



Evolution of the Industrial Revolutions and International Law: from mechanization to the regulatory challenges of the 4.0 Revolution

¹María Stephania Aponte García, ²Gabriel Andrés Arévalo-Robles, ³Alexander Romero-Sánchez

¹PhD Candidate in Law at Universidad Libre de Colombia, Master in Constitutional Law, Lawyer. Full-time Professor at Unidad Central del Valle del Cauca (UCEVA), Tuluá, Valle, Colombia. Email: maponte@uceva.edu.co. ORCID: <https://orcid.org/0000-0003-2642-2896>. Corresponding Author.

² PhD in International Studies, University of the Basque Country (Universidad del País Vasco/Euskal Herriko Unibertsitatea). Official Master's Degree in International Studies (UPV/EHU). Master's Degree in Decentralized International Cooperation (UPV/EHU). Lawyer, Universidad Libre. Sociologist, Universidad Nacional. Currently serves as National Director of Research, Universidad Libre. Email: gabriel.arevalo@unilibre.edu.co. ORCID: <https://orcid.org/0000-0002-4389-5997>.

³ PhD in Business Administration, Universidad San Buenaventura, Cali, Colombia. Master's in Economics, Management, and Business Administration, Università degli Studi di Salerno. Business Administrator. Vice-Rector for Research and Social Outreach and Full-Time Professor at Unidad Central del Valle del Cauca (UCEVA), Tuluá, Valle del Cauca, Colombia. Email: aromero@uceva.edu.co. ORCID: <https://orcid.org/0000-0003-1928-7315>.

ABSTRACT: This article examines the evolution of industrial revolutions and their influence on international law, from initial mechanization to the challenges of the digital age. The First Industrial Revolution spurred the consolidation of the first humanitarian treaties and international technical agreements, linking technological progress with the need for legal regulation. The Second Industrial Revolution, marked by electricity and mass production, generated an expansion of norms surrounding intellectual property, labor rights, and the limitations of mechanized warfare. The Third Industrial Revolution, characterized by automation and the expansion of information technology, strengthened an international institutional framework that included the United Nations and specialized agencies, along with new environmental, economic, and human rights regimes. Revolution 4.0, defined by artificial intelligence, biotechnology, and digitalization, poses unprecedented challenges to state sovereignty, human dignity, and legal accountability, highlighting the inadequacy of traditional regulatory frameworks. Debates are emerging regarding autonomous weapons, algorithmic governance, and digital trade, which require adaptive and polycentric regulations. Finally, Revolution 5.0 proposes a human-centric and sustainable paradigm that seeks to reorient technological development toward global justice, intergenerational equity, and the protection of digital rights. Overall, it concludes that the transition from fragmented international law to flexible and polycentric governance is imperative to effectively respond to contemporary technological challenges, preserving peace, justice, and fundamental rights in an increasingly complex global landscape.

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1. Introduction

Since the late eighteenth century, industrial revolutions have generated profound structural transformations in the economy, technology, and social organization, which have also influenced the development of law at both national and international levels. The First Industrial Revolution introduced the mechanization of production through steam power and factories; the Second brought electricity, mass production, and new forms of labor organization; the Third incorporated automation and the early stages of computing; and the current Fourth Industrial Revolution—marked by the convergence of digital, physical, and biological technologies—is provoking a systemic reconfiguration of human, state, and legal relations (Khan et al., 2022).

Each of these revolutions has posed specific challenges to international law, particularly in the fields of security, labor, trade, and human rights. However, the Fourth Industrial Revolution represents an unprecedented turning point due to the speed, scale, and multidimensional impact of emerging technologies, which demand an urgent review of existing regulatory frameworks. It is important to recognize that artificial intelligence, advanced robotics, quantum computing, and biotechnology are reshaping state and corporate capabilities while raising questions about responsibility, sovereignty, transparency, and the protection of fundamental rights in cross-border contexts (Brada & Park, 2024).

In the field of international relations, one of the main impacts of this technological revolution has been the intensification of geopolitical risks (Bussy & Zheng, 2023). In a manner reminiscent of a technological Cold War, there is a deep competition for leadership in strategic areas such as 5G networks, autonomous systems, and cyberwarfare capabilities, fostering new contexts of peace and conflict (Aponte & Sánchez, 2024), and turning technological innovation into a rapidly evolving battlefield for global hegemony. Recent studies have demonstrated a strong causal correlation between geopolitical risk and technological development, indicating that states invest in technology not only for civilian purposes but fundamentally as a tool for power projection and strategic control—a trend that has persisted even after the fall of the Berlin Wall (Chari, 2025).

Digital transformation is also affecting International Humanitarian Law (IHL), traditionally focused on conventional armed conflicts (Aponte & Llano, 2022). Today, algorithms can make autonomous attack decisions, personal data have become strategic weapons, and digital infrastructure can be targeted by cyberattacks comparable to kinetic strikes. These developments demand a reinterpretation of fundamental IHL principles such as distinction, proportionality, and responsibility to ensure their applicability in scenarios dominated by emerging technologies (Hernández Martínez, 2024).

In this context, international law faces a structural dilemma: how can it maintain its universalist and normative character in an environment dominated by technological fragmentation, digital power asymmetries, and geopolitical disagreement in a scenario of unprecedented technological innovation? As contemporary doctrine argues, the governance of emerging technologies—from cyberspace to artificial intelligence—requires more adaptive, plural, and inclusive approaches that transcend traditional models of state-led legal codification and that also consider the participation of non-state and transnational actors (Chari, 2025).

This article aims to analyze the impact of industrial revolutions on the international legal architecture, particularly focusing on the Fourth Industrial Revolution as a phenomenon of technological acceleration (artificial intelligence, Internet of Things, big data, biotechnology, etc.). The emergence of this historical phenomenon poses a challenge to the essential values of international law: human dignity, peace, equity, and multilateralism (Hernández Martínez & Calvillo Cisneros, 2024).

2. Methodology

The methodology of this article is grounded in a rationalist–idealist epistemological position (Romero-Sánchez et al., 2025) and is framed within the interpretative paradigm (Dhobi, 2022; Martínez et al., 2022; Martínez, 2025). This approach allows for the analysis of industrial revolutions not only as technological and economic milestones but also as processes endowed with social and legal meanings that reshape the

structures of international law. The interpretative paradigm is particularly relevant because it privileges the historical and normative understanding of phenomena, moving beyond merely descriptive or deterministic perspectives on technology and opening the way for a critical reading of global justice, human dignity, and sustainability (García & Morales, 2020).

The study adopts a qualitative approach with an explanatory scope (Guevara et al., 2020), aimed at identifying how each industrial wave—from mechanization to digitalization and biotechnology—has transformed the logics of normative production at the international level. Rather than developing an empirical case analysis, this work presents a theoretical exercise that contrasts traditional approaches in International Relations (realism, liberalism, constructivism, Marxism) with the contributions of critical theory and sociological internationalism, assessing their strengths and limitations in understanding contemporary dilemmas such as artificial intelligence, cyberwarfare, and digital governance (Román, 2023).

The research design was structured in three phases. First, a documentary review of classical and recent academic literature (2016–2024) was conducted using indexed databases and specialized sources (Romero-Sánchez et al., 2024; Martínez et al., 2024; Krippendorff, 2018). Second, an interpretative analysis of the epistemological and normative assumptions of each theoretical approach was carried out, with particular attention to the transformative role of international law in the regulation of disruptive technologies (Aponte-García et al., 2025). Finally, a comparative synthesis was performed to build bridges between theoretical traditions and industrial stages, identifying both their contributions and limitations concerning normative reconfiguration in the technological era (Llamas Covarrubias, 2020).

It is important to clarify that this methodology has an interpretative rather than empirical character. Its results lie in the realm of critical understanding and conceptual comparison, delimiting its validity to the theoretical field while leaving open the possibility of future empirical research or case studies that may deepen the findings presented here.

3. Results and Discussions

3.1. Structural and Technological Factors that Led to the Beginning of the First Industrial Revolution

The emergence of the First Industrial Revolution in the second half of the eighteenth century resulted from a combination of structural factors, among which technological innovations played a decisive role. The introduction of new devices, particularly in the textile and metallurgical industries, marked a turning point in the modes of production of the time. Inventions such as the mechanical spinning machine, the power loom, and the steam engine radically transformed traditional productive processes, allowing for greater efficiency, cost reduction, and the expansion of industrial scale (Valente, 2022).

These innovations were the result of formal scientific advances while also reflecting the inventive capacity of artisans and workers who, through empirical experimentation, managed to perfect pre-existing methods. In the textile sector, for example, domestic production—characteristic of rural areas where peasants spun and wove manually on behalf of merchants—was replaced by mechanized systems capable of producing more quickly (Octavia et al., 2024), with better quality and in larger volumes. The consumption of cotton fabrics from colonies such as India or the United States gradually displaced more expensive materials like wool or linen (Dong et al., 2022), fostering the expansion of an industry based on low-cost raw materials with high demand (Tomás-Miquel et al., 2019).

Within a short period of roughly two decades, multiple technical improvements were implemented in spinning and weaving: from the flying shuttle, which increased production speed, to the water-powered spinning frame (1769), and later the spinning mule (1779), which produced higher-quality yarns while drastically reducing the need for manual labor (Humphries & Schneider, 2019; Styles, 2020; Tertzakian, 2025). These innovations converged with the perfection of the steam engine, patented by James Watt in 1775, which made it possible to replace traditional energy sources such as water or human power with a more efficient and versatile thermal source (Hahn, 2020).

The application of steam power, initially intended to facilitate coal extraction at greater depths, quickly extended to various sectors such as textiles, steel, and transportation (Bailey, 2022). From 1796, Richard Trevithick developed the first steam locomotive (Hanlon, 2020), and in 1823 the first turbine combining hydraulic and thermal energy was designed, marking a new threshold in energy conversion applied to industry. In parallel, the iron sector experienced a less abrupt but equally significant evolution: the substitution of charcoal with coke reduced energy consumption and increased efficiency in smelting furnaces, thus driving the growth of the mining, metallurgical, and infrastructure industries.

This set of transformations culminated in the consolidation of a new organizational model: the factory system. Although there were precedents of concentrated manufacturing in pre-industrial times, the development of complex machinery powered by a central energy source led to the progressive centralization of production processes in large facilities. These factories enabled hierarchical control over production times and rhythms, imposing new forms of labor organization characterized by discipline, constant supervision, and task specialization (Pinheiro, 2024).

The emergence of the factory system initially faced significant challenges, such as the shortage of labor willing to migrate from rural areas. Only from the first half of the nineteenth century did internal migrations become more frequent, leading to accelerated—and often chaotic—urban growth (Keopasith & Neng, 2020). Industrial cities experienced an exponential population increase without having the minimum infrastructure necessary to ensure decent housing, sanitation, or safety conditions (Gür & Koyun, 2025). This precariousness was reflected in high mortality rates, especially among children, and in degrading working conditions (Johnson & Taylor, 2019).

In the early stages, factories predominantly employed women and children, who were forced to work up to sixteen hours a day for low wages, without social rights, and in unsanitary environments (Terry-Chandler, 2019). This phenomenon generated intense historiographical debates: a pessimistic view emphasizes the loss of well-being and extreme exploitation as a direct consequence of industrialization, while an optimistic perspective highlights the long-term emancipatory potential brought by wage labor compared to the structural poverty of the pre-industrial rural world (Hossain et al., 2023).

Nevertheless, these conditions also provoked the first forms of resistance. By the late eighteenth century, discontent over the introduction of machinery led to sabotage episodes known as “Luddism,” in which workers destroyed the devices they blamed for job losses (Smith, 2022). The British Parliament responded with repressive measures such as the Combination Acts (1799–1800), which prohibited labor unions and strikes. However, these restrictions did not entirely suppress the protests, and by the 1820s the first rudimentary trade unions began to emerge, marking the beginning of a new stage in the history of labor struggles (McGowan & Geobey, 2022; Hupfel, 2022).

3.2. The First Industrial Revolution 1.0: Mechanization and the Beginnings of Modern International Law (18th–19th Centuries)

The First Industrial Revolution (1760–1840) marked the transition from agrarian economies to mechanized societies. The introduction of the steam engine, patented by James Watt in 1769, revolutionized transportation (railways, steamships), textile manufacturing, and mining (Olaitan et al., 2021). This technological leap triggered unprecedented socioeconomic changes: factories emerged that attracted waves of migration from the countryside to the cities, causing an urban population boom. Between 1800 and 1850, the number of European cities with more than 100,000 inhabitants increased from 22 to 47 (Bruner & Miller, 2020). However, technical progress came with harsh labor conditions in early factory centers—exhausting workdays of up to 16 hours, the widespread employment of women and children for subsistence wages, and unsanitary environments that eroded workers’ dignity.

These injustices planted the first seeds of the international labor movement and highlighted the need for norms to protect people from the excesses of industrialization, an early germ of what would become international labor law (Mostaghimi, 2020). At the same time, the late eighteenth and nineteenth centuries witnessed the birth of modern international law. Following the Peace of Westphalia (1648), the system of

sovereign states had been consolidated, but it was in the nineteenth century that phenomena emerged shaping the international legal architecture. For instance, systematic efforts began to codify and organize international norms as interstate interactions increased due to the Industrial Revolution, global trade in raw materials, and the mass production of manufactured goods. Furthermore, imperial and colonial expansion—facilitated by mechanized weapons and transportation—created demands for common legal frameworks and struggles related to global corporate practices such as slavery (Blackett, 2021).

The need for efficient communication led to the establishment of the first international technical organizations, such as the International Telegraph Union (1865) and the Universal Postal Union (1874), which promoted cooperation among states in telecommunications and postal services, foreshadowing an emerging international administrative law. Similarly, the devastating experiences of industrialized wars (with more lethal weapons and massive armies) motivated the first humanitarian and arms treaties, such as the Geneva Convention of 1864, which codified principles for the protection of the wounded in war and became a precursor of international humanitarian law (Quataert & Wildenthal, 2019). Shortly after, the St. Petersburg Declaration of 1868 banned certain explosive projectiles, initiating arms regulation. The Hague Conferences of 1899 and 1907 also addressed the codification of the laws of war and peaceful dispute resolution mechanisms, reflecting the industrialized powers' commitment to common rules aimed at mitigating the brutality of war that technology had made possible (Benvenisti & Lustig, 2020).

The Industrial Revolution transformed both the economy and relations between nations, compelling jurists to build a more organized system of international law. Previously, norms among countries existed as a kind of improvised custom ("scattered customary law") without much order. But with the rise of industry, commerce, and mechanized warfare, states began to need clearer rules to cooperate—and to avoid mutual destruction. Thus emerged specialized associations such as the *Institut de Droit International* (founded in 1873), which professionalized the study of international law.

By the late nineteenth century, a more solid legal field had taken shape, with well-defined principles such as sovereign equality among states and the humanitarian limitation of war. Steam engines, railroads, and global trade had created such an interconnected world that it became urgent to establish modern international laws to manage the new interdependence among nations (Krylov, 2019).

3.3. The Second Industrial Revolution (circa 1870–1914) represented a technological leap marked by the spread of electricity, the internal combustion engine, and mass production processes.

Before delving into its legal implications, it is important to understand why industrial revolutions took root in Europe rather than in other advanced pre-industrial regions such as China or the Arab world. Comparative studies highlight that Enlightenment and early modern Europe enjoyed an exceptional institutional environment characterized by political pluralism, liberal thought, and strong protection of private property. Unlike China's bureaucratic absolutism or the instability of medieval Islamic powers, Europe featured autonomous institutions—constitutional monarchies, parliaments, cities, and universities—and granted merchants elevated social status, supported by extensive networks of business trust. Political diversity and competition among European states fostered incentives for technological innovation and the development of market-friendly institutions (O'Brien, 2020).

This framework encouraged free enterprise, technical innovation, and competition, while a more impersonal and rights-based legal system (e.g., *habeas corpus* in England) protected individual and property rights. Liberal philosophers like John Locke had spread the idea that governments must safeguard "life, liberty, and property," laying ideological foundations for emerging capitalism. Likewise, Enlightenment economists such as Adam Smith theorized that the pursuit of self-interest in a free market could lead to collective prosperity—the metaphor of the "invisible hand"—provided that the state limited its intervention to basic functions (security, justice, infrastructure) (Rössner, 2020).

In *The Wealth of Nations* (1776), Smith established principles of free competition, division of labor, and free trade that became fundamental to modern economic development (Skousen, 2016). His vision of a natural economic order guided by the "invisible hand" remains a cornerstone of economic theory (Knell & Kurz,

2024). Conversely, thinkers like Thomas Malthus offered a more pessimistic view of the relationship between population growth and resources. In his *Essay on the Principle of Population* (1798), he warned that population growth would outpace resources, leading to inevitable scarcity (Bonasera, 2024). Under such conditions, the Second Industrial Revolution (2.0) took off first in Western Europe and North America at the end of the nineteenth century. The application of electricity to industry (e.g., electric motors and lighting) and the introduction of assembly lines and mass production transformed the scale and speed of the world economy (Andrews, 2020).

Inventions such as Bell's telephone (1876), Edison's phonograph and light bulb (1878–79), and Karl Benz's gasoline-powered automobile (1886) illustrate the rapid pace of innovation. Mass production, epitomized by Ford automobile factories in the 1910s with their "Fordism," drastically reduced consumer goods prices (Turner, 2021). These advances promoted economic growth but also generated social tensions. The massive transfer of labor from rural to urban areas—initiated in the First Industrial Revolution—accelerated, giving rise to an urban industrial proletariat of millions of workers often living in precarious conditions: long hours, low wages, and unhealthy housing (Friedman, 2020).

Between 1870 and 1914, the world experienced a first era of economic globalization, enabled by transoceanic telegraphy, steam-powered rail and maritime transport, and the gold standard, which established a stable international monetary system. Alongside this came internal labor conflicts (strikes, labor movements) and external geopolitical rivalries (colonialism, the arms race), fueled in part by the search for markets and resources for new industries (Zinkina et al., 2019).

In response to these changes, international law entered an unprecedented phase of transnational codification by the late nineteenth century. Economic and technological interdependence drove the creation of international agreements in areas related to innovation and trade (Gaja, 2019). A landmark example was the global protection of intellectual property, previously confined to national law, now regulated internationally through the Paris Convention of 1883 (industrial property, patents, and trademarks) and the Berne Convention of 1886 (copyright on literary and artistic works), followed by the Madrid Agreement of 1891 on international trademark registration. These treaties laid the foundation for a shared doctrine recognizing inventors' and creators' rights beyond borders, stimulating the controlled dissemination of new technologies (De Rycke, 2022; Saray et al., 2021).

Industrial powers also saw the need to regulate the devastation of modern warfare. Technological innovations (repeating firearms, long-range artillery, submarines) made conflicts deadlier, leading to the Hague Peace Conferences of 1899 and 1907. In these conferences—pioneering for international humanitarian law—states codified the customs of war and adopted rules governing hostilities (regulations on weapons, prohibitions on certain projectiles, treatment of prisoners, etc.) (Chitadze, 2023). Although these conventions did not prevent World War I, they established humanitarian principles that later became customary, such as the prohibition of weapons causing unnecessary suffering.

After the catastrophe of World War I—closely linked to the industrial power of the belligerent nations—the Treaty of Versailles (1919) formally established the International Labour Organization (ILO) as a tripartite agency (governments, employers, and workers) dedicated to promoting global labor standards. The ILO quickly adopted international conventions on maximum working hours, child labor, and factory safety, reflecting the conviction that social justice was essential for universal peace (McGaughey, 2021).

During the Second Industrial Revolution—when humanity began connecting through cables, steam, and electricity—international law ceased to be an informal conversation among diplomats and became a more technical and ambitious system. The pace of inventions, global trade, and mechanized warfare forced states to move beyond custom and to write concrete rules through treaties and conventions, marking the transition from improvisation to codification (Beck, 2023).

Countries began signing agreements on how to protect investments, trade without mutual destruction, share scientific knowledge, and even limit cruelty in armed conflicts. It was, in essence, a desperate attempt to contain the collateral effects of modernity—preventing the theft of ideas in a world of patents, organizing

mass trade unleashed by factories, curbing labor abuses amplified by industrial production, and, hopefully, humanizing war that could now kill from miles away (Mälksoo, 2019).

However, this nascent legal order had an obvious flaw: it was an almost exclusive club of European powers. Most of the world—colonies, subjugated peoples, or nations outside the Western sphere—barely appeared as spectators. Yet even within that inequality, the foundations were being laid for what would later become modern international law with universal aspirations (Al Attar, 2021).

What this process clearly demonstrated is that technology and institutions do not evolve separately. Each new machine, each invention or industrial advance, pushed law to react—to create new norms to contain its impact. The history of international law thus became the story of how progress forced humanity to reflect on the consequences of its own ingenuity (Beck, 2023; Mälksoo, 2019).

3.4. The Third Industrial Revolution: Automation, Computing, and New Challenges for Global Governance

The so-called Third Industrial Revolution (after 1945, consolidated from the 1970s onward) introduced process automation, computing, and digital telecommunications, profoundly altering the world economy and the structure of international law. Technologically, this stage was characterized by the transition from mechanical-analog production to the electronic and digital era. The first computers (ENIAC, 1945) gave way to successive generations of increasingly powerful and affordable machines, revolutionizing information management. The invention of the microprocessor in 1971 enabled the mass diffusion of electronic devices and automatic control in factories (industrial robots, numerical control) (Jat et al., 2021).

By the late twentieth century, economic tertiarization became evident: the service sector and the knowledge economy expanded, driven by data networks, while manufacturing became more efficient with less direct labor thanks to robotics and automation (Smith et al., 2020). Simultaneously, technologies such as nuclear energy (first nuclear plant in 1954) and astronautics (Sputnik satellite, 1957; Moon landing, 1969) broadened the horizon of human capabilities but also generated unprecedented global risks (Slomberg et al., 2024).

The social and political impact of this “third” technological revolution was clear after World War II, which marked the destructive climax of the classical industrial age. A new bipolar international order (the Cold War) took shape in which technology—particularly military—played a central role. The existence of nuclear weapons capable of mass annihilation compelled the creation of unprecedented legal and global governance schemes to avert catastrophe. In 1945 the United Nations (UN) was founded with the explicit purpose of “saving succeeding generations from the scourge of war” through international cooperation and collective security (Keremidchieva, 2024). The UN Charter became the cornerstone of contemporary international law and an attempt to order international relations under universal principles; moreover, the threat of nuclear war spurred the formulation of international legal norms to prevent the use of such weapons and to promote global peace (Morrissey, 2019).

The UN represented the most advanced institutionalization of international law to date, incorporating a Charter that prohibits the use of force except in self-defense or with Security Council authorization (Clapham, 2021). Alongside the UN, a network of specialized agencies emerged covering virtually every domain relevant to an interconnected world: WHO (health), UNESCO (education, science, and culture), ICAO (civil aviation, needed amid the explosion of commercial air transport), ITU (telecommunications, carrying forward telegraph-era work into the satellite age), and the IAEA (Atomic Agency, 1957, for nuclear energy control), among others (Scicluna, 2021; Sabuj, 2021).

In the economic sphere, institutions were established to manage financial and commercial interdependence: the Bretton Woods Agreements (1944) created the International Monetary Fund and the World Bank, laying down monetary and development rules. In 1947 the General Agreement on Tariffs and Trade (GATT) was signed—the embryo of the future World Trade Organization (WTO)—to avoid the protectionism that had worsened the interwar crisis. Likewise, the rise of multinational corporations and global supply chains—facilitated by instantaneous communications (telephone, telex, later the nascent

Internet) and modern transportation—demanded the strengthening of international economic law, leading to a proliferation of bilateral and regional trade and investment treaties; at the global level, principles took shape on free trade, common industrial standards, and mechanisms for settling trade disputes (Bradlow, 2023; Gaeta et al., 2020).

In parallel, the international community confronted environmental pollution and the unsustainable use of natural resources. The ecological consequences of two centuries of industrialization (deforestation, pollution, pesticide use, nuclear accidents such as Chernobyl in 1986) gave rise to international environmental law: the 1972 Stockholm Conference—the first global forum on the environment; in 1987, the Brundtland Commission introduced the concept of sustainable development (Egute et al., 2019); and the 1987 Montreal Protocol on the ozone layer. Along with the emergence of global environmental awareness, these developments became an integral part of governance after the Third Industrial Revolution (Bolton & Landells, 2020).

Another front of legal advance was the international protection of human rights. Horrified by the atrocities of World War II—made possible in part by technology used without respect for human dignity—the international community adopted the 1948 Universal Declaration of Human Rights, followed in subsequent decades by the 1966 Covenants on Civil and Political Rights and on Economic, Social and Cultural Rights. Although not directly technological, these instruments reflect the consolidation of universal values in the post-industrial era and establish ethical limits on the exercise of state power even amid technical advancement (e.g., prohibiting inhumane medical experimentation, forced labor).

Global governance was thus reorganized along a functionalist logic in which each major area of human activity—collective security, the world economy, human rights, and increasingly science and technology—claimed its own corpus of norms. International law ceased to be a purely general, abstract architecture and became a system of interlinked normative subsystems differentiated by technical subject matter (Heath-Brown, 2015). Progress was no longer confined to the Earth's surface; humanity, turned into a cosmic agent, was compelled to extend the fundamental principles of international coexistence to the sky and the atom (Buono, 2020; Marboe, 2019).

The 1967 Outer Space Treaty enshrined the profoundly modern idea that even in the vastness of the cosmos the notion of the common good must prevail. By prohibiting the placement of weapons of mass destruction in orbit and establishing the peaceful use of outer space, international law projected its civilizational values beyond Earth. Law—born in the nineteenth century to order industrial rivalry—now became the guarantor of a planetary ethic (Buono, 2020).

Similarly, the 1968 Nuclear Non-Proliferation Treaty (NPT) reflected humanity's transition to an era in which energy and destruction shared the same scientific root. Confronted with the possibility of total annihilation, international law had to reinvent itself as a mechanism of moral balance between state sovereignty and collective survival. The supervision of the civil use of nuclear energy thus emerged as a symbol of a new kind of legal power—one that seeks to domesticate science without stifling its creative impulse (Heath-Brown, 2015).

These instruments were joined by the 1968 Agreement on the Rescue of Astronauts and the 1972 Convention on International Liability for Damage Caused by Space Objects, which assigned responsibilities for potential disasters and introduced a revolutionary notion of “cosmic solidarity” by articulating the duty to assist human beings as explorers of the universe. For the first time, international law affirmed a legal ethic beyond territory and nation, anticipating the principle of global cooperation that would mark the decades to come (Buono, 2020; Marboe, 2019).

In the labor realm, the ILO continued expanding its conventions and recommendations to adapt to the new reality: it addressed automation and its effects on employment, promoted the extension of social security, and—after the wave of decolonization—integrated dozens of new member states, extending labor standards universally (Liukkunen, 2021). Innovative organizations also emerged, such as WIPO (World Intellectual Property Organization), founded in 1967 to administer the Paris, Berne, and other conventions,

recognizing the growing importance of technological and cultural innovation for global trade (Jorgenson & Fink, 2023).

Nonetheless, a hallmark of this era was normative segmentation: international law fragmented into multiple thematic regimes—economic, environmental, humanitarian—each with its own treaties and bodies. While this enabled specific advances, it also generated coordination challenges. For example, GATT trade rules sometimes clashed with unilateral environmental measures, or investment protection collided with public health policies. This phenomenon laid the groundwork for future reflections on more integrated and adaptive governance mechanisms (Van Driel et al., 2022).

Finally, it should be emphasized that the Third Industrial Revolution fostered the rise of the global digital era. In 1969, as humankind reached the Moon, the first ARPANET link was established among U.S. universities, a prelude to the Internet (Crocker, 2019). By the late 1980s the World Wide Web was developed (Kaur Bakshi, 2023), ushering in, in the 1990s, the real-time global interconnection of people and markets. Although the Internet took off commercially after 1990, its foundations were forged in the context of the Cold War and the international scientific community, under collaborative and open logics that contrasted with traditional state frameworks—foreshadowing the new challenges of global governance that would become evident in the 4.0 revolution: a world in which digital networks transcend national jurisdictions, raising questions about sovereignty, jurisdiction, and the participation of non-state actors in norm-making (Mueller & Badiei, 2020).

Thus, the Third Industrial Revolution transformed the world through automation, electronics, and information, and international law responded by creating a dense institutional architecture: the UN and dozens of agencies, and a mosaic of treaties spanning peace and security, trade, health, the environment, and human rights. Although this architecture achieved notable successes—avoiding nuclear war, largely peaceful decolonization, global trade regimes—it also faced limitations due to the East–West divide, North–South gaps, and thematic fragmentation. Subsequent technological advances would demand more flexible, inclusive, and coherent governance mechanisms, especially in the face of the acceleration and unpredictability of technological change inaugurating the next stage (Zervoudi, 2020).

3.5. The Fourth Industrial Revolution: Artificial Intelligence, Biotechnology, and the Reconfiguration of Contemporary International Law

From the last decades of the twentieth century into the twenty-first, the world has experienced what has come to be called the Fourth Industrial Revolution (Industry 4.0), characterized by the convergence of digital, physical, and biological technologies. This new cycle is defined by the ubiquitous presence of artificial intelligence (AI), big-data analytics, the Internet of Things (IoT), advanced robotics, and unprecedented advances in biotechnology, gene editing, and nanotechnology (Kour, 2020). Unlike the mere automation of the previous era, Industry 4.0 introduces machines and algorithms capable of learning and making decisions, cyber-physical systems that fully integrate production and information, and the possibility of redesigning life (synthetic biology, bioinformatics) or the environment (geoengineering).

The emergence of these technologies has introduced an unprecedented dimension to warfare, in which the human being is no longer necessarily at the center of decision-making (Castellanos-Cortés & Arévalo-Robles, 2024). In this new scenario, machine autonomy, learning capacity, and the interconnection of military systems create a space where moral and legal responsibility becomes blurred. International humanitarian law, built on the idea of human judgment and the rational intentionality of the combatant, is today confronted with technical entities that act without conscience or guilt, but with lethal effectiveness.

The fundamental problem lies in the erosion of the principle of human control, which, since the Geneva Conventions, has constituted the ethical axis of regulated warfare. The autonomous weapon, powered by algorithms and data networks, can operate outside the time frame of human deliberation, transforming the act of killing into an automatic sequence of calculation. Hence arises an ontological crisis in the law of war: if the decision to attack no longer belongs to the will, can the very notion of responsibility survive? The

relationship among designer, operator, and state becomes uncertain, and the battlefield turns into a laboratory of legal indeterminacy.

Added to this is the technical opacity of intelligent systems and the unpredictability of their behavior. Law, which rests on the possibility of attributing acts and judging intentions, is overwhelmed by machines that neither lie nor tell the truth—they simply process. Thus, scientific progress has once again confronted jurists with a dilemma reminiscent of the very origins of international law: the need to domesticate force by means of norms—but this time in the face of a force that does not feel, does not reason, and does not fear punishment.

International law finds itself in a transitional phase, where awareness of danger precedes norm creation. Nations, faced with the irruption of autonomous weapons and AI applied to combat, recognize the gravity of the phenomenon but advance with the hesitation of those who attempt to legislate the future (Aponte et al., 2025). Added to this is the emergence of non-state actors—such as large transnational tech corporations—who acquire unprecedented weight in creating norms and standards, at times rivaling state sovereignty and the principles of twentieth-century international law. This transformation poses significant regulatory challenges, given that existing legal frameworks do not evolve at the same pace as disruptive technologies (Soh & Connolly, 2021).

This shift of normative power toward non-state actors, such as private corporations and technical communities—including ICANN (Internet Corporation for Assigned Names and Numbers)—poses a structural challenge to classical international law, founded on state sovereignty and on norm production through treaties among states (Vasilkovsky & Ignatov, 2020).

Since the late 1990s, a multistakeholder governance model has taken shape, bringing together governments, companies, civil society, the technical community, and academia to make decisions about critical resources such as domains, IP addresses, and protocols (Suzuki, 2020). This emerging form of decentralized, polycentric global governance has served as a reference for other technological spheres undergoing accelerated transformation (Jongen & Scholte, 2024).

Technologies such as artificial intelligence pose cross-cutting challenges to multiple branches of international law. In the realm of security and international humanitarian law, the introduction of lethal autonomous weapons (LAWS)—weapon systems capable of selecting and engaging targets without direct human intervention—raises questions about legal responsibility for acts committed by military algorithms (Aponte et al., 2025), as well as about the compatibility of these technologies with fundamental principles such as distinction, proportionality, and meaningful human control (Nnamdi et al., 2023). Moreover, there is concern over whether the current regulatory framework can provide adequate accountability mechanisms in the face of errors or abuses committed by such machines in wartime scenarios (Gunawan et al., 2022; Maqbool & Anwar, 2023).

In December 2024, the United Nations General Assembly adopted, by a wide majority, a resolution on lethal autonomous weapons systems (LAWS). It proposed a tiered method that begins by prohibiting machines capable of operating without meaningful human supervision and by regulating the remainder according to the principles of international humanitarian law. This gesture, however, is symbolic, merely signaling the birth of a new legal sensibility grounded in the understanding that technical progress, if not subjected to the moral judgment of law, can degenerate into a dehumanizing force.

Many experts argue that allowing an algorithm to make the final decision to kill a human being contravenes the inherent dignity of the person—understood as the intrinsic worth of each unique and unrepeatable individual who must not be treated merely as a means. It has been noted, for example, that “technologies to which decisions of great social or existential importance are delegated, without the possibility of understanding their dynamics, are contrary to human dignity”—a description that fits precisely the opaque (black-box) AI systems used in autonomous weaponry (O’Connell, 2023). The responsibility gap that opens among programmer, operator, and state threatens to turn war crimes into mere software failures.

To date, there is no universal treaty banning LAWS. The “solution” has been to invoke existing principles such as the Martens Clause of the Hague Conventions, which appeals to the principles of humanity and the dictates of public conscience to argue for a prohibition treaty on such weapons (Mauri, 2020). Forums such as the UN (within the Convention on Certain Conventional Weapons) have discussed possible measures since 2014, albeit without definitive consensus (Nadaradjane, 2023). This case exemplifies how technological advances require the reinterpretation—and perhaps the evolution—of current international norms: can existing humanitarian treaties be applied by analogy to algorithmic warfare? Should a new law of robotic warfare be created? The answer is still in the making, but pressure from civil society and some states suggests that international law will not be able to avoid specific regulations on military AI in the coming years.

Several countries are adopting GDPR-inspired laws, illustrating how domestic norms with extraterritorial ambitions can complement the absence of a comprehensive international treaty on personal data. Likewise, the issue of digital services taxes on large tech companies has spurred OECD/G20 negotiations toward a global fiscal agreement—an effort to update the international legal-economic order in the face of business models (e.g., online advertising) that the Westphalian, territory-based tax system did not contemplate (Ryngaert & Taylor, 2020).

Another pillar of the 4.0 revolution is biotechnology, where regulatory gaps are also evident. Sequencing the human genome and new gene-editing techniques such as CRISPR-Cas9 (popularized since 2012) opened the door to modifying the human germline and other forms of life, raising universal bioethical dilemmas. The case of the genetically edited Chinese twins in 2018 (announcement by He Jiankui) shocked the world and exposed the absence of a binding international treaty on genetic bioethics. Although UNESCO has, since 2005, a Universal Declaration on Bioethics and Human Rights— a non-binding instrument that proclaims principles such as the prohibition of interventions contrary to dignity and informed consent—and the WHO has issued guidance, the reality is that science advances faster than law (Poli, 2021).

Some experts hold that human rights law already contains normative principles applicable to germline editing, such as the precautionary principle or human dignity. In this vein, an international moratorium has even been proposed to allow for deeper ethical debate. In line with this, a WHO committee in 2019 recommended establishing a global registry of germline editing trials, and in 2020 more than 40 countries supported a temporary moratorium until regulatory frameworks could be agreed (Raposo, 2019).

In parallel, international law has instruments covering specific aspects of biotechnology, such as the Cartagena Protocol on Biosafety (2000), which regulates the transboundary movement of living modified organisms in response to environmental concerns over GMOs; and, on the biosecurity side, the older 1972 Biological Weapons Convention prohibits the development of bacteriological weapons—a crucial norm that today takes on renewed importance given the possibility of bioengineering pathogens. The COVID-19 pandemic (2020) tragically demonstrated the need to strengthen international cooperation on health and pathogen surveillance, with ongoing WHO negotiations for a pandemic treaty (Zavriev, 2022). All this reflects how the tools provided by 4.0 biotechnology must be accompanied by reinforced cooperative international law, lest humanity be exposed to global dangers lacking effective legal regulation.

Broadly speaking, the Fourth Industrial Revolution has transformed the international legal ecosystem in at least two ways. On the one hand, it has expanded the thematic scope of international law, incorporating areas previously not considered *juris gentium*—such as data governance, cybersecurity, artificial intelligence, global bioethics, and cyberspace management. There is already talk of “digital international law” or “cyber-law” (Von Struensee, 2021), acknowledging that information technologies have created a “space” (cyberspace) in which relations operate that require global regulation. This transformation is also reflected in AI’s impact on international economic law, which demands the reinterpretation of categories and principles in the face of a digitized, cross-border economic environment (Peng et al., 2021).

Indeed, various scholars have anticipated an approaching normative tipping point in which the transversal digitalization of social, economic, and institutional life will inexorably lead to generalized “cyber-juridification”—that is, the progressive absorption of digital logics into all legal subsystems. From this

perspective, the so-called cyber-law would cease to be a sectoral specialty to become the foundational regulatory infrastructure, reconfiguring the classic categories of public and private law according to the dynamics of the digital ecosystem (Qian, 2024). On the other hand, it has altered the *modus operandi* of international norm formation, requiring more flexible, participatory, and anticipatory approaches (Alkan-Olsson, 2021).

In a dynamic technological world, the traditional process of negotiating inter-state treaties—lengthy and relatively rigid—often proves insufficient. In its place, soft-law initiatives and voluntary international frameworks proliferate to guide conduct in emerging fields—for example, the OECD’s AI Ethics Guidelines (2019), later adopted by the G20; UNESCO’s Recommendation on the Ethics of AI (2021), which sets principles of transparency, fairness, and human control over algorithmic systems; or the Paris Call for Trust and Security in Cyberspace (2018), endorsed by states and companies to condemn certain malicious cyber activities. Although non-binding, these instruments help forge quick, updatable consensuses (Gutierrez, 2021), involving multiple stakeholders in their drafting and adoption—what some see as embryos of adaptive global governance.

The Fourth Industrial Revolution is prompting a real-time review and adjustment of international law. Foundational principles (sovereignty, territorial jurisdiction, state responsibility) are being tested by phenomena such as cross-border cyberattacks by diffuse actors or global corporate practices lacking clear state oversight. The international community faces the imperative of legal innovation if it is to channel the benefits of AI and biotechnology while minimizing their risks. Within the Convention on Certain Conventional Weapons (CCW), the Group of Governmental Experts (GGE) continues, year after year, the task of defining the indefinable: the permissible degree of autonomy in war. Jurists debate the concept of “Meaningful Human Control,” that subtle line separating tool from subject; yet while they debate, drones learn to decide, and technology advances without permission. Law seems condemned to legislate retrospectively, as if every norm were an elegy drafted after the catastrophe.

There is also reliance—whether with anachronistic faith or with perverse intent—on the theoretical applicability of International Humanitarian Law (IHL), as if its principles—designed for humans and armies—could contain algorithms and “thinking” machines. This recourse to *lex lata* constitutes a form of legal nostalgia, the belief that the text of the Geneva Conventions will suffice to tame autonomous calculation. However, lethal autonomous weapons (LAWS), with their advanced autonomy and opaque logic, erode the very foundations of legal attribution. Where there is no human intention, the notion of responsibility dissolves; where there is no deliberation, moral judgment becomes a fiction. The responsibility gap opening among programmer, operator, and state threatens to turn war crimes into mere software glitches—an alarming legal risk.

The window of opportunity lies in more agile, collaborative, and foresight-driven ways of making norms (Zorrilla & Yebenes, 2022), avoiding paralysis that could result from waiting for elusive universal consensuses while technology advances at breakneck speed. These issues point toward the still-incipient next stage—what some already call the Fifth Industrial Revolution—focused on reconciling technology with human and environmental needs, and on refining international governance for that end (Saniuk et al., 2022).

3.6. The Fifth Industrial Revolution: Human-Centered Governance, Sustainability, and Emerging Rights

The concept of the Fifth Industrial Revolution (or Industry 5.0) has emerged in recent years to describe a new technological and social paradigm taking shape on the near horizon. A makeover similar to what occurred with the notion of “sustainable development,” which made clear that “development” had brought the worst consequences for humanity and nature. However, it seems a strategy that many states could partially adopt within international regimes while confronting war-making increasingly piloted by algorithms. What does it entail?

Whereas Industry 4.0 emphasized digital interconnection, automation, and efficiency, Industry 5.0 places the human being and sustainable development at the center of innovation. According to the definition adopted by the European Union in 2021, Industry 5.0 seeks to integrate a humanistic and resilient perspective into the existing industrial model, “highlighting research and innovation as drivers of a transition toward a sustainable, human-centric, and resilient industry.” In practical terms, this means leveraging advances in AI, collaborative robotics, quantum computing, and other cutting-edge technologies not to replace but to enhance human creativity and well-being, and to provide long-term prosperity (Bakator et al., 2024).

A closer collaboration between humans and machines is envisioned, where people’s unique capacities (creativity, empathy, ethical judgment) are complemented by the precision and power of artificial intelligences. This synergy is central to the Industry 5.0 proposal, which promotes human-centered technological cooperation (Zia & Haleem, 2025). At the same time, environmental sustainability ceases to be an ancillary component and becomes a structural axis of technological design. The 5.0 Revolution proposes aligning production and consumption systems with global ecological thresholds (Shafique et al., 2024), advancing toward circular-economy models and climate neutrality, in line with the United Nations 2030 Agenda Sustainable Development Goals.

In this emerging context, international law faces the challenge of proactively adapting by incorporating new rights and principles that respond to the technological realities and social expectations of the twenty-first century. One primary focus is the so-called digital rights. Contemporary life unfolds largely in digital environments, which has led to proposals to formally recognize human rights applicable to the Internet and cyberspace— for example, the right to digital security in the face of threats such as cyberbullying or computer crimes.

Among these are discussions of the right to Internet access (essential for realizing other rights such as education or freedom of expression in the digital age), the right to personal data protection (already implicitly recognized in human-rights treaties as part of the right to privacy, but taking on new dimensions with Big Data), and the right to digital security (protection against cybercrime, online harassment, etc.) (Gupta, 2023). Notions such as the “right to digital identity” or the “right to be forgotten” online are also being explored (Moreno Bobadilla, 2020). Although these have thus far developed mainly in national or regional jurisprudence (such as in the European Union), they reflect a trend toward recognizing personal dignity and autonomy in virtual environments as well.

A fundamental component of human-centered governance is ensuring “algorithmic justice.” Since AI algorithms make decisions that affect people (in hiring, credit granting, medical diagnoses, judge-assisted sentencing, among other areas), there is growing concern that such decisions be transparent, fair, and accountable. The opacity of many AI systems—due to black-box machine-learning techniques—clashes with basic rule-of-law principles, such as the ability to explain and review decisions that affect rights. For this reason, various international forums advocate principles of ethical or trustworthy AI: that AI applications respect human rights, avoid unjust discrimination, incorporate values such as privacy by design, and maintain meaningful human control over high-risk decisions (Lo Piano, 2020).

UNESCO’s 2021 Recommendation on the Ethics of AI, for example, enshrines values such as transparency, non-discrimination, responsibility, and inclusive participation throughout the algorithmic lifecycle. Similarly, the European Union’s proposed AI Act—likely to become the first comprehensive supranational law in the field—adopts a risk-based approach, banning AI uses deemed unacceptable for violating dignity or other fundamental rights (Gstrein, 2022). This illustrates an effort to put into practice the idea that not everything technically possible is legally acceptable— a maxim that international law could also affirm through future global instruments. It is not out of the question that, in the medium term, an International Charter of Digital Rights will be negotiated under UN auspices, compiling these principles and extending to the universal level guarantees already recognized in some advanced legal systems (Hogan & Lasek-Markey, 2024).

Another hallmark of the 5.0 Revolution is the promotion of stronger, more permanent multistakeholder governance (Hofmann, 2016). If, in the 4.0 phase, this type of governance arose in specific instances, in 5.0 it is conceived as an ideal model to be expanded: complex, cross-border problems—such as AI ethics, the protection of global ecosystems, or pandemic response—require flexible collaboration and continuous learning among states, the private sector, academia, and civil society (Sharma, 2024). Adaptive governance precisely entails non-hierarchical, iterative decision-making processes that integrate diverse knowledge and perspectives and can be quickly adjusted to new information or changing conditions.

The complexity and cross-cutting nature of the challenges associated with the development and deployment of artificial intelligence have highlighted the need for multilevel institutional structures that go beyond traditional state frameworks. In this direction, in 2023 the UN Secretary-General proposed creating a High-Level Advisory Body on Artificial Intelligence, composed of government representatives, technical experts, private-sector actors, and civil-society organizations. This body published the report *Governing AI for Humanity*, emphasizing the need for multilateral regulatory frameworks that ensure human-centered technological development rooted in shared values (United Nations, 2024).

This initiative reflects a growing trend toward polycentric, multiactor governance models characterized by cooperative participation of diverse types of normative authority (state, technical, corporate, and social) in the formulation of regulatory frameworks. The institutionalized inclusion of independent experts and non-state actors with deliberative capacity indicates a transition toward emerging forms of distributed normative governance, in which rule-making for disruptive technologies is undertaken collegially and on the basis of technical, ethical, and legal legitimacy criteria (Apffelstaedt et al., 2023). This governance approach distributes responsibility and seeks to enhance the legitimacy and effectiveness of norms—legitimacy because it involves those who will be the direct recipients or implementers of the rules (thus gaining acceptance) (Mena & Palazzo, 2012); and effectiveness because it harnesses the expertise and resources of all sectors (Cai, 2024).

Sustainability—Industry 5.0's cornerstone—also drives emerging rights at the international level. One is the right to a healthy environment, which, after years of civil-society advocacy, was finally recognized by the UN General Assembly in 2022 as a universal human right (Knox, 2023). This recognition, although declaratory, reinforces states' obligation to cooperate in protecting the climate, biodiversity, and ecosystems (Aguila & Lichet, 2023), and provides greater grounding for legal initiatives such as climate justice (lawsuits against states or companies for climate inaction invoking *erga omnes* environmental protection obligations) (Toraldó, 2025).

Alongside this emerges the concept of the rights of future generations, closely linked to sustainability: the idea that people who will inhabit the planet in coming decades have interests that must be considered in today's decisions. Countries such as Panama and Canada have introduced ombudsperson-type figures for future generations, and at the international level there is discussion of integrating this perspective into UN bodies (a Special Envoy for Future Generations has been proposed). This approach responds to a growing concern for intergenerational equity in international environmental law, which recognizes the right of future generations to live in a healthy environment as part of sustainable development (Lawrence, 2019).

Another area of emerging rights relates to bioethics: the possibility of manipulating human genetics has led some philosophers to suggest a "Charter of the Rights of Humanity" to safeguard essential aspects of the human condition (for example, prohibiting genetic modifications that would compromise human identity or biological diversity). Although these proposals are still in their infancy, they reflect the gradual adaptation of the language of rights—central to international law since 1948—to new scientific-technological frontiers and to emerging frameworks of global, intergenerational responsibility. These articulate normative principles for challenges that transcend national jurisdictions and implicate ecological sustainability, digital equity, and the protection of global public goods (Garcia et al., 2017; Dupras et al., 2020).

Finally, the 5.0 Revolution will require substantive renewal in terms of international law's coherence and agility. Given the exponential pace of scientific and technological advances, states may opt for more

dynamic international regulatory frameworks—such as framework agreements accompanied by periodically updatable technical annexes, or treaties that include fast-track review clauses to incorporate emerging scientific developments. In this context, greater convergence between international law and mechanisms of technological self-regulation is also foreseeable.

For example, technical standards developed by private international standardization bodies such as the International Organization for Standardization (ISO) and the Institute of Electrical and Electronics Engineers (IEEE) could be formally referenced in multilateral treaties to give them binding legal force (Vyhmeister & Castañe, 2025). Likewise, voluntary commitments by technology companies regarding ethical AI could be incorporated into international monitoring and accountability mechanisms. This trend also extends to transnational corporate responsibility, where the need for an international treaty on business and human rights that explicitly includes large digital platforms is already under discussion, opening new normative horizons in the global governance of technology.

The Fifth Industrial Revolution sketches a renewal of international law in both values and subjects: a law that recognizes the primacy of human dignity even in the face of sophisticated artificial intelligences; that guarantees inclusive participation in the creation of technoscientific norms; that legally enshrines responsibility toward the planet and future generations; and that extends the protection of fundamental rights to the digital realm. It is, in essence, the transition from an international normativity that reactively adapts to technological change to a normativity proactively oriented toward channeling technology for the global common good. This shift entails overcoming the traditional fragmentation and rigidity of the international system by adopting more adaptive approaches.

As Puran (2024) emphasizes, the ethical and regulatory development of AI demands legal responses that transcend national frameworks, while Venkatesh (2023) underscores the need for a normative approach centered on human values, resilience, and sustainability in Industry 5.0. This normative evolution responds to the growing pressure to build a proactive and anticipatory international law—as noted by Fernández Liesa (2020) and Rame et al. (2024)—in a world where legal fragmentation can limit the effectiveness of multilateral frameworks in the face of interconnected global challenges.

4. Discussions

4.1. From Fragmented Normativity to Adaptive Governance of International Law in the Technological Era

Throughout the preceding sections, we have observed how each industrial wave generated new demands on the international legal order—often addressed in a fragmented, sector-based manner. The result is a normative mosaic composed of specialized regimes such as international human rights law, international economic law, international environmental law, international humanitarian law, the emerging cyber law, etc., each with its own principles, bodies, and compliance mechanisms. This normative fragmentation (Burchardt, 2023) reflects the compartmentalized way in which international society historically responded to concrete challenges: each technology or phenomenon propelled its own set of rules. Yet this stands in contrast to today's reality of systemic interconnection (Marcos, 2023; Mvogo, 2021).

In the current technological era, the boundaries between sectors are blurring. For example, a problem like climate change simultaneously involves science (energy technology), economics (fossil vs. renewable industries), human rights (impacts on vulnerable peoples), and security (resource conflicts). Similarly, the issue of personal data is at once commercial (cross-border data flows in digital business), tied to individual privacy (human rights), and a matter of national security (protection against external interference). In this context, legal compartmentalization becomes inefficient and even risky, as unconnected regulations may overlap or collide. A clear example is the tension between international trade rules and environmental commitments: traditional free trade agreements did not incorporate environmental safeguards, leading to conflict situations (investor–state claims against countries implementing ecological measures, etc.) (Young, 2021; Shlomo Agon, 2021).

It is therefore evident that we must evolve toward adaptive and cross-cutting governance of international law, especially in the face of rapid technological change. What does “adaptive governance” mean in this realm? It implies endowing the international system with flexible, integrated, and change-responsive mechanisms that allow rules to be adjusted on the fly as new developments arise, and coordinating responses across diverse sectors and actors (Akther & Evans, 2024; Cosens et al., 2021). Instead of waiting for legal gaps or conflicts to appear and only then negotiating tedious amendments or new treaties (often *ex post*), adaptive governance advocates a more preventive and dynamic approach (Lescrauwaet et al., 2022). Some concrete features would include:

- **Intersectoral approaches:** Foster communication and coherence among different international regimes. For example, when negotiating an instrument on artificial intelligence, involve not only technical experts but also representatives from human rights bodies, the WTO (for trade implications), and UNESCO (for sociocultural impacts). Creating joint commissions between organizations—e.g., a UN-WTO-WHO committee to study big-data governance in health—could help formulate common principles for multidimensional problems (Burau et al., 2020; Perez Arredondo et al., 2021; Gallardo, 2019).

- **Multi-actor and polycentric participation:** As noted earlier, structurally integrate non-state actors (private sector, academia, NGOs) into the development and implementation of international norms. This does not mean diluting state authority, but enriching deliberation with those who possess knowledge and implementation capacity. Experience suggests that regulations with multi-actor participation tend to be more realistic and acceptable (Rozenblit et al., 2025). An ongoing example is the Global Partnership on AI (GPAI), a forum sponsored by G7+OECD countries that includes civil experts to guide AI policy; if its recommendations are channeled into formal negotiations, they could accelerate informed consensus (Keith, 2024).

- **Use of evolving soft law:** While international treaties often take years to adopt and even longer to ratify, soft-law instruments (declarations, codes of conduct, technical standards) can be agreed relatively quickly and updated periodically. Adaptive governance recognizes the value of these flexible instruments—even without binding legal force—as normative laboratories where solutions are tested and later formalized. For example, the OECD AI Guidelines mentioned earlier could, after demonstrating effectiveness, inspire a binding UN agreement. This gradual approach reduces the risk of having no legal response while the “perfect solution” is being negotiated (Marchant & Gutierrez, 2020; Ekwueme, 2021; G. Marchant & Tournas, 2019).

- **Monitoring and feedback mechanisms:** Adaptability requires continuously measuring normative performance and learning from implementation. Thus, an adaptive regime would strengthen follow-up systems (periodic reports, indicators) and establish periodic review processes for commitments. A model to cite is the Universal Periodic Review mechanism of the UN Human Rights Council, where each country is evaluated periodically on its human rights obligations with multi-stakeholder participation. An analogous mechanism for, say, climate or AI governance would compel regular assessment of how effective adopted measures are and recommend adjustments (Takashina, 2024; Greenhill et al., 2020).

- **Framework principles and modular norms:** An adaptive legal technique is to negotiate broad “framework” treaties, complemented by protocols or technical annexes that can be modified without reopening the entire treaty. This method has been used successfully in environmental agreements (e.g., the 1992 UNFCCC and its 1997 Kyoto Protocol, or the 1985 Vienna Convention and its 1987 Montreal Protocol). In technological fields, this could be viable: imagine an international convention on artificial intelligence setting general objectives and principles, followed by specific protocols for different applications (autonomous transport, military domain, etc.) subject to revision as technology advances. This avoids both rigidity and normative obsolescence (Tzimas, 2021; Gupta, 2024).

The shift from dispersed normativity to adaptive governance is undoubtedly one of the most complex challenges of the contemporary international order. Such a transformation does not occur without friction: it requires states to sustain political will to cooperate more closely, accept interdependence as a structural principle, and support shared regulation. This ceding of prominence—natural in an interconnected

world—is hindered by persistent asymmetries between the Global North and South. Developing nations, lacking technological infrastructure and the capacity to influence standard-setting, risk becoming mere recipients of norms defined by digital powers unless they are actively integrated into international cooperation mechanisms. For adaptive governance to be legitimate, it must also be equitable.

Despite these tensions, certain advances signal a change in spirit. In the digital realm, the United Nations established in 2020 a High-Level Panel on Digital Cooperation, whose reports have advocated for a global governance architecture that is more “inclusive, evolutionary, and flexible,” capable of responding to the changing rhythms of technological innovation. Likewise, the creation of the Envoy on Technology within the UN system symbolizes an attempt to “coordinate international responses” to digital challenges transversally, overcoming the old institutional compartmentalization. These initiatives embody an implicit recognition: for technology not to become inhuman, it needs law—but a law capable of learning as fast as technology does.

The example can be seen in the field of climate change, where the adoption of the Paris Agreement (2015) established an unprecedented model of dynamic governance. Replacing the rigid agreements of yesteryear, the new regime is based on “nationally determined contributions,” subject to periodic review every five years, and explicitly incorporates “subnational and non-state actors”—municipalities, companies, civil society—as participants in the regulatory process (Sarkodie & Strezov, 2019). This paradigm introduces a notion of living law, in permanent adjustment with the planet’s material reality. Thus, we glimpse the seed of an international normativity that “manages change,” transforming regulatory rigidity into a higher form of legal prudence.

In conclusion to this cross-cutting discussion, it can be affirmed that the technological era demands a shift in international law: from a static, fragmented, and reactive approach to one that is dynamic, holistic, and proactive. Adaptive governance entails more resilient and pertinent norms, strengthening legal certainty, seeking to balance innovation with regulation, and equipping the international community with the institutional reflexes to learn and anticipate in a world where exponential change is the new normal. Perhaps international law can fulfill its fundamental mission of steering technological development toward the well-being of humanity and the preservation of peace and justice (Datta & Chaffin, 2022; Wang et al., 2018). For the moment, the escalation of 4.0 warfare does not show that we are heading in this direction, but it is the duty of humanity—embodied in its institutions and global regimes—to press for reorienting the shared path on the planet.

5. Conclusions

Throughout this article, the historical evolution of industrial revolutions and their interaction with the development of international law have been examined — from the age of steam to artificial intelligence. This comparative journey allows us to draw several key conclusions:

First, each subsequent Industrial Revolution expanded the scope of international law to new areas and previously unaddressed issues. The Second Industrial Revolution (electricity, mass production) catalyzed the codification of international norms in technical and humanitarian domains: postal, telegraphic, and industrial property conventions emerged; peace conferences were convened to regulate the horrors of mechanized war; and, after World War I, the ILO was created to address the social dimension of industrial labor on a global scale. The Third Industrial Revolution (automation, early computing) brought the consolidation of institutionalized global governance through the UN and dozens of specialized international organizations managing nuclear energy, public health, aviation, satellite communications, and more. Likewise, increasing interdependence led to the development of international economic law, universal human rights, and the first environmental agreements—all milestones of the mid-twentieth century. However, this normative growth was sectoral: rules developed in thematic silos (economy, human rights, environment) that were only partially connected.

Second, the current Fourth Industrial Revolution (digital) and the emerging Fifth (human-centric) are

forcing a transversal reconfiguration of international law, challenging its methods and scope. Contemporary global challenges—from climate change to algorithmic governance to pandemics—are so complex that they demand an integral and adaptive approach, overcoming the rigidities of the past. New rights are emerging (digital, environmental, scientific minorities), along with new duties (such as the responsibility not to cause transboundary harm through cyberattacks or pollution) and new legal actors influencing regulation (tech corporations, global cities, epistemic communities).

The very notion of sovereignty is being redefined—not only as exclusive territorial control but also as shared responsibility in managing global commons (climate, cyberspace, oceans, outer space) and protecting human dignity wherever it may be affected (physical or virtual). In this sense, the idea of “digital sovereignty” emerges, along with the need to coordinate its exercise internationally to avoid both fragmentation of the global network and the imposition of private monopolies not subject to democratic control.

Third, there is a transition from a predominantly reactive international law—historically trailing behind technological developments and regulating their effects *a posteriori*—toward a potentially proactive and guiding law capable of shaping the direction of technological development. The Fifth Industrial Revolution opens the possibility for the international community to anticipate, incorporating ethics, sustainability, and inclusion into technology design through pre-agreed normative frameworks. Initiatives such as the drafting of global AI ethics principles, the promotion of sustainable innovation (e.g., through the Paris Agreement and the SDGs), and the creation of multistakeholder governance platforms exemplify this shift in attitude. The goal is to avoid repeating past mistakes where technology advanced without sufficient consideration of its consequences (e.g., nuclear proliferation before the NPT). In other words, there is growing recognition that law must evolve as rapidly as technology to fulfill its preventive and protective function.

Finally, the history of industrial revolutions and international law is one of mutual influence and adaptation. Technology has been a driver of social change that has compelled international law to expand and transform; in turn, the existence of an international legal framework—though imperfect—has moderated the excesses of industrialization, channeling cooperation toward the common good. Today, before the Fourth and Fifth Industrial Revolutions, we stand at a similar crossroads: ensuring that technological progress is accompanied by equivalent legal and institutional progress. Only in this way can the “fourth machine”—artificial intelligence and related inventions—truly serve humanity without undermining its fundamental values. This article has laid the historical and conceptual foundations for understanding this task, which is, ultimately, the great challenge of contemporary international law: reinventing itself in the technological era to remain the guarantor of human dignity, peace, and global justice.

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