new round after the launch of the first artificial Earth satellite, Sputnik, by the USSR in 1957 (Dvořáčková & Franc, 2020).

However, to remain competitive in world-class stellar astronomy research, the Astronomical Institute of the CSAS lacked adequate instrumentation. The largest Czechoslovak instruments were 60-cm refractors in Brno and Skalnaté Pleso, whereas internationally, the diameters of the new instruments were on the order of meters, and the largest instrument in the world was the 5-m Hale Telescope of the Palomar Observatory, finished in 1949. The need for a "great reflector" for the new department of stellar research of the Ondřejov observatory was first officially voiced without particular specifications in February 1956 (Guth, 1956).

In November 1956, the CSAS organised an astronomical conference in order to prepare a perspective plan of astronomical research for the next ten years. Among other things, the future of stellar research was discussed, in particular, research into proper motions, radial velocities, spectral classification, and photographic and photoelectric photometry of faint stars. The resulting *Proposal for a long-term plan for Czechoslovak astronomy* voiced the need for a large astronomical instrument again, as "in many cases we are relying on data that observers in other countries have not been able to process themselves. It's almost unbelievable that in 1956 it is not possible to take a positional photo or to record a stellar spectrum" (MIA CAS (Masaryk Institute and Archives of the Czech Academy of Sciences). Collection I. sekce ČSAV 1952–1961. Inv. No. 19 Astronomický ústav 1954–1957. Návrh perspektivního plánu čs. astronomie 1956-1965). Multiple designs were discussed, including an astrographic camera with a 50 cm diameter and a 6 m focal length, a 2-m reflector for spectroscopy, a 120–80–240 cm Schmidt camera and a 120-cm Cassegrain reflector for photometry (Perek, 1998).

After the meeting of the Section for Mathematics and Physics of the CSAS in November 1956 in Prague, the final plan included the first two designs–the astrograph with triplet object lens made by Zeiss, and a 2-m parabolic reflector for observing faint stars around 13 mag.

In the end, the idea of a 2-m reflector won the competition; the arguments included the research focus of the Astronomical Institute and the fact that the Zeiss factory in Jena was just designing the 2-m universal telescope for the new Tautenburg observatory (Perek, 1998). The Zeiss project of the 2-meter reflector already gained the attention of the Czechoslovak astronomical community in 1952, as seen in the article ('Dvoumetrový', 1952) in the magazine *Říše hvězd*, published by the Czechoslovak Astronomical Society.

However, at the time of these discussions, CSAS was undergoing a period of political limitation in terms of international contacts and cooperation, and, in addition, financial limitations (Dvořáčková & Franc, 2020, pp. 425–426).

Discussions and Plans.

Constructing a large telescope requires extensive financial, material and human resources. From design through building infrastructure to installation of the instrument, the process takes many years. Therefore, a forecast of the future development of the relevant fields of astronomy is required, in order for the telescope to not become obsolete during its construction. Modern large telescopes needed to be as versatile as possible, which is achieved by basing the construction on the primary, usually parabolic mirror, in combination with secondary mirrors and correction systems. This "multiple telescope" should have combined all possible optical arrangements utilised at the time of this inception (prime focus reflector, Cassegrain, coudé and even Schmidt), and therefore one universal telescope would be sufficient instead of multiple single instruments (The Zeiss Archives. NL 51 Nr 32. Alfred Jensch: Universal Telescope (2-metre reflecting).).

Designing such a universal telescope is significantly complicated, as the constructor is in fact designing multiple instruments at once. The chief constructor of Zeiss' *Department for development of astronomical instruments and planetaria* (*Entwicklungsabteilung für astronomische Geräte und Planetarien*), Alfred Jensch (1912–2001), had several years of direct experience as an observer at the Sonneberg Observatory. He led the 2-meter-telescope project from its beginning in the early 1950s. His key requirements for the design included convertibility between systems (such as exchanging the secondary mirror) in one day; automatic compensation of physical phenomena connected with operating large heavy instruments; uniform clock drives to compensate Earth's diurnal motion; simple and accurate operation; precautions against maloperation; minimum maintenance; and work safety (The Zeiss Archives. NL 51 Nr 32).

The costs of the telescope and necessary accessories were estimated at ca. 20 million Kčs. This was comparable with the yearly budget of the CSAS for machine investments, and exceeded the import quota several times. Thus, the purchase could only be realised on the basis of a government resolution on the allocation of special funds. The proposal argues that several telescopes with diameters around 2 m were under construction in the USSR, the German Democratic Republic, the Federal Republic of Germany, and Britain, and a similar proposal was submitted in Poland (MIA CAS. Collection I. Section of the CSAS 1952–1961. Inv. No. 19. Dvoumetrový teleskop z NDR).

The CSAS Presidium approved the proposal on 21st March 1958 and tasked the Astronomical Institute with sending 1-2 people to Zeiss to negotiate technical details of the telescope and its accessories and to request a fixed-price offer, followed by rapid drafting of documentation to the proposal of the government resolution, in particular a detailed justification for importing the telescope (MIA CAS. Collection I. sekce ČSAV 1952-1961. Inv. No. 19.).

However, after Luboš Perek (1919–2020) and Boris Valníček (1927–2021) returned from negotiations in Jena in summer 1958, they were notified of a communication that the former director of the Astrophysical Observatory of CSAS, František Link (1906–1984), submitted to the CSAS Presidium, arguing against purchasing a 2-m telescope. Link was the director of the CSAS Astrophysical Observatory until 1953, when he left the position after pressure from the CSAS Presidium, which resulted from the complaints of his subordinates that he "has hitherto rejected any hints that purely astrophysical research is to expand" (Pavlíček, Hyklová, & Šolc, 2024, p. 131). According to further communication from the current director Bohumil Šternberk (1897–1983), Link had not previously shown any interest in commenting on the proposal of the 2-m telescope or joining the discussions at the institute, and submitted his communication directly to the Presidium without discussing it with the observatory staff, its union and party organisations. Šternberk mentioned that Link had also refused to cooperate on the earlier construction of a 60-cm telescope. The proposal for the 2-meter telescope, however, was supported by Czechoslovak émigré Zdeněk Kopal (1914–1993)—director of the radioastronomical observatory at Jodrell Bank in the United Kingdom and a veteran of nearly all major observatories worldwide—as well as by conclusions drawn from a Soviet delegation's visit to observatories in the United States (MIA CAS. Collection I. sekce ČSAV 1952–1961. Inv. No. 19).

The proposal of the 2-m telescope from 8 August 1958 was based on requirements for perfect photometric and spectroscopic functions. Direct photography was next in the list of priorities. As a result, wide-field photography by Schmidt and Matsukov cameras was abandoned as incompatible with the basic requirements (Perek, 1961).

Šternberk in this proposal argued that a 2-m diameter is "technically not an experiment, but a clear technical issue" (MIA CAS. Collection I. sekce ČSAV 1952–1961. Inv. No. 19). The first 2-m telescope in Tautenburg was not yet finished, but Zeiss had recently made a 120-cm telescope for Hamburg Observatory that proved successful in practice. Other custom diameters that Zeiss had not constructed yet would mean higher costs, and much a smaller, already tested design would significantly reduce its scientific value. In the Soviet bloc, only Carl Zeiss Jena and the Optical and Mechanical Institute in Leningrad were able to construct a 2-m telescope. However, the USSR had already been negotiating a 2-m telescope for Shamakhy with Zeiss, and the proposal even mentioned that 2-m telescopes for Poland and China were discussed (MIA CAS. Collection I. sekce ČSAV 1952–1961. Inv. No. 19).

At first, an English mount with the polar axis supported by concrete pillars on its northern and southern ends was suggested. Only the Cassegrain and coudé foci would be developed, because developing the primary focus would raise financial costs and the weight of the tube. The proposal also mentions a prism spectrograph for a range of dispersion 90 to 300 Å/mm.

The institute and Zeiss agreed on a delivery period of five years from signing the definitive order, if it happened in 1958, and on any system of payments. The plan of work was: pre-project in 1959, project in 1960, construction in 1961–1962, dome installation in 1962 and telescope installation in 1963. However, shortly before the contract with Zeiss was signed, Nikita Khrushchev, General Secretary of the CPSU and Chairman of the Council of Ministers of the USSR, de facto leader of the USSR in 1953–1964, visited Jena. Khrushchev signed a contract for the 2-m reflector for the observatory in Shamakhy.

This delayed the delivery of the telescope for Ondřejov by a year. Consequently, negotiations at the ministry level were launched to reduce the delivery times (MIA CAS. Collection I. sekce ČSAV 1952–1961. Inv. No. 19). Though the telescope still arrived later than originally plannet, Perek remarked on one unexpected advantage: the dome was "ready, cleaned and wiped-off of dust" when the instrument arrived, in contrast to being still in construction if the telescope was delivered at the original date (L. Perek, oral history interview, Autumn 2017).

Experiences and Opinions.

When entering the negotiations over the 2-m telescope, none of the Ondřejov astronomers had direct experience working with a large instrument. However, from 12th to 20th August 1958, the 10th General Assembly of the International Astronomical Union (IAU) took place in Moscow and gave Šternberk and Perek the opportunity to discuss their plans in person with astronomers from all around the world, including astronomers from Mt. Wilson and Mt. Palomar, who had experience with instruments larger than 2 meters. Šternberk in his report wrote about discussing the argument that "usage of optical telescopes is on the decline and the future belongs to modern methods of radioastronomy" with Otto Beckmann from Hamburg, but did not elaborate further on the origin of this argument. He also refers to Professor Kienle's recommendation that Czechoslovak astronomers spend several years in foreign institutions to acquire observational data and subsequently process it in specialised facilities in the CSR. However, this proposal was impractical for both the CSAS and the foreign institutes, and its results would not have represented a complete or unquestionable success for Czechoslovak astronomy or the state system (MIA CAS. Collection I. sekce ČSAV 1952–1961. Inv. No. 19).

After the IAU congress, the requirements were adjusted for spectrographs with a range of dispersion 4–400 Å/mm for all three focal points and a photoelectric photometer. In the prime focus, accessible from an observation bridge, astronomers could install an 80×110 mm grating spectrograph covering dispersions 33–400 Å/mm or a three-lens correction system for photographing on a 6x6 cm photographic plate, which corresponds to the field of view 21'45"x21'45" on the sky. At the Cassegrain focal point, accessible from an observation basket, a two-camera spectrograph with a 140×150 mm grating covering 10×72 Å/mm, a photoelectric photometer and devices for photography were installed. In addition, a second Cassegrain focal point for two Schmidt cameras could be created by a special optical system. The 150×180 mm grating in the coudé focal point, which was accessible from a coudé room and in which the working conditions for the astronomer were the best, covered dispersions in the range 4–24 Å/mm. (Bumba et al., 1964; Koubský, 1967; Perek, 1998).

The next month, an expert opinion from Kopal was submitted, dated 2 September 1958. The text compared perspectives of optical 2-m telescopes and mentioned an interferometer for radioastronomy (such as the one on the Jodrell Bank Observatory) and concluded that the future lay in optical astronomy. Kopal also highlighted the benefits of Ondřejov as a location, due to above-average conditions for observations, adequate altitude and proximity to Prague and its scientific infrastructure. He estimated that Ondřejov had 70 clear nights a year, which means that processing its observations would fully occupy 12 people; however, as of 1959, the department of stellar astronomy didn't even have proper rooms. To train these people, Kopal recommended sending young astronomers Luboš Perek and Mirek Plavec—who were involved in the 2-m telescope project—to international observatories equipped with large instruments. As they had invitations and/or stipends, those travels would not create any further costs for the CSAS (MIA CAS. Collection I. sekce ČSAV 1952–1961. Inv. No. 19).

In 1959, Luboš Perek and Miroslav Plavec (1925–2008) visited observatories at Mt. Wilson, Mt. Palomar, Tonantzintle (Mexico), Haute Provence, and Dominion Astrophysical Observatory, and brought that experience to negotiations with Zeiss. Later, in 1963, when the 2-m Ondřejov telescope was already under construction, Perek visited Kitt Peak Observatory and Lick Observatory, and was able to implement small adjustments of the design—in particular, Perek remembers the inspiration for "vivid colours, as opposed to Zeiss 'field grey'" (Perek, 1998).

In 1962, Luboš Kohoutek (1935–2023) got the opportunity to work with the Tautenburg 2-m telescope during his study trip to Germany (Kohoutek, 1963). This telescope was specific, as it included a Schmidt camera, which was abandoned in the Shamakhy and Ondřejov projects. However, it provided an opportunity for astronomers to get experience with the Jensch 2-meter universal telescope and for engineers to test it in practice.

The Negotiations.

The approval of the purchase of the 2-m telescope by the Czechoslovak government was proudly announced to the broader astronomical community in June 1959 as "a great appreciation of the work done so far", and also "a proof of the great care of the [Communist] Party and the government for the universal development of science in our state" ('Ondřejovská observatoř', 1959). However, Perek considered the approval a miracle, prompted among other things by the popularity of astronomy after the recent emergence of artificial satellites, the persuasive speech of astronomer Mirek Plavec at the CSAS Presidium meeting and the visit of Minister of Culture, Václav Kopecký, to the observatory and his expectations of the usefulness of astronomy to atheism (Perek, 1998).

Kopal assessed the price offer from Zeiss as realistic. However, a letter from the Ministry of Foreign Trade from 15 May 1960 to the Deputy Prime Ministers on the basis of information from the foreign trade company KOVO mentioned a competing offer from Britain, with "significant price differences", and that as a result, the price offer was negotiated with Zeiss several times "with partial success" and the signing of the contract was postponed to 20 October 1959. According to a further letter from Ondřejov economist Vladimír Rajský (1926–2000), the ministry confused the plan of meetings at the Zeiss factory with delivery dates and considered the delays "unexpected", although Šternberk stated in his proposal that Zeiss had available production capacity for 1959 in case the contract closed in 1959. From 1960, KOVO tried to negotiate the shortening of delivery dates at the level of government delegations. Some issues also arose in the CSAS itself; at the end of 1960, the board of the Section for Mathematics and Physics recommended the Astronomical Institute to contact directly the CSAS Presidium on economic and technical issues and only inform the section bureau.

The negotiations with Zeiss were held during more than thirty meetings, taking place in Jena, Prague or Ondřejov, as in the following years, many new questions and problems emerged. Luboš Perek remembered approximately four meetings every year in the range of eight years of planning and construction. After every meeting, the meeting notes were cut up and glued together by subject areas (the dome, the telescope, the research program, the accompanying instruments), in order to have an overview of what had been agreed upon a year or two earlier. Perek described the negotiations with Zeiss as "very good" (L. Perek, oral history interview, Winter 2017).

On the CSSR level, this large project, including not only production, but also transportation and on-site construction of the instrument, many other corporation from CSSR and GDR entered the negotiations. As a result, in addition to representatives from CSAS, KOVO and VEB Zeiss Jena, representatives from VEB Sächsiger Brücken- und Stahlhochbau Dresden, Krajský projektový ústav Praha, Průmstav Kolín and Hutní montáže Ostrava are listed as participants in meeting protocols in Zeiss Archives.

In the meeting protocols by Zeiss, the negotiations with KOVO were described as "very lengthy and difficult", as the Czechoslovak side did not want to accept the price and delivery dates, but in the end, they signed the contract. It was "clearly expressed that the reflector is necessary for an extremely important government programme for CSR scientists and must thus be delivered at all costs, whereby the government may still want to exert influence to bring forward the delivery dates". Even financial issues are hinted at; the protocol states that, in case of any additional requests, ensuring that the full price is charged is essential. In contrast, meetings with astronomers from Ondřejov and their experience with Zeiss devices were described as very positive (The Zeiss Archives. BACZ 19529. Bericht von der Dienstreise des Kaufmännischen Direktors [KD] in die CSSR, nach Ungarn und Bulgarien vom 20.10. bis 4.11.1959 sowie Protokolle von Besprechungen mit den Disponenten).

As the productions of the Azerbaijan and Czechoslovak telescopes overlapped, a unique situation occurred – the three sides, Czechoslovak, Azerbaijan and GDR, negotiated a double order of the same type of telescope for two different observatories. This reduced costs, but Czechoslovak and Azerbaijani astronomers had to compromise.

Azerbaijan astronomers Sultanow, Krat, Michelson and Stepanov came with requirements for the accompanying instruments that evoked various responses from the Czechoslovak side. Luboš Perek in particular reminisces that Azerbaijan astronomers were interested in photographic photometry, which was being abandoned in Czechoslovakia in favour of photoelectric photometry (L. Perek, oral history interview, Autumn 2017). Perek also mentioned apodizing grid cassettes and gearbox for observations of the Moon and planets, which Czechoslovak astronomers considered redundant. On the contrary, automatic compensation of atmospheric refraction was greatly appreciated. The optical correction system for a broader field of view seemed at first a good idea, but in the end, it wasn't used in practice (Perek, 1998).

Though the construction project for the dome was already completed, there were additional changes. An improvement of the German mount was invented by Jensch, moving the centre of the mass of the telescope, including its counterweight, to the centre of the hydrostatic bearing, improving the precision of guiding of the telescope, allowing unobstructed usage of movable observation platforms, and extending the lifetime of bearings in the hour axis (Figure 1). This mount was installed at both the Azerbaijan and the Czechoslovak telescopes. Automatic dome rotation and slit-curtain (which allowed the dome slit to be partially closed in the vertical direction) adjustments made nightly observations much easier, especially at the coudé focal point. In total, Jensch concluded that all the joint consultations of Zeiss employees and Czechoslovak and Azerbaijan astronomers enabled technological fine-tuning and precise manufacturing (The Zeiss Archives. NL 51 Nr 81. Manuskripte von A. J. über die Konstruktion astronomischer Großgeräte).

Technical requirements were difficult even during the installation of the dome in Ondřejov. The rotating dome was 20 m in diameter, and itself weighed 195 tons; the whole building weighed more than 1000 tons, and the pillar another 960 tons. The telescope's infrastructure included a transformer station and a service building to house the air conditioning and provide facilities for the observatory staff (Figure 2) (Perek, 1998).

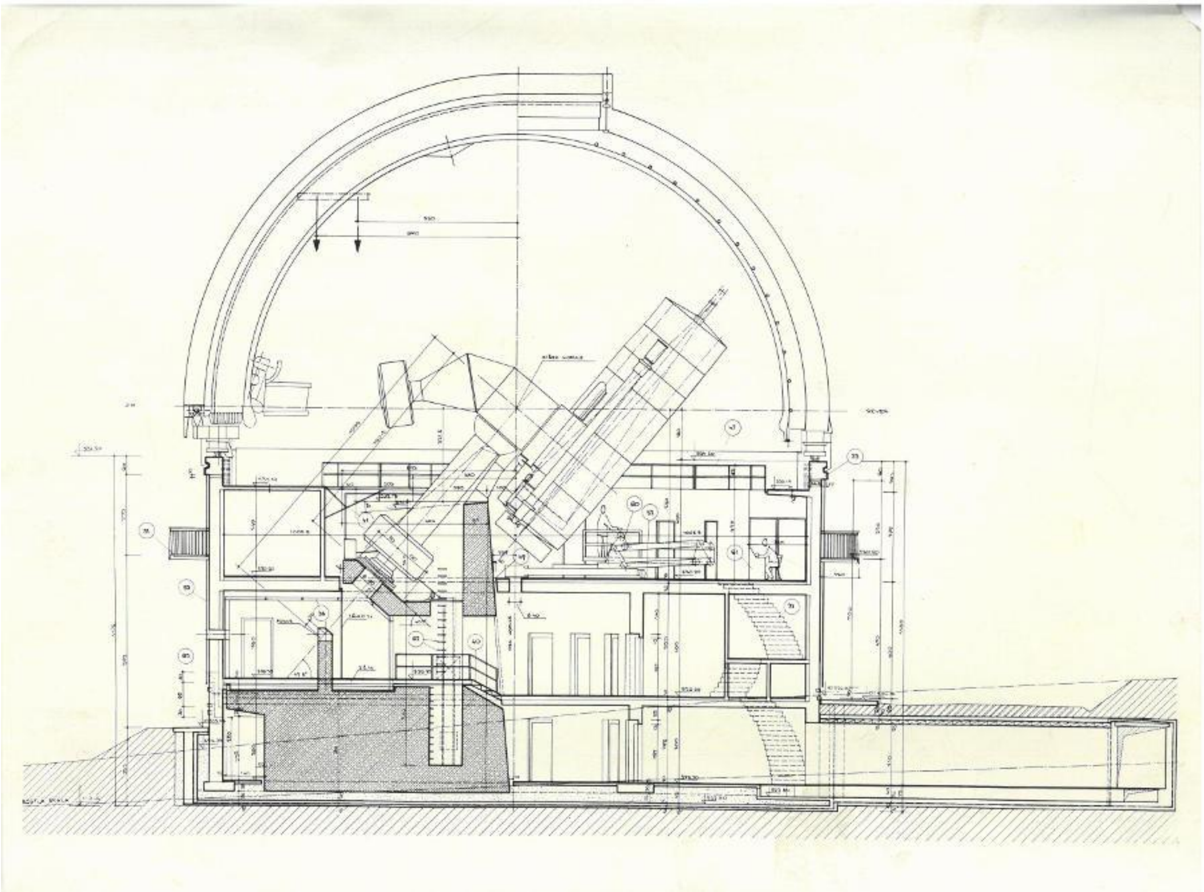

Figure 1. Final project of the Ondřejov 2-m telescope (Source: Archive of the Astronomical Institute of the CAS).

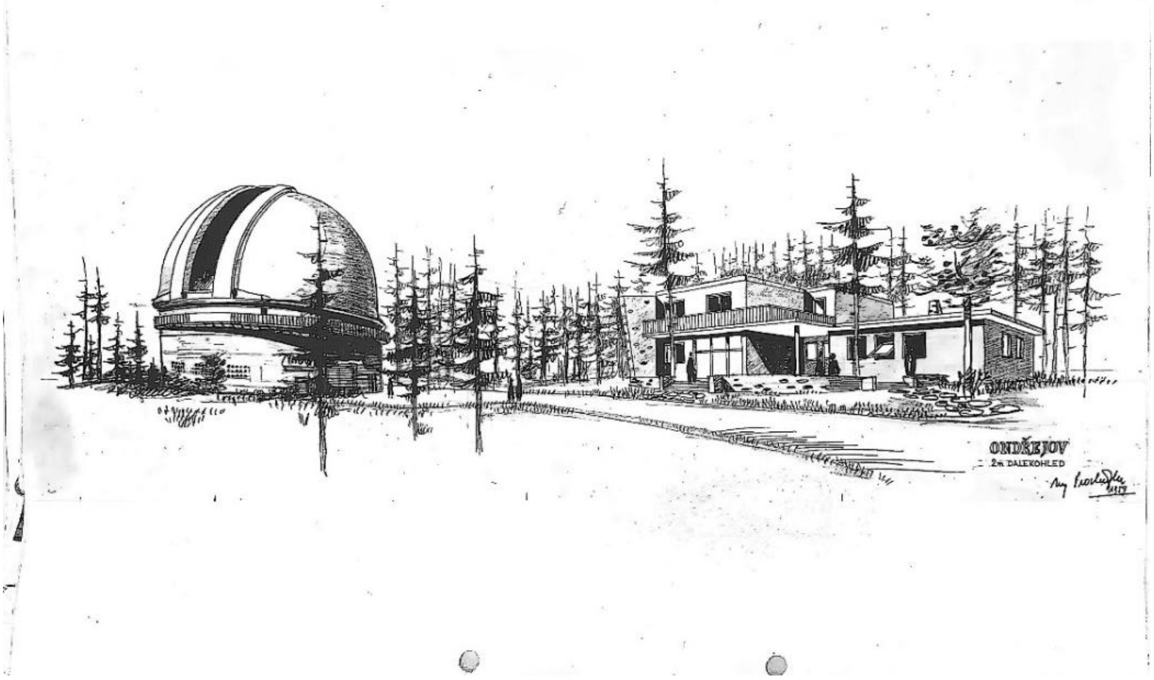

Figure 2. Drawing of the telescope building, service building, and their surroundings (Source: MIA CAS).

However, the necessary infrastructure for a large telescope extends beyond its immediate surroundings. The quality of observations also depends on the reduction of external interference. Some of that interference, such as light and air pollution, can be avoided by careful choice of the location for the instrument; in the case of Ondřejov, the land in the surrounding area was purchased and, if needed, planted with trees (Perek, 1998). Forests ensured thermal stability of the terrain, which prevented excessive heat generation in the night that would distort the air in the telescope's surroundings (MIA CAS. Collection I. sekce ČSAV 1952−1961. Inv. No. 19). Others, such as vibration from the rotational movement of the dome and thermal turbulence of air inside the dome, can be resolved by good thermal insulation and structural isolation of the dome and the pillar of the telescope from each other, which was usually achieved by creating a sand bedding for the building and the pillar.

The Inauguration and Further Developments.

Both telescopes were finished before the 50th anniversary of the Russian October Revolution (1917). The Shamakhy 2-m telescope was handed over by Zeiss on 12 September 1966 and named Telescope of the German-Soviet Friendship (The Zeiss Archives. NL 51 Nr 81. Manuskripte von A. J. über die Konstruktion astronomisches Großgeräte). The Ondřejov telescope, whose final price exceeded the first estimates more than twice (more than 40 million Kč in contrast to the first estimates of 20 million Kčs), was inaugurated during the 1967 IAU General Assembly in Prague (Pavlíček, Hyklová, & Šolc, 2024; Perek, 1998).

At the time of the inauguration, there were nine reflecting telescopes with a diameter of 200 cm or more in the world. These were at Mt. Palomar (508 cm), Mt. Hamilton (305 cm), Crimea (260 cm), Mt. Wilson (254 cm), Kitt Peak (210 cm), McDonald (208 cm), and the three 2-m telescopes in Tautenburg, Shamakhy and Ondřejov. Of those, four were finished before 1958, of them three in the USA and one in the USSR, and another one was finished in the USA in 1958. The Kitt Peak and Crimea telescopes were finished in the early 1960s (Koubský, 1967).

Czechoslovak astronomers had, of course, high hopes for the 2-m telescope. The telescope was expected to enable observation at all three foci, while the photoelectric pointer checked the settings; photographing on 6x6 cm plates; photoelectric photometry in primary and Cassegrain foci in six colours; and spectroscopic measurements in all three focal points (Bumba et al., 1964, p. 76).

Although the preparations were thorough, many issues could be revealed only by practice. The photoelectric photometer of a yet-untested principle was never put into full operation due to unreliable technology. Using spectrographs at Cassegrain focus proved to be too complicated, as confirmed by experience from other telescopes (Zicha, 1998). Luboš Perek described that, as Zeiss focused on optics and mechanics, the electrical instruments around the 2-meter telescope consisted of electronic components from various eras, which were later replaced by electronics from the Hungarian company VILATI (L. Perek, personal communication, Autumn 2017).

However, the biggest problem that the technical staff, led by chief technician Josef Zicha (1939–2024), had to deal with was the failure of the hour axis hydrostatic oil bearing in 1969. The problem manifested by oil leaks and happened a few weeks after the two-year warranty period expired. However, as the defect resulted from manufacturing—the used material composition proved to be unsuitable for the slow movements of the telescope—the repair was carried out under warranty. It took 9 months, but most of the time was spent on preparations in the Zeiss factory. The whole telescope needed to be lifted by 2 cm, for which special hydraulic devices had to be constructed.

The Zeiss 2-meter universal telescope project continued with telescopes for observatories in Rozhen (1981) and Terskol (1995). The Zeiss engineers were able to draw on experience not only from the construction process, but also from their involvement in warranty and routine maintenance, as well as from subsequent modernisations of these telescopes.

In the case of Ondřejov, there were several large modernisations in the early 1980s, in 1996–1998, in 2006 and 2009, and in 2018–2019 (Šlechta, n.d.-b, 2020). Though the primary mirror and mechanics remained the same, many other parts of the telescope were modernised or replaced. The present-day 2-m telescope (Figure 3) uses Siemens electronics from the late 2000s, standard CCD chips since 1996 (Šlechta, n.d.-a), the "Ondřejov echelle spectrograph" since 2005, and the optical system feeding light from the primary focus to the coudé focus consists of optical fibres since 2019 (Pitoňák, 2023).

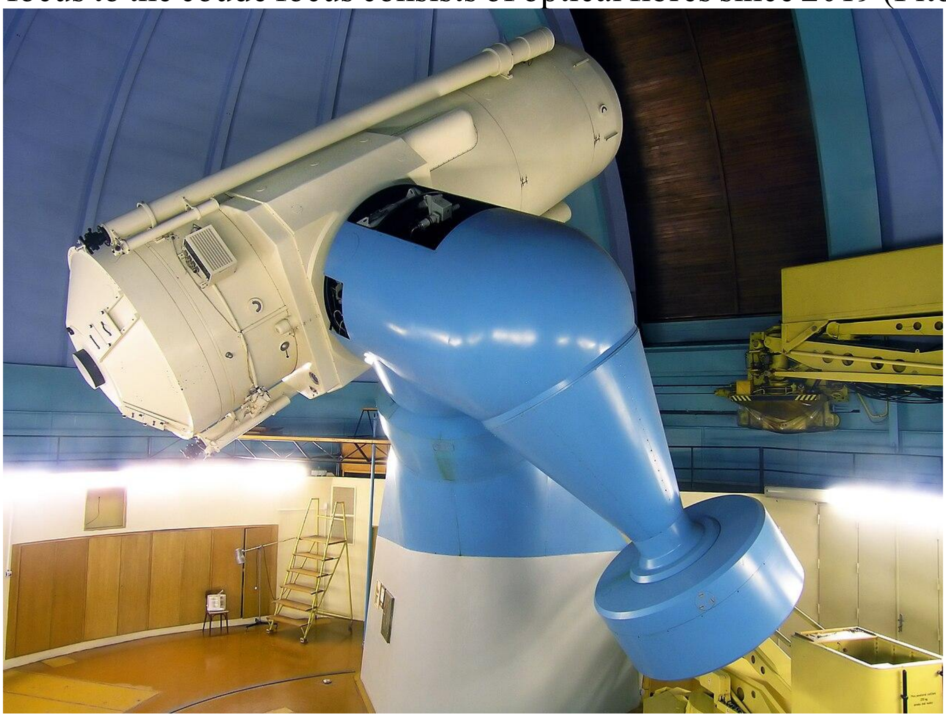

Figure 3. The Perek Telescope in 2007. (Source: CC BY-SA 2.5/Wikimedia Commons/Packa).

And in 2012, the Ondřejov 2-m telescope received its new name: the Perek Telescope.

Conclusions.

The project of the Ondřejov 2-m telescope was negotiated in the context of the 1950s formation and development of the Czechoslovak Academy of Science, following the ideals of the new Socialist society with top-level science that should not fall behind western science. Especially astronomy was a promising field, with the emergence of artificial satellites as a Soviet success and the perceived and real historical entanglements of Czechoslovak astronomy and atheism in the 20th century, as shown in Pavlíček et al. (2024). However, this still did not mean the project would be successful due to the high costs of large telescopes and the political and financial limitations of the CSAS's international cooperations.

The whole construction of the telescope took 13 years of expert work from a wide range of fields. In the words of Luboš Perek, it was not a long time for such an instrument in the Czechoslovak context of the late 1950s and the 1960s, but long enough to „take one generation to build and another to bring into operation and achieve a level of excellent results" (Perek, 1998).

All of the 2-meter Jensch telescopes remain operational today, having undergone the necessary modernisations to accommodate advances in technology and scientific practice.

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Conflicts of interest.

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Переговори щодо створення великого телескопа: Випадок Чехословаччини

Анотація. *Наприкінці 1950-х та на початку 1960-х років Астрономічний інститут Чехословацької академії наук розпочав довгу й складну роботу над отриманням двометрового рефрактора, співставного з найбільшими телескопами світу. Телескоп було урочисто введено в експлуатацію під час XIII Генеральної асамблеї Міжнародного астрономічного союзу, що проходила 22–31 серпня 1967 р. у Празі. Цей процес можна відтворити за архівними матеріалами та записаними спогадами очевидців. Унікальність ситуації* *полягала в тому, що два дуже подібні телескопи були замовлені майже одночасно для Чехословацької Соціалістичної Республіки та Азербайджанської РСР. Їх розробляли паралельно, щоб знизити витрати, і вони стали другим і третім у серії універсальних 2-метрових телескопів Zeiss. Астрономічні інститути ЧССР та АзССР мали погоджувати й узгоджувати свої вимоги. Додатковою складністю було те, що створення та введення в експлуатацію великого телескопа триває багато років, тому потрібно було передбачати майбутній розвиток відповідних галузей, а також вимоги до оснащення та конфігурації. Успішне завершення цього міжнародного проєкту вимагало великої кількості переговорів між астрономами обох інститутів, виробником інструментів VEB Zeiss Jena, вищими рівнями державного управління, чехословацькою зовнішньоторговельною компанією KOVO та численними підприємствами з ЧССР і НДР, залученими до будівництва та постачання телескопа, його купола й супутнього обладнання. Очікувано, проєкт супроводжувався низкою проблем – непорозумінь, затримок тощо, з якими всім учасникам довелося мати справу. Результатом цих ранніх зусиль став телескоп, який, після численних модернізацій, досі використовується для наукових досліджень у сучасній Чеській Республіці. У статті розглядається рання історія цього телескопа – від перших пропозицій до його постачання й монтажу в обсерваторії Астрономічного інституту ЧСАН в Ондржейові – з особливою увагою до переговорів між ключовими учасниками, а також до їхніх особистих рефлексій і спогадів про цей процес.*

Ключові слова: *2-метровий телескоп; зоряна астрономія; VEB Zeiss Jena; Ондржейов; Астрономічний інститут Чехословацької академії наук*

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Pneumatics, acoustics and digital sound: The organ in the history of science and technology

Abstract. *This article analyzes the historical development of the organ as a complex technological system whose evolution reflects successive transformations in scientific knowledge, materials, and engineering practices from antiquity to the digital* *age. The study employs a combined methodology of historical textual analysis, examination of archaeological and material evidence, and interpretation through the technological-systems approach, supported by modern acoustical and engineering research. The results demonstrate that each major stage in organ history corresponds to a distinct scientific and technological environment. The Hellenistic hydraulis reveals early applications of pneumatic and hydraulic regulation grounded in the mechanical theories of Ctesibius and described by Vitruvius, while Roman and Byzantine adaptations illustrate how metalworking, woodworking, and empirical acoustics shaped early organ design. The medieval period shows a shift toward large wooden structures, the refinement of tin-lead alloys, and the emergence of elaborate tracker mechanisms suited to the architectural acoustics of Romanesque and Gothic churches. Renaissance and early modern developments link organ building to the rise of mathematical acoustics, with theorists such as Zarlino and Mersenne providing conceptual explanations for pitch, scaling, and harmonic structure that informed workshop practice. During the Industrial Revolution, machine tools, standardized materials, and pneumatic assist devices enabled unprecedented increases in size, reliability, and mechanical complexity, while nineteenth-century acoustical science, particularly the work of Helmholtz, clarified the physical basis of pipe tone. Electrification in the late nineteenth and twentieth centuries reshaped organ control systems, separating console and pipes, introducing electromagnetic actions, and integrating the organ into broader electromechanical networks. The second half of the twentieth century and the early twenty-first century reveal the growing influence of electronics, digital sampling, physical modeling, CNC manufacturing, and hybrid designs that combine traditional pipes with computational sound generation. Taken together, these findings show that the organ evolved not through the replacement of old technologies by new ones but through their continuous accumulation, reinterpretation, and integration within changing scientific paradigms. The article concludes that the organ's two-millennia history offers a distinctive case study for understanding long-term interactions between scientific knowledge, material innovation, and technological continuity.*

Keywords: *history of technology; history of keyboard musical instruments; organ; history of music; history of art*

Introduction.

Among the musical instruments that accompanied the development of Western and Middle Eastern cultures, the pipe organ occupies a distinctive position as one of the earliest and most durable examples of complex mechanical engineering applied to artistic ends. From the Hellenistic hydraulis of the third century BCE to contemporary hybrid and digital instruments, the organ has continually adapted to new materials, new scientific knowledge, and new technological environments. Its long history is not only a history of musical practice but also a record of changing understandings of pneumatics, acoustics, mechanical control, metallurgy, electricity, and digital signal processing. Because of this unique technological depth, the organ offers an unusually rich lens through which to view broader transformations in science and engineering across more than two millennia.

Despite this potential, historical writing on the organ has been shaped by disciplinary boundaries that tend to separate music history, craft practice, acoustics, and technological change. Standard reference works (such as the *Grove* article on the organ (Owen, Williams, & Bicknell, 2021) or the overview chapter in *The Cambridge Companion to the Organ* (Thistlethwaite, 1999) provide reliable chronological and stylistic syntheses, but they generally treat scientific and technological developments as peripheral rather than central to the narrative. Regional and cultural studies, including Snyder's *The Organ as a Mirror of Its Time* (2002), demonstrate how individual instruments reflect their social and artistic contexts, yet they focus on specific centuries and limited geographies. Technical treatises from the nineteenth century, such as Hopkins and Rimbault (1877), document industrial-era workshop practices but do not relate them to earlier scientific traditions or later technological revolutions. Meanwhile, acoustical studies and STS-oriented research (Science & Technology Studies) address sound production and socio-technical identity but offer only partial historical coverage.

Taken together, these works illuminate many aspects of organ history, yet they leave several important problems insufficiently addressed. First, no existing study traces in a single, continuous narrative how developments in scientific knowledge (ranging from ancient pneumatics and early modern acoustics to nineteenth-century materials science and late-twentieth-century digital engineering) systematically reshaped organ design. Second, the historiography often isolates historical periods rather than examining how earlier technological logics constrained or informed later innovations. Third, although the organ is frequently described metaphorically as a "mirror of its time," previous literature rarely analyzes it explicitly as a technological system whose subsystems (wind production, action mechanisms, pipe acoustics, electrical control, digital sound generation) evolved in response to specific scientific and industrial contexts. Finally, the most recent transformations of the organ (CNC fabrication, hybrid digital-pipe architectures, and computational sound modeling) are seldom integrated into long-duration historical accounts, leaving a conceptual gap between pre-industrial traditions and contemporary engineering practice.

Addressing these unresolved problems requires a methodological approach capable of integrating textual sources, material evidence, scientific analysis, and the technological-systems perspective. This article adopts such an approach, combining historical reconstruction with insights from acoustics, engineering, and material science to situate organ building within the broader evolution of scientific and technological knowledge.

The purpose of this article is to provide the first comprehensive, long-term historical analysis of the organ as a technological system, demonstrating how changes in scientific understanding, material technologies, and engineering practices shaped the instrument's evolution from the Hellenistic period to the digital age.

Methodology.

In light of the diverse historiographical traditions surrounding the organ (ranging from encyclopaedic surveys to regional case studies, technical treatises, acoustical analyses, and STS-oriented interpretations), this article adopts a methodological approach designed to integrate these fragmented perspectives into a coherent, long-duration technological history. The study proceeds from the premise that the organ is neither solely a musical instrument nor solely a cultural object, but a technological system whose components, materials, and operational principles evolved in step with broader scientific and engineering developments.

To reconstruct this evolution, the article employs historical textual analysis combined with material and archaeological evidence. Primary sources such as Vitruvius, Hero of Alexandria, Theophilus Presbyter, Marin Mersenne, and Hermann von Helmholtz are used not only for the technical information they contain, but also for the scientific assumptions and conceptual frameworks they document. These texts are interpreted alongside surviving instruments, documented reconstructions, and detailed organological surveys, allowing the study to align written evidence with material practice across different periods.

The analysis is further guided by the technological-systems approach familiar from the history of technology (Strelko, Pylypchuk, Berdnychenko, Hurinchuk, Gamaliia, & Sorochynska, 2019; Pylypchuk, O. Ya., Strelko, & Pylypchuk, O. O., 2021; Vaniuha, Zharkova, Markovych, Pryidun, & Drevnitskyi, 2022). This framework makes it possible to treat the organ's subsystems (wind production, mechanical and pneumatic actions, pipe acoustics, control interfaces, and later electrical and digital components), as interdependent elements that respond to changes in available materials, manufacturing tools, and scientific understanding. This perspective complements, rather than duplicates, the historiographical literature: whereas previous studies have typically emphasized stylistic schools, regional traditions, performance practice, or acoustical measurement, the present study uses those same sources to trace long-term patterns in the organ's technological architecture.

Modern acoustical, engineering, and materials-science research is incorporated selectively to clarify why certain empirical solutions persisted or how specific design choices affected mechanical or acoustic outcomes. These scientific perspectives are not retroactively imposed on earlier builders; rather, they help articulate the underlying physical principles that shaped historical workshop practice and explain transitions that textual sources sometimes describe only indirectly.

Finally, the study follows a chronological comparative method, linking each historical stage to the scientific and technological environment in which organ building operated. This structure allows the analysis to highlight both discontinuities, such as the introduction of electrification or digital signal processing, and deeper continuities in the organ's technological logic. In this way, the methodology complements the historiographical review by offering a unified analytical lens through which disparate strands of scholarship can be connected and reinterpreted.

Historiography of the Problem.

The history of the organ has been described many times, but mostly within musicological or organological frameworks rather than as a long-term history of a technological system. The most widely used point of entry remains the article "Organ" in *Grove Music Online*, which offers a compressed but authoritative narrative from antiquity to the twentieth century, structured around periods, regional schools, and major builders (Owen, Williams, & Bicknell, 2021). This overview is invaluable for chronology, terminology, and basic typology, yet it treats scientific and technological contexts largely as background. Pneumatics, acoustics, metallurgy, and later electronics are mentioned in passing or under specialized subheadings, but they are not framed as drivers of technological change in their own right. The present study builds on this canon by taking many of the same chronological milestones and reinterpreting them explicitly through the lenses of the history of science and technology.

A similar role is played by Nicholas Thistlethwaite's chapter "Origins and development of the organ" in *The Cambridge Companion to the Organ* (1999). Thistlethwaite offers a compact survey from the hydraulis to the modern concert and church organ, with particular attention to action types, case design, and liturgical or musical functions. His narrative is exemplary as a clear organological synthesis and has shaped how students and practitioners understand the broad arc of organ history. Yet, like the *Grove* entry, it stops short of treating the organ as a technological system in the sense used in science and technology studies. Machine tools, industrial materials, electrification, and digital electronics appear as contextual elements rather than as interconnected subsystems whose evolution can be traced in parallel with developments in acoustics, materials science, and control engineering. The present article retains Thistlethwaite's chronological scaffolding but reorients it toward these technological dimensions.

Kerala Snyder's edited volume *The Organ as a Mirror of Its Time: North European Reflections, 1610–2000* moves closer to the perspective adopted here, though on a different scale (Snyder, 2002). The essays in that collection show how specific North European organs reflect confessional, political, and cultural histories, and several contributions explicitly link technical features to patronage, liturgical reform, and changing musical aesthetics. Snyder's own introductory essay formulates the idea of the organ as a "*mirror*" of its time, a metaphor that has been influential in later work. At the same time, the volume is geographically and temporally bounded: it concentrates on the period from the early seventeenth century to the late twentieth century and focuses on Northern Europe. The central aim is to understand how individual instruments embody particular local or regional histories, not to reconstruct a continuous, two-thousand-year trajectory from the hydraulis to digital hybrids. The present study is indebted to Snyder's conceptual framing but extends it backwards into antiquity and forwards into the digital age, and it shifts the emphasis from cultural microhistory to the long-term coevolution of organ design and scientific–technical knowledge.

Older nineteenth-century treatises, especially Edward Hopkins and Edward Rimbault's *The Organ, Its History and Construction*, represent another important layer of historiography (Hopkins & Rimbault, 1877). Hopkins and Rimbault combined what they called a "new history of the organ" with detailed descriptions of construction methods, specifications, and workshop practice as understood in Victorian Britain. Their work is not a modern secondary study in the contemporary sense but a primary source for how organ builders and organists in the industrial era perceived the past and justified current practices. It documents late nineteenth-century attitudes to pneumatics, wind systems, tonal ideals, and factory production at the moment when organ building was deeply entangled with steam-powered machine tools and expanding transport networks. In the present article, such treatises are used less as historiographical models and more as empirical witnesses to the industrial phase of organ technology, to be reinterpreted in light of later acoustical and materials-science research.

More recent scholarship has begun to connect organ history directly to scientific analysis. Albrecht Schneider's chapter "*Aspects of Sound Structure in Historic Organs of Europe*" in the volume *Sonic Design* sketches the development of European organs from Roman times to the Baroque specifically to provide context for detailed spectral analyses of historic instruments (Schneider, 2024). Schneider's organological survey is concise but important because it explicitly links historical design choices to measurable acoustic outcomes. Nevertheless, his primary goal is to characterize sound structure in a defined historical window, not to follow the instrument's technological evolution into the eras of electrification, electronics, and digital signal processing. The present study takes inspiration from this combination of historical outline and acoustic detail, while extending the narrative into the twentieth and twenty-first centuries and broadening the focus from sound structure alone to include materials, mechanisms, and control systems.

A complementary, more localized approach can be seen in the article by Karol Czajka-Giełdon and Krystyna Kirschke on the organs of St. Mary Magdalene's Church in Wrocław (Czajka-Giełdon & Kirschke, 2025) Their study traces a sequence of instruments from the Middle Ages to the present in a single building, analyzing changes in case design, architectural integration, liturgical function, and technical solutions.

This microhistory demonstrates how organ building is embedded in specific architectural, institutional, and urban contexts, and it includes careful documentation of successive reconstructions and restorations. While the scope is intentionally narrow, the article models how to connect technical history, acoustic environment, and cultural practice in one concrete site. The present work follows this logic of contextualization but at a much larger temporal and geographic scale, and with stronger emphasis on linkages to parallel developments in science and engineering.

Two further strands of research, emerging from science and technology studies, are especially relevant for the conceptual framing of this article. Peter Peters's and Darryl Cressman's study "*A sounding monument: How a new organ became old*" examines how a late twentieth-century replica of a fifteenth-century organ in Amsterdam gradually acquired the status of a historic monument (Peters & Cressman, 2016). Peters and Cressman treat the instrument as a socio-technical object whose "newness" and "oldness" are negotiated through performance practice, institutional discourse, and restoration choices. Here, the focus is less on mechanical or acoustical detail and more on how organ technology becomes entangled with questions of authenticity, heritage, and identity. Karin Bijsterveld and Peter Peters, in their article "*Composing Claims on Musical Instrument Development: A Science and Technology Studies' Contribution*," take an even more abstract step back (Bijsterveld & Peters, 2010). They analyze how makers, historians, and users tell "development stories" about instruments (organs among them), showing that narratives of progress, decline, or revival are themselves constructed and contested. Musical instruments are treated as "black boxes" and "boundary objects" that sit between scientific knowledge, craft practice, and cultural meaning.

These STS-oriented studies do not provide a comprehensive chronological history of the organ, but they sharpen the questions that a technologically informed historiography should ask. They suggest that any account of organ development must consider not only technical innovations but also the narratives that surround them, the ways in which builders and users claim novelty or continuity, and the institutional settings that shape which technologies become dominant. The present article follows this insight by combining long-term historical reconstruction with attention to how different ages understood and justified their own organ technologies.

Taken together, the existing literature offers rich but fragmented coverage. Encyclopedic and companion-volume surveys outline the main chronological and stylistic stages; nineteenth-century treatises document contemporary industrial practices; case studies and regional histories illuminate specific instruments and contexts; acoustical research relates historical designs to measurable sound structures; and STS-inflected work interrogates the narratives and heritage regimes around organs. What remains largely missing is a single, integrated account that traces the organ from the Hellenistic hydraulis to contemporary hybrid and digital instruments while consistently relating changes in design to parallel developments in pneumatics, acoustics, materials science, electrotechnics, and digital engineering. It is this gap that the present article seeks to address, by treating the organ explicitly as a long-lived technological system whose components and meanings have coevolved with broader scientific and technological transformations.

Antiquity. The *Hydraulis* and Early Pneumatic Engineering.

The story begins in Alexandria, a city known for its concentration of engineers and natural philosophers. Ctesibius, whose work survives primarily through references in Hero of Alexandria and Vitruvius, developed several devices based on the behavior of air and water under pressure (Dessì, 2020; Filson, 2025; Morgan, 2022). The *hydraulis* appears to have been one such invention. Although modern reconstructions must rely on limited archaeological evidence (such as the fragments from Dion and Aquincum) and literary descriptions, scholars generally agree that the instrument used a water-regulated chest to maintain stable air pressure before distributing that air to metal pipes.

Vitruvius's account describes the mechanism in enough detail to demonstrate that its creator understood the importance of constant pressure for controlling sound (Nikolic, 2011; Dessì, 2020). Water served as a natural regulator: fluctuations in airflow from manual pumps were absorbed by the water level in the chamber, ensuring that the pipes received a steady supply. This principle, while conceptually simple, required a careful balance of materials and geometry. Bronze pipes had to be cast or hammered to precise dimensions, and the valves that admitted air needed tight tolerances to avoid leaks.

The existence of such an instrument in the third century BCE indicates that Hellenistic artisans had achieved a high degree of competence in small-scale metalworking and hydraulic control systems. Their ability to manufacture pipes with smooth internal surfaces and predictable acoustical behavior suggests that techniques such as hammering, annealing, and the shaping of thin-walled cylinders were already quite advanced. Historians of ancient technology, including Andrew Barker (1989) and Stefan Hagel (2009), have noted that the hydraulis marks one of the earliest documented applications of scientific theory to a practical acoustic device.

The Roman period brought modifications rather than conceptual breakthroughs. By the second century CE, the hydraulis had been transformed into a largely pneumatic instrument, operated by foot-powered bellows rather than a hydraulic regulator. The well-preserved organ discovered at Aquincum in 1931, now in the Budapest Museum of Aquincum, reveals the integration of wooden components, leather bellows, and metal pipes arranged in a compact chest (Erdmann, 2023; Filson, 2025). The instrument also indicates a degree of standardization: pipes are grouped by scale, and their construction suggests established workshop practices.

At public events across the empire (amphitheater games, banquets, and military ceremonies), the organ became a symbol of mechanical ingenuity. The Roman fascination with automata and hydraulic devices provided a cultural environment that encouraged such engineering feats. Writers such as Claudian, Ammianus Marcellinus, and later medieval chroniclers mention organs as marvels of craftsmanship, implying that their technological complexity was widely recognized (Bittermann, 1929; Huysmans, 2015).

Yet the organ's history after late antiquity is more a story of transmission than innovation. Some knowledge persisted in the Byzantine Empire, where organs were used in court ceremonies. The famous organ sent by Emperor Constantine V to the Frankish ruler Pippin III in 757, mentioned by the chronicler Theophanes, suggests that the technology gradually moved westward, but the mechanics described in later sources differ significantly from their ancient predecessors (Apel, 1948; Filson, 2025). What survived was not a continuous technical lineage but a general idea, – an instrument powered by air, capable of producing sustained tones through pipes.

The Middle Ages. Wood, Metal, and the Rebirth of Large Mechanical Instruments.

The revival of organ building in medieval Europe should be understood in relation to developments in craft technologies rather than the rediscovery of ancient engineering texts. Early medieval references, such as the organ built for the church of Winchester in the tenth century (recorded in Wulfstan's Narratio Metrica), describe instruments of striking size and power (Lapidge, 1972; Quirk, 1957). These organs relied almost entirely on wood for their structure, with metal used mainly for the resonant parts. The bellows were operated by teams of assistants, highlighting the instrument's dependence on human energy as a mechanical resource.

Medieval woodworking underwent important changes between the ninth and thirteenth centuries. The increasing availability of well-seasoned timber, improvements in hand tools, and advances in joinery techniques allowed for more stable and airtight windchests. Glue production (made from animal collagen), became more reliable, enabling builders to construct large composite structures that could withstand variable humidity and pressure. These workshops were often located in monasteries or cathedral precincts, where access to skilled labor and specialized tools was relatively consistent.

The parallel evolution of metalworking also played a decisive role. The alloy of tin and lead used for organ pipes became increasingly standardized by the twelfth and thirteenth centuries. Treatises such as Theophilus Presbyter's De Diversis Artibus (early twelfth century) describe methods for casting sheets of metal, forming them into cylindrical shapes, and soldering the seams, – a process strikingly similar to what organ builders continued to use for centuries (Adámková, 2021). The ability to control the alloy ratio influenced both durability and sound quality: higher tin content produced a brighter tone, whereas lead offered ease of shaping. This interplay of acoustics and metallurgy demonstrates how the organ served as a testing ground for material properties long before modern materials science formalized such studies.

Wind supply systems also evolved significantly. While ancient organs used water or simple pumps, medieval organs relied on multiple wedge bellows, each lifted by hand or foot. The design of these bellows reflects a growing understanding of pressure dynamics. Builders learned to match the size and number of bellows to the air requirements of different ranks of pipes. Surviving examples from later centuries, such as those in the Arp Schnitger school, show the continuity of this approach (Crandall & Bush, 2013). Although the principles were empirical, they nonetheless required careful measurement, predictable materials, and long-term familiarity with pneumatic behavior.

Architecture shaped the organ just as much as technology did. The transition from Romanesque to Gothic building styles, with their soaring vaults and expansive interiors, changed the acoustical environment in which organs were heard. Longer reverberation times and increased volume encouraged the development of larger pipe scales and more prominent façade pipes. Modern acoustic studies, such as those by Leo Beranek, have shown that the medieval cathedral offered an unusually supportive acoustic for sustained tones, making the organ a natural complement to monastic chant and ecclesiastical ritual (Beranek, 1960, 1992, 2004).

By the thirteenth century, the organ had become one of the most complex mechanical devices in Europe. The action that connected keys to valves (typically a system of levers, trackers, and pallets), required fine tolerances and coordinated movement. Although far simpler than the actions of later centuries, these early mechanisms nonetheless reflect a sophisticated understanding of mechanical advantage and motion transfer. In many respects, the medieval organ stood alongside astronomical clocks as one of the period's most advanced engineered artifacts.

The instrument's cultural significance also grew. Chronicles, such as those by Orderic Vitalis and Richer of Reims, describe organs as both musical and technological marvels (Chibnall, 1997; Reilly, 2013). Their inclusion in major churches symbolized institutional power, while their construction offered opportunities to develop and preserve specialized craft knowledge. Even without a continuous transmission of ancient engineering treatises, Europe had recreated a form of large-scale mechanical instrument that rivaled the complexity of its Roman predecessors.

Renaissance and Early Modern Transformations. Precision, Acoustics, and Expanding Mechanical Ambitions.

The Renaissance brought a new intellectual climate that shaped the development of organ building in profound ways. Unlike the medieval period, where the transmission of technical knowledge relied primarily on workshop practice and monastic craft, the Renaissance saw the emergence of a more self-conscious engagement with mathematical proportion, mechanical design, and acoustical theory.

These influences did not replace the empirical traditions of organ builders, but they reshaped the direction of experimentation and offered new frameworks for understanding the instrument's possibilities.

One of the most significant changes was the refinement of the key action. Earlier medieval organs often had short key levers with long pallets beneath them, requiring considerable physical effort (Hopkins & Rimbault, 1877; Maurette, 2018). During the fifteenth and sixteenth centuries, builders developed more sophisticated tracker mechanisms capable of transmitting motion over greater distances. Surviving instruments from builders such as Lorenzo da Prato (Bologna, Italy) and the workshop of Conrad Schott in Germany show an increasing attention to balanced movement, reduced friction, and predictable mechanical response (Davies, 2019; Milner, 2000). These improvements reflected broader changes in mechanical engineering. The same period witnessed advances in clockmaking, automata, and precision metal tools, creating an environment in which mechanically complex devices could flourish.

Renaissance acoustical theory also influenced organ design. Gioseffo Zarlino's *Le istitutioni harmoniche* (1558) systematized musical intervals and tuning systems in a way that had direct implications for pipe scaling and temperament (Callegari, Lisboa, Gregório, dos Reis, & Martins, 2023; Da Col, 2017). Although Zarlino did not write specifically for organ builders, his ideas circulated widely among musicians and theorists, shaping expectations about consonance and the mathematical basis of harmony. Marin Mersenne's *Harmonie Universelle* (1636–1637) provided an even more explicit scientific treatment of pipe acoustics (Callegari, Lisboa, Gregório, dos Reis, & Martins, 2023; Fabbri, 2007). Mersenne discussed the relationship between pipe length and pitch, the influence of diameter on tone, and the behavior of vibrating air columns. His observations, derived from experiments with organ pipes, helped formalize principles that builders had long understood intuitively. The exchange between scientific treatises and artisanal practice during this period demonstrates the increasingly porous boundaries between craft knowledge and early modern science.

Materials also changed. While tin–lead alloys remained dominant for pipe production, improvements in refining and casting techniques allowed for more consistent sheets of metal. Larger façade pipes, wider scalings, and greater tonal variety emerged in part because builders could rely on predictable mechanical properties. Woodworking likewise benefited from more accurate saws, planes, and drills, producing smoother surfaces and more reliable joints. These tools were sometimes adapted from techniques introduced through military engineering manuals, shipbuilding, and architectural carpentry, – fields that also required geometric accuracy and standardized measurement.

The cultural context of the Renaissance supported this technical complexity. Courts, cathedrals, and civic governments commissioned instruments not only for liturgical purposes but also as expressions of prestige and technological sophistication. Descriptions of court organs in the Duchy of Burgundy, at the Habsburg courts, and in

Italian city-states reveal a fascination with devices that combined mechanical ingenuity with symbolic power (Owen, Williams, & Bicknell, 2021; Snyder, 2002). The organ became a marker of technological modernity, much like elaborate astronomical clocks or hydraulic automata. Its decorative façades often hid intricate inner workings, blending art and engineering in a single architectural object.

By the early seventeenth century, the organ had reached a degree of mechanical and acoustical refinement that set the stage for the great regional schools of the Baroque era. Builders such as Esaias Compenius, Arp Schnitger, and the Silbermann family produced instruments that reflected both local musical traditions and a shared understanding of mechanical design (Povilionis & Povilionienė, 2023). Their work cannot be separated from the broader scientific currents of the time, especially the rise of mathematical acoustics, the dissemination of printed engineering manuals, and the growing use of standardized measurement systems (Milner, 2000; Thistlethwaite, 1999). The organ builder's workshop had become a site where craft, mathematics, and emerging scientific theory met with unusual intensity.

The Industrial Revolution and the Mechanization of Organ Building.

The eighteenth and nineteenth centuries brought transformations to the organ that paralleled major technological shifts in industrial society. No previous era had altered the materials, labor practices, and mechanical systems of organ building so radically. The Industrial Revolution introduced new metals, new production techniques, and new sources of power that reshaped both the scale and the internal logic of the instrument.

One of the most consequential changes was the introduction of machine tools. Precision lathes, drills, and milling machines made it possible to fabricate components with tolerances far beyond what earlier workshops could achieve. This precision influenced several aspects of organ building. Pipe-making, for instance, benefited from more accurate rolling mills that produced uniform sheets of metal. Conical and cylindrical pipes could be formed with predictable dimensions, and voicing practices became more standardized. Steel production, which expanded dramatically in the nineteenth century, enabled builders to incorporate metal frames and supports capable of bearing the weight of increasingly large instruments. The iron-framed organs built in the factories of E. F. Walcker & Co in Ludwigsburg are perhaps the clearest examples of this industrial turn (Huntington, 2006; Thistlethwaite, 1999). Their monumental instrument for Ulm Minster (1856) illustrates how the vocabulary of industrial materials infiltrated ecclesiastical architecture.

The organ also changed through advances in pneumatic systems. The need to operate large instruments with multiple manuals and stops strained the limits of purely mechanical actions. Builders such as Charles Spackman Barker introduced pneumatic lever systems in the 1830s and 1840s, which used bellows-like mechanisms to lighten the touch and expand the possibilities for complex registrations (Casson, 1905; Owen, Williams, & Bicknell, 2021). Barker's lever was documented by contemporaries and discussed in engineering journals, indicating that its significance extended beyond organ building into the broader development of pneumatic assist mechanisms (Owen, 2002; Thistlethwaite, 2018). The use of pneumatics corresponded to the rise of pressure-based technologies in industry, including steam engines, gas lighting, and compressed-air tools. The organ thus participated in a wider exploration of energy transfer and mechanical advantage in an age when engineers were increasingly attentive to efficiency and responsiveness.

The development of new materials also played a role. Industrial-scale production of leather, felt, and adhesives created more uniform and durable components. Metal alloys could be specified with greater precision thanks to metallurgical research, such as that conducted by Henry Clifton Sorby and others who investigated crystal structure and material properties in the mid-nineteenth century (Kimberley, 1979; Louthan Jr., 2007). Although organ builders did not always engage directly with scientific publications, their material choices benefited from this new knowledge. Metal fatigue, corrosion resistance, and acoustic behavior became more predictable as alloys and treatments improved.

Transport networks (especially railways) had unexpected consequences for organ building as well. Factories capable of producing large components could ship them across Europe or even to the Americas. This contributed to a growth in export-oriented firms such as Cavaillé-Coll in France, Walcker in Germany, and Elliot & Hill in England (Owen, 2002; Thistlethwaite, 2018). Their instruments spread not only musical styles but also standardized engineering practices. The organ was no longer a purely local artifact created within a single workshop; it became part of an international industrial economy.

Scientific research also deepened during this period. Hermann von Helmholtz's *Die Lehre von den Tonempfindungen als Physiologische Grundlage für die Theorie der Musik* (1863) offered the most comprehensive explanation to date of how pipes and resonators produced sound. Helmholtz's work influenced generations of acousticians and engineers, and his experimental use of resonators inspired organ builders seeking to understand tonal brightness, harmonic content, and pipe scaling (Fletcher & Thwaites, 1983). While builders continued to rely heavily on empirical voicing methods, the theoretical framework provided by acoustical science offered new ways to rationalize and systematize tonal design.

By the late nineteenth century, the organ had absorbed many of the defining features of industrial modernity. It incorporated mass-produced parts, used new energy sources, relied on pneumatic and mechanical amplification systems, and often required engineering expertise to design and install. Organs of this period could be enormous, incorporating thousands of pipes, miles of tubing, and increasingly complex control systems. Exhibitions such as the Paris Exposition of 1889 showcased organs alongside other engineering marvels, reinforcing their status as technological achievements as much as musical ones (Fauser, 2017).

Yet these developments also prompted debates about authenticity and craftsmanship. Some musicians and builders lamented the industrialization of the organ, arguing that the refinement and subtlety of earlier instruments risked being lost. This tension between mass production and artisanal tradition foreshadowed similar debates in many other fields, from architecture to instrument making, as industrialization transformed older craft practices.

Electrification and the Redefinition of Control Systems.

The final decades of the nineteenth century and the early twentieth century introduced another set of transformative technologies: electricity, electromagnets, and eventually early electronics. These innovations did not merely supplement existing mechanisms; they redefined the basic logic of how organs were controlled and expanded the conceptual distance between the console and the pipes.

The earliest experiments with electricity in organ actions appeared in the 1860s and 1870s. Builders such as Charles Spackman Barker and later Robert Hope-Jones explored ways to use electromagnets to operate valves (Ramsbottom, C. E., & Ramsbottom, A. J., 1989; McKirdy, 1990; Owen, 2002). Electrical actions eliminated the limitations imposed by mechanical tracker lengths. While older organs required the console to be close to the windchests, electrical connections made it possible to place the console almost anywhere. This opened new architectural possibilities and allowed for much larger instruments without corresponding increases in physical key resistance.

Hope-Jones, working in England and later the United States, became one of the most influential figures in this transition (Miller, 1913). His patents detailed systems that used electric relays, combination pistons, stop controls, and unit-chest designs that separated each pipe from its traditional rank structure. Although many of Hope-Jones's musical ideas were controversial, his engineering contributions were undeniable. His relay systems anticipated later developments in telegraph switching and electrical logic, and they illustrate how organ building began to intersect with fields that would eventually form the basis of computing and automatic control.

The introduction of electric blowers was equally significant. Before this change, large organs required teams of calcants (bellows pumpers). With the advent of compact electric motors, wind supply became far more stable and predictable. Builders could design higher-pressure systems, expanding the tonal range and power of the instrument. Reliable electric blowers also made it feasible to install organs in concert halls, theaters, and public institutions that lacked the traditional staffing of a cathedral.

Electrification coincided with new materials that were becoming increasingly common in manufacturing. Early plastics such as Bakelite appeared in the early twentieth century and were soon used for stop knobs, key coverings, and small insulating components. Advances in wire production, coil winding, and electromagnetic design (technologies also driven by the telephone and telegraph industries), directly influenced organ actions. Although these developments may appear minor compared to the monumental changes of the industrial period, they altered the organ's internal dynamics and its relationship to the built environment.

By the 1920s and 1930s, the organ had entered a new conceptual era. It was no longer solely a mechanical or pneumatic device but a hybrid machine incorporating electrical, electromagnetic, and mechanical subsystems. In some cases, such as the theater organs built by Wurlitzer, the instrument became part of a larger technological entertainment system, integrated with cinema projectors, lighting controls, and electro-acoustic effects (Landon, 1973). The organ now belonged to a world shaped by electromechanical communication, amplified sound, and industrial entertainment.

The emergence of early electric organs, such as the Hammond Model A (1935), further complicated the picture (Popular Mechanics, 1936). Although not pipe organs, these instruments appropriated many of the organ's traditional forms (multiple manuals, pedalboards, drawbars) and used them to control entirely new sound-generation technologies. Laurens Hammond's tonewheel generator drew on principles of electromechanical induction and owes as much to contemporary engineering research as to organ-building traditions. While the Hammond did not replace the pipe organ, it demonstrated that new scientific knowledge could create electronic analogues of traditional acoustic phenomena.

Throughout this period, organ builders continued to negotiate the tension between technological innovation and musical identity. The electrification of control systems expanded creative possibilities, yet it also raised questions about the nature of the instrument itself. Was an organ with no mechanical connection between the player and the pipes still the same instrument? Debates of this kind reflect broader cultural anxieties about automation and mediation in the early twentieth century, – anxieties that were felt not only in music but in industry, labor, and communication technologies.

Electronics, Digital Technologies, and New Acoustical Paradigms (1930–2000).

By the mid-twentieth century, the worlds of acoustics, electronics, and digital computation were expanding rapidly, and organ builders found themselves navigating a landscape far removed from the craft traditions of earlier centuries. The trajectory from electropneumatic organs to fully electronic and later digital instruments was neither linear nor uniform; yet taken together, these developments reveal how deeply the organ has always been shaped by contemporary scientific knowledge.

The earliest major shift occurred with the invention of electromechanical tone generation. Laurens Hammond's first instruments, introduced in 1935, famously used rotating tonewheels and electromagnetic pickups to create stable waveforms. Although designed primarily as economically accessible alternatives to pipe organs, Hammond's machines became influential for reasons that went beyond cost or portability (Flynn, 1954; Werner & Abel, 2016). They demonstrated that the distinctive features of organ sound (steady-state tones, harmonic structures, and responsive control interfaces) could be produced through entirely different means.

This period also saw important advances in the scientific study of organ acoustics. Acousticians such as W. J. M. Rankine, later followed by Arthur Benade and others, examined the behavior of air columns in pipes using increasingly sophisticated experimental and theoretical tools (Marsden, 2013). Benade's *Fundamentals of Musical Acoustics* (1976) synthesized many decades of research, offering explanations of harmonic structure, pipe scaling, and resonator acoustics that previous generations of builders could only have approached empirically. Although much of this research addressed the physics of wind instruments more broadly, organ builders drew upon it, especially those working in large firms in Germany, the United States, and Japan. The renewed interest in historically informed performance in the latter half of the twentieth century (coupled with a revival of mechanical tracker actions), reflected not a rejection of science but a desire to apply new knowledge to historically grounded construction methods.

Parallel to these developments, postwar electronics opened new possibilities for sound generation. Companies such as Baldwin, Conn, and later Allen Organ Company experimented with vacuum tubes, oscillators, and frequency divider circuits (Rossing, 1975). These instruments (sometimes labeled "electronic organs"), occupied an ambiguous space between pipe organs and fully digital synthesizers. They often used loudspeakers to project sound, which immediately distinguished their acoustic presence from that of classical pipes, but they retained interfaces reminiscent of traditional organs. Technical literature from the 1950s and 1960s reveals how engineers adapted technologies from radio, radar, and early computing to create stable oscillators and efficient amplifier circuits. For example, Allen's 1971 introduction of the first commercial digital organ, based on digital sampling and microprocessor control, relied on innovations in semiconductor fabrication and digital memory that had emerged only a few years earlier (Riley, 2006).

Digital sampling represented a conceptual turning point. By recording real pipe tones and replaying them through digital circuitry, builders could imitate traditional acoustics with a degree of realism that analog oscillators never achieved. Although early systems required substantial compromises (limited memory, short loops, and a lack of dynamic nuance), they demonstrated the potential of computational approaches to organ design.

The material environment of the late twentieth century also influenced organ construction. The availability of advanced plastics, composite materials, and new adhesives changed workshop practices. PVC and ABS pipes appeared in educational and experimental instruments, valued for their stability and low cost. Carbon-fiber reinforcements were occasionally used in structural elements to reduce weight while maintaining rigidity. CNC (computer numerical control) tools increasingly found their way into organ workshops, enabling precise cutting of wood, metal, and plastic components. These machines, adapted from the manufacturing sector, allowed builders to standardize parts with unprecedented accuracy. The contrast with earlier centuries is striking: where Renaissance builders relied on hand tools and eighteenth-century builders on simple machine tools, late twentieth-century builders could draw on the same digital design and fabrication methods used in aerospace and automotive industries.

Through these developments, the organ remained connected to the technological ethos of each era. In the mid-twentieth century it intersected with electromechanical engineering; by the 1970s it absorbed techniques from digital computation; by the 1990s it incorporated advanced materials and numerical modeling. Yet despite these transformations, the instrument retained its historical identity, preserving a continuity that bridged craft traditions and scientific innovation.

Hybrid Organs, CNC Manufacturing, and the Contemporary Technological Landscape (2000–2025).

The early twenty-first century has been characterized by a fusion of mechanical, electrical, and digital technologies that would have been difficult to imagine even a few decades earlier. Organ building today exists in a hybrid space shaped simultaneously by historical scholarship, material science, computer engineering, and digital acoustics. This synthesis has led to new ideas about authenticity, sustainability, and technological heritage.

One of the most visible trends in recent decades has been the rise of hybrid organs, those that combine traditional pipe ranks with digital extensions or substitutes (Czajka-Giełdon & Kirschke, 2025). This phenomenon reflects practical, economic, and technological factors. The ability to reproduce certain timbres digitally allows institutions with limited budgets or space to expand the tonal palette of their instruments. High-quality digital stops, based on multichannel sampling or physical modeling, complement real pipes without requiring additional windchests or structural reinforcements. Companies such as *Allen, Rodgers*, and *Hauptwerk*-based manufacturers have pushed this integration further, providing systems in which digital and pipe components are regulated from a unified console. Scholarly commentary in journals such as *The Diapason* and *Organists' Review* has highlighted the practical challenges of maintaining historical tonal ideals while incorporating contemporary digital tools.

Parallel to this hybridization, CNC machining has reshaped workshop practices. The precision of CNC routers allows builders to produce windchests, keyboards, pallets, and structural components with repeatable accuracy. While the artistic aspects of voicing and tonal finishing remain largely manual, the foundational work of cutting and shaping parts increasingly relies on automated systems. This development mirrors broader trends in the crafts, where digital fabrication supports (but does not replace) human expertise. For example, modern reconstructions of historical instruments, such as the North German organs inspired by Schnitger, benefit from CNC-milled racks and templates that ensure structural fidelity (Crandall & Bush, 2013; Schneider, 2024; Thistlethwaite, 1999). At the same time, the delicate process of scaling, cutting, and finishing metal pipes still depends primarily on the hands and ears of skilled artisans.

Material science continues to influence construction choices. Concerns about environmental sustainability have shifted attention toward responsibly sourced timber and alternatives to tropical hardwoods traditionally used for keyboards and structural frames. Modern adhesives and sealants, based on polymer chemistry, offer stability and resistance to humidity that earlier glues could not provide. Metal pipe alloys remain largely tin-lead based, but some builders have experimented with alternative compositions to achieve specific tonal effects or improved durability. Research on corrosion-resistant materials, discussed in publications such as *Materials and Corrosion*, has found occasional application in organ maintenance and restoration, particularly for instruments exposed to fluctuating climate conditions.

The acoustic design of performance spaces has also changed. Whereas medieval and early modern organs were built for reverberant stone churches, many contemporary instruments are installed in concert halls, universities, and multipurpose venues. Acousticians and builders collaborate to model how sound will propagate in spaces with variable acoustic treatments. Digital simulation tools, adapted from architectural acoustics, help visualize reflections, diffusion, and reverberation times before construction begins. These methods, derived from the same scientific tradition that began with nineteenth-century acoustical research, represent an extension of the iterative relationship between organ building and acoustical science.

The digital revolution has further transformed interfaces and control systems. Modern combination actions are essentially computer-controlled memory systems that allow organists to preset registrations across thousands of levels. MIDI (Musical Instrument Digital Interface) integration enables organs to communicate with other electronic instruments, sequencers, and recording systems. Some builders experiment with gestural interfaces or touchscreen controls, though these remain secondary to traditional keyboards and stop controls for most performers. The debate between mechanical authenticity and technological innovation continues, but the presence of digital systems is now widely accepted as part of the practical toolkit of contemporary organs.

In parallel, digital-only organs (software-based systems using sampled or modeled sound) have grown increasingly sophisticated. Hauptwerk and other platforms allow for high-resolution sampling of historic organs, providing musicians with access to instruments that may be geographically distant or fragile (Czajka-Giełdon & Kirschke, 2025; Schneider, 2024). These systems raise new questions about preservation and authenticity. They function as a kind of digital organological record, preserving not only the repertoire but also the acoustic identity of instruments that may not be permanently accessible.

Taken together, these developments demonstrate that contemporary organ building is a fundamentally interdisciplinary practice. It intersects with digital engineering, architectural acoustics, materials science, conservation studies, and performance traditions. The organ remains a living, evolving instrument precisely because it adapts to the scientific and technological ecosystems within which it is built.

Discussion.

The Organ as a Mirror of Scientific and Technological Change.

Across more than two millennia, the organ has repeatedly absorbed, adapted, and repurposed scientific and technological innovations. This resilience raises broader questions about how technological systems evolve over long periods (Casson, 1905; Thistlethwaite, 1999). Unlike many artifacts whose relevance faded with shifts in scientific thinking, the organ retained its identity even as its internal mechanisms changed dramatically (Hopkins & Rimbault, 1877; Snyder, 2002). The hydraulis of Ctesibius, with its hydraulic regulator and bronze pipes, shares little mechanically with a twenty-first-century hybrid organ equipped with digital sampling and CNC-milled components. Yet the conceptual core (the controlled excitation of air to create sustained tone) provides continuity.

This continuity, however, can obscure the ways in which the organ has served as a site of scientific experimentation. In antiquity, it embodied Hellenistic knowledge of pneumatics and hydraulics; in the Middle Ages, it reflected advances in woodworking, metallurgy, and architectural acoustics; in the Renaissance, it became entangled with mathematical theories of harmony and mechanical precision; during the Industrial Revolution, it absorbed machine-tool practices, new materials, and pneumatic amplification; in the twentieth century, it intersected with electricity, electronics, and digital computation. Each phase of its development illustrates how scientific knowledge and material technologies enter into dialogue with existing cultural forms.

The organ also reveals how technological change is shaped by both scientific theory and hands-on experimentation. Builders often learned through a combination of inherited technique and iterative modification. Scientific treatises, when they appeared, offered explanations or new conceptual frameworks rather than direct construction manuals. For example, the acoustical principles described by Mersenne and later by Helmholtz did not dictate pipe construction, but they helped rationalize practices already familiar to voicers and builders. Conversely, empirical knowledge occasionally preceded scientific understanding, as in the long-standing workshop awareness of how pipe scale and cut-up height influence tone, – phenomena that received rigorous explanation only with the rise of acoustical science (Fabbri, 2007; Miller, 1913; Owen, Williams, & Bicknell, 2021).

Another important theme is the relationship between the organ and its architectural setting. Because organs are often built for specific spaces, their design inevitably reflects the intersection of acoustics, engineering, and spatial planning. This interplay became particularly visible in the Gothic cathedral, the nineteenth-century concert hall, and the modern multipurpose venue. In each case, the organ served as a technological response to a particular acoustic and architectural environment (Huntington, 2006; Landon, 1973; Quirk, 1957).

Finally, the organ provides a clear example of how mechanization and digitization do not simply replace earlier technologies but layer upon them. Mechanical tracker actions coexist today with electropneumatic and digital controls. Hand-voiced metal pipes coexist with digitally modeled stops. CNC fabrication coexists with traditional planing and hand carving. The organ thus represents a technological system that grows through accumulation rather than substitution. It does not discard older forms but redistributes them within new frameworks.

Conclusions.

The organ's two-millennia evolution demonstrates how a single class of artifact can continually absorb and reinterpret advances in scientific knowledge, materials, and engineering while retaining a recognizable structural identity. From the hydraulic regulators of the Hellenistic hydraulis to the electrically driven, digitally assisted instruments of the present, each major transformation in organ design coincided with shifts in wider technological paradigms. Pneumatics, acoustics, metallurgy, machine tooling, electrification, and digital computation entered organ building not as isolated innovations but as part of broader scientific cultures that shaped how builders understood air, motion, resonance, energy, and information.

Reconstructing this process shows that the organ did not evolve through simple replacement of older solutions with newer ones. Instead, its history is characterized by accumulation and reconfiguration: mechanical tracker actions coexist with electropneumatic and digital controls; empirically voiced metal pipes function alongside digitally sampled or physically modelled sounds; and handcrafted components now sit within assemblies shaped by CNC manufacturing and contemporary materials science. This layered structure reflects the persistence of deeply rooted craft traditions as well as the instrument's readiness to accommodate new scientific and technological frameworks.

The analysis also clarifies several conceptual gaps in previous scholarship. Earlier studies have documented individual periods, regional schools, or specific instruments, yet they rarely examined the organ in a continuous, long-duration narrative that links developments across antiquity, the medieval and early modern worlds, the industrial era, and the digital present. Likewise, while organology, acoustics, and STS research have each highlighted particular dimensions of the instrument, few works have treated the organ explicitly as a technological system whose subsystems co-evolve with scientific advances in pneumatics, acoustics, materials science, control engineering, and computation. By synthesizing these perspectives, the present article seeks to demonstrate that the organ's history is inseparable from the history of science and technology itself.

Understanding the organ in this way not only enriches the historiography of the instrument but also provides a model for studying other long-lived technological artifacts whose development spans multiple scientific revolutions. Future research might extend this approach by examining regional technological traditions in greater depth, comparing organ building with parallel developments in other acoustic or electromechanical systems, or analyzing how digital modelling and fabrication are reshaping contemporary concepts of authenticity and historical continuity. Viewed across its full historical arc, the organ stands as a uniquely instructive case of technological persistence, adaptation, and innovation, – an artifact in which scientific thought and material practice have been intertwined for more than two thousand years.

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Пневматика, акустика та цифровий звук: Орган в історії науки і техніки

Анотація. *У статті проаналізовано історичний розвиток органа як складної технологічної системи, розвиток якої відображає послідовні зміни в наукових знаннях, матеріалах та інженерних практиках від античності до цифрової доби. У дослідженні використовується комбінована методологія історичного текстового аналізу, вивчення археологічних та матеріальних свідоцтв, а також інтерпретації за допомогою технологічно-системного підходу, підкріпленого сучасними акустичними та інженерними дослідженнями. Результати показують, що кожен основний етап в історії органу відповідає певному науково-технічному середовищу. Елліністичний «гідравліс» розкриває раннє застосування пневматичного та гідравлічного регулювання, заснованого на механічних теоріях Ктесібія та описаного Вітрувієм, у той час як римські та візантійські адаптації ілюструють, як металообробка, деревообробка та емпірична акустика сформували ранній дизайн органу. У середньовічний період спостерігається перехід до великих дерев'яних конструкцій, удосконалення сплавів олова та свинцю та поява складних механізмів стеження, адаптованих до архітектурної акустики романських та готичних соборів. Епоха Відродження та ранній Новий час пов'язують створення органів з розвитком математичної акустики. Такі теоретики, як Царліно та Мерсенн, запропонували концептуальні пояснення висоти звуку, масштабування та гармонійної структури, які вплинули на практику роботи у майстернях. Під час промислової революції верстати, стандартизовані матеріали та пневматичні допоміжні пристрої сприяли безпрецедентному збільшенню розмірів, надійності та складності механізмів, тоді як акустична наука XIX століття, зокрема роботи Гельмгольця, прояснила фізичну основу звуку труби. Електрифікація кінця XIX і XX століть перетворила системи управління* *органом, розділивши пульт управління та труби, ввівши електромагнітні механізми та інтегрувавши орган у ширші електромеханічні мережі. Друга половина XX століття та початок XXI століття демонструють зростаючий вплив електроніки, цифрового семплювання, фізичного моделювання, виробництва на станках з ЧПУ та появу гібридних конструкцій органів, що поєднують традиційні труби з обчислювальною генерацією звуку. У сукупності ці результати показують, що орган розвивався не шляхом заміни старих технологій новими, а шляхом їхнього постійного накопичення, переосмислення та інтеграції в рамках змінних наукових парадигм. У статті робиться висновок про те, що двохтисячолітня історія органу є унікальним прикладом для розуміння довгострокової взаємодії наукових знань, інновацій у галузі матеріалів та технологічної спадкоємності.*

Ключові слова: *історія техніки; історія клавішних музичних інструментів; орган; історія музики; історія мистецтва*

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The history of the emergence, development and improvement of high-speed railways: Technical, socio-economic and cultural aspects

Abstract. *The article deals with a comprehensive historical and analytical study of the formation and evolution of high-speed railway transport as one of the key technological and sociocultural transformations of modern society. The aim of the article is to reveal historical patterns of formation, technical evolution and socio-cultural significance of high-speed railway transport in a global context. The authors aim to show how the desire for speed became not only an engineering challenge, but also a driver of economic, urban and civilisational modernisation. An interdisciplinary approach combining historical-technical, comparative and socio-economic analysi has been used. Such a combination is justified by the essence of high-speed railways.*

They are not just a transport technology, but a phenomenon that combines material engineering, state policy, the culture of speed, and human perceptions of space and time. For this reason, the logic of the study is not limited to a list of technical facts, but aims to show how an engineering idea gradually became a social reality. The source base includes peer-reviewed scientific publications, technical reports from railway companies, documents from international organisations, and contemporary research on the history of transport and engineering. The technical background of high-speed rail transport has been analysed since 19th-century railways to post-war projects of the mid-20th century, including Japan's Shinkansen system, France's TGV and Germany's ICE, as well as the subsequent development of a global high-speed railway network in China, Europe and other countries. The article combines technical, engineering, socio-economic, and cultural-civilisational approaches. It is shown that high-speed railway is not only an infrastructural phenomenon but also a social one, shaping mobility, urbanisation, regional integration, and environmental sustainability. The latest innovations of the 21st century: magnetic levitation, Hyperloop systems, and digitalisation, determining the transition to the era of energy-intelligent mobility have been considered separately. It has been concluded that the history of high-speed railway transport reflects the overall evolution of engineering thought, public policy and the culture of speed, which is transforming humanity's understanding of space, time and steady development.

Keywords: *high-speed raiwayl (HSR); transport modernisation; mobility; railway engineering; innovations; steady development*

Introduction.

In a modern world where pace of life and mobility have become key indicators of social and economic growth, the development of high-speed railway communication is becoming important not only from an engineering perspective, but also in terms of culture and civilization (Strelko, Solovyova, Berdnychenko, Kyrychenko, & Solovyova, 2023; Strelko, Toropov, Horban, Hrushevska, & Bernatskyi, 2024). The idea of speeding up transportations by railway transport is the driving force behind infrastructure modernisation, technological progress and government policy. In this article we examine the history of emergence, evolution, and improvement of high-speed railways (HSR), focusing on technical and engineering aspects (materials, structures, traffic systems) and socio-economic factors (government policy, impact on urbanisation, mobility, and the economy).

The term HSR usually refers to railway lines designed for commercial passenger service at speeds significantly higher than traditional railway systems (generally over 200 km/h) and using specialised infrastructure or upgraded systems.

The engineering and technological innovations underpinning high-speed railways are not just about increasing speed. This is a complex: improvement of railway infrastructure (tracks, sleepers, stabilization), optimization of train aerodynamics, new materials for carriages and bridge as well as tunnel structures, power supply and automated traffic control systems. At the same time, these changes are associated with large-scale capital investments, government programmes, international technology transfers and a change in established mobility models: from 'travel = journey' to 'travel = a functional component of the economy and megaregion'. For instance, empirical studies of Chinese cities show that the opening of HSR lines contributes to the concentration of investments, talents and technologies in cities connected to the network – that is, the railway becomes a factor in innovative agglomeration.

In this regard, historical research into the development of high-speed railways has great potential: it allows us to trace how railway transport was transforming engineering thought, what technological barriers were overcome, how infrastructure implementation policy influenced regional development, and how perceptions of time, space and mobility changed. This article proposes two components of the approach: first, technical-engineering (technologies, materials, structures); second, socio-economic (public policy, urbanization, mobility, economic impact).

The historical understanding of HSR development was shaped relatively late – only when the phenomenon itself had already become a reality for several leading industrial countries. The first serious historical and technical studies appeared in the 1980s and 1990s and were focused primarily on the Japanese experience. Roderick A. Smith's study "*The Japanese Shinkansen: Catalyst for the Renaissance of Rail*" (2003), is considered to be a landmark work. In this publication Shinkansen appears not only as a technological breakthrough, but also as a socio-cultural experiment. Smith showed that Japanese high-speed railway model grew out of a combination of technical rationalism and national discipline – two traits that transformed transport into a symbol of modernity.

At the same time, another direction of historical research focused on comparative analysis was being formed in Europe. The publications by Javier Campos and Ginés de Rus, "Some Stylised Facts about High-Speed Railway: A Review of HSR Experiences Around the World" (2009), summarized decades of experience in various countries and offered a structured outline of the stages of HSR development. The authors traced patterns of funding, political support, and social effects, thus laying the groundwork for further economic and historical researches. Their analytical model was continued by Moshe Givoni (2006) and Roger Vickerman (2018), who emphasised that the history of HSR is primarily a history of institutional evolution: each state adapted the technology to its own political and cultural contexts.

In the 1990s, there appeared works that for the first time considered high-speed transport in the context of politics and public administration. The article by James A. Dunn Jr. and Anthony Perl, "Policy Networks and Industrial Revitalization: High Speed Rail Initiatives in France and Germany" (1994), showed that the *Train à Grande Vitesse (TGV)* and *InterCity Experimental (ICE)* projects were not only the product of engineering genius, but also of political compromises between the government, industry and society. Further researches have expanded the scope of analysis to the level of spatial planning, highlighting the impact of HSR on the formation of a 'new geography' of Europe.

Studies devoted to the Chinese experience play a particular role in contemporary historiography. The World Bank report China's High-Speed Rail Development (Lawrence, Bullock, & Liu, 2019) describes the phenomenal transformation of China's transport system over two decades and analyses this process as a socio-engineering experiment that combined centralized management, large-scale infrastructure and state ideology of modernization. Despite a large number of scientific publications, contemporary historiography of high-speed railways remains focused on several established topics, primarily the Japanese *Shinkansen*, French *TGV*, German *ICE*, and Chinese *Fuxing*. These models are rightly regarded as benchmarks for technical and managerial development, but this focus narrows the analytical field. Other national experiences remain in the shadows, as do issues of the interaction between speed, culture and social transformation, which are increasingly emerging in contemporary humanities studies.

For this reason, new researches seeking to integrate the technical, economic and cultural history of high-speed railways are becoming particularly relevant. Their task is not only to reconstruct the sequence of engineering decisions, but also to reveal the deeper meaning of this phenomenon as part of civilizational experience. Viewing high-speed rail through the prism of cultural dynamics, government policy and global socio-economic shifts allows us to overcome a narrow 'technological' vision and raise questions about the role of speed as a symbol of modernity, mobility and time.

In this context, the presented article is a timely attempt to critically summarize previous historical models, compare key paradigms of HSR development in different regions of the world, and trace how technical innovation is transformed into the social and cultural code of modernity. It is aimed not only at filling gaps in scientific descriptions, but also at expanding the boundaries of the history of technology itself in the direction of interdisciplinary analysis, where engineering, economics and culture are considered as components of a single process of high-speed transport evolution.

The aim of this article is to identify historical patterns in the formation, technical evolution and socio-cultural significance of high-speed rail transport in a global context. The authors attempted to show how the pursuit of speed has become not only an engineering challenge, but also a driver of economic, urban and civilizational modernization.

Methodology.

This study is based on a combination of several approaches that are not usually found in a single work: historical, technical, socio-economic and cultural. Such a combination is justified by the very nature of high-speed railways. They are not just a transport technology, but a phenomenon combining material engineering, state policy, the culture of speed, and human perceptions of space and time. That is why the logic of the study is not limited to a list of technical facts, but seeks to show how an engineering idea gradually became a social reality.

The article's source base covers a wide range of materials, from technical reports and statistical reference books to historical monographs and contemporary publications in peer-reviewed journals. Documents from Japan National Railways, SNCF, Deutsche Bahn, CRRC, as well as analytical reports from the World Bank, International Union of Railways (UIC), European Commission, International Energy Agency (IEA), etc. have been used. These materials were supplemented by the works of transport historians, in particular Wolmar (2010; 2012), Urry (2007) and Virilio (2006). All this made it possible to combine technical and humanitarian perspectives and regard HSR not only as a system of rails and wheels, but as part of contemporary history.

The logic of the analysis was consistent. First, we sought to recreate the context in which the very idea of speed emerged in the industrial age: what 'speed' meant to 19th-century society and why it became a measure of progress. Next, we examine the technical breakthroughs that made new types of trains possible, from Japan's *Shinkansen* to France's *TGV*. At the same time, we analyse not only the engineering level, but also the political and economic logic of the states that invested their national prestige in high-speed lines.

Methodologically, the study is based on the principle of historicism, therefore each technical solution has been considered in its specific temporal and political context. Technology never exists outside society, and railways are no exception. Another important principle is consistency: every change in the speed or design of a train is considered as part of a broader network of changes – energy, urban, cultural. In this sense, the history of HSR is not a line of technical progress, but a sophisticated network of interdependencies.

The Soviet experiments with the *CR3-1000* and *ER-200* electric trains are seen as attempts to catch up with Western technological trends within a different economic model.

The scientific value of this work lies not so much in the discovery of new facts as in the attempt to combine technical history with humanities. High-speed railway is considered here as a 'text' – a kind of message of the era, which tells how humanman overcomes space, changes his ideas about time and creates a new geography of movement around himself. Such an approach allows us to see the evolution of HSR not only in drawings and speed records, but in a deeper sense, as the history of human desire to move faster, more efficiently and more intelligently.

Results and Discussion.

The Origins of High-Speed Transport (1830s–1930s).

The beginning of the railway era in the 19th century laid the technical, engineering, and socio-economic foundations for the further development of high-speed transport technologies. As early as in 1825, on the First Journey of Locomotion No. 1 line between Shildon and Stockton, George Stephenson demonstrated the efficiency of steam locomotive transport as a key factor in industrialization. Although this event was not directly related to the concept of high speed, it opened up new opportunities for the technical hunt for speed.

It is estimated that in 1854, commercial trains' speeds were around 60 km/h, several times faster than the efficiency of the mail coach services of a decade earlier. Thus, the railway became not just a means of transport, but an infrastructural form that transformed perceptions of space and time, mobility and communication between cities.

In technical terms, this period was characterized by several key engineering innovations: improvements in steam traction, improvements in track layout and geometry, widespread introduction of steel rails instead of cast iron ones, increased length and width of sleepers, and improved installation accuracy. All this contributed to increased speed and reliability of transportations. Thus, from the mid-19th century onwards, we can talk about technological dynamics that would later become the foundation for formalizing the concept of "high-speed railways".

While commercial operation of high-speed passenger lines was still a long way off, the practice of setting speed records appeared at the turn of the 19th and 20th centuries. For example, according to *UIC*, speeds of about 100 km/h were achieved by 1850. The German project is particularly noteworthy: in 1901–1903, during tests of an experimental electric carriage (three-system three-phase current), speeds of over 200 km/h were achieved, including 210 km/h in October 1903. This experimental speed was a significant technical breakthrough, but at the same time it revealed a number of limitations: the weakness of the track, the instability of the carriages, the inadequacy of curved sections and the high cost of electrification. In this respect:

• increasing speed requires a significant increase in curve radii, improvement of bogies and suspension, and stabilisation of the track;

• economic feasibility was low because materials, installation, and electrification required large capital investments;

• infrastructure and operational requirements (power supply, cooling, ventilation, maintenance) were not yet adapted to high-speed systems.

This stage can truly be considered a 'preparatory' stage for the emergence of HSR: it conducted technical verification of speed limits and identified engineering challenges that were later resolved in the following decades.

In addition to simple traction and rail facilities, the first decades of the 20th century gave an impetus to the development of specific technologies aimed at increasing speed: optimization of rolling stock design (smooth contours, streamlined noses), use of lighter materials (aluminium or alloy steel structures), improvement of suspension and bogies, electrification of lines, etc.

Although these methods have not yet been systematically implemented on commercial HSR networks, they have significantly changed the engineering culture of railways. For example, the German experimental *Schienenzeppelin*, proclaimed as the '*Zeppelin on Rails*' (see Figure 1). This train promised to start a new era in travel (Howard, 2022). It had a lightweight aluminium body and an aircraft propeller engine, enabling the Schienenzeppelin to set a new speed record for railways on 21 June 1931, travelling at around 230 km/h on the Berlin-Hamburg line in Germany.

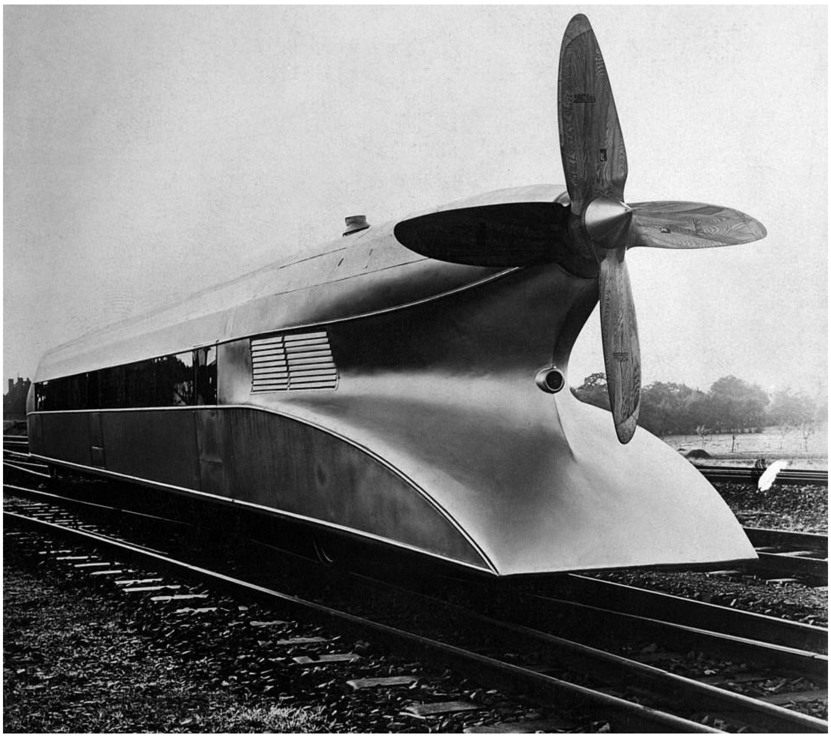

Figure 1. The train is seen on test rails in October 1930, when it achieved a speed of 93 miles per hour with 40 passengers on board (Howard, 2022).

The Daily Mail reported how it covered a distance of almost 290 kilometres in 1 hour and 44 minutes (Howard, 2022). The fastest train at the time could only cover this journey in three hours and 15 minutes. The record set by the *Zeppelin* ultimately lasted 23 years. Such experiments had a great impact: they showed that not only traction, but also design, streamlining, weight and air resistance become critical at high speeds. For the promising HSR, this meant: reduced weight, improved streamlining, a more rigid track, better suspension, and more precise balancing.

Technical prerequisites at the beginning of the development of high-speed railway transport were one component; socio-economic and institutional factors that shaped the demand for speed were no less important. In the 19th century, railways contributed to urbanization, the development of industrial centers, reduced delivery times for goods and passengers, and created new mobility opportunities.

Therefore, even in the pre-high-speed era, railways served to accelerate the economy, reduce distances between cities, and integrate markets. Industrial growth, population concentration in cities, and the need for a mobile workforce all created a strong incentive to reduce travel times. At the same time, governments and private railway companies were evaluating investments in the modernization of railway infrastructure, although not yet in a "high-speed" version.

International competitive dynamics should also be taken into account: countries that perceived railways as a symbol of modernity (e.g. France, Germany, Italy) were motivated to create faster routes as an analogue of industrial modernization and national prestige.

In the 1930s, there was a clearer transition to systems that can be considered the forerunners of modern high-speed railways. The *Fliegender Hamburger (Hamburg Flyer*) (Figure 2) was the first in a whole series of *Flying Trains* with which Deutsche Reichsbahn created an early high-speed rail network in the 1930s (DB Museum, n.d.). This made it an ancestor of today's *ICE*. The *Flying Trains* were diesel-electric railcars: a 12-cylinder Maybach diesel engine drove a generator, which in turn powered an electric motor. Engine and passenger seating were combined in the same coach – a principle that had proved unsuccessful with steam propulsion but was highly efficient with the new diesel engines. This made the train lighter and allowed higher speeds with lower energy consumption. In 1933, the *Fliegender Hamburger* express train between Hamburg and Berlin reached a speed of 160 km/h in regular service (Lambernd, 2024). This figure indicates that the engineering and institutional prerequisites were in place for the transition to speeds that had previously been considered fiction. However, full-scale operation of the HSR was not yet achievable: problems remained with infrastructure specialisation, safety, standardisation, capital investment and sustainable high-speed operation.

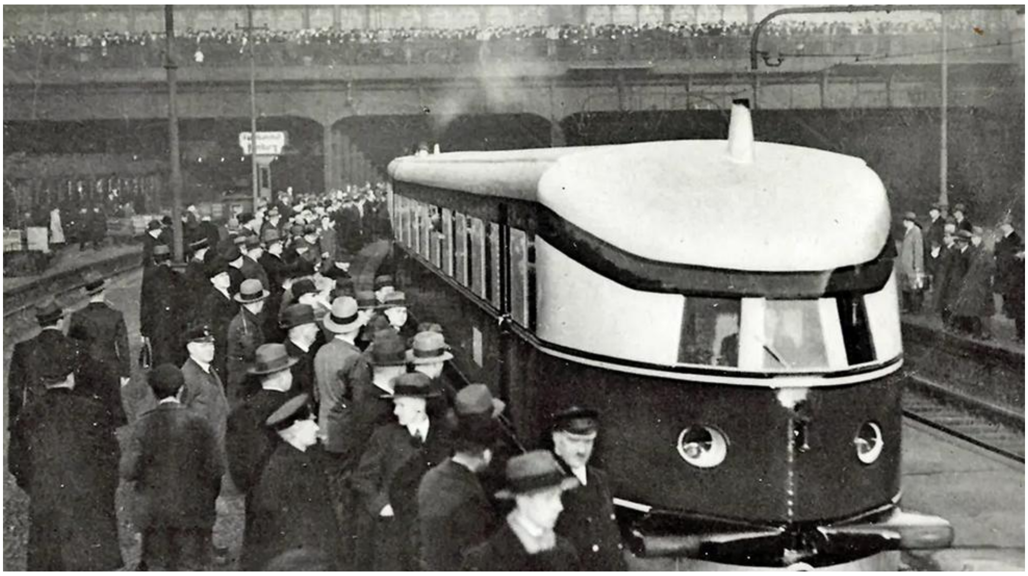

Figure 2. Fliegender Hamburger (Lambernd, 2024).

During this same period, experiments were conducted with electrification, lightweight rolling stock, aerodynamic designs, improved track quality, and control systems. Thus, it was the 1930s that formed the technical and social platform from which the HSR era would grow.

Thus, the period from 1830 to 1930 can be considered as the foundation for the further development of high-speed railway technology. Technological breakthroughs (from improvements in steam traction and track infrastructure to experiments with electrification, streamlining and materials) formed key technological elements. At the same time, socio-economic dynamics (urbanization, industrial development, population mobility, state modernization policy) created a demand for speed as an infrastructural value. It was at the turn of the 1930s that the formative phase began, from which the first systems closer to the concept of modern high-speed railways emerged.

Formation of High-Speed Railway Concept (1945–1964).

After the end of World War II, the global transport system found itself on the brink of change: infrastructure destruction, growing numbers of cars and air travel, urbanization, and accelerated economic growth. In this environment, the railway had to respond to new challenges: reducing travel time between cities, improving traffic reliability, and reducing operating costs.

In Western European countries and Japan, competition between different modes of transport was growing, putting pressure on railway administrations to modernize.

In engineering terms, this meant: increasing design speeds, switching to electrification, improving rolling stock and infrastructure designs (rails, sleepers, tracks with large curve radii), using lighter materials and streamlined shapes. According to the *UIC*, speeds of over 200 km/h were achieved in tests as early as the beginning of the 20th century, which in itself demonstrates technical feasibility, but did not mean commercial operation (International Union of Railways, n. d.). However, there were still significant barriers to the widespread introduction of such speeds, both technical and socio-economic.

After 1945, technological development of the railway system received a new impetus. European and Japanese engineers focused their attention on two areas: (a) adapting existing lines to higher speeds and (b) designing completely new routes and rolling stock focused on speed.

In Japan, for example, engineers from Japanese National Railways (JNR) studied Italian and French projects in the mid-1950s, attended electrical engineering conferences, and adopted the experience of alternating current switching for traction and track standardisation. This allows us to claim that the foundation of the modern HSR system was laid in the technical solutions of that period.

One of the important achievements was the improvement of the suspension and bogies: increased rigidity, stabilization of wave oscillations (“hunting oscillation”) at high speeds, improved rail connections, and all these engineering solutions were critical. For example, in France in the early 1950s, during tests of the *CC 7121* electric locomotive (Figure 3), a speed of 243 km/h was achieved on standard gauge track (Dumitru et al., 2024). This fact confirms that technological boundaries of motion have already been significantly shifted, but have not been adapted for mass operation yet.

Figure 3. *CC 7121* during the presentation of the Blue Ribbon, Paris-Gare de Lyon (Broncard, 1954).

Technical prerequisites required a political and institutional response, which became key in shaping the concept of HSR in the middle of the century. In Japan, the state, which suffered from oil dependency and the need for mobility (rapid movement of large passenger flows) between large megacities (the Tokyo-Osaka transport corridor), created a long-term programme for the development of high-speed railway transport. This policy included state funding, infrastructure standardization, and management models that allowed high-speed lines to be integrated into the overall network.

In Europe, as early as the late 1950s and early 1960s, the French, German and Italian governments began discussing national programmes to modernise rail transport as a means of competing with aviation and road transport, as well as a symbol of a modern state project (Cohen, 2014). For example, in France, Infrastructure Minister Edgard Pisani set a target in 1966 to reach a speed of 200 km/h on the Paris-Toulouse line. This meant not just engineering modernisation, but a state strategy aimed at changing mobility, economic planning and the symbolism of modernity.

The launch of high-speed systems required radical changes in infrastructure: the construction of new tracks with large curve radii, reinforced subgrades, special sleepers, straighter routes, bridges and tunnel structures that ensured high speeds without sacrificing safety. It should be noted that the use of conventional tracks with significant curves and very large gradients did not allow for a steady speed of 200 km/h or more.

The transition to alternating current traction (e.g. 25 kV 50 Hz), the use of lightweight materials (aluminium alloys, multi-car train designs) and aerodynamic streamlines were also important. These technologies began to be intensively implemented during this period: their development and tests took place in the 1950s and 1960s as a preparation for the introduction of commercial HSR lines. An example of this is the work of the French railways on the *TGV 001* prototype in 1969–1970, which, although beyond the exact date of the middle of the century, is already a result of the efforts of this period.

The culmination of this stage was the launch of Japan's first commercial HSR line, the *Tōkaidō Shinkansen* (Tokyo–Osaka), in 1964. At the time of launch, its trains were running at speeds of around 210 km/h. This step was not only a technical milestone, but also a symbolic one: it effectively opened a new era of railway transport. For Japan, it was part of a strategy of 'economic miracle', megaregion mobility, infrastructure standardisation and building a national brand through technology. Thus, the middle of the 20th century can be considered the period when the HSR concept was transformed from an engineering possibility into a national transport strategy.

The launch of HSR had significant socio-economic consequences: reducing logistical and time barriers between cities, stimulating urbanisation and economic agglomeration, increasing the share of passenger transport by railway, and changing the model from "trip = journey" to "trip = everyday mobility". For example, studies show that the development of HSR facilitates the concentration of technology and talent in cities connected to new corridors. In addition, the modernisation of railway infrastructure has become part of many countries' national modernisation policies, as a symbol of progress and modernity. It is not only a transport project, but also a tool for economic development, labour mobility and the spread of innovation.

The period of the middle of the XX century was critical for the formation of the HSR concept: technical and engineering solutions (suspension, electrification, infrastructure, rolling stock) and state policy (plans, standardisation, financing) created the basis for the emergence of the first commercial line. At the same time, this stage outlined the socio-economic transformations that accompanied high-speed movement, changes in mobility, the creation of agglomerations, and new economic corridors.

The Birth of the Shinkansen Era (1964–1980).

After World War II, Japan faced the dilemma of upgrading its transport system. On the one hand, the traditional railway was overcrowded; for example, the Tokyo–Osaka line carried over 80 million passengers annually, and the journey time exceeded six hours. On the other hand, motor and air transport developed slowly due to limited space and energy dependence. With the rapid urbanisation of the 1950s, the Japanese government prioritised railways as the basis for creating a "high-speed transport corridor" that would be part of its economic growth strategy (Gubbins, 1989).

The *Shinkansen (新幹線 – 'New Main Line')* concept was born as an engineering and government project headed by Hideo Shima, head of the technical research department of Japanese National Railways. It was his technical vision of creating a completely new standard gauge of 1,435 mm (as opposed to the narrow 1,067 mm), specialised for speeds of over 200 km/h, that became the key breakthrough. This decision made it possible to get rid of the limitations of the old dimensions and curve radii, ensuring smoothness, stability and aerodynamic efficiency of movement.

The *Tōkaidō Shinkansen line* (515 km, Tokyo–Nagoya–Kyoto–Osaka) was opened on 1st October 1964 and became the world's first example of the systematic implementation of HSR technology (Nakanishi & Kurauchi, 2021). Its *Series 0 Shinkansen* trains (see Figure 4) reached speeds of 210 km/h, more than 30% faster than any commercial trains at the time.

Figure 4. The ribbon-cutting ceremony for the launch of the *Shinkansen* bullet train between Tokyo and the Shin-Osaka station on Oct. 1, 1964, in Tokyo. (Flippen, 2014).

The main technical features included: a special double-track line with increased curve radii (minimum 2,500 m), which reduced centrifugal loads; continuous welded rails, which eliminated shocks and vibrations; concrete sleepers and elastic fastenings, which ensured track stability; 25 kV 50 Hz AC electrification, which provided high traction power; aluminium-steel bodies with reduced air resistance; an automatic train control system, which prevented collisions (Mochizuki, 2011; Mindur L., Zamiar, & Mindur M., 2024).

All this turned Shinkansen into a unique technical ecosystem, where the train, track, signalling and control operated as a single integrated system. It was this 'systemic approach' (as opposed to the isolated improvement of individual components in Europe) that became the key to the success of the Japanese model (International Union of Railways, n. d.).

The Shinkansen project was not only an engineering phenomenon, but also a political one. It was financed (approximately 380 billion yen, or ≈1 billion USD at the exchange rate of that time) through a combination of the state budget, World Bank loans (approximately 80 million USD) and JNR bonds (Shima, 1994).The World Bank considered the project to be "a model of transport planning that integrates economic feasibility and technological innovation" (World Bank Report No. P-408). The political support of Prime Minister Hayato Ikeda (the initiator of the 'Income Doubling Plan') made the Shinkansen a part of a broader national modernisation strategy. Its launch in October 1964 coincided with the opening of the Tokyo Olympics, which strengthened its international resonance and emphasised the symbolic significance of speed as a sign of a new Japan (Wolmar, 2012).

During its first five years of operation, the Tōkaidō Shinkansen carried over 100 million passengers, and by 1980, over 1 billion (Okada, 1994). The project's profitability increased so much that the capital investment was repaid in less than seven years. The main socio-economic outcomes: the formation of the "Tokai megalopolis" (a mixture of urbanised areas of Tokyo, Nagoya, Kyoto and Osaka); an increase in the share of domestic passenger railway transportations to 80%; the stimulation of regional integration and labour mobility; reduction of energy consumption by 30–40% compared to air transport.

In the 1970s, large-scale enhancements of rolling stock began: noise reduction, improved aerodynamics, transition to lighter designs and integrated traction systems (Figure 5). The development of the 100 series (1979) involved the application of aluminium bodies, air conditioning, reduced air resistance, and comfort for journeys over 250 km/h. At the same time, the network continued to expand: in 1975, the *Sanyō Shinkansen* line (Osaka–Fukuoka) was opened, and in the late 1970s, construction was started on new routes (Tōhoku, Jōetsu) (Smith, 2003; Takatsu, 2007; Nakanishi & Kurauchi, 2021).

Figure 5. Shinkansen bullet trains at a depot in Fukuoka in 1975 (Brasor & Tsubuku, 2014).

Japanese engineering thought shifted from "achieving speed" to "controlling speed": stability of movement, comfort, low noise levels, automated control systems – all this laid the technological foundation for the further development of global HSR systems (Figure 6).

Figure 6. The Shinkansen Lines (Nippon.com, 2025).

The success of the *Shinkansen* had a huge impact on other countries. France launched the *TGV* programme, relying on Japanese research into track stabilisation and electrification. Germany (*Deutsche Bundesbahn*) began developing experimental *InterCity Experimental* electric trains, which later led to the *ICE series* (Ebeling, 2005). Italy and Spain adapted the principles of control and technical monitoring. Thus, *Shinkansen* became a global standard – not only as a technology, but also as a concept of a "national infrastructure project aimed at maximum speed and safety". It was this Japanese experience that defined the further direction of development of European and Chinese HSR networks (International Union of Railways, n. d.).

The period from 1964 to 1980 became the turning point in the history of railway transport. *Shinkansen* incorporated engineering innovation, systematic planning, government policy and socio-economic effects into a single model. It was proved that speed and volume can coexist without affecting safety and stability if the system is built as a complex: infrastructure, energy, rolling stock, and management. From a technical point of view, it was the Japanese model that first created a true "high-speed ecosystem." From a socio-economic viewpoint, *Shinkansen* showed that transport could be a tool for national modernisation.

The Shinkansen became not just a technological project, but a symbol of the 20th century, combining engineering, economics and the culture of travel (Figure 7).

Figure 7. Crown prince Naruhito on board a *Shinkansen* bullet train in 1968 (Brasor & Tsubuku, 2014).

The European High-Speed Era (1980–2000).

Following the success of Japan's *Shinkansen* in the 1960s, European countries began to consider high-speed railway as a strategic tool for regional integration and engineering modernisation. In the early 1980s, the European railway sector was experiencing a crisis: aviation was actively conquering the market for medium distances (400–800 km), while road transport dominated in short trips. State-owned railway companies such as *SNCF* (France), *Deutsche Bundesbahn* (Germany), *FS* (Italy) and *RENFE* (Spain) needed a new technological response to achieve new heights of speed, comfort, schedule accuracy and economic efficiency.

It was at this time that the concept of the European HSR model was born, based on a combination of three principles:

1. integration into the existing railway network (unlike the isolated Japanese model);
2. state-private funding based on national budgets, the European Investment Bank and regional funds;
3. infrastructure compatibility between EU countries (unification of signalling standards, track gauge, traction systems).

The French *Train à Grande Vitesse* was the first European HSR system to enter into commercial operation. In 1981, the *Ligne à Grande Vitesse* (*LGV*) Sud-Est line (Paris–Lyon) was opened, where *TGV 001 series* trains operated at speeds of up to 260 km/h (International Union of Railways, n. d.; Lacôte, 2001). The *TGV* platform combined an aerodynamic body shape, 25 kV 50 Hz electric traction, continuous welded rails, reinforced suspension and a *TVM* (*Transmission Voie-Machine*) signalling system. A distinctive feature of the French approach was the use of a new high-speed track *LGV* compatible with traditional stations. This allowed to combine speed on highways with flexibility for access to city centres.

The success of the *TGV* was possible thanks to the political will of President Valéry Giscard d'Estaing and Prime Minister Raymond Barre, who supported the *SNCF* as a symbol of French technical leadership. During its first 10 years, the *TGV* carried over 100 million passengers, and from 1981 to 1990, its average speed increased to 300 km/h. Opening the *TGV Atlantique* (1989) and *TGV Nord* (1993) lines expanded services to Belgium, the Netherlands, and the United Kingdom via the Eurotunnel (International Union of Railways, n.d.). This had economic consequences. In particular, passenger traffic between Paris and Lyon increased by 65% during the first three years; tourism and business mobility were stimulated; and domestic air travel declined (some airlines were shut down). Thus, the *TGV* became not only a transport phenomenon, but also a social one: it linked the country into a single economic space and became a symbol of French technological nationalism (Perl, 2002).

In Germany, the *Deutsche Bundesbahn* engineering school developed the experimental *InterCity Experimental (ICE-V)* train in the 1970s, which broke the world record on 1 May 1988, reaching a speed of 406.9 km/h (Ebeling, 2005). This demonstrated the technical maturity of German engineering. Commercial operation of the *ICE 1* began in 1991 on the Hanover–Würzburg line. The *ICE* differed from the *TGV* in its modularity and multi-system capability: trains could operate under different types of electrification (15 kV 16.7 Hz AC / 25 kV 50 Hz AC) and automatically adapted to the signalling standards of other countries. The design featured lightweight steel alloys, soft swivel bogies, active suspension and a high level of safety. The German HSR model focused on integration with the regional network: *ICE* supplemented rather than replaced conventional trains. This enabled balanced regional development and decentralised mobility. The national strategy provided for co-financing of lands and the federal government. By 2000, the length of high-speed lines exceeded 1,100 km, and *ICE* became an integral part of Germany's transport policy (Perl, 2002; International Union of Railways, n. d.).

An Italian engineering school proposed an alternative solution, which involved increasing speed without building new tracks. The company *FIAT Ferroviaria* developed the *ETR Pendolino train* (1976), equipped with an active body tilt system that compensated for centrifugal force on curves and allowed the train to travel at speeds of 250 km/h on existing tracks (Lacôte, 2001).This technology was subsequently exported to Spain, the Czech Republic, Poland and Finland, and in the 1990s it was licensed by the company *Alstom. The Pendolino* solution had a strategic advantage for countries with difficult terrain and limited budgets: it demonstrated that the HSR effect could be achieved even on modernised old lines.

Spain became the next country to invest in HSR, opening the Madrid–Seville *AVE line* (1992) as part of the *Plan AVE 2000* national infrastructure development programme. The Spanish model combined French *TGV* technology with state funding and links to regional policy (Albalate & Bel, 2012).

In the United Kingdom, on the contrary, the development of HSR was slower. It was only in 1994 that the *Channel Tunnel Rail Link* (later *High Speed 1*) was opened, connecting London with the continent (Givoni, 2006). This was a key step towards the creation of a single European high-speed area.

At the same time, the *Trans-European Transport Networks* (*TEN-T*) initiative was launched in Europe to integrate national HSR systems into a single infrastructure network (European Commission, 1996). In the 1980s and 1990s, the main challenge was the compatibility of systems: different countries used different signalling standards (*TVM, LZB, ETCS*), traction voltage, dimensions and control languages. To solve this problem, in 1996 the EU initiated the development of a single standard, *ETCS* (*European Train Control System*), which became the basis for future integration (Lundström, Jäcker-Cüppers, & Hübner, 2003). From a technical point of view, it was during this period that new generations of rolling stock appeared: *TGV Atlantique* (1989) with speeds of up to 300 km/h; *ICE 2* (1996), which featured a modular design combining electric cars and locomotives; *Pendolino ETR 480* (1997), which had a fully digital tilting system. The introduction of these innovations allowed Europe to catch up with Japan and become the second centre of global HSR technology development.

High-speed railway became a key driver of urbanisation, tourism and economic integration. For example, after the launch of the *TGV Sud-Est*, 70% of business travel between Paris and Lyon shifted from air transport to the railways. In Germany, the *ICE* has contributed to the creation of a “knowledge corridor” between Munich, Nuremberg and Frankfurt, while in Spain, the *AVE* reduced the journey time between Madrid and Seville from 6 to 2 hours. Socially, HSR created a “space-time compression” effect by extending daily commuting zones to 200–300 km and forming “polycentric megaregions.” Economically, HSR strengthened the links between innovation hubs, universities and labour markets (Vickerman, 1997).

The period from 1980 to 2000 established Europe as the second global centre of HSR after Japan. The French *TGV* demonstrated the effectiveness of state technonationalism, the German *ICE* demonstrated engineering precision and integration, and the Italian *Pendolino* demonstrated innovative flexibility. Together, they formed the European school of high-speed transport, based on standardisation, energy efficiency and transport integration. The European HSR model became not only a technical project, but also a socio-economic one, demonstrating how infrastructure shapes the continent’s space and mobility.

Soviet Experiments with High-Speed Travel.

The idea of high-speed transport in the Soviet Union emerged independently of Japanese and European experiments, but within a different technical and political logic. Soviet science regarded high-speed trains not as a tool for market mobility, but as a manifestation of scientific and technological progress that demonstrated the “advantages of the socialist engineering school.” Since the 1960s, researchers into aerodynamics, rolling stock, and electrical systems for speeds exceeding 200 km/h have been started in the USSR. The development centres were the Central Research Institute of the Ministry of Railways, the All-Union Scientific Research Institute of Railway Transport (*VNIIZhT*), and factories in Riga, Kalinin, Kharkiv, and Leningrad.

Soviet experiments in the 1960s and 1970s were focused on creating laboratory electric trains to determine the limits of stability and safety at high speeds. In 1965, the *CR3-1000* train (based on the *ER-1* electric train) was tested on the Gorkyi Railway, reaching a speed of 185 km/h (VNIIZhT, 1966). In 1972, the Riga carriage works designed an experimental electric train, the *ER-200*, intended for speeds of 200–250 km/h (Figure 8). In 1973–1975, it set a record of 250 km/h on the Moscow–Leningrad section, exceeding the commercial performance of Europe at that time (VNIIZhT,1975). The main technical features of the *ER-200* are: aluminium car bodies with alloy frames; wheel sets with disc brakes; 3000 V DC power supply; aerodynamic shape of the main cars; regenerative braking system; improved noise insulation and comfortable interiors. These experiments did not become commercial, but laid the engineering foundation for subsequent developments and became direct analogues of the Japanese *Shinkansen 0*.

Figure 8. *ER-200 RVR* High speed train (Kirkland, 2019).

In the late 1970s and early 1980s, experiments with electromagnetic suspension and tube transport were carried out in the USSR. Projects of the Radio Technical Institute of the USSR Academy of Sciences envisaged the creation of magnetic levitation transport platforms moving in vacuum tubes at speeds of > 400 km/h. However, they remained at the experimental stage due to a lack of political priority and limitations of funding. Unlike in the West, where HSR was part of infrastructure mobility policy, in the USSR speed had ideological significance, namely, demonstrating technical might.

The researches of the *VNIIZhT* were financed through five-year plans and programmes of the USSR Transport Strategy. However, the lack of economic incentive (demand was planned rather than market-based), a shortage of currency to purchase components, and centralised management slowed down the introduction of HSR into serial production. Until the mid-1980s, the *ER-200* was operating on limited routes between Moscow and Leningrad, but due to track wear, energy costs, and service instability, the project was shut down in the 1990s (Westwood, 2001).

Soviet experiments show that the technical potential for high speeds has existed since the 1970s, but institutional, financial, and political factors determined the pace of its implementation. The USSR created a powerful engineering basis (*ER-200*, laboratory trains, magnetic levitation projects), but failed to transform it into a stable infrastructure due to its centralised economy.

China and the Global Era of High Speeds (2000–2020).

At the beginning of the 21st century, China became the main driving force in the field of high-speed railway transport. According to data from the International Union of Railways for 2024, in the last decade alone, China constructed a network with a length of 45,390 km, which is more than two-thirds of the global network with the length of 64,698 km. (Davenne, 2024, p. 5). The *Chinese High-Speed Railway* (*CHSR*) has become not only an engineering achievement, but also an element of the national strategy for economic development and spatial integration.

According to the *Medium- and Long-Term Railway Plan* (Zhou & Qiu, 2018), the Chinese government has set a goal of creating "eight vertical and eight horizontal railways (the so-called '8+8 network'") that will connect all metropolitan areas with a population of over 500,000 (Lawrence, Bullock, & Liu, 2019).

Such a scale is unique in the history of transport and was made possible by a combination of state planning, technology transfer and centralised funding. The reforms of the 1990s, initiated after the "*Reform and Opening-Up*" policy, created the conditions for large-scale infrastructure modernization (Wang, Strauss, & Zheng, 2021). After China's accession to the WTO (2001), the government decided to make high-speed transport a domestic market tool that stimulates consumption, employment, and technological independence.

The first HSR line was the *Qinhuangdao–Shenyang Passenger Line* (2003) – two-track electrified main line, allowing traffic up to 250 km/h (Tang & Sun, 2020). Later, in 2008, *Beijing–Tianjin Intercity* – was opened, the first full-fledged high-speed line designed for 350 km/h, which became the «technological testing ground» for the entire network). At the same time, the government approved funding through the State Railway Corporation (China Railway Corporation) and the Ministry of Finance. HSR infrastructure spendings from 2008 to 2020 exceeded $970 billion, equivalent to ≈ 1.2% of China's GDP each year (Lawrence, Bullock, & Liu, 2019).

In the early 2000s, China did not have its own high-speed technology, so it resorted to a licensed transfer model:

– *Siemens* (Germany) – platform *ICE 3* (*Velaro*);
– *Alstom* (France) – *TGV Duplex* technology;
– *Kawasaki Heavy Industries* (Japan) – *Shinkansen E2*;
– *Bombardier* (Canada) – *Regina X2000* (for tilting bodies).

Between 2004 and 2008, more than 100 agreements were concluded with these corporations in the amount of about 12 billion USD, with the condition of production localization at CSR and China CNR enterprises (Pepermans, 2020; Tang & Sun, 2020; Rui & Bruyaka, 2021).

Since 2011, China has introduced a fully localized *CRH380A* series (Tang & Sun, 2020; Yang, Qi, Li, & Wang, 2022), developed under license from the *Siemens Velaro*, but with improved aerodynamics, lighter bodies, and its own control systems (*CTCS-3*). In 2017, the production of the *Fuxing CR400AF/BF*, the first truly all-Chinese train designed for 400 km/h, was begun (CRRC Annual Report, 2018). The main technical features of the *Fuxing CR400AF/BF* were: a lightweight aluminum body, an aerodynamic "arrow" nose; a dynamic stabilization and noise reduction system; a GSM-R wireless communication system; and intelligent traction and braking control.

By 2020, China over 1,500 HSR railway junction had been in operation, with integration into urban metro networks and air transport. The track was standard (1,435 mm), concrete ballasted or slab track, which reduces vibration and maintenance costs (Watson, 2021; Zeng et al., 2022). The average design speed was 300–350 km/h, the minimum radius was up to 7,000 m. For safety, multi-level signaling systems *CTCS-2/3* (analogous to *ETCS*) are used.

The energy efficiency of *CHSR* is estimated to be 45–50% higher than that of air travel over the same distance (Lawrence, Bullock, & Liu, 2019). The system is supported through automated diagnostic centers that collect data in real time, a typical example of the transition to *Smart Rail 2.0.*

China's HSR has created a new geography of mobility. According to World Bank (Lawrence, Bullock, & Liu, 2019), 95% of China's population lives within a 50 km radius of the HSR station. Passenger traffic increased from 237 million (2009) to 2.3 billion (2019). In the 2010s, HSR provided ≈ 0.5% of GDP growth each year due to the agglomeration effect. Studies show that cities connected to HSR show 25–30% higher productivity, higher R&D investment and increased access to labor (Lawrence, Bullock, & Liu, 2019; Tang & Sun, 2020; Watson, 2021). Socially, HSR became a catalyst for second-level urbanization, namely, the emergence of accompanying cities around stations (HSR new towns), similar to the phenomenon of Japanese "economic corridors" (Miwa, Bhatt, & Kato, 2022).

China's "*One Belt strategy, One Road*" sees HSR as the infrastructural equivalent of «soft power», as a tool for diplomacy and export standards. China has become the second exporter of railway technology after France, and the company *CRRC* is the world's largest manufacturer of HSR rolling stock (Lawrence, Bullock, & Liu, 2019).

Despite the scale, the *Chinese HSR* has a number of challenges. Among which the most significant are the following: debt burden: the total debt of *China Railway Group* in 2020 exceeded 830 billion USD; uneven use: part of the lines in remote regions has an occupancy rate of < 50%; environmental consequences: electricity consumption and impact on land resources. However, in terms of efficiency, HSR remains the most environmentally friendly form of mass transport: CO_2 emissions per passenger kilometer are three times less than that of airplanes (International Energy Agency, 2019).

The Chinese era of HSR (2000–2020) marked a shift in the center of gravity of technological progress. China has demonstrated that in 20 years it is possible to create a large-scale, integrated, high-tech transport system that surpasses the historical counterparts of Europe and Japan. Three key lessons from the Chinese experience:

1.The synergy of state planning and technological localization ensures rapid scaling.

2.The integration of HSR into regional policy creates an economic effect of agglomerations.

3.Infrastructure as a strategic «soft force» forms a new geopolitical architecture.

China has become the world standard "of mass high-speed transport", combining engineering complexity, efficiency and social impact. It is this model in the XXI century determines the further direction of global development of HSR technologies.

Technological Innovations of the 21st Century: Maglev, Hyperloop, Environmental and Energy Efficiency.

After two decades of dominance of classic high-speed systems, a new phase began at the beginning of the 21st century, which was aimed at finding technologies capable of exceeding the limits of rail contact and increasing energy efficiency. This stage is often called the "post-HSR era", in which research is aimed at magnetic levitation, vacuum transport and automated control systems. The main goal of this stage is to increase the speed over 500 km/h without losing stability, noise reduction and reducing energy consumption (International Energy Agency, 2019).

Magnetic levitation (in English. *Magnetic Levitation, or Maglev*) eliminates contact between the train and the track: the «car floats» on a magnetic field created by electromagnets or superconductors. This reduces friction to a minimum, allowing speeds of over 600 km/h to be reached. There are two main technologies: EMS (Electromagnetic Suspension), when electromagnets in carts attract the wagon to the guide (*Transrapid system*, Germany); EDS (Electrodynamic Suspension), when induction repulsion between superconducting magnets and the guide is used (*SCMaglev* system, Japan).

The first commercial example was the *Shanghai Maglev Train* (opened in 2004), a joint project between Siemens and Transrapid International connecting downtown Shanghai to Pudong Airport (30 km in 7 minutes, max. 431 km/h) (Singh et al., 2023; Gieras, 2025). Transrapid technology uses a linear synchronous motor and a real-time deviation stabilization system. Although the operation proved reliable, the project proved expensive: the construction cost was more than USD 1.2 billion (Baohua, Huang, & Shunping, 2008).

The Japanese response was *SCMaglev* (*Superconducting Maglev*), created by the *Central Japan Railway Company* (*JR Central*). During the 2015 tests, the *L0 Series* train reached a speed of 603 km/h, setting a world record (Mindur L., Zamiar, & Mindur M., 2024). A plan for a commercial line called *Chūō Shinkansen* (Tokyo – Nagoya – Osaka) is to start operations in 2030s and trains are to move at an average speed of 500 km/h.

The idea of vacuum pipe transport was proposed by Robert Hutchings Goddard in the 1910s, but received its modern implementation in 2013, when Elon Musk presented the *Hyperloop Alpha concept* (Musk, 2013). *Hyperloop* is a capsule that moves in a sealed tube with reduced pressure (≈100 Pa), using magnetic levitation or an air cushion, reaching speeds of 1000–1200 km/h. In 2020, *Virgin Hyperloop One* (USA) conducted the first test with passengers (Nevada Test Site) at a speed of 172 km/h. *Zeleros* (Spain) is developing a European version with a self-contained compressor and a grid-independent drive (Lluesma, Arguedas, Hoyas, Sánchez, & Vicén, 2021). *TransPod* (Canada) and *Hardt Hyperloop* (Netherlands) are developing a common standard for certification (*European Hyperloop Centre,* 2023). Although *Hyperloop* remains an experimental technology, its developers position the system as an evolutionary successor to HSR, with a potential rate three times that of current maglevs.

Modern HSR, *Maglev and Hyperloop* technologies are aimed not only at speed, but also at reducing the carbon footprint. According to the International Energy Agency (International Energy Agency, 2019), the average CO_2 emissions for HSR are: 14 g/pass-km for electric trains; 42 g/pass-km for aviation; 68 g/pass-km for cars. *Maglev systems* consume ≈20–25 kWh per 100 km/pass, which is 30% less than medium-range aircraft (International Energy Agency, 2019). *Hyperloop* will potentially be able to reduce energy consumption to 8–10 kWh/100 km/pass thanks to the vacuum environment. The environmental advantage of high-speed transport is becoming crucial in the context of the European Green Deal (2019) and Paris Agreement (2015) climate targets, which provide for a 90% reduction in transport emissions by 2050.

The current development of HSR is complemented by intelligent control systems that provide unmanned traffic, track monitoring, energy saving and passenger flow management. AI-driven Predictive Maintenance and IoT Sensors technologies are used in the networks of China, Japan and the EU. Using machine learning algorithms to manage traffic allows you to reduce energy consumption by up to 15 %. Thus, "smart rail" combines HSR with digital control systems, which creates a new quality of mobility – automated, environmentally friendly, efficient. The stage of the 21st century demonstrates that the technological evolution of rail transport is moving from mechanical improvement to an energy-intelligent system, where speed, efficiency and sustainability form a triune goal. *Maglev* and *Hyperloop* remain expensive experiments for now, but they indicate the direction of further development:

– reduction of physical limitations (contact, friction);
– full electrification and renewable energy;
– real-time digital transport management.

In the coming decades, the technological integration of magnetic levitation, vacuum tubes and artificial intelligence could create the third revolution in the history of high-speed transport – after the emergence of HSR (1960–1980) and its global expansion (2000–2020).

Cultural and Civilizational Dimension of Speed.

From the very beginning of the development of railway transport, speed was not only an engineering characteristic, but also a symbol of the era. In the 19th century, it meant “the mechanical overcoming of space”, in the 20th century, “the mechanization of time”, and in the 21st century, it became a metaphor for global interaction. Speed in the cultural dimension has become a reflection of how society perceives progress, risk and space (Virilio, 2006; Schivelbusch, 2014). HSR is not only a technology, but a form of social organization of time. It changed the perception of distance and mobility: traveling between cities ceased to be an event because it became part of everyday life.

In the 20th century, HSR became a “cultural icon” of modernism. The Japanese *Shinkansen* is a symbol of the “economic miracle”; the French *TGV* is a symbol of technonationalism; the German *ICE* is a symbol of engineering precision; the Chinese *Fuxing* is a sign of state power. As Urry (2007) notes, infrastructure shapes a “new sociality of mobility,” where people measure the world not in kilometers but in minutes (Figure 9). Speed becomes cultural capital: countries demonstrate technological maturity through the speed of their trains. This creates the phenomenon of “railway aesthetics,” through the architecture of stations, the design of trains, and public perceptions of comfort and the future.

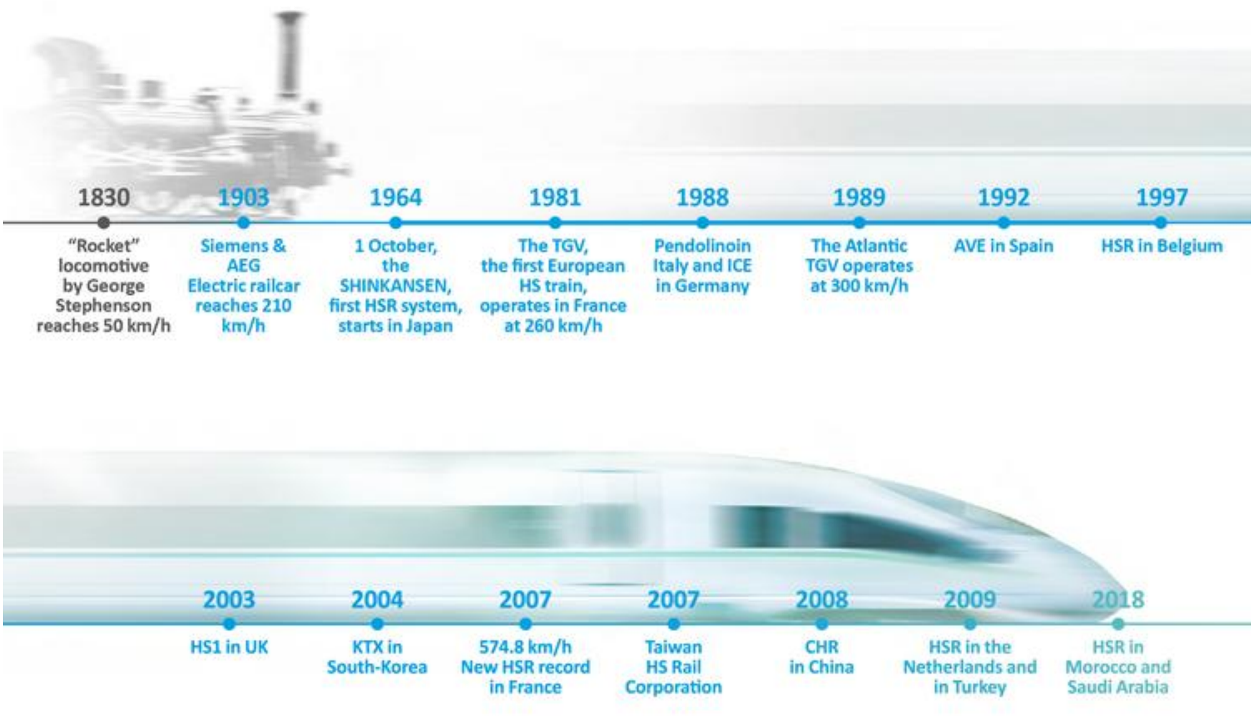

Figure 9. High-Speed Rail History (International Union of Railways, n.d.).

In a socio-economic sense, HSR has become a tool for shaping regional labor and knowledge markets. It reduces the space between cities, creating “megalopolises” and agglomerations of a new type (e.g. Tokyo–Osaka, Paris–Lyon, Madrid–Barcelona, Beijing–Shanghai). This phenomenon was called time–space compression – «space-time compression» (Harvey, 2008). At the same time, HSR contributed to the balancing of spatial disproportions. It became a catalyst for the development of secondary cities, which, thanks to convenient connections, received investments and new opportunities. In China, for example, HSR stimulates the growth of medium-sized cities (Suzhou, Zhengzhou), and in France it is the formation of «*TGV-towns*» (Reims, Le Mans).

In the 21st century speed enters a new dialogue with the concept of sustainable development (SDGs 9, 11, 13). HSR is positioned as one of the most environmentally friendly modes of transport: energy consumption per passenger kilometer is half that of aviation, and CO_2 emissions are three times lower (International Energy Agency, 2019). Modern researches consider the railway as a key component of the «green transformation», combining speed, mass and energy efficiency. The ethical dimension of speed, it is also an issue of accessibility: speed must serve not only as a privilege of large cities, but as an instrument of social cohesion. Therefore, the latest programs of the EU and China provide for the creation of HSR networks that cover peripheral regions, ensuring a balance between economic efficiency and justice.

High-speed railway, it's not just transportation, it's the language of engineering, reflecting the spirit of the times. Its architecture – is stations with glass and steel; its rhythm – is continuity of movement; its meaning – is overcoming the distance between the center and the periphery. Speed technology is becoming a form of culture that combines engineering, economics, and time philosophy. Thus, the idea of speed, born from technical experiments of the 19th century, went through the path to the global cultural code of the 21st century. The high-speed railway became a mirror of technical evolution and at the same time a projection of the human desire to overcome space and time. Its history — is the history of engineering, state will and the culture of modernity, which together form the face of modern civilization.

Conclusions.

The history of the development of HSR, it is at the same time the history of engineering evolution, public policy and changing ideas about space and time. Over the course of two centuries, humanity has transformed the railway from a means of transportation into a system that shapes the economic, social and cultural dynamics of civilization.

From steam locomotives of the 19th century to the *Shinkansen, TGV* and *Fuxing* electric trains, the development of the HSR was driven by the continuous search for a balance between speed, safety and efficiency. The key engineering milestones were:

– application of jointless track and automatic control system (Japan, 1960s);
– aerodynamic design and high-voltage electrification (France, 1980s);
– digital signaling *ETCS* and *CTCS* (Europe, China, 2000s);
– emergence of magnetic levitation and vacuum transport systems (XXI century).

HSR proved that transport infrastructure could be a tool for economic growth and regional integration. In Japan, *Shinkansen* stimulated the development of the Tokaido metropolis; in France, *TGV* became a factor of decentralization; in China, HSR created a network of urban agglomerations generating up to 0.5% of GDP each year. The economic effect of HSR is seen in the reduction of transport costs, increased labor productivity, the development of tourism, as well as in changes in the spatial structure of the country by creating "knowledge corridors" and new urban centres.

Speed in railway transport has turned into a cultural symbol of modernity. HSR embodies society's desire to overcome the limitations of space, and its architecture, design and rhythm of movement became part of the visual culture of the industrial age. The phenomenon of "space-time compression has changed the perception of distance, thanks to which a person began to think about geography in minutes, not kilometers.

In the 21st century, high-speed transport is entering the phase of energy-intelligent mobility: combining electrification with renewable energy sources; application of artificial intelligence for traffic control and maintenance; implementation of contactless systems (*Maglev, Hyperloop*). These trends shape the «third mobility revolution», in which the main thing is not so much to increase speed as to optimize time, energy and space.

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Історія появи, розвитку та вдосконалення швидкісних залізниць: Технічні, соціально-економічні та культурні аспекти

Анотація. *У статті представлено комплексне історико-аналітичне дослідження становлення та еволюції високошвидкісного залізничного транспорту як однієї з ключових технологічних і соціокультурних трансформацій модерного суспільства. Метою статті є виявлення історичних закономірностей формування, технічної еволюції та соціально-культурного значення високошвидкісного залізничного транспорту у глобальному контексті. Автори прагнуть показати, як прагнення до швидкості стало не лише інженерним викликом, а й рушієм економічної, урбаністичної та цивілізаційної модернізації. Застосовано міждисциплінарний підхід, що поєднує історико-технічний, порівняльний та соціально-економічний аналіз. Таке поєднання виправдане самою природою високошвидкісних залізниць. Вони не є лише транспортною технологією, це явище, що поєднує матеріальну інженерію, державну політику, культуру швидкості й людське уявлення про простір і час. Саме тому логіка дослідження не зводиться до переліку технічних фактів, а прагне показати, як інженерна ідея поступово перетворювалась на соціальну реальність. Джерельну базу становлять рецензовані наукові публікації, технічні звіти залізничних компаній, документи міжнародних організацій та сучасні дослідження з історії транспорту й інженерії. Проаналізовано технічні витоки швидкісного руху від залізниць XIX століття до післявоєнних проєктів середини XX ст., зокрема японської системи Shinkansen, французької TGV та німецької ICE, а також подальше розгортання глобальної мережі високошвидкісного залізничного транспорту у Китаї, Європі та інших країнах. Стаття поєднує* *техніко-інженерний, соціально-економічний і культурно-цивілізаційний підходи. Показано, що високошвидкісна залізниця виступає не лише інфраструктурним, а й соціальним феноменом, який формує мобільність, урбанізацію, регіональну інтеграцію та екологічну стійкість. Окремо розглянуто новітні інновації XXI ст. – магнітну левітацію, системи Hyperloop та цифровізацію, що визначають перехід до епохи енергоінтелектуальної мобільності. Зроблено висновок, що історія високошвидкісного залізничного транспорту є відображенням загальної еволюції інженерної думки, державної політики та культури швидкості, яка трансформує уявлення людства про простір, час і сталий розвиток.*

Ключові слова: *високошвидкісна залізниця (HSR); транспортна модернізація; мобільність; залізнична інженерія; інновації; сталий розвиток*

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Silent cinema as a technological system: Infrastructure, innovation, and institutialization (1890–1930)

Abstract. *This article examines the period from the 1890s to the late 1920s as the stage in which cinema became a stable technological and social institution through the interaction of five key developments: the system introduced by the Lumière brothers, the emergence of permanent movie theaters, the formation of the first film studios, the* *introduction of early special effects, and the appearance of recognizable film genres. The study applies a historical-technological approach combining the analysis of primary technical documentation, architectural evidence, studio infrastructure records and recent international scholarship to identify how concrete innovations in mechanics, optics, illumination, chemical processing and exhibition design reshaped moving-image production and spectatorship. The results show that the Lumière system established reproducible projection standards and enabled the international circulation of moving images; that permanent movie theaters created controlled visual environments, standardized viewing schedules and supported longer narrative formats; and that early studios introduced regulated lighting, set construction and division of labor, transforming filmmaking into an industrial process. The analysis also demonstrates that special effects expanded representational capacity through multi-exposure, miniature models, masking techniques and color processes, and that genres emerged in relation to technological conditions, with comedy tied to variable cranking, melodrama to controlled lighting, epic and adventure films to large-scale staging and horror to manipulated architectural space and shadow. These developments collectively contributed to the global diffusion of cinema, the formation of shared cultural reference systems and new modes of social interaction grounded in collective spectatorship. The conclusion suggests that further research should investigate how these foundations supported the later adoption of synchronized sound and influenced the long-term evolution of audiovisual media.*

Keywords: *visual arts; cinematography; history of cinema; technological modernization; visual effects*

Introduction.

The period from the 1890s to the late 1920s marks the stage in which cinema moved from a short-lived novelty to a stabilized technological and social institution. This transformation was driven by a set of developments that occurred in sequence yet interacted with one another: the work of the Lumière brothers as the first large-scale system for producing and exhibiting moving images; the emergence of permanent movie theaters that standardized projection conditions and spectatorship; the formation of the first film studios, which organized production through controlled lighting, architectural design and division of labor; the introduction of the first special effects, which expanded what could be represented on screen; and the appearance of recognizable film genres, which structured production methods, distribution strategies and audience expectations. Recent research shows that these developments were closely linked to advances in mechanics, optics, electrical illumination, chemical processes, architectural planning and equipment standardization (Beugnet, 2022; Strickland, 2024; Toporivska, Dyadyukh-Bogatko, Belinska, Balan, & Patsaliuk, 2025).

The technological contributions of the Lumière brothers established cinema as a reproducible system rather than a demonstration device, enabling films to circulate internationally. The spread of permanent theaters in cities such as Paris (1895), Berlin (1895), London (1896), and later New York, Chicago and Tokyo created new public environments in which moving images were presented under controlled visual conditions. The establishment of studios in Paris (Pathé, Gaumont), New York and later Los Angeles (Biograph, early Hollywood facilities), Berlin (UFA complexes), Moscow and St. Petersburg, and Tokyo (Nikkatsu) introduced continuous production workflows supported by lighting systems, mechanical staging and laboratory processing. Early special effects in France, Britain, the United States and Germany demonstrated that cinema could depict transformation, space, scale and motion beyond direct photography (Abel, 1996; Brownlow, 1984; Kobel, 2007). Genre differentiation emerged when these technical capacities aligned with production specialization and audience familiarity, resulting in identifiable forms such as slapstick comedy, melodrama, adventure epics, horror and early science fiction (Schuchman, 2004; Withall, 2014; Frymus, 2023).

These developments did not merely shape film style – they altered patterns of spectatorship, labor organization, cultural circulation and public space (Zhu, 2021; Lewis, 2024; Peng, 2024). Cinemas contributed to new habits of collective viewing, evening leisure and urban social mixing. Studios created new professions linked to modern technical work. Special effects supported changing perceptions of science, technology and imagination. Genres standardized viewing expectations across different regions and markets. By the end of the silent era, cinema had become the first globally circulating medium supported by shared technological specifications and synchronized audience practices, laying the groundwork for the later introduction of synchronized sound.

This article analyzes these developments through a technological and social lens, drawing on research that reassesses early cinema not only as an artistic formation but as a system shaped by material innovation, industrial organization and societal transformation. The aim is to clarify how the key milestones, – the Lumière system, the first movie theaters, the first film studios, the first special effects, and the emergence of genre cinema, – collectively reshaped the medium and contributed to wider changes in modern societies during the late nineteenth and early twentieth centuries.

Methodology.

This study approaches the development of cinema from the 1890s to the late 1920s by examining how concrete technological changes shaped the ways films were produced, distributed and viewed. The research is based on the principle that cameras, projectors, lighting systems, film stock, studio design and exhibition environments were not secondary to film history but were central factors influencing the evolution of the medium. The methodology therefore focuses on material evidence, technical documentation and historical analyses that describe how equipment functioned, how production practices were organized and how viewing conditions were constructed during the silent era.

The source base consists of recent academic publications that analyze early cinema through technological, industrial and societal perspectives. These studies provide information about the development of projection mechanisms, the formation of permanent movie theaters, the establishment of studio infrastructure, the refinement of special effects techniques and the emergence of film genres linked to equipment capabilities and production workflows.

Comparative analysis plays an important role in the methodology. The study examines how cinema developed in different regions, including Western Europe, the United States, the Russian Empire and Soviet Union, Japan, India, Australia and parts of South America and North Africa, and considers how variations in electrification, industrial manufacturing, urbanization and access to imported technology resulted in distinct trajectories. This comparative approach makes it possible to distinguish between developments driven by global technological standardization and those arising from local social, economic or infrastructural conditions.

The methodology also investigates how cinema intersected with broader societal transformations, such as changes in labor organization, urban leisure patterns, public gathering practices and new modes of visual perception. By analyzing the Lumière system, permanent theaters, early studios, special effects and genre formation as interconnected developments, the study treats the silent era as a technologically consolidated phase rather than a preliminary stage overshadowed by the later introduction of synchronized sound.

Overall, this methodological framework enables the article to interpret early cinema as a technological system embedded in the modernization processes of the early twentieth century. It supports an understanding of cinema as both a technical and social institution whose influence extended beyond entertainment into communication, cultural circulation and everyday life.

Results and Discussion.

The Lumière Brothers as a Technological Starting.

The Lumière brothers occupy a central position in the early development of cinema because they introduced not only a recording device but a complete, technically unified system for producing, duplicating and projecting moving images. Recent research (Lipton, 2021a; Vaniuha, Kyreia, Lemishka, Spolska, & Patron, 2024; Toporivska, Dyadyukh-Bogatko, Belinska, Balan, & Patsaliuk, 2025) emphasizes that the cinematograph represented a significant technological integration: it combined camera, printer and projector into a single mechanism that used perforated 35 mm film stock and an intermittent movement system that ensured stable image registration. This configuration allowed films to be manufactured in multiple copies, transported across long distances and projected repeatedly without recalibration. The Lumière company's existing industrial infrastructure for photographic materials enabled large-scale production of both equipment and film stock, which facilitated the rapid spread of screenings beyond France.

The first public screenings in Paris in December 1895 were followed within months by presentations in London, Brussels, Vienna, Madrid, St. Petersburg and New York. Studies (Lipton, 2021a; Gibson, 2022; Strickland, 2024) show that Lumière operators traveled with standardized projection units, screens and printed programs, creating consistent viewing conditions in cafés, theaters, exhibition halls and other enclosed environments. These screenings introduced a new form of collective spectatorship structured around fixed seating, controlled illumination and synchronized attention. Strickland (2024) links this mode of presentation to broader changes in urban social life, including emerging leisure patterns, regulated public time and new forms of visual concentration associated with industrial modernity. The subjects of Lumière films (factory workers, city streets, transportation systems, domestic routines) reflected contemporary technological transformation and framed cinema as a medium that documented everyday life shaped by mechanization. The appeal of these films lay in their ability to visualize processes that audiences recognized from their own surroundings, reinforcing cinema's association with modern labor, mobility and urban scale. At the same time, the limitations of the cinematograph (short reel length, absence of synchronized sound and reliance on hand-cranked motion) stimulated subsequent innovation, encouraging filmmakers to develop editing practices, longer narrative formats and improved projection systems.

The international circulation of Lumière equipment also influenced the emergence of local film cultures (Şerban, 2016; Gibson, 2022; Toporivska, Dyadyukh-Bogatko, Belinska, Balan, & Patsaliuk, 2025). Screenings in Asia, North Africa and Latin America between 1896 and 1900 introduced moving images in regions where electrification, urban architecture and entertainment infrastructure were unevenly developed. In several cities, Lumière screenings preceded the installation of permanent theaters and contributed to public interest in modern technologies more broadly. In some areas, these screenings intersected with existing performance traditions, shaping distinct paths of cinematic adoption.

The significance of the Lumière brothers therefore lies not only in their chronological priority but in their role in establishing cinema as a reproducible and distributable technological system. Their work created expectations regarding image stability, projection conditions, audience arrangement and commercial circulation. It also linked cinema to the broader technological and social transformations of the late nineteenth century, positioning moving images within the dynamics of industrial production, urbanization and global communication. As later developments (permanent movie theaters, studio production, special effects and genre formation) took shape, they did so within a framework first defined by the Lumière system and its rapid international diffusion.

The First Movie Theaters and the Technological Stabilization of Exhibition. The transition from temporary screening spaces to permanent movie theaters began within a few years of the Lumière screenings and played a central role in transforming cinema into a regular and technically standardized form of public entertainment. The first permanent cinema generally identified in Europe, the "Salon Indien" at the Grand Café in Paris, began operating regular paid screenings in late 1895, but it was soon followed by dedicated venues adapted specifically for projected moving images. In 1896, the Alhambra and the Empire Theatres (Figure 1) in London incorporated fixed projection equipment (Hirsch & O'Rourke, 2017; Raisbeck, 2018), and by 1901 the Warwick Bioscope Theatre in London was operating as a year-round cinema. In Germany, the first purpose-built venue, the Wintergarten in Berlin, adapted its stage for ongoing projection in 1896 (Narath & Guttmann, 1966), while fixed cinemas began to proliferate after 1905, particularly in industrial cities such as Hamburg and Munich (Bergfelder, Carter, Göktürk, & Sandberg, 2020). Research Brockmann (2010) show that by 1910 Germany had more than 1,000 registered cinemas, many operating with standardized projection booths and regulated seating environments.

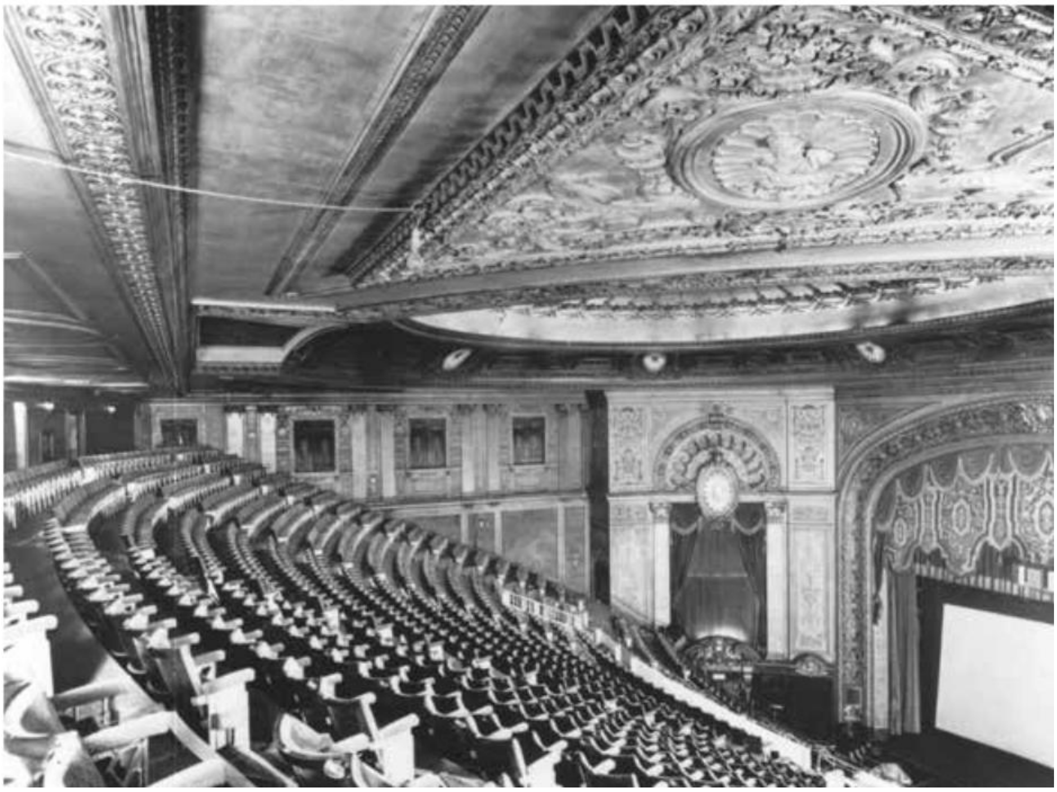

Figure 1. The grand and sumptuous Empire Leicester Square (Raisbeck, 2018).

In the United States, permanent movie theaters emerged slightly later but expanded more rapidly. The Vitascope Hall in New Orleans (1896) and the Nickelodeon in Pittsburgh (1905) are frequently cited as early examples (Labosier, 2004), but that nickelodeons operating between 1905 and 1907 created the first nationwide exhibition system. By 1910, more than 10,000 nickelodeons were operating across the country, supported by improved carbon-arc illumination, enclosed projection booths and standardized rental distribution (Allen, 1979). The introduction of electrically driven projectors allowed larger auditorium sizes, and by the 1910s urban centers such as New York, Chicago and San Francisco saw the rise of "movie palaces," whose architectural scale reflected cinema's integration into commercial entertainment infrastructure.

Outside Europe and North America, the development of permanent cinemas followed different timelines shaped by colonial, economic and technological conditions. In Japan, fixed cinemas appeared in Tokyo and Osaka by 1903, initially combining projected images with live benshi narration, reflecting the coexistence of imported technology and established theatrical culture (Standish, 2006; Bernardi & Ogawa, 2021). The Japanese cinemas adopted standardized projection speeds later than Western venues because of the persistence of manual cranking techniques. In the Russian Empire, permanent cinemas emerged in major cities such as St. Petersburg and Moscow around 1907, spreading more slowly into provincial regions due to limited electrification (Stites, 1992; Pryt, 2022). After 1917, state priorities influenced cinema distribution, and by the early 1920s urban centers operated fixed projection facilities while rural exhibition relied on portable setups.

On other continents, cinema infrastructure developed unevenly. In Australia, permanent cinemas appeared in Sydney and Melbourne by 1906 (Allen, 2025), and by 1911 the continent had a circuit-based exhibition system supported by imported projectors and film stock. In Mexico, Buenos Aires and Rio de Janeiro saw permanent cinemas by 1907–1908, reflecting strong urban commercial sectors (Burns, 2013; Navitski, 2013). In Africa, fixed cinemas emerged first in colonial port cities such as Cairo, Alexandria and Algiers, mainly between 1906 and 1912, while in sub-Saharan regions cinema often remained itinerant until the 1920s. In India, Calcutta and Bombay hosted permanent cinemas by 1907, with Burns (2013) linking their growth to electrified commercial districts and railway connectivity.

The spread of permanent theaters had several technological consequences. Standardized projection booths reduced fire risk associated with nitrate stock; regulated illumination allowed films to be shown consistently regardless of time of day; and fixed seating and sightline arrangements encouraged longer films and more complex narratives. Cinemas also facilitated the adoption of consistent frame rates, reducing flicker and stabilizing image rhythm. These developments contributed directly to changes in production: studios began making films of predictable length because theaters required regular programming. Distribution practices also evolved, since permanent cinemas demanded continuous supply rather than occasional novelty.

The societal impact of these venues was equally significant. Cinemas became central urban meeting places, offering inexpensive leisure accessible to women, workers and young people. The theaters contributed to new public behaviors, including evening socializing, mixed-class gathering and collective spectatorship (Burns, 2013; Hirsch & O'Rourke, 2017; Peng, 2024). The darkened auditorium and synchronized viewing experience shaped patterns of attention associated with modernity and mechanized time. As cinemas spread geographically, they linked diverse populations through shared visual content, contributing to the early globalization of cultural experience.

By establishing stable exhibition conditions, permanent movie theaters transformed cinema into a predictable and repeatable social practice. They provided the infrastructure needed for longer films, narrative coherence and industrial expansion. This stabilization shifted the center of innovation toward production, where the emergence of the first film studios introduced systematic methods of creating moving images and further consolidated cinema as a technological and cultural system.

The First Film Studios and the Industrialization of Production.

The emergence of the first film studios between the early 1900s and the early 1920s marked a decisive transformation in how moving images were created. While early films were shot outdoors using available light, the establishment of dedicated studio spaces made it possible to regulate illumination, control exposure and organize production as a continuous, predictable process. The first glass-enclosed studios appeared in France around 1902–1903, with the Pathé and Gaumont facilities in Paris often cited as early examples (Ghertman & Hadida, 2005; Jacobson, 2015). These studios used large glass roofs and adjustable shutters to diffuse natural light and reduce harsh contrast, and that this architectural innovation enabled longer shooting days and improved image consistency. By 1907, Pathé operated what historians consider the first vertically integrated studio system, complete with its own film laboratories, set construction workshops, and distribution arm, allowing the company to produce hundreds of films annually for international markets.

In the United States, the Biograph studio in New York constructed a rooftop glasshouse stage in 1906, and by 1910 studio production was shifting to California, where more consistent sunlight complemented expanding artificial lighting systems (Jacobson, 2015). The establishment of studios in Los Angeles, including the early facilities in Edendale and later in Hollywood, reflected both technical and economic considerations. By the mid-1910s, American studios had adopted electric arc and incandescent illumination, allowing interior shooting independent of weather conditions. This drove the expansion of feature-length films and more elaborate staging, supported by the division of labor among camera operators, lighting technicians, set builders and laboratory specialists.

In Germany, the development of studio infrastructure followed a different trajectory (Kreimeier, 1999; Brockmann, 2010). The early Berlin studios of companies such as Deutsche Mutoskope & Biograph and Messter-Film experimented with artificial lighting earlier than many of their European counterparts (Blom, 1995). After the formation of Universum Film AG (UFA) in 1917, Germany built some of the most advanced studio complexes of the era, including the Tempelhof and Neubabelsberg facilities (Kreimeier, 1999). The these studios incorporated sophisticated lighting grids, large-scale stage architecture and precision optical equipment, enabling the stylized visual environments associated with German Expressionist cinema (Bergfelder, Carter, Göktürk, & Sandberg, 2020). The technical capabilities of these studios (particularly their ability to control shadow, scale and architectural distortion) had a direct influence on cinematic aesthetics and helped define a national style recognized internationally.

In the Russian Empire, early studio activity began in St. Petersburg and Moscow around 1908, but expansion accelerated after 1917 when the Soviet state nationalized production (Stites, 1992; Nebesio, 2009). While resources were more limited than in Western Europe or the United States, Soviet studios emphasized editing and montage because they lacked extensive lighting and set-construction capacity. The material conditions of production (shortages of stock, limited artificial lighting and restricted access to imported equipment) shaped the development of montage theory and the technical experimentation of the 1920s. As a result, Soviet innovation occurred less in scenic construction and more in mechanical manipulation of filmed material.

In Japan, the first permanent studios appeared in Tokyo and Yokohama by 1909–1910, operated by companies such as Yoshizawa and later Nikkatsu after its consolidation in 1912 (Ruot, 1932; Bernardi & Ogawa, 2021). These studios adapted imported cameras and projectors but retained staging practices rooted in kabuki and shinpa theater, leading to hybrid production methods. Research Standish (2006) show that Japanese studio development was shaped by limited access to imported lighting equipment, resulting in slower adoption of electrically lit interiors and continued reliance on natural light well into the 1910s.

The industrialization of film production had several broad consequences. First, it increased the scale and speed of filmmaking, allowing companies to produce films continuously rather than sporadically. Second, it created new professions, including lighting engineers, lab technicians, carpenters, costume specialists and camera assistants. Third, it contributed to the emergence of standard narrative structures, since continuous production required predictable story formats suited to distribution schedules. Finally, it transformed cinema into an exportable industrial product, contributing to early global media circulation.

The establishment of the first film studios therefore marked a shift from artisanal experimentation to industrial organization. It provided the technical and logistical framework within which longer films, narrative clarity, repeatable performance styles and recognizable genres could emerge. With production aligned to industrial principles, filmmakers began to explore new visual possibilities, leading directly to the invention and refinement of the first special effects, which expanded the representational capacity of the medium and reshaped audience expectations.

The First Special Effects and the Expansion of Screen Possibilities.

The development of the first special effects between the late 1890s and the 1920s expanded what cinema could represent and played a crucial role in shifting moving images from simple visual records to a medium capable of depicting transformation, fantasy and phenomena that could not be captured directly. While Georges Méliès is frequently associated with the origins of screen illusion, recent researchs (Coleclough, 2022; Ioan, 2023; Kim, 2025) shows that early special effects emerged from a wider set of technological practices including stop-camera substitution, reverse motion, double exposure, matte blocking and scale miniatures. Méliès began using substitution splicing after 1896 at the Théâtre Robert-Houdin studio in Paris, where controlled lighting and fixed camera placement made it possible to align multiple exposures accurately. The these effects depended on stable tripod-mounted cameras and perforated film stock that allowed multiple passes without frame drift. His later productions, such as *Le Voyage dans la Lune* (1902), used painted sets, smoke effects and mechanical stage devices, illustrating how theatrical stagecraft merged with emerging cinematic optics (Figure 2).

Figure 2. Georges Méliès, image from *Le Voyage dans la Lune* (1902 as cited in Ioan, 2023).

In Britain, special effects developed through different technical conditions. Filmmakers associated with Hepworth and G. A. Smith experimented with reverse motion and masking techniques between 1898 and 1903, producing films in which objects assembled themselves or figures appeared and disappeared. Research Lipton (2021b) notes that these effects relied on precise camera registration and laboratory techniques that ensured consistent exposure across multiple passes. In the United States, Edwin S. Porter used matte work and miniature models in films such as *The Life of an American Fireman* (1903) and *The Great Train Robbery* (1903), combining staged and documentary footage. The American effects development was accelerated by the availability of industrial optical equipment and the emergence of professional film laboratories by the 1910s.

German cinema developed a distinctive approach to effects based on architectural distortion, lighting manipulation and optical filters. Films associated with German Expressionism (including works produced at the UFA studios after 1917) used painted perspectives, angled constructions and controlled shadow to create environments that appeared psychologically charged rather than physically realistic. Research (Kreimeier, 1999; Brockmann, 2010; Bergfelder, Carter, Göktürk, & Sandberg, 2020) attributes these effects to the advanced lighting grids and precision lenses available in Berlin studio complexes, which made it possible to shape contrast and depth deliberately. These techniques influenced not only fictional cinema but also stage design, advertising graphics and visual culture more broadly, demonstrating the permeability between cinematic technology and other fields.

Color manipulation formed another dimension of early effects (Burns, 2013; Lipton, 2021b). Tinting and toning became widespread by the 1910s, with blue signifying night, amber for interiors and red for fire or danger. The practices to chemical processes that altered the film emulsion rather than the image content, allowing color to be applied after editing. More advanced systems followed: Kinemacolor appeared in Britain in 1908, using alternating red and green frames projected with a synchronized filter wheel, while Technicolor introduced subtractive dye-transfer methods in the United States beginning in 1916. The systems required precise mechanical alignment and laboratory calibration, making color not only an aesthetic choice but a technical achievement that depended on engineering accuracy and industrial capacity.

Special effects also appeared in scientific, educational and military films. High-speed photography, microcinematography and time-lapse imaging were used in laboratories to document chemical reactions, mechanical stress, biological growth and ballistic trajectories (Blom, 1995; Ioan, 2023). The applications contributed to cinema's legitimacy as a research tool and linked the medium to scientific modernity. These uses demonstrate that effects were not restricted to fantasy but helped visualize processes otherwise invisible to the human eye.

The societal impact of special effects was substantial. Audiences were introduced to representations of flight, outer space, microscopic life, industrial power and supernatural transformation – subjects aligned with technological aspiration and cultural fascination with progress (Bergfelder, Carter, Göktürk, & Sandberg, 2020; Kim, 2025). The early effects contributed to new ways of imagining modernity, reinforcing public interest in science, exploration and mechanical innovation (Coleclough, 2022; Ioan, 2023). Furthermore, effects-driven films supported the emergence of screen genres such as fantasy, science fiction and adventure, encouraging distribution strategies based on spectacle and novelty.

By the late 1920s, special effects had become integrated into studio practice, supported by dedicated technicians, laboratory specialists and optical units. Their technical requirements shaped camera design, lighting systems, film stock composition and projection standards. As a result, effects work contributed directly to cinema's industrialization and to the expansion of its expressive and commercial potential. With representational capacity widened, cinema could support more differentiated narrative forms, leading to the development of recognizable genres that organized production, distribution and audience expectations.

The Emergence of Genre Cinema as a Technological Outcome.

The appearance of recognizable film genres between the 1910s and the late 1920s was closely connected to the technological conditions under which films were produced, edited and exhibited. Although genres are often described as narrative or cultural classifications, studies (Kobel, 2007; Jacobson, 2015; Bergfelder, Carter, Göktürk, & Sandberg, 2020) emphasize that the formation of genre categories was driven by mechanical constraints, equipment capabilities and production workflows. Films came to be identified as comedy, melodrama, adventure, horror, historical epic or science fiction not simply because they shared themes, but because specific technologies enabled distinctive visual rhythms, staging practices and performance styles that audiences learned to recognize and anticipate.

Comedy provides one of the clearest examples of how technology shaped genre identity. Variable cranking speeds and uneven projection rates produced accelerated motion, contributing to the characteristic kinetic exaggeration associated with slapstick. This effect depended on standardized projection speeds adopted in permanent theaters after 1908, which made under-cranked footage appear comically fast (Montgomery & Wisdom, 2022). Physical stunt work relied on wide-angle lenses and deep focus, enabling action to be captured clearly without rapid cutting. In the United States, studios in Los Angeles and later Hollywood developed dedicated stunt teams and reinforced sets, reflecting the growing technical demands of comedic filmmaking.

Melodrama developed in parallel with advances in lighting, lenses and set construction. The introduction of artificial studio illumination around 1907–1912 made it possible to control contrast, highlight facial expression and shoot interior scenes consistently. This close-up shots depended on improved lens precision and faster emulsions, which allowed emotional emphasis and contributed to melodrama's characteristic intensity. Tinting and toning further reinforced emotional coding, with colors applied to signal mood and narrative transitions. These technical factors made melodrama one of the dominant genres in Europe and North America during the 1910s.

Adventure films and historical epics emerged where production infrastructure could sustain large-scale staging. In the United States, the growth of studio backlots and outdoor sets after 1912 enabled crowd scenes, battles and expansive landscapes. Research (Allen, 1979) links the rise of these genres to logistical capacity, including costume manufacturing, transport coordination and camera mobility. In Italy, early epics such as *Quo Vadis?* (1913) and *Cabiria* (1914) drew on large studio complexes in Turin and Rome, supported by architectural resources and mechanically operated tracking systems (Schenk, 2024). In Germany, UFA's studio facilities enabled monumental set construction, contributing to historically themed spectacles that circulated internationally.

Horror and Expressionist cinema developed largely in Germany during the 1910s and 1920s, shaped by controlled lighting systems, optical filters and stylized architectural design (Kreimeier, 1999; Brockmann, 2010; Bergfelder, Carter, Göktürk, & Sandberg, 2020). This films relied on precise shadow shaping and perspective distortion, techniques made possible by advanced lighting grids and lens manufacturing. The result was a distinctive genre defined by visual deformation rather than narrative violence. These stylistic effects influenced international cinema and contributed to later sound-era horror conventions.

Science fiction and fantasy emerged where special effects capabilities had matured. Films that depicted flight, space travel, futuristic cities or supernatural transformation depended on double exposure, miniature models, matte compositing and early color systems. Studies (Burns, 2013; Coleclough, 2022; Ioan, 2023) note that these genres appeared in France, the United States and Germany first because these industries possessed laboratories capable of precise optical alignment. The expansion of these genres reflected both technical skill and public fascination with technology, aviation, astronomy and industrial modernity.

Genre development differed across global regions due to local technological conditions. In Japan, the coexistence of imported cameras and traditional theater influenced jidaigeki (period drama), which relied on stylized acting and slower cutting rhythms. In the Soviet Union, limited studio resources and strong editorial practices fostered genres defined by montage, collective struggle and industrial themes, rather than spectacle or fantasy. In India, early studios combined mythological narratives with simple effects and outdoor shooting, reflecting both cultural continuity and constrained infrastructure. The genre differences reflected disparities in electrification, film stock supply, projection standards and labor organization.

By the late 1920s, genres had become essential to production planning, distribution scheduling and audience expectations. Theaters programmed films according to genre because projection conditions (illumination, auditorium size and musical accompaniment) varied with different types of content (Anderson, 1987; Carli, 1995). Distribution companies marketed films internationally using genre labels that required minimal translation, facilitating global circulation. Genre cinema thus emerged as a technological and industrial system that structured how films were made, circulated and understood. With genre formation established, cinema became a medium capable of standardization and worldwide dissemination. The next stage of development involved the integration of these industrial and stylistic systems into a global network of production, distribution and exhibition, laying the groundwork for cinema to become the first mass medium with internationally coordinated technological standards.

Integrated Impact on the Global Development of Cinema.

By the 1910s and especially by the 1920s, the combined effects of the Lumière system, permanent movie theaters, industrialized studio production, special effects techniques and genre differentiation produced a technological and organizational framework that enabled cinema to develop as the first globally circulating mass medium. The decisive factor in this transformation was the standardization of equipment, formats and exhibition conditions. The widespread adoption of 35 mm perforated film stock, consistent projection apertures and increasingly regulated frame rates meant that films could be shipped between countries and projected without mechanical modification. This compatibility preceded similar international harmonization in radio transmission, sound recording or household electrical systems, positioning cinema as a technological forerunner in global media integration.

Distribution networks expanded in parallel with these standards. By 1915, American distributors were circulating films across Latin America and parts of Asia, while European companies such as Pathé supplied prints to North Africa, the Middle East and Eastern Europe. This film rental systems, introduced first in the United States and then adopted elsewhere, allowed theaters to program new material weekly, creating synchronized viewing rhythms across regions. The result was a coordinated flow of visual content that linked geographically distant populations through shared imagery and narrative forms.

At the same time, cinema influenced and was shaped by different socioeconomic environments. In industrial centers such as Berlin, Chicago and Tokyo, theaters became focal points of urban culture, supporting nightlife economies and influencing commercial advertising, fashion and behavioral norms. In colonial contexts such as India, Egypt and West Africa, cinema functioned both as a tool of cultural importation and as a catalyst for emerging local production. In the Soviet Union, cinema was designated a strategic instrument of communication after 1917, and its distribution networks expanded accordingly, though unevenly across rural territories. These variations demonstrate that while cinema's technological base was increasingly standardized, its social functions were shaped by political and infrastructural conditions.

The expansion of cinema also altered patterns of literacy and perception. Whereas printed texts required reading proficiency, film communicated visually, enabling mass audiences (including children, recent urban migrants and populations with limited formal education) to engage with complex narratives. This accessibility reshaped cultural participation, contributed to new modes of collective spectatorship and accelerated the formation of shared visual reference points across different social groups. At the same time, the technological conditions of projection (darkened auditoriums, fixed seating and synchronized attention) encouraged forms of concentrated perception associated with modern industrial time.

By the end of the silent era, cinema had become a globally coordinated technological system supported by standardized materials, mechanical specifications, distribution logistics and audience expectations. These developments created the platform upon which synchronized sound could later be introduced. Electrical amplification, optical soundtracks and new architectural acoustics built directly on the infrastructure established during the silent period. Thus, the integrated impact of the foundational developments discussed in earlier sections positioned cinema not only as a cultural form, but as a technological network that reshaped communication, leisure, industrial organization and social life on an international scale.

Long-Term Societal Consequences.

By the close of the 1920s, the technological, industrial and cultural transformations that had shaped silent cinema had already begun to alter broader patterns of social life, communication and collective experience. The cinema influenced society not only through narratives and stars, but through the technological structures that organized spectatorship, labor, memory and public space. The spread of permanent movie theaters created new forms of urban gathering and standardized leisure schedules tied to fixed screening times, reinforcing rhythms associated with industrial working hours. Cinemas also functioned as mixed social environments in which women, young workers and recent migrants participated in public cultural activity, contributing to changing norms of visibility, mobility and social interaction.

The industrialization of film production introduced new professions and reorganized labor practices. Camera operators, lighting technicians, set designers, laboratory workers and projectionists formed specialized workforces whose skills paralleled developments in electrical engineering, optics and chemical processing. These occupations reflected the increasing technical complexity of modern industry and contributed to the professionalization of media work. Furthermore, the international circulation of films linked distant audiences through shared reference points, contributing to early forms of global cultural familiarity long before broadcast radio or television.

Cinema also reshaped perception and visual literacy. The concentration required in darkened auditoriums, the sequencing of images and the synchronization of collective attention encouraged new habits of focused looking. The expansion of special effects and imaginative visual representation contributed to new conceptions of scientific possibility, exploration and technological progress, influencing popular understandings of aviation, astronomy and mechanization.

In political and educational contexts, cinema became a tool for shaping public opinion and transmitting information. The governments, reform movements and industrial organizations used film to communicate reforms, promote public health initiatives and document infrastructure projects. The ability to display moving images to large audiences made cinema an early instrument of mass communication, predating the widespread adoption of sound reproduction and radio broadcasting.

With the emergence of recognizable genres, audiences developed expectations and interpretive skills that facilitated shared cultural frameworks. Comedy, melodrama, adventure, historical epics and horror became reference systems that structured emotional response and social meaning. As these genres circulated globally, they contributed to early forms of cultural standardization, even as local variations persisted. Meanwhile, the stability of projection systems, film stock formats and distribution networks made cinema one of the first technologies to synchronize cultural experience across continents.

By creating new forms of spectatorship, labor organization, communication and shared visual reference, silent-era cinema helped establish the foundations upon which later audiovisual media developed. The introduction of synchronized sound in the late 1920s built directly on the technological infrastructure and audience habits formed during the silent period. These long-term consequences suggest that the history of early cinema is inseparable from the history of modernization, urbanization and global communication. Understanding the silent era as a technologically driven phase clarifies its enduring impact on media systems, cultural practices and social life, and points to future research directions in archival reconstruction, material analysis and digital restoration that continue to reveal how early cinema shaped the modern world.

Conclusions.

The analysis of cinema's development from the 1890s to the late 1920s confirms that the silent era should be understood as a period in which moving images became a coherent technological, industrial and social system. Rather than viewing early cinema as a preliminary stage awaiting later refinement, the study shows that this era produced the fundamental structures that determined how film would operate as a medium throughout the twentieth century. The Lumière system established the technical conditions for reproducibility and circulation; permanent movie theaters created stable environments for collective spectatorship; early studios introduced organized production based on controlled lighting, architectural planning and division of labor; the first special effects expanded the visual and conceptual boundaries of screen representation; and genre formation linked production practices with audience expectations and distribution mechanisms. These developments did not occur independently but reinforced one another, resulting in cinema's integration into urban culture, labor organization, patterns of leisure and emerging forms of mass communication. By the end of the 1920s, cinema functioned as a standardized international medium capable of synchronizing cultural experience across geographically and socially diverse populations. The findings therefore indicate that the silent era represents a decisive phase in the history of technology, during which film became both a modern industrial product and a shared cultural institution, shaping the foundations upon which sound cinema and later audiovisual media were built.

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The authors declare no conflict of interest.

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Німе кіно як технологічна система: Інфраструктура, інновації та інституціоналізація (1890–1930)

Анотація. *У цій статті розглядається період з 1890-х до кінця 1920-х років як етап, на якому кінематограф став стабільним технологічним та соціальним інститутом завдяки взаємодії п'яти ключових подій: системи, створеної* *братами Люм'єром; появи стаціонарних кінотеатрів; утворення перших кіностудій; впровадження ранніх спецефектів; появи кіножанрів. У дослідженні застосовується історичний підхід, що поєднує аналіз первинної технічної документації, архітектурних свідчень, документації про студійну інфраструктуру та сучасні міжнародні дослідження, щоб виявити, як конкретні інновації в механіці, оптиці, освітленні, хімічній обробці та дизайні кінопоказу перетворили виробництво та глядацьку аудиторію. Результати показують, що система Люм'єр встановила відтворювані стандарти проекції і сприяла міжнародному поширенню зображень, що рухаються. Стаціонарні кінотеатри створювали контрольоване візуальне середовище, стандартизували розклад переглядів та підтримували більш довгі оповідальні формати. Перші студії впровадили регульоване освітлення, конструкцію декорацій та поділ праці, перетворивши кіновиробництво на промисловий процес. Аналіз також показує, що спецефекти розширили можливості репрезентації завдяки мультиекспозиції, мініатюрним моделям, технікам маскування та колірним процесам, а жанри виникали залежно від технологічних умов: комедія була пов'язана зі змінним звучанням, мелодрама – з керованим освітленням, епічні та пригодницькі фільми маніпуляцією архітектурним простором та тінями. Ці досягнення в сукупності сприяли глобальному поширенню кінематографу, формуванню загальних культурних систем відліку та нових способів соціальної взаємодії, що ґрунтуються на колективному глядацькому сприйнятті. На закінчення слід зазначити, що подальші дослідження повинні вивчити, як ці основи сприяли подальшому впровадженню синхронізованого звуку та вплинули на довгострокову еволюцію аудіовізуальних медіа.*

Ключові слова: *візуальні мистецтва; кіномистецтво; історія розвитку кінематографа; технологічна модернізація; візуальні ефекти*

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