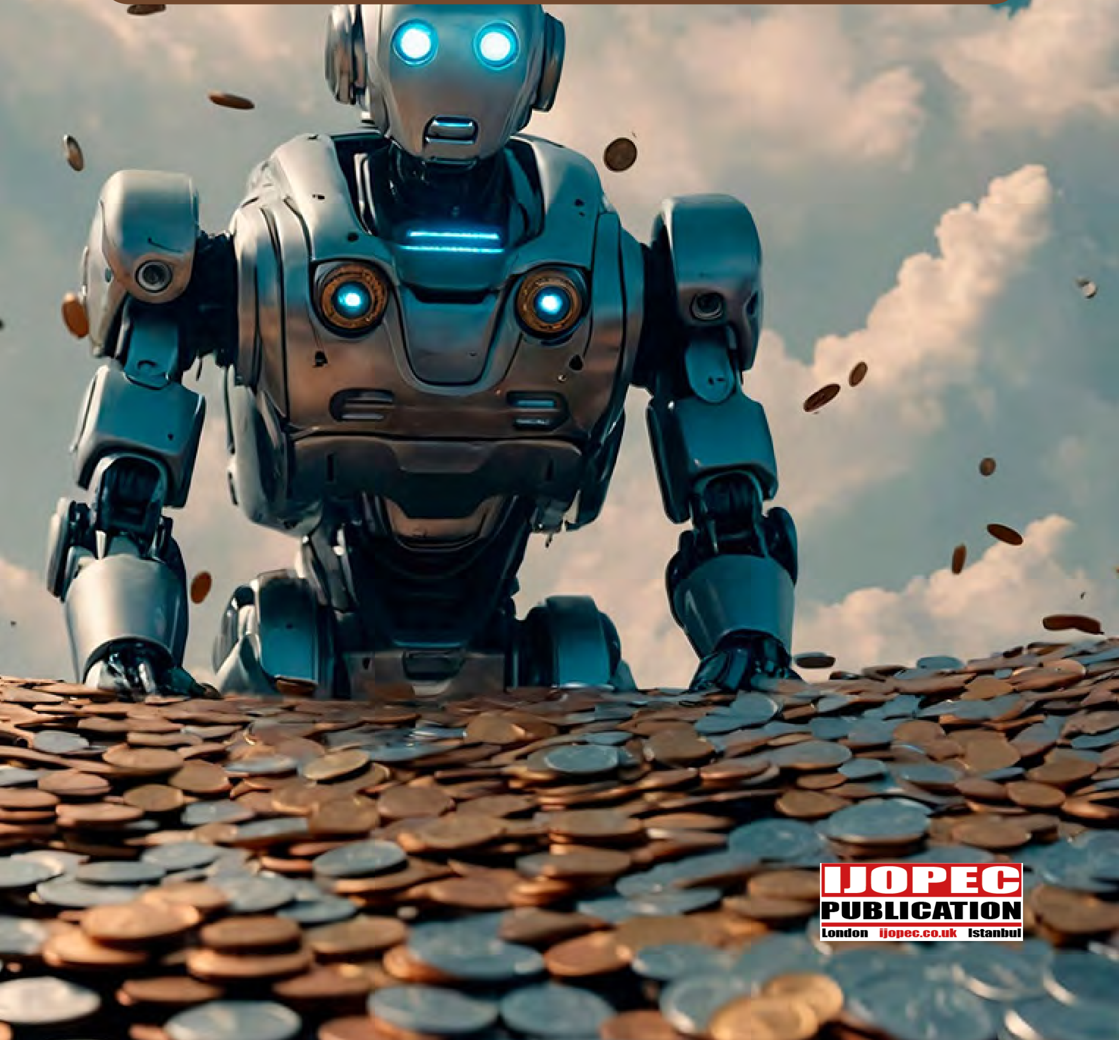
ARTIFICIAL INTELLIGENCE & THE FUTURE OF HUMANITY

EDITED BY
M. MUSTAFA ERDOĞDU, EDGAR ZAYAGO LAU, & ARMIDA CONCEPCIÓN GARCÍA



IJOPEC PUBLICATION
London ijopec.co.uk Istanbul

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EN7 6JR London

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Just Futures: Sustainability, Inclusivity and Education
First Edition, June 2025
IJOPEC Publication No: 2025/01

ISBN: 978-1-913809-51-5

A catalogue record for this book is available from Nielsen Book Data, British Library and Google Books.

The publishing responsibilities of the chapters in this book belong to the authors.

Printed & published in London.

Cover Design & Composer:
IJOPEC Art Design & Arin Şiriner

Cover images & illustrations by Freepik

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ACKNOWLEDGMENTS

This publication would not have been possible without the invaluable support of dedicated colleagues and the institutional backing of Beykoz University and other academic partners.

We are particularly grateful to Beykoz University for its generous financial and institutional support—both in the organisation of the 15th International Conference on Political Economy, held on 6–7 December 2024 under the theme "The Political Economy of Artificial Intelligence," and in the subsequent preparation and publication of this edited volume. The chapters included here were selected from papers presented at the conference, developed further by their authors, and subjected to a rigorous double-blind peer review process before being accepted for inclusion.

We extend our sincere thanks to Professor Dr Burak Küntay, Rector of Beykoz University; Professor Dr Selahattin Kuru, Chair of the Research Support Committee; Research Assistant Güler Sağlam; Corporate Communications Director Ayşegül Telgeren; and Professor Dr İsmail Şiriner of Batman University for their ongoing encouragement and valuable contributions throughout this project.

Finally, we wish to express our deep appreciation to all the contributors to this volume for their scholarly commitment and intellectual generosity. Their insights have greatly enriched this collective endeavour on artificial intelligence and the future of humanity.

Introduction: Artificial Intelligence & The Future of Humanity

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Introduction

Artificial intelligence (AI) has emerged as a defining force of the twenty-first century, reshaping not only technological paradigms but also the foundations of social, political, economic, and environmental life. No longer confined to speculative science fiction or niche applications, AI now permeates domains as diverse as governance, agriculture, warfare, labour, healthcare, and environmental management. Its rapidly expanding reach compels a reconsideration of long-standing assumptions about power, sovereignty, agency, and responsibility. In this context, AI is not merely a tool or innovation but a transformative actor in global affairs, challenging traditional categories of thought and governance (Crawford, 2021, p. 67).

The present volume, Artificial Intelligence & the Future of Humanity, brings together a diverse range of scholarly perspectives that interrogate the promises and perils of AI. While the dominant narrative often celebrates AI as a universal driver of progress and efficiency, this book adopts a more nuanced and interdisciplinary approach. It asks not only what AI can do but for whom, at what cost, and under what conditions. In doing so, it challenges technological determinism and foregrounds the complex, often uneven ways in which AI is integrated into social systems (Eubanks, 2018, p. 23).

This book is structured around twelve chapters that engage with AI from multiple vantage points. The opening chapters (1–3) set the conceptual foundation, examining how AI is reshaping political economy, state power, and its reciprocal development with nanotechnology. The next set of chapters (4–7) explores the political, regulatory, and labour-market implications of AI in both the Global North and Global South, with a special focus on Latin America. Chapters 8–11 delve into sector-specific applications of AI in areas such as healthcare, agriculture, and environmental policy, while the final chapter (12) offers a sobering assessment of AI's role in the militarization and dehumanization of conflict.

A distinctive feature of this volume is its transnational perspective. Contributors draw from case studies in Argentina, Mexico, Turkey, Sweden, Germany, South Korea, China, and the United States, offering a rich comparative lens through which to examine AI's local adaptations and global ramifications. The inclusion of chapters by scholars based in Latin America—many of whom contribute first-hand empirical research—adds a critical South–South dimension that is often underrepresented in AI discourses (Couldry & Mejias, 2019, p. 89). This volume, therefore, not only de-centers Western narratives but also emphasizes the diverse ways in which AI technologies are shaped by and shape different geopolitical contexts.

Another key strength is the book's commitment to interdisciplinarity. Drawing on political economy, sociology, environmental studies, law, philosophy, and public policy, the chapters collectively construct a mosaic of the AI-humanity nexus. This methodological plurality reflects the complexity of the subject matter, as well as the necessity of cross-sectoral thinking in grappling with AI's societal consequences. The range of perspectives ensures that the ethical, political, economic, and ecological implications of AI are considered together rather than in isolation (Zuboff, 2019, p. 328).

The central thesis unifying these contributions is that AI is not merely a technological evolution but a socio-political and ethical frontier that requires active governance, critical scrutiny, and democratic engagement. The volume does not offer simplistic conclusions or deterministic forecasts; rather, it aims to open a space for deeper reflection on the futures we are shaping with and through artificial intelligence. It raises important questions: Can AI be deployed without exacerbating structural inequalities? What forms of regulation can safeguard public interest? How do we ensure that AI technologies remain accountable to democratic values rather than corporate or authoritarian interests (Pasquale, 2020, p. 105)?

In the spirit of this critical inquiry, we invite readers—scholars, practitioners, policymakers, and students alike—to engage with the contributions that follow. Whether addressing the dehumanization of warfare or the informalization of platform labor, the overreach of surveillance systems or the promise of precision agriculture, each chapter poses urgent questions that must inform how we envision and enact the future of humanity in the AI age.

This book also serves as a call to action. As AI technologies evolve, so must our frameworks for understanding and guiding them. Public policy must keep pace with innovation, ensuring that emerging technologies serve collective well-being rather than narrow interests. Academia must continue to produce critical knowledge that scrutinizes AI's embedded assumptions and power structures. Civil society must demand transparency, accountability, and justice in technological governance. And technologists themselves must reflect on the ethical dimensions of their work, recognizing their role not just as engineers of systems but as co-creators of futures (Benjamin, 2019, p. 142).

Importantly, the book does not portray AI as inherently dystopian or utopian. Instead, it recognizes its ambivalence. AI can enhance human capacity, reduce inequality, and address pressing challenges such as climate change and global health. But it can also exacerbate surveillance, displace labor, and concentrate power in unprecedented ways. This dual potential makes AI one of the most consequential arenas of struggle in the 21st century (O'Neil, 2016, p. 204).

The contributors to this volume share a common conviction: that meaningful engagement with AI must be rooted in democratic values, social justice, and ecological sustainability. They call for a vision of technological development that is inclusive, participatory, and oriented toward the public good. As such, this book not only analyze the world AI is creating—it also helps imagine the world AI could help build, if governed wisely and ethically.

In the first chapter, titled Unravelling globalization 4.0: Towards a Political Economy of Time and Space of Labour, Eduardo Meneses establishes the book's theoretical backbone, linking globalization and technological evolution. It critically examines the transformations in labor and development in the Global South. The chapter introduces the concept of Globalization 4.0, analyzing how technological change reconfigures the spatial and temporal dimensions of social life. While dominant narratives often present technological change as a linear and inevitable process, this article critically examines such assumptions from a political economy perspective. The political economy framework offers a robust lens to understand globalization's entanglement with AI and technological paradigms, particularly for developing economies.

In the second thought-provoking chapter, titled Can States Survive in the AI Age? Çağdaş Başar Bahar and Murat Çetin critically interrogates the future of statehood in an AI-dominated world, offering a compelling synthesis of political theory, digital sovereignty, and technological determinism. The chapter frames AI not merely as a tool but as a transformative socio-political actor capable of redefining legitimacy and control. Drawing parallels with feudalism and advancing the notion of technofeudalism, the authors creatively reinterpret classic political theory. Particularly insightful is the parallel with feudal structures and the discussion on potential scenarios emerging from U.S.-China tech competition. The chapter raises crucial questions about governance, legitimacy, and societal order in the digital era.

In the third transdisciplinary chapter, titled Artificial Intelligence, Nanotechnologies and the Dialectics of Life Eduardo Meneses and Guillermo Foladori bridge natural and social sciences to examine the co-evolution of AI and nanotechnologies, calling for a paradigm shift in scientific progress. Through a political ecology lens, they critique the uncritical acceleration of techno-science and highlight the ecological and ethical tensions it creates. Using graphene as a focal point, they expose metabolic rifts deepened by capitalist production. By framing AI and nanotech as dialectically linked, they advocate for a precautionary slowdown—urging a transition toward a science guided by care rather than profit.

In the fourth chapter four, titled Artificial Intelligence Regulation in Argentina: Advances and Challenges in the Latin American Context (2018–2024) Betiana Elizabeth Vargas introduces legal and regional governance dimensions and provides an in-depth examination of Argentina's evolving AI governance landscape. It analyzes state-led and legislative initiatives to regulate AI technologies within the broader Latin American context. Emphasizing the tension between global digital agendas and local developmental needs, the authors advocate for technological sovereignty. The chapter is a valuable case study in regulatory experimentation and highlights the uneven terrain of AI policy outside the Global North.

In the fifth chapter, titled AI in the Management of the US Immigration System Mónica Guadalupe Chávez Elorza, Claudia Leal Jiménez, and Teodoro Aguilar Ortega provide a critical and timely analysis of AI's integration into the U.S. immigration system, with a focus on the CBP-One application. It reveals how AI facilitates border externalization, surveillance, and policy automation—often at the expense of due process, privacy, and human dignity. Grounded in strong empirical and regional context, the authors expose the human cost of digital migration control and the rise of algorithmic injustice. By linking national policy to global digital border regimes, the chapter provides a vital contribution to debates on AI, techno-sovereignty, and migrant rights in the Global South.

Grounded in fieldwork, in the sixth chapter Cooperative Collective Action: Digital Platform Drivers' Response to Regulatory Absence in Zacatecas, Mexico Mayra Selene Lamas Flores and Armida Concepción García offer a micro-level analysis of structural barriers to labor mobilization among app-based drivers in Mexico. Blending empirical research with collective action theory, the authors reveal how algorithmic control, regulatory inertia, and neoliberal individualism hinder unionization. Yet, they also uncover emerging support networks formed via social media, demonstrating non-contentious forms of organizing. The chapter provides a sharp counterpoint to macroeconomic analyses by emphasizing local dynamics and systemic neglect. Its contribution to global debates on labor precarity and platform economies in the Global South is both timely and insightful.

In the seventh chapter, titled Main Indicators of Labor Displacement by Industrial Intelligence Worldwide José Javier Lozano Noriega and Edgar Zayago Lau offer a critical political economy perspective on AI-driven labor displacement, linking automation to the structural contradictions of capitalist accumulation. Drawing on historical context and international indicators, the authors highlight widening inequalities, particularly in Latin America, Europe, and the Global South. They present AI as a dual-edged force—fueling capital accumulation while disempowering labor. The analysis covers post-pandemic trends like nearshoring and platform capitalism, emphasizing patent monopolies and geopolitical asymmetries. The chapter's strength lies in its holistic understanding of labour dynamics and its well-supported call for urgent regulation to protect workers and address the systemic disparities.

In the eighth chapter, titled Precision Agriculture in the Age of AI and Nanotechnology: Global Trends and Latin America's Transition María del Carmen Arreola Medina and Edgar Záyago Lau offer a timely and critical analysis of precision agriculture (PA) through the lens of AI, nanotechnology, and political economy, highlighting its global ascent and uneven adoption in Latin America. Grounded in development theory and structuralist analysis, the chapter reveals how industrial revolutions reshape labour, land, and access. The authors explore risks such as technological dependency, land concentration, and labor exclusion, while emphasizing the need for institutional support, public investment, and technological sovereignty. With rich case studies and historical insight, the chapter critically frames PA as a contested field of innovation, equity, and sustainability.

In the ninth chapter, titled Artificial Intelligence in Healthcare: Transformative Applications, Ethical Challenges, and Future Pathways Sevda Akar and M. Mustafa Erdoğdu deliver a comprehensive and structured analysis of AI's transformative role in healthcare. Covering diagnostic imaging, robotic surgery, administrative optimisation, and introducing the AI-Driven Healthcare Transformation Framework (AI-HTF), the chapter highlights how AI enhances clinical precision, operational efficiency, and macroeconomic outcomes. Critical ethical issues—including data transparency, bias, and accountability—are rigorously addressed. Well-structured and empirically grounded, the chapter calls for responsible innovation and provides a strategic roadmap for building sustainable, patient-centred healthcare ecosystems.

In the tenth chapter, titled Examining the Effects of Green Taxes on Environmental Pollution in Central Europe Marigonë Plakaj Vërbovci and Shenaj Haxhimustafa present a well-structured, data-driven analysis of green taxes' role in reducing environmental pollution across ten Central European countries from 2010 to 2022. Using robust econometric models, the authors demonstrate that higher green tax rates significantly reduce PM2.5 levels, supporting fiscal tools as effective levers for pollution control. Anchored in the Environmental Kuznets Curve framework, the study explores tensions between economic growth and sustainability. It offers valuable insights for policymakers and connects empirical findings with broader governance issues, emphasizing regional cooperation and evidence-based strategies for green transitions in developing economies.

In the eleventh chapter, titled The Use of Artificial Intelligence: The Challenge of Environmental Protection in México Sol Ortega Cruz offers a critical, politically engaged analysis of AI's role in Mexico's mining sector, questioning whether technology can support sustainability or merely deepen extractivist capitalism. Framed within environmental justice and structuralist critique, the authors argue that AI often accelerates resource exploitation rather than mitigating ecological harm. Drawing on Mexico's socio-environmental struggles, the chapter challenges techno-optimist narratives and emphasizes the need to reorient innovation toward community rights, ecological integrity, and democratic governance. It makes a compelling case for rethinking technological progress through a Southern, justice-oriented lens, contributing meaningfully to debates on AI, extractivism, and sustainability.

In the final chapter, titled The Dehumanization of Warfare: The Role of Unmanned Combat Vehicles and Artificial Intelligence in Modern Conflict M. Turan Çağlar presents a sobering and critical analysis of AI's militarization and its role in the dehumanization of warfare. Focusing on UCAVs and autonomous systems, the chapter explores how AI reshapes military strategy, reduces human oversight, and blurs lines of accountability. The author highlights ethical concerns around civilian harm, democratic erosion, and conflict escalation, arguing that technological ease may encourage unchecked warfare. With references to contemporary conflicts and the shifting civil-military balance, the chapter contributes valuable insights to debates on AI, security, and governance—urging global norms to ensure political control over emerging military technologies.

This volume will be of interest to a wide audience. Scholars and students in fields such as political science, sociology, development studies, law, environmental studies, and science and technology studies will find it a rich resource for research and teaching. Policymakers will benefit from the empirical case studies and normative frameworks, which can inform evidence-based regulation. Practitioners in technology and innovation will encounter new perspectives on responsibility and impact. Civil society actors will find arguments and evidence that support advocacy for ethical and inclusive AI governance.

Ultimately, Artificial Intelligence & the Future of Humanity is more than a collection of academic essays. It is a platform for collective reflection and dialogue on one of the most pressing issues of our time. We hope it sparks new conversations, inspires critical thinking, and contributes to building a future in which technology serves humanity, not the other way around.

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PART I

REIMAGINING GLOBALIZATION AND THE FUTURE OF STATES

"We must reinvent the future, because otherwise we are condemned to live in a future not of our choosing."

— Alvin Toffler, *Future Shock (1970), Introduction, p. 3.*

Globalisation is not merely accelerating; it is mutating—reshaping the very dimensions of time, space, labour, and political authority. In a world of globalisation in flux, the assumption of inevitable progress collapses under the weight of political, technological, and ecological disruptions.

What if the future is not something to await, but something to confront and contest? As machines permeate labour, as states struggle with their fading sovereignties, and as science races ahead of ethics, the urgent need for political, social, and ecological rethinking becomes undeniable.

From reimagining labour in the Global South under the pressures of Globalisation in flux, to interrogating the viability of the state in the age of artificial intelligence, to exposing the hidden fractures of techno-scientific expansion, these chapters offer a critical roadmap for navigating an increasingly unstable century.

Who reclaims the future—and how—remains the central struggle of our time. The journey toward an alternative begins here.

1

Unravelling Globalization 4.0: Towards A Political Economy of Time and Space of Labour[1]

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Abstract

This article explores the profound transformations in capital-labour relations and development paradigms in the Global South under the influence of contemporary technological change, particularly within the framework of Industry 4.0. While dominant narratives often portray technological innovation as a linear and inevitable process, this article critically examines such assumptions from a political economy perspective. It argues for the need to reconceptualize technological change through the lens of a mutually constitutive relationship with globalization, a dynamic the article refers to as Globalization 4.0. The core contribution lies in foregrounding the spatiotemporal dimensions of these transformations, proposing that one of the defining characteristics of 21st-century techno-economic paradigms is the radical reconfiguration of the time and space of social, cultural, and economic relations. By developing a political economy of time and space of labour, the article offers a framework to better understand how globalization and technological innovation co-determine each other and how this interplay is reshaping development trajectories in the Global South.

Key Words: nanotechnologies, political economy, political ecology, risk assessment.

JEL Codes: I30, I39, J01, J48

[1] This text is part of the project Frontier Science #304320, supported by SECIHTI, Mexico.

1. Introduction

The economic transformations driven by Industry 4.0 technologies have sparked a fundamental debate over the past decade, spanning academia, business forums, and media outlets. Discussions on the challenges and consequences of these innovations continue to gain traction. From a structural perspective, scholars such as Foladori and Ortiz-Espinoza (2022) argue that the interconnection of these technologies constitutes a genuine technological revolution, qualitatively reshaping modern social and economic dynamics.

Similarly, business groups such as the World Economic Forum have, for over a decade, promoted the need to embrace a revolution that will transform "the way we live, work, and relate to one another in ways never before seen in human history" (Schwab, 2017). These actors seek to construct a hegemonic narrative around contemporary techno-economic transformations, aligning with specific interests in the ongoing struggle over capital-labour relations.

Notably, their discourse, imbued with a clear technological determinism (Diéguez, 2005, p. 75), promotes a singular, linear, and inevitable trajectory of technological development in modern societies. While this "linear model" is very difficult to defend when implementing a historical analysis of how technology transformation unfolds (Edgerton, 2004), its influence and hegemony in the public debate and common sense is undoubted (Leyden & Menter, 2017). When approaching this narrative from a Global South perspective, one may be particularly surprised how well it aligns with the hegemonic development narratives advanced in the second half of the 20th century by the IMF, the World Bank, and other multilateral actors (Veltmeyer, 2012). We can indeed find the same paradigms of linearity, catch-up perspective and inevitability of social and economic trajectories. These similarities lead, thus, to a theoretical and methodological study that can unveil the structural connection between those narratives and their role in the 21st century.

It is worth noting that engaging in this discussion from a Global South perspective is particularly relevant, as debates on development and underdevelopment have historically been closely tied to discussions of technological change. Indeed, throughout the 20th century, discussions on development addressed issues such as the global division of labor, varying levels of industrialization, and concepts like modernization. These debates gave rise to analyses and proposals aimed at guiding impoverished countries toward transforming their structural conditions, much of which stem from the colonial legacy that shaped capitalist modernity (Cypher, 2011, p. 18; Veltmeyer, 2012). Thus, the ongoing transformations call for a renewed examination of such debates.

In this context of accelerated techno-economic transformations has emerged the need for a better understanding on how the so-called "fourth industrial revolution" is reshaping the process of globalization but also, as this article seeks to point out, how globalization dynamics have historically shaped technological innovation from its own economic needs. This mutual determination could be encompassed by incorporating explicitly this determination into the study of the ongoing technological transformations, in what could be encompassed in the idea of a Globalization 4.0. Studying this mutual determination can unveil essential tendencies for the ongoing dynamics that are reshaping the future of capital-labour relations and the development perspectives for the Global South. This transformation extends to the material, political, and social relations across the whole planet.

This article aims to produce a theoretical contribution to this discussion in two areas. The first one is a critique, from a political economic perspective, of the hegemonic perspective of the linear and deterministic perspective for technological innovation. This critique has concrete consequences for understanding of how technological change impacts our social, cultural and economic dynamics (and vice versa). While this first contribution is mainly a synthesis of what many political economic scholars have already developed in the past, this article develops a specific approach highlighting the spatiotemporal dimension of this critique.

It is this specific approach that will lead to the second area of contribution which is based on the hypothesis that one of the main specificities that emerge in the new techno-economic paradigms of the 21st century is the way in which the time (rates) and the space (extension) of our social, cultural and economic relations are being deeply reshaped. These reflections will fall into what could be called a political economy of time and space of labour. Finally, this will open to a last reflection where it will be pointed out how this specific spatiotemporal perspective can have concrete contributions when studying the way in which globalization 4.0 is reshaping the social and economic relations in the Global South.

2. A Political Economy Approach to Technological Transformation

2.1. The Need for a Critique of Technological Neutrality and Determinism

One of the most influential models of how technological change occurs and impacts our society's economic and social dynamics is what has been called the "linear model of innovation", which was largely discussed during the second half of the 20th century (Leyden & Menter, 2017). This model presents a simplified step by step process where basic Science research appears as the ground basis for the development of technological innovation, seen as inventions that are adopted in the markets and become profitable (Leyden & Menter, 2017). Many of the commonly spread perspectives on this linear model use a simplified version of Schumpeterian perspectives of "destructive creation" (Schumpeter, 1997), where "radical innovations" coming from basic scientific and technological advancements are able to redefine and revolutionize the trajectory of economic dynamics. One of the most relevant examples of the impact of this perspective can be found in the OECD's "Oslo manual for Collecting and Interpreting Innovation Data" (OECD, 2008), which has become one of the main sources for guidelines and public policy related to innovation worldwide. We will find the presence and influence of this linear and sequential model of basic Science research, then development, then innovation, in almost every public debate related to technological transformation and innovation.

The main consequence of this linear perspective, where technology appears as a "natural" and predefined deployment of basic Science, is a false sense that technology could be considered as "neutral". Technology shows itself, in this perspective, as part of a "neutral" rationality of basic Science (which is already questionable). It appears then because of an autonomous rationality that would belong to the category of the laws of nature (as applied Science) and would not be influenced by social relations. In fact, as mentioned previously, this idea of tech neutrality, and a technological determinism (Diéguez, 2005), share a same linear paradigm and a single and unequivocal directionality towards a unique possible future with the hegemonic idea of Development that has emerged from neoclassical economic perspectives that also formulate "natural laws" for economic processes (Kay, 2019).

In this sense it is not a coincidence that many scholars find the roots of the modern formulation of both models in the same historical moment and brought from the same political source. Indeed, the idea of a linear technological innovation has been traced to the famous report "Science, The Endless Frontier" written by the north American engineer Vannevar Bush for the president of the United States in 1944 (Edgerton, 2004; Leyden & Menter, 2017). The main ideas of this report were reformulated and strongly integrated in the inaugural speech of the US president Harry S. Truman in 1949. This is the same speech that formulated the modern hegemonic concept of development and underdevelopment that has been debated for more than half a century.

Undoubtedly, these linear and unidirectional paradigms of technological evolution and development played a key role in the hegemonic ideological battle that unfolded during the Cold War. Many of these perspectives were developed on both sides of this geopolitical dispute, as we could clearly find a determinist interpretation of technology, development and progress in the capitalist side (Veltmeyer, 2020), and some may also argue that a deterministic interpretation of those concepts was central to some of the widespread formulations of technology and social progress in the socialist discourse (Saito, 2023).

While this chapter will not discuss the fundamental differences between those historical approaches, it is enough to point out that, after the end of the Cold War, emerged an hegemonic perspective on technological change that has deeply impregnated our modern societies. Indeed, the perspective of technological neutrality, technological determinism and technological utopianism (that underlies the hegemonic linear paradigm of development and progress) have deeply shaped the debates around the future of our societies. The importance of these concepts is particularly relevant to be pointed out in a moment where structural technological transformations are taking place around the so-called "4th industrial revolution".

This perspective of technological innovation has been widely criticized, from many different perspectives. Historians of Technology like Langdon Winner

(1980, 2011) or Lewis Mumford (Mumford, 2020) have shown that the technological innovation process is much more complex than this linear and unequivocal model and has occurred in many different, complex and parallel ways. One of the most iconic examples of this critique from a historic perspective can be found on the way in which emerged one of the key technologies that shaped the initial industrial capitalism: the steam engine. This key technology was in fact developed by a trial-and-error pragmatic experience unfolded by engineers, rather than the application of basic Science discovery, from which it was totally disconnected (Mumford, 2020). There is clear evidence that a steam engine, in fact, was already developed in the 1st century by Heron, an inverter of Alexandría, when modern Science was far from being formulated (Fisher, 1998).

From the field of the sociology of science authors like David Bloor have criticized this perspective, stating that technology does not have a unique trajectory defined by "natural laws" based on basic Science, instead stating that technology needs to be considered as a social construction. In this sense, he defends the fact that the reasons for explaining the successful "adoption" of a technology have to be searched much more on social relations instead of natural principles (Bloor, 1996). Building on this idea, Bijker and Pinch (2008) proposed a deeper critique when highlighting the fact that the successfulness of a technological artifact is not a consequence of a scientific unique rationality but comes from the adoption of specific "relevant social groups" that see on this artifact the solution for a specific problem (which can be a problem for this group but not for others for example). This introduced the notion of power relations on the shaping of technological trajectories, Furthermore, many authors have also recalled that the Schumpeterian perspective that is frequently attached to the linear models of innovation is in fact an inaccurate and reduced simplified perspective of the idea of "destructive creation" which answers more to specific political agendas rather than an academic development of Schumpeter's perspective (Moll, 2021; Piano, 2022).

Nonetheless, despite all the arguments that have demonstrated the limits and contradictions inherent to the hegemonic paradigms of neutrality, linearity and inevitability of tech and development, these concepts seem to have regained a new vitality during the so-called 4th industrial revolution. Indeed, they appear to play a key role in reinvigorating a process of globalization 4.0, that has renewed its outworn promises of progress, by surfing in a techno-utopistic interpretation of the ongoing technological transformations (Moll, 2021).

In front of this challenge, this article proposes to add a complementary contribution to the critique of the hegemonic paradigms of neutrality, linearity and inevitability of tech and development that was formulated in the late 20th century. This contribution is proposed through revisiting some of the foundational formulations of the critique of the political economy at the light of the new technological paradigms of the 21st century. This approach will develop the idea that any critical perspective of the hegemonic views on modern technological innovation need to integrate a deep problematization on how the dimensions of time (rates) and space (extension) are subdued to the logic of the capitalist relations of production. Indeed, the inclusion of time and space at the centre of the debates of the ongoing technological revolution allow to open a discussion that seems more than ever relevant, in a moment where acceleration of economic and social times, as well as the global extension of social and economic relations seem to characterize our digital era. This proposal, integrating a spatiotemporal dimension at its centre, seems particularly fit to understand the specific impact of this historical transformation on the Global South.

2.2. A Political Economy Approach to Technological Innovation

Every living organism requires the transformation of external natural elements to sustain both its individual life and the collective life of its species. Since the 1830s, various scientists, most notably Liebig, have worked on the concept of metabolism. Positioned at the intersection of biology, cellular physiology, physics, and chemistry, this concept seeks to describe and analyse the material interaction between humans and nature (Bellamy Foster, 2013; Saito, 2023). Later, this notion was expanded within the framework of critiques of classical political economy, particularly in Marxist thought, where it was fundamentally characterized by focusing on the fact that what mediates this metabolic process between humans and nature is labour. Besides, acting upon external nature necessarily entails a social organization and the establishment of social relations for the immediate production of existence which implies that labour is necessarily socially determined, embedding always in its specific historical form the contradictions and power relations of its time.

Furthermore, it is important to emphasize that what fundamentally distinguishes humans from other species is precisely the use and specific creation of tools, echoing Benjamin Franklin's characterization of humans as a "tool-making animal." While other animals also create tools for their survival and reproduction—for instance, spider webs or beehives—humans are unique in their ability to develop tools through the advancement of language. This linguistic capacity enables a forward-looking perspective, allowing for the design and accumulation of tools in increasingly complex forms over extended periods of time. Unlike other species, this process transcends intra-generational survival, shaping a long-term horizon of development and innovation.

Through this unique specificity of human labour, we can then formulate a first approach to a political economy of technological innovation. Indeed, it is precisely based on the uniqueness of this specific human capacity, and through the historical observation of the evolution of tools, their complexity, and technical development, that the concept of the means of production can be conceptualized. This notion involves a dual mediation in which humans "produce things that produce things—that is, they produce means of production" (Foladori, 1990). It is this very process of refining the means of production, and consequently improving their productivity, that has enabled the development of the material foundation upon which human history unfolds.

At this point, it is essential to emphasize that the mediation of human metabolism with external nature through labour cannot be fully understood if humans are conceived merely as "isolated" beings in the immediate production of their existence. This is particularly important in a moment of history where the specific process of innovation, in the digital era, exalts the idea of the individual and disruptor innovator capable of producing structural and large economic transformations, as an ideal of success (Piano, 2022). In this sense, it is crucial to return to the critique made by the political economy of postulates such as the ones developed by Smith and Ricardo, who constructed an ideal of the isolated producer based on an abstraction of the forms of labour they observed at the time. This abstraction formed the basis of their ahistorical approach to economic laws.

These assumptions, which extrapolated the historically specific form of wage labour under capitalism to the entirety of human history, were later adopted by neoclassical schools and rational choice theory. In these frameworks, "collectives do not act, have no interests, and make no plans. It is the individual who truly acts, has interests, and makes plans. This, in essence, is the thesis of methodological individualism" (Schwartz et al., 1993, p. 29).

In contrast, the critique of methodological individualism from the perspective of political economy argues not only that this idealized individual never existed but also emphasizes that the human being is essentially a ζῷον πολιτικόν (Zōon politikón in Greek, referencing the concept introduced by Aristotle). This principle has been extensively explored through numerous historical studies conducted in the 20th century, which have demonstrated the fundamental role of cooperation as an explanatory factor in the evolution of human society (Gomez Portillo, 2013). Following this perspective, technology, as much as labour, appears as social constructs that imply specific social organizations to reach its specific historical forms.

This social construction has largely been studied by the political economy perspectives during the last two centuries (Foladori & Melazzi, 2019, p. 38), as a result of the mutual determination between the productive forces from one side (natural determinations, means of production, technological development, specific pre-existing forms of labour…) and the social relations of production on the other side (slavery, community forms, wage labour…).

This perspective implies a material determination from the first, that can be understood, in a very simplified way, as the material basis that determines all the possible forms of modes of production that can exist in a moment of history, while the social relations will define the specific trajectory adopted, by unfolding its specific tensions (class struggle). One of the deepest contributions of political economy has been the understanding of how these two categories are in constant mutual determination, since the social relations of production will also define specific historic trajectories for the evolution of productive forces. Is precisely in this last idea of dialectical relationship that lies the specific relevance of a political economy approach to technology.

Having set this first approach, it is worth of highlighting that the transformations of the labour-capital relationship related to the technologies that have emerged in the last decades, have brought a large amount of debates during the on how to renew this perspective in the digital era (Foladori & Ortiz-Espinoza, 2022; Hardt & Negri, 2003; Ramírez, 2018; Ramírez & Sztulwark, 2018; Roberts, 2021; Varoufakis, 2024). While this chapter does not have the intention to resolve these profound debates, it will propose to return to discussion centred into the idea of social metabolism between man and nature, in order to highlight the key specificities of labour and technological innovation in the digital era.

2. 3. The Machine as a Synthesis of Social Division of Labour

To understand the specific characteristics that define the historical process through which technological innovation unfolds from the mutual determinations of productive forces and social relations of production, this chapter draws on the work of authors such as Pasquinelli, who has been able to situate this process in a way that reinstates the centrality of labour and material determinations in the process of technological innovation. This perspective appears as particularly relevant in a context of an increasingly digitized economy that creates an illusion of virtuality without material limitations.

According to Pasquinelli, a historical review of technological innovation allows to highlight how its historical unfolding consists of a synthesis of the social division of labour in which it is placed (Pasquinelli, 2019). When questioning who the inventor of a machine is, Pasquinelli's response is neither the worker, the engineer, the entrepreneur, nor the factory owner. For Pasquinelli, the machine emerges as a synthesis of the collective worker, referring to a specific historical configuration of the social division of labour (Pasquinelli, 2019, p. 45). In this sense, the creation of technology does not arise "by the 'analysis' of nature by science, but by the 'analysis' of labour" (Pasquinelli, 2019, p. 47).

It is possible to see the materiality of this process from the simplest forms of technology (let's say a hammer that imitates an arm with a stone) to the mechanized industrial lines (based on Fordist division of labour) and even in the most recent Artificial Intelligence models (based on the social division of intellectual work). Through this process, the social division of work under capitalism and its inherent specialization (D. Harvey, 2019) allows the progressive separation of complex processes on individual tasks that are more and able to be automated and replace human labour.

This perspective allows not only to highlight how any development in technology has a material and social basis, but also how it necessarily integrates a materialization of a specific division of labour that results in historical power dynamics. This analysis clearly converges with those, previously mentioned, of the historical approaches and sociological approaches of tech, with the difference that it can allow to integrate the specific contradictions between material determinations and social determinations as the process of historical unfolding of technology.

In this sense Pasquinelli states that under capitalism "any machinic interface of labour is a social relation, just like capital; and the machine, like money, mediates the relationship between labour and capital—what could be called a theory of labour value mediated by machines" (Pasquinelli, 2019, p. 45). One of the most iconic historical examples of this argumentation can be, again the steam engine. Indeed, Pasquinelli highlights the following:

"It was not the invention of the steam engine (means of production) that triggered the industrial revolution (as it is popular to theorize in ecological discourse), but rather the developments of capital and labour (relations of production) demanding a more powerful source of energy" (Pasquinelli, 2019, p. 34).

Based on this perspective, Pasquinelli will identify some fundamental dynamics that will define the tendencies upon which is based the trajectory of technological innovation and its consequences:

1) the invention of machinery through the division of labour,
2) the alienation of knowledge by machinery,
3) the devaluation of capital by knowledge accumulation and
4) the rise of the collective worker.

While some of these dynamics have already been treated in a synthetic way, it is important for the present argumentation to deepen the analysis of the third and fourth of these tendencies, the ones related to the devaluation of capital by knowledge accumulation and the rise of the collective worker. Indeed, in one hand, the devaluation of capital in this case refers to the structural tendency, under the pressure of competition between individual producers, to replace human labour in the production process by mechanized processes. This, in the labour-value theory, is what leads to the tendency of the rate of profit to fall. What seems worthy to develop upon this tendency is that its consequence is a pressure towards the creation of more quantity of profit within the same time. In other words, it pushes towards the acceleration of the times of production, exchange, distribution and consumption.

On the other hand, the rise of the collective worker can relate to the unfolding of the social division of work, which under capitalism is characterized by the geographical expansion of its footprint in the same spheres of production, exchange, distribution and consumption. This is what has been materialized in the globalization process that started in the 20th century and has given rise to globalization 4.0, that can be seen now as a synthesis of the globalized division of labour.

Following this analysis, emerges now a spatiotemporal perspective of acceleration of economic times and extension of its space, as a historical necessity of capital contradictions and not because of a natural law of technological development. This is a key conclusion since it is a radically different perspective from an explanation of the disruptive consequences over society of an "autonomous" sphere of science and technology, when explained from a linear, neutral and unidirectional perspective of innovation. Indeed, in this hegemonic perspective, globalization and acceleration of time appears because of natural technological development. But this perspective is inverted when, from a political economy perspective, we understand technological innovation as the synthesis of the social division of labour and thus, as the materialization of capital contradictions.

The trajectory of technological advancement, which appears now as a consequence of capitalist social relations, appears not anymore as a unique and "natural" possibility for technological development, but instead as one of many possibilities that can be then socially built, one of the possibilities of modernity Bolivar Echeverría would say (Echeverría, 2009).

This is an essential question when approaching two key civilisation questions of our time: growing inequalities and ecological destruction resulting from the modern industrial system of production. While this understanding of the mechanisms of technological innovation from a political economy perspective allows a better unveiling of its tendencies, this article aims to develop the idea that it is from a critical analysis of its spatiotemporal paradigms that alternatives and resistances to the modern socially unequal and ecological predatory dynamics can be thought. This implies a further advancement on what we can call a political economy of time and space of labour.

3. A Political Economy Perspective of Time and Space of Labour in the 21st Century

3. 1. A Critique of Neoclassical Approach of Time and Space

The acceleration of social and economic times, as well as the expansion of the geographical footprint in which the production and consumption circuits unfolds are often viewed as a key characteristic of the globalization 4.0, This is something shared in a wide variety of ideological spectrums: from entrepreneurial perspectives and hegemonic scholars to radical anti-globalization movements and intellectuals (Foladori & Melazzi, 2019; Foladori & Ortiz-Espinoza, 2022; M. G. Harvey & Grifith, 2007; Ramírez Gallegos, 2020; Ramírez, 2022; Tombazos, 2014). Nonetheless the problematization of time and space itself are radically different, this problematic has had different configurations throughout history.

Indeed, time and space have been fundamental elements in discussions concerning the very definition of reality and the ways in which humans engage with it. Drawing on Heidegger's reflections in *Being and Time* (Heidegger, 2012), the common-sense perception of time and space has been constructed based on concrete human experience. Time, in its modern "vulgar" conception, is understood as a linear sequence of homogeneous instants (past, present, and future), a notion derived from Newtonian classical physics and a philosophical tradition extending from Aristotle to Kant. Meanwhile, "vulgar space" is perceived as an empty, homogeneous, and measurable extension, akin to the concept of absolute space in Newtonian physics or Euclidean geometry. These two concepts are regarded as essentially distinct and independent from one another.

Although a wide variety of approaches to time and space have existed across different human cultures throughout history, each one has developed, to a certain extent, some means of addressing these dimensions.

The vulgar conception of time and space became dominant in science from the 17th century to the late 19th century, largely due to the hegemonic dissemination of Newtonian classical physics. This paradigm postulated that time is characterized by a continuous flow, independent of events or physical objects. It was thought to be uniform and absolute, existing in and of itself without reference to any external matter. For Newton, absolute time is “true and mathematical,” contrasting with relative time, which he developed in his theory of reference frame changes and which refers to time as perceived or measured in relation to observed movements (Newton, 2011, p. 88). Space, on the other hand, was conceived as an infinite and immobile container within which physical objects exist. This space was considered absolute, independent of the objects or the relationships between them (Newton, 2011, p. 88).

Extensive philosophical debates (see Descartes or Engels for example) and advancements of modern physics (Einstein’s relativity theory or quantum mechanics for example) have demonstrated the invalidity of Newtonian time and space. Despite this, it can be argued—extrapolating from Heidegger's thought—that even today, the Newtonian perspective of time and space continues to shape the hegemonic "vulgar" conception that organizes the modern everyday experience of these dimensions. This influence extends beyond daily experience and manifests in the way dominant neoclassical economics approaches these concepts.

Indeed, following the analysis made by scholars like Broeger (2016), the traditional Newtonian perspective of time and space tends to be the one used by neoclassical economy. The roots of this paradigm can be searched on its resonance with the "universality" of economic laws postulated by neoclassical perspectives, like the equilibrium paradigms based on market laws. This perspective disregards any dialectical approach related to social dynamics and, as Broeger demonstrates, postulates an immutable and absolute view of time and space. These dimensions are reduced to mere variables that define the state of a given system (or, more precisely, a system modelled by "natural" economic laws) at a specific moment and location.

It is important to note that the limit of this modelling approach has been stated even by some of the most influential neoclassical theorists. This can be seen for example in the conclusions drawn by Blaug (2003), when analysing how authors like Samuelson in his famous book "Foundations of Economic Analysis" (Samuelson, 1983) noted the limits of this kind of static analysis. In fact, Samuelson calls out the need for a deeper analysis of the "stability" of the equilibriums postulated by the neoclassical modelling theory. It is worthy to note that Samuelson does this critique not from an ideological perspective, but rather from a mathematical one which becomes even stronger in terms of the determinist modelisation pretensions inherent to the neoclassical paradigm. What Blaug points out from this remark is that what Samuelson is calling out is the need for including a dynamic perspective of time and space in its logic. This implies the recognition of dialectical relations inside the economic analysis.

Later in the 20th century, the complexity studies that built their perspective upon the impossibility of a deterministic Newtonian understanding of physics, expanded this critique to the neoclassical economic perspectives. While it is not possible to make a complete synthesis of its postulates here, what is worthy to be pointed out is the necessity to abandon deterministic perspectives when analysing complex and adaptive systems, like economy. As complexity studies have shown, those are systems where very slight changes in initial conditions can produce enormous different outputs over time. Even if we could have very clear ideas of natural laws, it becomes impossible to develop a deterministic perspective in those contexts. One of the most used examples of complex systems is the weather systems, but economy has widely followed in this analysis as well.

While this can seem as an impasse where complexity is assumed as a chaos where only localized dynamics (in time and space) can be really well understood, authors like Osorio (Osorio, 2012) will argue that instead of a paradigm of abandonment of the knowledge of totality, implied in deterministic models, political economy can bring another perspective, which is intelligibility. In this perspective what is recognized is that, while deterministic laws cannot be applied, the understanding of dialectical dynamics that can unfold on its own complex contradictions may allow us to identify historical tendencies. Those tendencies are not deterministic but allow to bring a historical perspective of how these contradictions unfold and understanding of a result which is always a social construction in dispute.

3.2. Conceptual Proposal for a Political Economy of Time and Space

What this chapter aims to propose is that in fact many of the concepts of modern physics suit much more to the analysis of time and space as a social construction rather than the Newtonian paradigms used by neoclassical theories. Indeed, the concept of a spatiotemporal continuum can be brought from relativistic physics to highlight the fact that there has been a permanent mutual determination between, on the one hand the rates and on the other hand, the extension of social and economic dynamics throughout history. Many historical examples of this can be found from the creation of the clock that allowed the synchronization of work in large extensions of space and allowed a wider footprint of production. This is what led historians like Mumford (2020) to consider that it was the clock and not the steam engine, the key technological creation that gave birth to the industrial modern era. Other examples showing the opposite determination can be found in one of the dynamics of the globalization process where the increased extension of the production footprint resulting from delocalization of industries, has resulted in an increased pressure on the accelerations of times of production and transportation to accelerate the valorisation cycles of capital.

Besides the concept of unity of time and space, united by a permanent mutual determination in the case of a political economy approach, relativistic physics can also bring another key concept which is the fact that a spatiotemporal paradigm can only exist in relation to matter, energy and its transformation process. For modern physics the idea of an absolute and immutable spatiotemporal paradigm makes no sense without the presence of these elements. These considerations are particularly aligned with the idea of a social metabolism in which labour mediates the transformation of nature on the material means of social reproduction for societies. Here the rates and extensions of production processes are directly related to the materiality, the energy and the transformation dynamics of the social metabolism and appear in fact as a social construct of it.

In these two cases, in the spatiotemporal unity and in the centrality of matter, energy and transformation, what is particularly relevant is that technology plays a key role in the deployment of these concepts. As mentioned before, here the approach of technology is not made from a neutral, linear and unequivocal paradigm, but rather form a dialectical perspective, where the mutual determination of social relations of production on the one hand, and technic relations of production on the other hand are the ones determining its historical trajectory.

To encompass this perspective of inherent dialectic logic instead of a deterministic logic, the analysis of time and space can also gain from borrowing concepts from other fields of modern physics, in particular quantum mechanics and complexity studies. Indeed, the idea of an inherent indetermination at incredibly small scales (quantum physics) and at human scales (in the complex adaptive systems), do not appear at all as contradictory with the conformation of observable tendencies and regularities in modern physics. This perspective can easily be applied to a political economy paradigm where the individual scale cannot be understood separated from contradictory social relations and thus has an inherent indetermination in both levels. This aligns with the Osorio's paradigm of intelligibility instead of totality in the political economy, mentioned previously. It is relevant to note that in modern physics the methodological consequences of this perspective result in a methodology of consecutive approximations of time and space (Gell-Mann, 1995). This can be easily related to the classic method of consecutive approximations of political economy in the process that goes from the study of the concrete historical forms towards the abstraction of its underlying principles and bringing back intelligibility to the concrete social and economic complexity (Osorio, 2012).

While much more things can be said at the theoretical level, we will finish this proposal of integration of modern physics concepts for the structuration of a political economy of time and space by highlighting the fact that this perspective of a social construction of time and space, based on the dialectical relations of labour can be specially suited for the two of the fundamental debates of our era that were mentioned previously. The first is the ecological crisis, where the studies of the "metabolic" rift created by the contradiction between the of the social metabolism of capitalism and the metabolism of nature, and their correspondent specific spatiotemporal paradigms, have been deeply analysed by authors like Saito (2023) or Bellamy Foster (Bellamy Foster, 2013). The second fundamental debate that can gain from this specific approach of time and space is related to the way in which social and economic inequalities unfold in different time and space paradigms. While this chapter will not have the possibility to go further in the late aspect which has much more to be studied, we can mention some of its concrete consequences from a Global South perspective, as a conclusion.

4. Conclusion: The Consequences of the Specific Spatiotemporal Paradigm of Capitalism for the Global South and Its Horizons of Development

As Saito mentions in his book "Marx in the Anthropocene: Towards the Idea of Degrowth Communism" (Saito, 2023), the idea of integration the specific dimension of time and space in a political economy perspective is not only to describe specific configuration, but to add intelligibility on how the metabolic rifts are spatially and temporally (re)distributed, reinforcing power dynamics and social inequalities (Saito, 2023, p. 28).

This is particularly relevant when studying the consequences for the global south in the context of Globalization 4.0. Indeed interesting time studies made by authors like René Ramirez (Ramírez Gallegos, 2020; Ramírez, 2022) show the inequality of distribution of time for the "good living" which brings structural critics to the hegemonic concepts of development based on the measure of money. The study of time appears here as a way to unveil new centre peripheral dynamics reinforced by globalization 4.0 that reinforce new forms of dependence linked to new technologies (Ramírez & Sztulwark, 2018; Varoufakis, 2024) but also as a way to build a political dispute for a new social order that can integrate specific global south epistemologies (Ramírez Gallegos, 2020). While there may be many debates on this late approach inside the political economy field, that are related to the role of knowledge in the modern mode of accumulation, the study of time and space from a political economy perspective, appear as a relevant tool for unveiling the dynamics of a periphery 4.0, key for the Global South.

A second key contribution in the same sense could be done to the study of the consequences for the Global South of the new globalized capital labour relations based on technological configurations such as platforms technologies or remote work. Including the dimension of time and space can be crucial to understand the consequences of this new spatial (globalized) and temporal (real time) paradigm for Global South Labour. Much of the studies that have been developed in recent years point out to a reinforcement of extractives' models in the Global South under the pressure of the new global division of labour (Veltmeyer, 2013), and can definitely gain for a contribution from a political economy of time and space to understand not only the dynamics underlying this re-primarization of Global South economies, but also the consequences for the unequal distribution in space of the metabolic rift that is eroding the global ecosystems. This may build an interesting bridge between ecological and political economy studies.

Finally, in relation to the topic of development studies that have been mentioned since the beginning of this chapter, this critical perspective of technological innovation can highlight the role that techno utopic is playing in reinforcing structural precarization of labour on the Global South under renovated promises of a technological progress that last to (will never?) come. The inclusion of time and space on how this technological mediation of the capital-labour relation is done can bring important insights on how technology is not neutral neither in the capital-labour relation, nor in the global north - global south relation.

It appears that many other concrete applications of this specific approach of technology and its effect on time and space configuration can be unfolded for the study of globalization 4.0, and this field appears yet to be much more explored. This requires a renewed theoretical approach, that this article has tried to contribute to, as a first draft that certainly needs to be criticized and discussed. It appears also as an urgent task to unfold the methodological consequences that these specific theoretical postulates may have, and in this field the new time and space studies that are emerging from the global south sound very promising into their contribution to a new epistemology.

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2

Can States Survive in the Artificial Intelligence Age?

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Abstract

Technology is perhaps the most influential factor in determining how human societies are being organized. The agricultural revolution paved the way for the establishment of first settled societies, which required hierarchical political organizations to regulate daily affairs. A couple of millennia later, the industrial revolution transformed these organizations into highly centralized, territorial entities that we now call States. Nowadays, the State—though challenged by globalization and neoliberal governance—is still considered the only territorially sovereign organisation. However, the current scholarly debate suggests that artificial intelligence threatens the State's definitive characteristics in conjunction with its digital sovereignty. This paper seeks to contribute to this debate by focusing on functional rather than institutional aspects of the State, which appears to be the main analytical focus in this topic. More specifically, this chapter discusses how AI, as an unprecedented cognitive technology, affects the relationship between the State and society? Results indicate that it provides private actors with means that were previously unavailable—or accessible only to the State—enabling them to alter the ordering of societies to the point where states may cease to exist. However, it should be noted this chapter does not address several important aspects, such as the global geopolitics of AI, its strictly economic dimensions, and its focus primarily on the Western world.

Keywords: artificial intelligence, the concept of state, existential threat, digital sovereignty

I. Introduction

Debates over the concept of the state, mainly its legitimacy and sovereignty, have been reopened due to globalization and consecutive breakthroughs in information and communications technologies, which began to transform the internal dealings of societies as well as relations among the international community. This debate began to receive scholarly attention as big tech companies and digital platforms – like Alphabet, Amazon, Meta, Apple, and Microsoft – increased their societal reach and influence through developing “cognitive” technologies such as AI, big data, and Web 3.0. These innovations allowed companies to extract, store, analyse, and repurpose the private and sensitive data of their users. Consequently, these transnational entities gained an extensive understanding of human behavioural patterns as well as maintained constant surveillance of their actions (Van Dijck, 2014; Zuboff, 2019; Sadowski, 2019; Manheim and Kaplan, 2019; King and Meinhardt, 2024). Naturally, Big Tech companies were compelled to cooperate with States under the pretext of territorial sovereignty and national security. However, as States and societies become increasingly dependent on the products and services provided by these companies, it cast serious doubts on the very core principles of the modern State: sovereignty and autonomy (Pistor, 2020).

The aforementioned argument mainly revolves around the term “digital sovereignty,” which emerges as an ambiguous notion compared to the somewhat clearer concept of territorial sovereignty, due to the fact that the digital realm virtually has no boundaries and lacks global governance mechanisms with appropriate regulatory frameworks (Pohle & Thiel, 2020). This term shall be revisited in the subsequent section; however, it should be noted here that it is predominantly being analysed within Weber’s institutional framework of the modern State, possibly overlooking theories that explain its functional contours. Thus, we seek to fill this gap by first discussing the political economy of artificial intelligence, focusing on its cognitive aspects. Secondly, the concept of the State shall be analysed. Subsequently, the concept of digital sovereignty as well as global and national politics of AI will be discussed. Lastly, we will attempt to formulate a coherent theory regarding the future of States in the AI age.

2. Cognitive Political Economy of Artificial Intelligence: Power of Prediction, Persuasion and Possession

AI has no generally accepted definition, and we will not attempt to provide one here; readers may conceive it as they wish. That being said, focusing directly on its development process and functioning might give us a clearer picture without carrying the conceptual baggage. Firstly, training AI models requires huge datasets that were previously either unattainable or economically infeasible. However, factors such as the invention of the World Wide Web in the 1990s, the development of a global internet infrastructure, and cost reductions in producing digital hardware – especially data storage technologies – made it possible to collect and store vast amounts of data. However, as training AI also required considerable computing power – which was unavailable at that time – its use remained marginally limited compared to its current extent. The development of advanced graphics processing units and central processing units finally allowed large datasets to be used in training AI systems for various tasks. Shortly, data became an immeasurably valuable asset for both creating and utilizing AI for various purposes (Sadowski, 2019; McAfee et al., 2012; Brynjolfsson and Ng, 2023).

Furthermore, big tech companies use this information to provide personalized "experiences" via recommendation systems ("if you like this, you might like that one") aimed at increasing engagement with their platforms, whether it be watching another episode on Netflix, buying an unnecessary product on Amazon, or continuing to scroll on Instagram for another hour (Peters, 2022). Here, it should be highlighted that the actual revenue gained by direct purchases (subscriptions, products, etc.) becomes marginal compared to the value of the data they extract from individuals (Sadowski, 2019). Moreover, Zuboff (2019: 20) claims that the whole aim of big tech companies is to achieve "the instrumentation and instrumentalization of human behavior for the purposes of modification, prediction, monetization, and control." Similarly, scholars like Sass (2024), Susser et al. (2019), Samaniego (2023), and Milano et al. (2020) warn against the risk of losing individual autonomy amidst such invasive, involved, and intense persuasion, manipulation, and coercion of the human psyche.

This brings us to yet another dimension of the cognitive aspects of AI: its utilization for political ends. The most notorious example of this phenomenon is the Cambridge Analytica scandal, in which a private company illegally collected and analysed the personal data of millions of Facebook users to create psychological profiles. It then used AI to target individuals with personalized messages, aiming to sway them to vote for Donald Trump in the 2016 U.S. presidential election (Isaak and Hanna, 2018). Additionally, states' police and intelligence services, either by using AI systems directly or by cooperating with Big Tech companies to 'borrow' their surveillance mechanisms, heavily rely on these technologies. This ranges from personal use, as in the case of Hungarian populist Viktor Orbán, to regional use, as demonstrated by the Hesse police department in Germany, to supranational usage, as seen in the Europol case (Knight, 2022; Panyi, 2023; "The EU's own "Snowden Scandal": Europol's Data Mining", 2022). Yet again, as Saura García (2024) and Taylor (2021) point out, States allow these companies to integrate into what was previously exclusive to public institutions (policing, national intelligence, etc.). The reason behind this penetration is that whilst States possess technical and technological capabilities, they lack access to data, at least not to the same extent that Big Tech companies hold.

As such, big tech and digital platform companies gain significant political (vis-à-vis States) and economic (vis-à-vis dependent companies) power that scales with the data they can collect, analyse, and effectively use to predict, persuade, and/or coerce individuals, societies, and States. Of course, there are other aspects of AI that transform political, societal, and economic domains. However, these cognitive capabilities, often provided by illegal and unethical extraction and processing of personal data to subdue the human mind, make artificial intelligence an unprecedented technology that may challenge the one of the most established norms of society: regulator of daily affairs, establisher of laws, the Leviathan, shortly, the State.

3. The Concept of State and Territorial Sovereignty

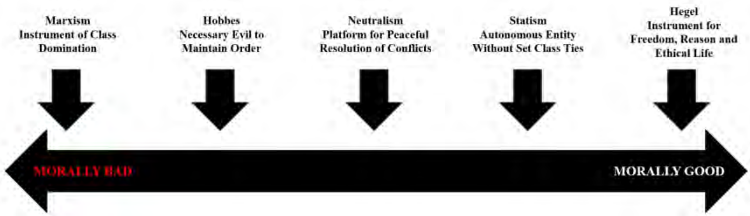
The origin of political entities is widely linked to the Agricultural Revolution (circa 10,000 BCE), which necessitated mechanisms to address internal and external threats to human settlements. Two dominant explanatory frameworks attribute the emergence of these organizations either to violence or subjugation. Hobbes, advocating the former, depicts humans as naturally violent beings in a "state of nature," where life is marked by insecurity. In his view, a "Commonwealth" (not State per se) emerges as a social contract, wherein individuals relinquish natural rights to a sovereign authority in exchange for protection of their life and property (Hobbes, 1651|2008; Mann, 1984; Tilly, 1990). Conversely, the latter framework, advanced by Marx and contemporary Marxist scholars, sees the State as a tool for perpetuating class exploitation, evolving with the modes of production (Engels and Marx, 2004; Abrams, 1988; Morris and Scheidel). Then again, Diamond and Ordunio (1999) contend a deterministic stance, arguing the State's emergence as a functional response to societal needs arising from increased population or external threats.

Here, it is necessary to commence the debate with an etymological analysis of the term. As such, "State" originates from the Latin status, denoting "standing," "condition," or "position." One of the earliest references to the State – as in political jargon – appears in Machiavelli's (1532) The Prince, where it initially meant dominions governed by rulers. This only makes sense when juxtaposing "State" and "Real Estate." Put differently, owning real estate makes one a "landlord," while owning a State makes one "Lord of the Land." Obviously, the land itself does not make someone a ruler; rather, it is the people's obedience, ensured either through consent or coercion, that does so. Subsequently, influential political theorists Bodin (1576|1992) and Hobbes (1651|2008) further refined this notion, emphasizing sovereignty as a central principle. Today, it may be considered as something given; however, during the medieval age, sovereignty was a serious point of contestation that was challenged primarily by monarchs, feudal lords, and the Church. However, the Peace of Westphalia (1648) marked a turning point, establishing the principle of State sovereignty in internal affairs and diplomatic relations.

Around the time of the French Revolution (1789), State structures began to transform from being the personal property of monarchs to impersonal and somewhat autonomous entities, alongside the rise of nation-states with relatively more cohesive societies and centralized control. In the period between then and the post-Cold War era, States enjoyed near-universal recognition in their dealings. However, as stressed before, factors such as globalization, consecutive breakthroughs in ICTs, the rise of supranational entities (e.g., the EU), neoliberal governance (e.g., the WTO), and the considerable increase in the political power of multinational companies cast doubt on the viability of the nation-state's sovereignty. It can be argued that the debate over digital sovereignty includes all of these factors. However, before moving on to discuss this emerging concept, another point must be covered: the relationship between State and society.

Society is derived from the Latin word "societas", meaning "fellowship," "partnership," or "alliance" of individuals often bound by a mutual relationship or a common purpose. As such, social contract theorists such as Hobbes, Locke, and Rousseau claim that the State (though they use the term "Commonwealth") and society come into existence at the same moment when individuals agree upon a set of rules, ending the "state of nature" where early humans lived in anarchy. Conversely, (neo-)Marxists such as Althusser (2010) and Gramsci (1978) claim that States are built to maintain and further class domination by excluding certain people from means of production since the invention of irrigation technology in ancient times. Accordingly, it requires not only physical coercion but also the ideological alignment of individuals to maintain its existence. Hence, Althusser (2010) argues that institutions such as media and public education serve to align society in accordance with the needs of the dominant class. Furthermore, the seemingly neutral structure under an impersonal bureaucracy serves nothing but a façade to disguise this fact.

Yet again, this view is challenged by scholars such as Evans et al. (1985), who assert that the State is a nearly autonomous entity with its own needs and processes above and beyond society. Accordingly, the State elite emerges as a distinct class separate from society and the economically dominant class (currently capitalists); however, it might ally itself with either of them as necessities demand. Between these extremes, the State serves mainly as a platform or an arena for competing (and often conflicting) interests within society to resolve its affairs peacefully. This means that the State is a polycentric political entity with no fixed functioning and objectives distinct from society itself (Dahl, 1957; 2020). Now, the concept of digital sovereignty can be covered in conjunction with its implications regarding the State-society relationship. For Hegel (1821 | 1991), though, the State is the only ethical environment in which a human being can achieve highest point in his/her life. For this, the State provides the necessary order and ethical guidance that individuals cannot find anywhere else. Figure below summarises the arguments given above.



Consequently, the concept of State cannot be reduced to its formal features (e.g. territorial sovereignty). As per shown above, different theories of State denote different functional aspects to the concept. Therefore, it is of paramount importance to take into account these functions when considering effects of a technological revolution. Subsequent section will focus on the concept of digital sovereignty.

4. The Concept of Digital Sovereignty

Digital sovereignty emerged as a discourse in EU politics, advocating for a digitally sovereign Europe. However, given its recentness, it lacks a clear definition. It is a multidimensional concept spanning from individual self-sovereignty to States' ability to maintain control over their "digital territory" (Roberts et al., 2021; Floridi, 2020). By now, it should be clear that the problem arises from the fact that the digital realm is in a "state of nature," making it anarchic as no actor has yet asserted dominance. From this perspective, how could actors ensure their digital sovereignty? The logic of sovereignty relies on the superiority of an entity to have the final say in the state of affairs within a defined territory. However, as the digital realm lacks these boundaries, a literal conception of the term would mean that one State – or another actor – emerges to possess sovereign power over others to establish rules of conduct and, of course, enforce them with predictable certainty (Mueller, 2020; Ruohonen, 2021). From this perspective, digital sovereignty becomes an absurdly utopian wishful thinking.

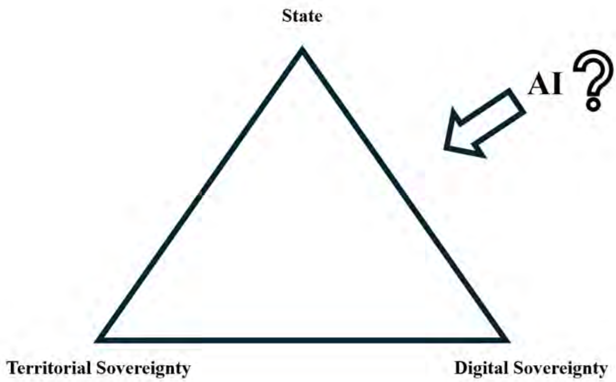
However, as Moerel and Timmers (2021) argue, what the term actually refers to is "digital autonomy," meaning actors' (individuals, States, etc.) autonomous capability of decision-making by reducing dependencies on constraining factors. Similarly, Floridi (2020: 370-371) defines the term as "the control of data, software (e.g., AI), standards and protocols (e.g., 5G, domain names), processes (e.g., cloud computing), hardware (e.g., mobile phones), services (e.g., social media, e-commerce), and infrastructures (e.g., cables, satellites, smart cities), in short, for the control of the digital."

How, then, does this affect the territorial sovereignty of States and, thus, State-society relations? To begin with, human societies progressed from hunter-gatherer societies to feudal, to industrial, and to Beck's risk society. Most recently, it has been depicted as the "networked society," reflecting the idea that everything is connected in a way that empowers global corporations and digital platforms. Accordingly, as Chapdelaine and McLeod-Rogers (2021: 2) argue, "issues of state sovereignty are now intertwined with issues of personal data and subject sovereignty, whereby the consumer and communicative choices of citizens—'behavioral surplus' associated with content viewing and social media habits—are constantly tracked." As such, Pohle and Thiel (2020: 13) argue that "the digital sovereignty of a state cannot be reduced to its ability to set, communicate and enforce laws" as it "means not only actively managing dependencies but also creating infrastructures of control and (possible) manipulation."

Therefore, digital sovereignty translates into territorial sovereignty as States' ability to maintain control and command over their ideological state apparatuses to ensure obedience and loyalty from their populations. Conversely, some scholars argue that the narrative of digital sovereignty is a façade, a pretext to increase State control over the internet by enacting urgency to legitimize rather draconian measures. Moreover, they did so in cooperation with big tech companies and digital platforms, signalling an alliance between States and digital empires (Poelert, 2016; Tikk and Kerttunen, 2022; Mainwaring, 2020). Let us now have a glance over politics of AI and how it is affecting the concepts of both territorial and digital sovereignties of States.

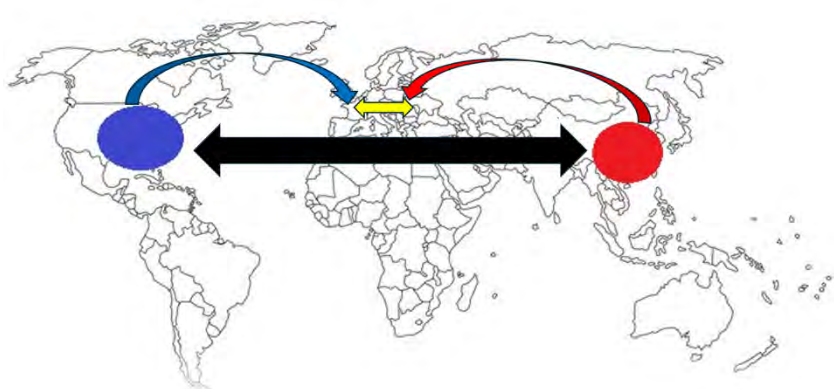
5. Politics of AI and the State

In order to determine the underlying reality of the transformation that the concept of State is experiencing (or will experience), the politics of AI must be examined. To begin this inquiry, one must possess a solid understanding of how politics of AI is linked to digital and territorial sovereignty of States. Refer to the figure below for visualisation of these interplays.



Source: Prepared by authors according to the earlier discussions.

Let us one more time explain these intersections. As you will remember, the concept of State traditionally was bound to the notion of territorial sovereignty that is the ability of the organisation (the State) to control the institutions and population within a determined geographical area. Then again, the digital sovereignty was the most recent challenge to this conception of sovereignty due to the (somewhat) limitless and borderless nature of the internet. The reason of this challenge, of course, is the interconnection between concepts of territorial and digital sovereignty. To reiterate the argument, the digital sovereignty was linked to the territorial sovereignty because, contrary to the past, of the fact that transnational actors (other states or big tech corporations) obtained considerable influence in affecting the traditional functions and functioning of the State. All of these have previously been discussed. Now, let us pose the question: "What are the current affairs of national, regional and global politics of AI and in what trajectory are these political affairs transforming the concept of the State?" Answering this question requires a geopolitical overview of AI.



Note: Bahar, Ç.B. 2025: Chapter 4.1.

Let us first examine the map above. The black arrows indicate the global technological confrontation between the USA and China. Blue and red arrows indicate for these superpowers' actions to influence Europe. Yellow arrows highlight the growing rift within the EU. Now, how this global rivalry between the USA and China is linked to the concept of State and its future? As will be remembered, the abundance of data is needed for developing – hence competing with each other - artificial intelligence. Then again, such data is enormous (measured in zettabytes) and therefore requires a really high-speed internet for transmitting it in the shortest possible time. Here, American and Chinese companies[1] (and of course governments) are competing with each other to set up the infrastructure. One possible reason for that is that it allows the one that owns the infrastructure to control the data transmission itself. Secondly, it gives ability to restrict export of the equipment (such as modems, receivers etc.) compatible with that infrastructure (Schindler et. al., 2024). Besides the fact that it is almost completely counteract against the notion of digital sovereignty, there is a more intricate truth beyond this simplicity. On the one hand, the USA and other Western countries (along with their companies) are based on liberal market

[1] Whereas there are variety of different Western originated companies such as Qualcomm, Nokia, Ericsson, CommScope, AT&T, Samsung and Fujitsu; There are two Chinese originated companies that play major role for infrastructure construction, namely Huawei and ZTE (Derrick, 2023). As a result, Chinese companies become even more competitive in terms of cost as well as technical qualities (Nagy, 2020).

ideology that allows for free competition. On the other hand, China endorses socialist market ideology that paves the way for State-owned or associated enterprises to consolidate their economic, technical, and political powers with the State of China. Implications of this difference shall be elaborated in the subsequent section, however, let us now move to national politics of AI which is deeply related to this divergence.

Then again, on the Western side, because of the individualistic values, owners of Big Tech companies such Elon Musk, Mark Zuckerberg, and Jeff Bezos along with CEOs and other high-level executives of these companies gain considerable influence in decision-making processes of liberal democracies. In addition to their influence at home, these individuals can also affect – either directly or indirectly – national politics abroad. Most notable example this is the regulatory battle between the U.S. tech giants and the European Union (including member states). For example, just after the inauguration of Donald Trump for the second time, Elon Musk and Mark Zuckerberg called President Trump to "rescue" them from the harassment of Europeans. Moreover, Elon Musk, just after the event, boasted that he put Trump in the White House (Hernández-Morales, 2025; Psaropoulos, 2025). A similar remark had been made by Cambridge Analytica CEO Alexander Nix in 2018 (McKee, 2018). This shows that the tech giants effectively possess the capacity of influencing and even determining the political processes as well as elections in the U.S. On the contrary, China incorporates leaders of technology companies into decision-making bodies. For example, most recently the founder and CEO of DeepSeek – an AI model that rivalled ChatGPT – Liang Wenfeng had been invited by the Chinese Premier Li Qiang to a symposium (Geopolitechs, 2025). This, along with the fact that Chinese companies are somewhat related to the government, shows that there is a consolidation of power, compared to the diffusion in the Western countries. This key difference, as will be discussed momentarily, plays a definitive role in the future of the concept of State.

States, particularly Western elites, are not passive against political influence and interference from Big Tech. Under the Biden Administration, the U.S. pursued executive orders and legislation to regulate these companies. Zuckerberg claimed the administration pressured Meta to censor information during the COVID-19 pandemic. Biden also sought bipartisan support for Big Tech legislation in 2023 and signed an executive order in 2024 on data regulation (Kelly, 2023; Rajan and

Bose, 2024; Stiglitz, 2024). However, many of these efforts were reversed when President Trump assumed office in 2025 (Wheeler, 2025).

Across the Atlantic, the EU has long aimed to limit Big Tech's influence, particularly that of U.S. companies. The General Data Protection Regulation in 2016 restricted data collection, usage and transfer, though companies repeatedly violated it despite heavy fines. In 2022, the EU introduced the Digital Services Act and Digital Markets Act to combat misinformation and monopolies (especially of the U.S. companies). In 2024, it passed the first AI regulation to address AI's societal risks. All in all, what is clear from these documents is that the EU and its member states were more interested in taking control of AI technologies than establishing a robust legal framework their citizens (space does not permit us to go in details, however, see Bahar, 2025; Öhman, 2023; Manokha, 2023; Atzori, 2024; Goujard and Volpicelli, 2022; Davies, 2024).

Thus, AI politics involves more than clashing interests; it reflects a deeper conflict between emerging techno-oligarchs and dominant capitalist classes as well as the institutional constraints within which capitalism evolved. The next section explores what this means for the concept of the State.

6. Discussions and Conclusions

Can States survive in the age of artificial intelligence? This was the central question of the study, which was explored through engagement with contemporary debates. First, the answer depends on how one conceives of "the State." If the concept is stretched to encompass every political organization across time and space, the answer is likely "yes." After all, expecting a "Stateless" society to thrive within the interconnected and increasingly authoritarian structure of today's so-called networked society would seem unreasonable. Conversely, if the concept is narrowed to refer exclusively to the State as it emerged during early modernity, it risks becoming "a conceptual straitjacket that ignores the fundamentally dynamic and dialectical nature of human social organization" (Morris and Scheidel, 2009, pp. 4–5). How, then, can the concept of the State be understood without diluting its analytical value?

To begin with, the condition for the continuation of States must be logically established. This condition, of course, refers to the existence of at least two States.

If the number of States existing at any given time across the world is either zero or one, then we cannot argue that "States continue their existence." In such a case, there would either be only one State or no State at all. The question, then, should be asked here: "Can AI be capable of reducing the number of States to either zero or only one?" And if so, how?

To answer these questions, Weber's (2013, pp. 77-78) widely cited definition of the State as "a human community that (successfully) claims the monopoly of the legitimate use of physical force within a given territory" serves poorly as a starting point, as it focuses primarily on the institutional image of the State (Mann, 1984). As we argue, the concept of territorial sovereignty is rather a pure fantasy in the current interconnected, digital world. Moreover, digital sovereignty—often framed as autonomy rather than sovereignty in the traditional sense—appears increasingly unattainable, as both states and private individuals, whether officially or unofficially, seek to impose their own sovereign claims. In this context, two possible scenarios emerge concerning the future of States, particularly in relation to the ongoing technological rivalry between the United States and China. The first scenario imagines the U.S. emerging victorious, leading either to China's dissolution or its liberalization. The second envisions a Chinese victory, resulting in the dissolution of the U.S. or widespread adoption of Chinese norms. We now turn to a closer examination of these scenarios and their potential impact on the concept of the State. For analytical clarity, we will treat the first scenario as representing the hollowing out of the state—namely, the effective disappearance of States as traditionally conceived.

As discussed in this study, the first functionality of the State is to terminate the "state of nature" —an anarchic condition in which individuals are effectively engaged in a constant struggle against one another. Through the formation of a social contract, society establishes the State by surrendering certain natural rights to a sovereign authority in exchange for the protection of life and property. However, the digital realm is inherently anarchic, making it difficult—if not impossible—for States to guarantee the safety of their citizens from external threats. This digital anarchy spills over into physical reality, as foreign actors can now influence individuals' psychological, physiological, and financial well-being through digital means (Zuboff, 2019; Ienca, 2021).

It is conceivable that an unholy alliance between States and Big Tech could emerge to further subjugate society. However, as Fukuyama (2015) argues, a sovereign— regardless of its form—is expected to represent public rather than private interests. From the perspective of social contract theory, such an alliance would signify a breach of the contract, as the sovereign would be abdicating its fundamental responsibilities. While this philosophical debate may appear abstract, it serves as a critical point of departure for deeper analysis.

Conversely, Marxist scholars argue that the very purpose of the State is to perpetuate class exploitation and domination. Regardless of whether an unholy alliance between States and Big Tech exists, artificial intelligence renders States either obsolete or burdensome. In the former case, AI already functions as a more efficient ideological apparatus, and it is only a matter of time before it acquires comparable capabilities in physical coercion through autonomous lethal weapons. Consequently, Big Tech companies may no longer find it necessary to maintain systems that require allocating portions of their profits to corrupt government officials.

If a direct confrontation were to occur between States and these digital empires, it would signal a clash between traditional and emergent modes of production—physical versus digital. In such a scenario, the continued reliance of States on outdated mechanisms of subjugation would merely preserve the hegemony of legacy capitalist structures. As Pistor (2020) suggests, this dynamic could lead to a restructuring of the State in which public and private actors share sovereign competencies—or, more radically, to the complete replacement of States by corporate entities.

According to the Statist approach, state autonomy derives from the autonomy of individuals in their interactions (Evans et al., 1985). However, if artificial intelligence indeed overrides human autonomy, State autonomy would likewise disappear (Peters, 2022; Floridi, 2020). As Mann (1984) argues, this autonomy is what distinguishes the State from other organizations, making it a uniquely "socio-territorial" entity. If this autonomy is eroded, the State would begin to merge indistinguishably with other forms of organization. At this juncture, Dahl's (1957; 2020) conception of the State as a neutral forum for peaceful conflict resolution becomes obsolete, as external actors—including other States and private corporations—acquire the capacity to interfere in and influence domestic affairs.

Consequently, the concept of the State would be profoundly hollowed out, and it becomes debatable whether the remaining entities could genuinely be considered States. As a result, global societies may devolve into arenas of personal contestation among powerful individuals. This scenario strongly resembles the Feudal Monarchic Era, wherein sovereignty was continuously contested by monarchs, feudal lords, and ecclesiastical authorities. Varoufakis (2024), in his seminal work Technofeudalism: What Killed Capitalism, has already identified this trajectory. Our contribution extends this analysis by asserting that feudalism, in its most disordered form, is, as Davies (2003) contends, a fundamentally "stateless" society.

While hierarchical structures may persist, a singular sovereign authority would be absent. The concept of digital sovereignty exacerbates this fragmentation, further implying a stratified order. As a result, digital and territorial sovereignties may become increasingly opaque, especially in a scenario where the U.S. emerges as the dominant power. In such a context, Big Tech corporations could function simultaneously as churches, feudal lords, and monarchs.

At the nexus of digital and physical realms—most notably on social media—these corporations would "guide" individuals in ways reminiscent of religious institutions in the past. Furthermore, they could elevate their preferred individuals to positions of power, such as heads of state and parliamentary representatives. This dynamic would mirror the dependency monarchs once had on feudal lords to sustain their rule. Unlike the closed nature of historic monarchies, however, today's "technofeudal" societies are transnational. A single tech magnate—be it Elon Musk, Mark Zuckerberg, Jeff Bezos, or another—could assume the role of a "kingmaker" across multiple nations. Should such individuals exert influence over enough world leaders, their global stature would exceed traditional notions of sovereignty. In such a scenario, the term "sovereignty" itself might become obsolete.

On the other hand, if China were to become the sole global power and thereby control all data flows, it would effectively herald the rise of a singular, dominant sovereign entity. How would this occur? As China gains control over global data processing, it could adopt the same roles currently played by Big Tech firms—but with a critical distinction: Chinese companies would operate under a unified State authority rather than in competition with one another. In doing so, other States would effectively be reduced to the status of municipalities, merely administering their local territories under broader Chinese oversight. In such a context, true sovereignty and autonomy would cease to exist. This scenario would position China as the de facto global sovereign—if not officially, then functionally.

As discussed, in both scenarios, the notion of the "State" ceases to exist in its traditional sense, whether through the dilution of its functions under Western individualism or its consolidation under Eastern collectivism. This study argues that framing these outcomes as a binary opposition presents a false dichotomy. The reality is likely to emerge in the grey zone between these extremes. Future research should therefore concentrate on exploring hybrid governance models that reflect the convergence of public authority and private power, addressing the evolving structure of sovereignty in the age of artificial intelligence.

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3

Artificial Intelligence, Nanotechnologies and the Dialectics of Life[1]

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Abstract

The rapid and successful expansion of artificial intelligence (AI) across economic sectors masks the important fact that this relationship is not unidirectional. AI itself benefits from advancements made in various other sectors. Nanotechnologies exemplify this type of reciprocal dynamic. Indeed, on the one hand, artificial intelligence is playing a key role in the research and development of new nanomaterials and nanotechnologies. At the same time, by providing raw materials and strategic devices for the development of communication, storage, and information processing equipment, nanotechnologies support the emergence of the next generation of technologies that will enable the development of artificial intelligence over the coming decades. In this text, we examine the reciprocal relationship between AI and nanotechnologies, and address the insurmountable risks that scientific and technological development poses to environmental health. We conclude by advocating for a slowdown of scientific research and development, employing the precautionary principle as a crucial measure to mitigate risks.

Keywords: Artificial Intelligence; Nanotechnologies; Political Economy; Political Ecology.

JEL Codes: A13, F60, I30, I39

[1] This text is part of the project Frontier Science #304320, supported by SECIHTI, Mexico

1. Introduction

This article explores the case of graphene—a two-dimensional material that has recently emerged as a focal point of both high expectations and considerable risks—and its relationship with artificial intelligence (AI). This article analyses the reciprocal feedback between artificial intelligence and nanotechnologies, while also addressing the insurmountable risks posed by scientific and technological development to environmental health. This example illustrates the inherent contradictions involved in the development of new materials in relation to AI. We conclude by advocating for a deceleration of scientific research and development, applying the precautionary principle as a crucial measure to mitigate risks.

2. The Impact of Nanomaterials in Large Industry Sectors

Technological innovation linked to nanomaterials has proliferated in various sectors of the economy like medicine, agriculture, food industry, aeronautics, automobiles, energy industry and many more (Mekuye & Abera, 2023; Singh et al., 2022). In the last five years, and thanks to artificial intelligence, it has received a new impetus, as highlighted in a dossier of the French newspaper *Le Monde* (De Laurier, 2024). That article lists some economic sectors oriented towards mass consumption that seem to be booming with the applications of such materials, for example:

- The automotive and aeronautics industry, where applications of nanomaterials have demonstrated properties that make it possible to increase the energy storage capacity and recharging times of batteries. It also highlights the automotive and aeronautics industry's interest in reducing its dependence on certain raw materials, which today are essential for the construction of batteries used in electric cars (Song, 2022). The development of lubricant additives has also been one of the main applications of nanomaterials for enhancing combustion engines in the automotive and aeronautics industry (Singh et al., 2022).

- The agro-industry, where the development of antifungal-agent or antibacterial agents based on nanomaterials has proven its efficiency on the germination inhibition for different pathogens (Mekuye & Abera, 2023). The use of nanocomposites as coating materials for fertilizers has also been increasingly widespread because of their strong controlled release characteristics (Singh et al., 2022).

- The biomedical industry, where nanomaterials are being used in the development of Nano sensors that are capable of detecting a wide array of biochemical compounds linked to widespread diseases like cancer, hepatitis or diabetes (Singh et al., 2022). Treatments against the advancement of medical treatments against a series of diseases or disorders are being developed through new nanomaterials that can unfold efficient methods for drug delivery (Singh et al., 2022).

- The cosmetics industry, where nanomaterials make it possible to take advantage of specific properties, such as protection against UV rays while, at the same time, facilitating aesthetic criteria, such as textures closer to those of the skin or more defined colours (Chemical Watch, 2021).

- The food industry, where nanomaterials are used for food preservation and colouring (Cushen et al., 2012).

The place that nanomaterials hold in the global production chains, being part of the material basis for the 4.0 industry, has resulted in a quick and wide proliferation of nanomaterials in a very large array of economic sectors. In addition to this structural dynamic, this article aims to highlight the way in which the advancement of artificial intelligence has been a key factor for the acceleration of the research and development of nanomaterials. This synergy has become a key dynamic of the ongoing technological shift.

3. Artificial Intelligence *vis a vis* Nanotechnological Material Resources

Although the above examples of nanotechnological applications have existed since the first decade of the century, artificial intelligence has boosted research by facilitating combinations of nanometric materials and identifying the possible substitution of some of high costs and commercial restrictions, such as certain rare earths or lithium, for other more economical ones such as the different varieties of graphene (Graphene Flagship, 2023).

But in a more fundamental way, artificial intelligence has completely changed, in less than a decade, the way in which the research and development of nanomaterials was traditionally organized. Indeed, the classical trial and error approach used for the research on new nanomaterials was characterized for its high time-consuming and resource-intensive processes (Olawade et al., 2024). However, artificial intelligence has allowed a new paradigm based on predictive modelings and virtual materials screening. These new methods, based on the data analysis upon large databases of physical and chemical properties, as well as interdisciplinary knowledge, have already proven its efficiency on the development of new nanomaterials and are quickly reshaping the benchmarks for research approaches (Olawade et al., 2024). Artificial intelligence also collaborates in the discovery of new materials or optimizing the structure and functionality of known materials, as in the case of graphene, where artificial intelligence models allow a more accurate calculation of the oscillation of the atoms and, consequently, of the thermal properties of the materials (Butler et al., 2018; Rowe et al., 2018).

Some of the most meaningful results in the development of nanomaterials, in the last years, have been obtained through the new methodologies enabled by artificial intelligence. The size of the silver nanoparticles (Ag-NPS) was predicted, for example, by Artificial Neural Networks with extremely low error margins (Olawade et al., 2024). It is also important to highlight that the application of artificial intelligence is not limited to the only field of research of new materials, it has also been used for discovering new properties in the chemical space. One of the most typical examples of this use is the development of the Crystal Graph Convolutional Neural Network developed by Tian Xie and Jeffrey C. Grossman (Xie & Grossman, 2018). Their work has allowed the development of the use of machine learning methods for the design of crystalline materials. This has fundamentally accelerated the research on material properties for eight different types of crystals, expanding in significant ways the research possibilities for material scientists in this field (Olawade et al., 2024).

The process of experimental validation of all these AI-enhanced theoretical predictions has also been deeply impacted by artificial intelligence through the redefinition of material screening processes. In this case, artificial intelligence has coupled with robotics in order to design particularly efficient and rapid streamline materials testing.

4. The Specific Case of the Graphene

One of the more paradigmatic and relevant examples of the implementation of nanomaterials in wide arrays of economic sectors and the geopolitical consequence of its development is graphene, indeed, one of the most representative two-dimensional ("2D") nanomaterials, with wide presence in the market and versatile applications.

This nanomaterial, discovered two decades ago, is particularly resistant, lightweight and thermally conductive, which has enabled it to be increasingly present in, for example, the aeronautics industry. Likewise, its characteristics as a semiconductor and its exceptional photosensitivity have enabled it to be integrated into optical sensors, photodetectors and light modulators (Graphene Flagship, 2023).

Graphene and its different derivatives hold today a key strategic place in the shaping of the future of the nanomaterials industry. This can be seen through an overview of the strategic public policy that has been developed in the main countries that are unfolding the global competition for becoming the leaders for the research, development and production of nanomaterials. The reason behind the special interest in this specific material is linked to the geopolitical dispute to produce computational micro - and nano- chips. Indeed, one of the main expectations that has emerged from the graphene research is linked to the possibility of developing new graphene-based semiconductors that could replace the silicon made semiconductors that are at the base of today's microchips (De Laurier, 2024; Graphene Flagship, 2023).

The global dispute around microchips has shown, on one hand, its wide impact across a variety of industries, as shown during the microchips shortage that resulted from the COVID pandemic and unfolded from 2020 to 2023 affecting more than 169 industries, from the automobile industry or the consumer electronics to the healthcare and aerospace sectors (Fusion Worldwide, 2021; Howley, 2021). The dependency from the data centres infrastructure on the silicon based semiconductors is particularly strategic in the context of the unfolding of the globalization 4.0 economic dynamics (Moll, 2021). It is worth mentioning that this pressure on replacing the silicon-based microchips is exacerbated by the three main limitations that are emerging from this technology. First, there is a tendency that has been unfolding related to the slowing pace of processing power that has been observed in recent years. This slowing dynamic has allowed new competitors to catch up previous leading companies, causing prices to fall from 10 to 15 percent (Batra et al., 2018). A second dynamic is linked to the growing capital and R&D costs linked to the need of incorporating new manufacturing equipment in order to confront competition (Batra et al., 2018). One third tendency that appears as a key factor for the need of replacing silicon semiconductors is the physical limitations that silicon is approaching due to the consequences of a constant reduction of its size (Batra et al., 2018).

These specific economic tensions are added to the geopolitical ones that had resulted from the trade conflicts between US-China and Japan-Korea based on their competition upon becoming key players in relation to advanced manufacturing technologies. Even before the COVID pandemic, those tensions resulted in microchip shortages between 2018 and 2019 (Fusion Worldwide, 2021).

All this economic and geopolitical tensions have resulted in a structural pressure on graphene research, as a promise to a replacement of traditional microchips, and a direct active involvement of governments and global economic corporations searching for leading this emerging field. Indeed, Europe, being the birthplace of the graphene discovery, was the first to launch a 10-year strategy for becoming one of the leaders in the research and development related to these varieties of nanomaterials. Its key program, the "Graphene Flagship" was founded by a billion euros budget that has allowed the European researchers and producers of graphene related materials to maintain a relevant role on the international scene. Nonetheless, it is China that has emerged as one of the most important players in this international context. Indeed, China is the country that has developed the most graphene related patents since its discovery and has positioned itself as the main global producer (Yang et al., 2018).[2]

The United States's industrial sector has already been facing structural challenges due to China's dominance in the production of silicon (Jaganmohan, 2024) which has resulted in important public and private funding in order to prevent the same situation to be reproduced in relation to the next generation of graphene-based microchips. One of the most significant initiatives in this direction is the "Chips and Science Act", passed in 2022 by the U.S. congress as a bipartisan proposal that should fund 50 billion dollars in additional investments for American semiconductor manufacturing. The explicit objective of this act is to build efforts in order to keep the United States the leader in the industries of tomorrow, including nanotechnology, clean energy, quantum computing, and artificial intelligence" (The White House, 2022). Those efforts are not limited to public funding; private corporations like IBM in the United States or Samsung and SK Hynix in Korea also join the trend (Fusion Worldwide, 2021).

It is important to highlight that even if the graphene is one of the materials on which many expectations are being placed to replace the silicon-based microchips, this doesn't mean that nanoelectronics are not already a key component of the current microchips. Indeed, Jari Kinaret, former director of Graphene Flagship, states that we are at a point where "by definition, all microelectronics today is actually nanoelectronics" (De Laurier, 2024).

Having set this overview of the strategic importance that graphene has developed in recent years; it is worth noting the fact that all this structural dispute has a particular relevance for the development of the future of artificial intelligence. Indeed, the future development of the material basis of artificial intelligences, in terms of simultaneous computing power, storage and, therefore, acceleration of information and communication times, appears as directly related to the nanomaterials current research. Adding to this, another emergent technology, Quantum Computing, shares the same kind of material determination (De Laurier, 2024).

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[2] Other National Initiatives to advance graphene research and development are: South Korea, Graphene Research & Commercialization Programs (2013); India, Mission on Nanoelectronics & Graphene (2020); U.S, National Graphene Association (2017).

It is in this sense, as a synthesis of what has been analysed till now, that it is possible to identify a mutual determination that is being unfolded and increasingly strengthening between artificial intelligence and Nanomaterials. Indeed, on the one hand, it is possible to see how artificial intelligence has become a key technology for the acceleration of the research and development of nanomaterials, while, on the other hand, we can see how nanomaterials, like the graphene, have become a central component for the future development of artificial intelligence. It is essential to highlight that this mutual determination shares a common denominator that is the acceleration of times in each sector: acceleration of time research and development in one case (nanomaterials), and material enablement of the acceleration of computing time for data analysis and predictive models in the other (artificial intelligence). This article seeks to critically examine and problematize this specific dynamic of temporal accelerations, with particular attention to their socio-environmental implications and the potential disruptions they may pose to ecosystems that underpin human existence.

5. Environment Cannot Be Ignored

The dialectic relationship between nanotechnologies and artificial intelligence has its Achilles heel when analysed in a broader context, particularly in its interaction with living beings and ecosystems. Concern about the potential risks to human health and the environment of new materials is an ever-present agenda; but here we are interested in drawing attention to a not explicitly noticed aspect: the contradiction that arises between the different times and spaces between the techno-scientific logic and the logic of life.

While science and technology increase the speed of productive processes and the extent of their application in different geographical spaces, with no other limit than the intrinsic difficulties of knowledge and its application, the different living organisms respond to their times of evolution and colonization of spaces. The result of this contradiction has shown concrete risks for humanity. A simple example illustrates it: once science and technology discover new materials or invent novel combinations, always subject to the rhythms, speed and needs of capitalist profit, such materials go through various regulations when it comes to applications that can be hazardous to health or the environment, as in medicines, food, cosmetics and others. Such regulations require physicochemical toxicological tests, commonly called risk assessment, which are carried out in laboratories with controlled equipment and rigorous protocols (Foladori & Robles Berumen, 2024).

These are analyses and studies whose procedures are tied to techno-scientific time and space. Thus, they are limited in time, for example to projections of five or ten years, while certain diseases derived from toxic products manifest themselves after 20 or 25 years of toxic exposure/accumulation; or scientific and political development explicitly discovers or assumes the dangerousness of goods without restricting market access for decades, as has recently been the case with plastic micro- and nanoparticles in oceans and watercourses, assumed after decades of flooding of ecosystems and living beings (Foladori & Robles Berumen, 2023). In other words, the technical restriction does not always correspond to the times of living beings. The same is true for the space variable. Laboratory testing establishes, for example, thresholds of consumption without toxic effects, but it is impossible to know the toxicity when one cannot control the volume of such materials entering the market, their combinations, their own dynamics (Foladori & Robles Berumen, 2024). Some of these new materials change over time for various reasons, such as oxidation or action of solar radiation (Lin et al., 2024).

In addition, the risk analysis for a new chemical element are made under conditions of the material in a pristine state in many cases; but, when they reach the market, their properties have already changed because they are incorporated into matrices with other elements with which they interact (ECHA, 2024). The same happens when the consumer product completes its life cycle and ends up as waste. Thus, the contradiction between the restricted space of analysis by the laboratory and the unlimited space of physicochemical and biological activity on Earth is exposed. These incompatibilities have been evidenced, for example, by studies on the transformations of graphene oxide in aquatic ecosystems, which have demonstrated the scientific limits of what is possible in the laboratory (ECHA et al., 2022).

It becomes clearly urgent to better study and understand the consequences of such contradictions between the time/space paradigms of economic logic (under enormous competition and geopolitical pressure when it comes to the development of nanotechnologies an artificial intelligence), modern laboratory logic (under a strong influence of the economic dynamics) and the logic of life.

Only with the integration of these specific time and space contradictions within risk assessment methodologies, will it be possible to evaluate the extent of the impact of these new technologies on human health and ecosystems. Thereby, this article will conclude by opening some reflections that can be used as a basis for further developments in this field.

6. The Contradiction Between the Spatiotemporal Paradigm of Capitalist Production and the Paradigm of the Living Beings and Ecosystems

The concept of social metabolism, and specifically the idea of a "metabolic rift", proves particularly relevant when critically examining the contradictions between, on the one hand, the spatiotemporal paradigm inherent in the capitalist economic logic and the modern techno scientific logic subsumed under it (Foladori, 2014; Harvey, 2019), and, on the other hand, the logic of life. This concept was developed, based on Marx's Capital, by authors like Bellamy Foster (2013) Paul Burkett (2006) and more recently by Kohei Saito (2023). The latter made a good synthesis of this concept as follows:

> *"the metabolic interaction of humans with the rest of nature constitutes the basis of living, but the capitalist way of organizing human interactions with their ecosystems inevitably creates a great chasm in these processes and threatens both human and non-human beings" (Saito, 2023, p. 23)*

Of particular interest within this concept is the notion of a 'metabolic rift,' originally developed by Marx and subsequently expanded upon by later scholars. This rift encompasses three dimensions, with the primary and most significant being the disruption of natural metabolic processes under the economic logic of capital (Saito, 2023, p. 24). This is based on the idea that what mediates the interaction between humans and nature, the social metabolism, is labour. Labour is undoubtedly determined by its material context, but nonetheless its concrete configuration is inherently a social and historical construction. In its evolution from precapitalist to capitalists forms of production, what Marx and the authors that continued his work have highlighted is an "increasing predominance of the social element, [...] by means of the social division of labour, cooperation, communication and various social norms, laws and institutions" (Saito, 2023, p. 87). What this implies is an historic tendency within modern societies to depend less and less on the processes, and dynamics that are inherent to the "universal metabolism of nature" and more on the dynamics related to the form that social relations adopt over history (Bellamy Foster, 2013).

In this sense, the study of technology will necessarily imply the understanding of the way in which human societies relate to nature to assure the material basis of its reproduction, but also require the analysis of social relations, of the specific historic form in which a society organizes itself to unfold this social metabolism.

A particularly relevant aspect of this concept, especially when analysing the impact of emerging technologies such as artificial intelligence and nanotechnology on life processes, is the recognition that knowledge of nature is fundamental to shaping specific historical forms of labour. This highlights a reciprocal dynamic: on the one hand, knowledge arises from the interaction between humans and nature, while on the other, this knowledge actively transforms the social metabolism. What is particularly relevant in this dialectical context is that the technologies that are being referenced in this article are playing a key role into the configuration of both mutual determinations. Indeed, as it has already been stated, artificial intelligence is fundamentally changing the way in which knowledge is created in the beginning of the 21st century, as well as nanotechnologies are shaping the future of this process and in a much wider perspective, the way in which society is transforming its material basis.

This underscores the necessity, particularly in the context of risk analysis related to the impact of new technologies on life, of adopting a critical perspective on the methods and applications of the natural sciences in concrete practices. Such an approach, as referenced earlier, must deeply integrate social relations, including considerations of class, gender, and race (Saito, 2023, p. 89).

When examining the specific impact of nanotechnologies on the environment, human health, and ecosystem processes, the other two additional and complementary dimensions of the "metabolic rift" emerge as particularly significant for understanding the limitations of current laboratory methods used to assess associated risks. Specifically, the other two dimensions of the metabolic rift manifests as a spatial rift on one hand and a temporal rift on the other. The first one, the spatial rift, has made historically reference to the antagonist relation between the country and the town. More broadly, this spatial rift can be understood as linked to the spatial division related to the sites of production, which provide the material basis for the social reproduction of life (such as food or raw materials for basic consumption goods), and the spaces of consumption.

Without entering much into the detail of this spatial analysis, there is a specific consequence that was already identified since the beginning of the industrial revolution that remains more than ever relevant: the problem linked to waste. Waste implies a spatial perspective that is unfolded in the whole complexity of ecosystems, which largely surpasses the context of controlled environments like fabrics, workshops (in the example of production) or individual housing (in the case of consumption). Thus, the problem of the impact of waste of production and waste of consumption over ecosystems, in the age of nanomaterials, calls more than ever to the need of a deep and specialized analysis that can encompass its wide spatial impact. This spatial impact needs to incorporate the spatial rift mentioned above and its complexity, particularly the perspective of the ecosystemic waste impact. Nonetheless, as mentioned, laboratory analyses are mainly directed on controlled and simplified environments, where the end destination of these nanomaterials is not approached from a large ecosystemic perspective.

The second dimension of the metabolic rift is a temporal dimension. Here, the temporal rift is based on the structural need of capital to shorten its turnover cycle, as a way of compensating the decreasing rate of profit by creating more quantity of it within the same time. This acceleration of production, circulation and consumption times has produced an ever-increasing distance in relation to natures and life rhythms in ways that need to be problematized from a risk analysis perspective. Indeed, much of the nanomaterials being produced are created under this economic rationality based on acceleration of processes, but also evaluated under this paradigm, with short temporal perspectives. Nonetheless, the time of ecosystems and evolution of nanomaterials in interaction with them cannot be reduced to the time of economic rationality. One of the most quoted examples of this type of rift is the erosion of the soil's fertility under industrial capitalistic exploitation. In the case of nanomaterials, the example of the evolution of their toxicity over time, and in interaction with the ecosystem is a critical perspective to be included in risk analysis methodologies.

Finally, as Saito synthesizes, capitalist labour is structured around the need of valorisation, and thus its spatiotemporal paradigm. Nonetheless, in a capitalist economy, "value becomes the organizing principle of metabolism between humans and nature, it cannot fully reflect the complexity of the biophysical metabolic processes between them" (Saito, 2023, p. 24). In this sense, emerges from this spatiotemporal critical perspective the need to expand the laboratory, spatially reduced and temporally shortened spatiotemporal paradigms and incorporate the idea of complexity into risk analysis.

In this sense, it is relevant to highlight the fact that the field of complexity studies has been developed throughout the XX century and has acquired a particularly strong dynamic in the beginning of the XXI century with the development of computational power (Gell-Mann, 1995a). Interestingly, artificial intelligence has been presented as a disruptive technology that can fundamentally change the way in which complexity can be studied. Nonetheless, a structural problem emerges in the way in which this technological disruption is presented. Indeed, one of the bases of complexity studies has often been misunderstood in the wider public debate as just the difficulty of processing large amounts of information. But, while information plays a key role in complexity studies, it is not only the potential analysis of large amounts of information that define complexity. This has been a measure for complexity (for example, how long a computer would take to solve a specific problem) but needs to be distinguished from the idea of complexity itself.

In fact, complexity is much more linked to the idea of in determination, and it is fundamentally linked to the need of abandoning the idea of classic determination in science. This determination can be understood as the idea that if we have very good knowledge of the laws of nature and the initial conditions related to a system that is studied, we could make a prediction of its future evolution. But the reality of physics, of nature and social phenomena has shown that this perspective can no longer be generalized, expert to very specific cases.

One of the most influential scholars in the field of complexity for decades, the physicist Nobel Prize winner Murray Gell-Mann, points to two fundamentals indeterminations that call for the abandonment of a deterministic idea of science even in the case of theoretical physics, where those principles were historically the strongest.

The principle of indetermination inherent in the quantic scale is the first of these principles, and can be, in the case of nanomaterials, particularly relevant since phenomena like the quantum confinement effect or the quantum dots can change the properties of nanoparticles (Taylor-Smith, 2020). One of the biggest challenges that arise from this perspective is the impossibility of deterministic prediction of nanoparticles, based on the inherent logic of quantum physics. Risk assessment needs to adopt in this case a new perspective linked to probabilistic principles instead of deterministic and strong predictive traditional approaches and even in this case the need of the precautionary principle stands out as a key sociotechnical approach, scientifically based not only on past human experience but on present scientific loops.

But besides the specific indetermination of the quantum realm, Gell-Mann makes a particular emphasis of it, introduced by chaotic systems. Those are systems that have a structural instability, in the sense that very small changes in the initial conditions can result in very important differences in the evolution of the whole system (Gell-Mann, 1995b, p. 36). One of the classic examples of this chaotic system is the weather dynamics, which are very difficult to approach from a predictive perspective. In the case of this discussion, it is particularly relevant to highlight how Gell-Mann recognizes ecosystems as paradigmatic complex systems. In fact, it is from ecological studies that many of the definitions of complexity have arisen (Gell-Mann, 1995b, pp. 38-39). Without entering on a deep description of the complexity theories, it is worthy to highlight that in the case of the impact of nanomaterials on the ecosystems in long time periods, those two phenomena - the quantic indetermination, and the chaos indetermination - seem in fact to engage in an amplification dynamic. Indeed, referencing the later work of complexity scholars like Todd Brunn, Gell-Mann emphasizes the fact that chaos and quantic indetermination seem to interact in specific dynamics where chaotic systems tend to amplify it of the quantic scale (Gell-Mann, 1995b). This is particularly relevant when dealing with the long-term effects of nanomaterials on ecosystems and life cycles.

All these considerations are particularly important when approaching the techno-utopistic promises of artificial intelligence when dealing with complexity. Indeed, there are fundamental indeterminations that cannot be solved, even with unlimited computational power, and that are inherent to chaotic systems. In fact, many of the regularities that we can observe in nature are much more based on the adaptability that characterizes our ecosystems rather than deterministic laws that need to be unveiled by the analysis of large amounts of data (Gell-Mann, 1995b, p. 29). Here emerges a need to abandon very strong deterministic perspectives embedded in neoclassical economy and traditional sciences, to use the emergent technologies in new paradigms that can incorporate the dialectical dynamics of life. Adaptability in complex systems such as natural ecosystems is not a characteristic that can be easily simulated even if there are enormous amounts of data available, when this data is only related to short term and spatially reduced contexts. It emerges that there is an irreducible characteristic of time and space of the complexity of life that cannot be reduced to the dominant economic spatiotemporal paradigms. New approaches need to be developed that need to integrate long-term perspectives and wide spatial scales into risk assessment if artificial intelligence expects to become a useful technology in this context.

7. Conclusions

Since human beings require a living ecosystem, the contradiction between human production spatio-temporal paradigms—determined by economic restrictions and demands—and the times and spaces required by living species and organisms for their healthy reproduction and metabolism is profound. There is a permanent danger of an environmental crisis, something that manifests itself systematically (Stengers, 2018). When it comes to the assessment of the risks for ecosystems and human health related to the use of the dialectical unity of artificial intelligence (AI) and nanotechnologies, these metabolic rifts cannot be approached based on current laboratory conditions. Even if the future effective use of AI for studying the long-term evolution of nanomaterials within ecosystems cannot be ruled out, such use necessarily requires the generation of extensive longitudinal data.

Indeed, it is evident that the spatio-temporal paradigm of life cannot be reduced to the needs of the modern capitalist economy. In this sense, the need to decelerate techno-scientific development would be a precautionary and humanitarian alternative to the current acceleration caused by the desire for greater profit that drives scientific and technological development. Only with deceleration is it possible to develop robust scientific approaches, even supported by artificial intelligence, that can study the impact of nanomaterials on ecosystems and human health.

The slowdown of scientific research and development does not imply a sceptical position; on the contrary, it represents a precautionary attitude to ensure that human activities do not create irreversible living conditions in the future. To this end, the core of science and technology policy should be the reasoned control of the impact of market laws and profit motives on research and development.

From this perspective, it appears that the transdisciplinary approach required for risk assessment must develop a view not only of how scientific methods are socially constructed by relations of power, but also incorporate these relations as part of the concept of risk itself. As Saito highlights, the metabolic approach not only questions how knowledge, science, and technology emerge from social relations, but also integrates the dynamics of power into its analysis.

Indeed, the use of a metabolic perspective is not limited to acknowledging the static existence of metabolic rifts, but must also raise the question of how these rifts are spatially and temporally (re)distributed, reinforcing power dynamics and social inequalities (Saito, 2023, p. 28). This opens a wide horizon of discussions when developing risk assessment frameworks related to emerging technologies in the 21st century.

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PART II

REGULATING THE UNREGULATED: POWER, TECHNOLOGY, AND THE LAW

"Power without responsibility—the prerogative of the harlot throughout the ages."
— Stanley Baldwin, speech at Queen's Hall, London, 17 March 1931

As technology gallops ahead, legal and institutional frameworks stumble in its wake—revealing stark imbalances between innovation, accountability, and human dignity. Yet beyond the race to regulate lies a deeper question: **what happens when systems govern without justice, and codes decide without conscience?**

This part examines the complex struggles to regulate emerging digital systems, particularly in regions and sectors often marginalised by global power structures. From Argentina's bold but uneven experiments in AI governance, to the weaponisation of algorithms in the U.S. immigration system, to the grassroots resistance of app-based workers confronting digital exploitation in Mexico, these chapters expose the fractures in contemporary regulatory regimes.

Rather than passively accepting technological determinism, they highlight how communities, states, and workers in the Global South are actively negotiating, resisting, and reimagining the terms of the digital future.

In an era where power multiplies without responsibility, the twilight between innovation and injustice has become the new battleground.

4 |

Artificial Intelligence Regulation in Argentina: Advances and Challenges in the Latin American Context (2018-2025)

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Abstract

Considering the growing prevalence of artificial intelligence (AI), international organisations have introduced new agendas, recommendations, and regulatory frameworks. In Latin America, particularly in Argentina, various initiatives have emerged to plan and regulate different aspects of AI. These efforts are unfolding within the context of the Fourth Industrial Revolution—a transformative process reshaping industries, particularly education—and have gained momentum since the onset of the COVID-19 pandemic. This study explores the evolution of AI regulation in Latin America from 2018 to 2025, with a particular focus on Argentina. It examines public policy initiatives led by the Executive Branch and legislative proposals presented in the National Congress. This research is part of a broader investigation that examines how AI is reshaping accumulation schemes originating in digital spaces, with significant implications in political, social, regulatory, and developmental contexts. Moreover, it underscores the urgent need to advance a technological sovereignty agenda in Argentina and across the wider region.

Keywords: artificial intelligence, regulation, national strategy, Argentina

JEL Codes: F6, L1, O3, O36

1. Introduction

AI governance has emerged as a critical international process, focused on data management, the establishment of ethical frameworks, and the construction of regulatory systems (Issar & Aneesh, 2022). The advance of these disruptive technologies is contradictory given that, while offering opportunities to improve economic efficiency and quality of life, they also generate unintended consequences and pose new forms of risk and harm (Filgueira, 2023).

Latin American democracies face unique challenges, including the formation of public spheres, institutionalizing decision-making and deliberation processes, and addressing institutional instability. These challenges often hinder the establishment of cohesive national strategies and regulations that extend beyond the tenure of specific governments.

Within this framework, the study examines the development of AI regulation in Latin America between 2018 and 2025, with a particular focus on the Argentine case. The analysis focuses on public policy initiatives by the Executive Branch and legislative proposals within the National Congress. Methodologically, the study employs a documentary review and comparative analysis of AI recommendations, regulations, national strategies, and public policies in four regional countries: Brazil, Colombia, Mexico, and Argentina, with special emphasis on the latter.

The findings highlight a regional trend towards adopting a risk-based approach, akin to the European model, except in Argentina, where regulation is more closely aligned with market needs. In general, AI regulation across Latin America has advanced unevenly and non-linearly. In Argentina, public policies and regulations often appear fragmented, addressing isolated or sector-specific issues with limited success.

Regarding the structure of the study, it begins with an introduction to the field of AI. Secondly, a brief overview of the global context is given, followed by an analysis of the state of AI regulation in the region based on the cases of Brazil, Colombia, Mexico and Argentina. In the fourth section, the Argentine case is examined in more detail. Finally, the final conclusions are presented.

It is important to note that this study forms part of broader research which seeks to reveal, from an educational perspective, the impact of AI on new accumulation schemes originating in digital spaces, with significant political, social, regulatory, and developmental implications. It also seeks to strengthen a perspective of technological sovereignty in Argentina and the region.

2. What is AI?

The European Commission's High-Level Expert Group on Artificial Intelligence (AI)[1], argues that:

"Artificial intelligence (AI) systems are software (and possibly also hardware) systems designed by humans3 that, given a complex goal, act in the physical or digital dimension by perceiving their environment through data acquisition, interpreting the collected structured or unstructured data, reasoning on the knowledge, or processing the information, derived from this data and deciding the best action(s) to take to achieve the given goal. AI systems can either use symbolic rules or learn a numeric model, and they can also adapt their behavior by analyzing how the environment is affected by their previous actions" (European Commission, 2019: 6).

On the other hand, experts also note that, as a scientific discipline, AI includes approaches and techniques such as machine learning, among which deep learning and reinforcement learning stand out; automatic reasoning, which includes planning, scheduling, knowledge representation and reasoning, search and optimization; and robotics, which includes control, perception, sensors, and actuators, as well as the integration of all other techniques in cyber-physical systems.

The term Artificial Intelligence (AI) was coined in 1956, when a group of scientists (McCarthy, Minsky, Rochester, and Shannon) initiated, at Dartmouth College in the United States, the "Artificial Intelligence" research project. Initially, their goal was that human intelligence could be described so precisely that a machine would be able to simulate it. This concept was also known as "generic Artificial Intelligence", consisting of AI equal to or greater than the average human capability (Porcelli, 2020).

[1] More information: https://digital-strategy.ec.europa.eu/en/policies/expert-group-ai

According to IBM (2023), there are currently three types of AI classified by capabilities and scope: a) *Narrow Artificial AI* is the only type of AI currently in existence, such as intelligent assistants or OpenAI's ChatGPT, which performs text-based chat tasks; b) *General AI (AGI)* or *strong AI* remains to this day a theoretical concept to the extent that it has the ability to solve new challenges in diverse environments without the need for human instruction; and c) *Artificial Superintelligence* or *super AI* remains a theoretical concept, with the potential to surpass human cognitive abilities in thinking, reasoning, learning, and decision-making.

AI is one of the technological areas with the greatest economic projection in the short and medium term. So much so that its market value could surpass the US$300 billion barrier by 2026, reaching over US$800 billion by 2030 (Statista, 2024).AI is considered a General-Purpose Technology or GPT. (Bresnahan and Trajtenberg, 1995) that are part of the so-called "Fourth Industrial Revolution" (Schwab, 2017) or "Industry 4.0" (Basir et.al., 2019; Foladori and Ortiz-Espinoza, 2022). It stands out for its ability to rapidly transform numerous sectors, from industry to education, and to contribute to the reconfiguration of global capital that has given way to a "new digital phase" (Aguilera, 2023). Other authors, such as Zayago Lau (2024), warn that the concept of Industry 4.0 operates fundamentally as a narrative that drives and legitimizes digital transformation. According to the author, the convergence between nanotechnology and AI resulted in the miniaturization of electromechanical devices, and it was within the narrative space of Industry 4.0 that this process materialized.

Finally, both Crawford (2021) and Eubanks (2018) have made fundamental contributions to the theoretical framework of AI governance. Crawford (2021) offers a comprehensive analysis of the environmental, economic, social, and political implications of AI systems; she also questions the dominant interests underlying them and warns how AI can reinforce undemocratic governments, deepen inequality, and cause enormous environmental harm. Eubanks (2018), for her part, focuses on the field of social policy in the United States and points out that the opacity of these systems tends to disproportionately harm historically excluded social groups based on class, race, and gender.

3. Global Context

The rapid transformation of the world, driven by disruptive technologies like AI, has led to a growing need for their regulation. “AI regulations became a key issue for global geopolitics” (Vercelli, 2024:126). One of the main precedents at the global level is the European Union's White Paper on AI (European Commission, 2020), which aims to promote the adoption of artificial intelligence and address the risks associated with certain uses of this technology. To this end, the paper formulates policy alternatives and explicitly excludes the development nor the use of AI for military purposes.

Other significant documents and reports have emerged from the Organization for Economic Cooperation and Development (OECD, 2019a; OECD, 2019b), the United Nations Educational, Scientific and Cultural Organization (UNESCO, 2020; 2021), the World Intellectual Property Organization (WIPO, 2019) and United Nations (ONU,2024). It should be noted that UNESCO (2021) lists the following principles for AI governance:

a) *Proportionality and harmlessness*, if harm to humans occurs, the application of risk assessment procedures and adoption of measures should be ensured.

b) *Safety and security*, unintended harm should be avoided throughout the life cycle of AI systems to ensure the safety and protection of humans, the environment and ecosystems.

c) *Equity and non-discrimination*, AI actors should promote social justice, equity and fight against all types of discrimination, in accordance with international law.

d) *Sustainability*, continuous evaluation of the human, social, cultural, economic and environmental effects of AI technologies.

e) *Right to privacy and data protection*, the use of data for AI should be in accordance with international law.

f) *Human oversight and decision-making*, attributing ethical and legal responsibility to existing natural persons or legal entities.

g) *Transparency and explainability*, opportunity to request information from the person responsible for the AI system and to inform users when a product or service uses AI systems. They are related to the reliability of AI systems.

h) *Responsibility and accountability*, monitoring mechanisms, impact assessment, auditing and due diligence.

i) *Awareness and education*, through open and accessible education.

j) *Adaptive and multi-stakeholder governance and collaboration*, through multi-stakeholder participation.

In terms of core country strategies, the United States signed the Executive Order on the Safe, Secure, and Reliable Development and Use of Artificial Intelligence (White House, 2023) and the Memorandum on Advancing U.S. Leadership in Artificial Intelligence, Leveraging Artificial Intelligence to Meet National Security Objectives, and Promoting the Safety, Security, and Reliability of Artificial Intelligence (White House, 2024). Both documents seek to position the United States as a global leader in AI. The Executive Order focuses on establishing specific regulatory frameworks and practices to ensure safety, reliability and fairness in the use of AI, while the Memorandum emphasizes national security and defense objectives to maintain U.S. technological supremacy in the global context.

On the other hand, China is moving forward with its governance framework. In 2021 it published the "White Paper. Trusted Artificial Intelligence" and 'Ethical Standards for Next-Generation Artificial Intelligence' (Wu, 2022). In 2024, it published the "AI Security Governance Framework" to implement the "Global AI Governance Initiative." That framework is designed around a people-centered approach and recognizes AI as a new area of human development that presents opportunities, risks, and challenges (Tobbey, et.al., 2024).

Unlike the EU AI Law that divides AI systems into four different risk levels (unacceptable, high, limited and minimal), the Chinese Governance Framework only classifies AI safety risks, i.e., identifies the areas where AI systems could generate risks, and not the level of risks or negative impact or consequences that could be caused by AI systems (Tobbey, et.al., 2024). Finally, on March 13th, 2024, the European Parliament passed the Artificial Intelligence Act with a large majority, making it the first AI regulation in the world (European Parliament, 2024). The objective of the Law is:

"to improve the functioning of the internal market by establishing a uniform legal framework, in particular for the development, placing on the market, putting into service and use of AI systems in the Union, in accordance with the values of the Union, in order to promote the adoption of human-centred and trustworthy artificial intelligence (AI), while ensuring a high level of protection of health, safety and fundamental rights as enshrined in the Charter of Fundamental Rights of the European Union, including democracy, the rule of law and the protection of the environment, in order to protect against the harmful effects of AI systems in the Union, and to support innovation" (Reglamento UE 2024/1689, 2024).

The EU AI Law proposes a risk-based approach and defines four classes: a) unacceptable risk; b) high risk; c) limited risk; and d) minimal/no risk. While some AI systems are prohibited, the law imposes specific obligations on providers and implementers of high-risk AI systems, including testing, documentation, transparency and reporting (Farinella, 2024). The EU AI Law has also had a significant impact on regional regulatory proposals. As Ulloa (2024) states, there is a clear trend in the law proposals of several Latin American countries towards the adoption of a risk-based approach, in line with the European model.

4. Evolution of AI Regulation in Latin America

Three factors explain the development of standards at the regional level: 1) weak integration ties, 2) low normative density in international regulation, and 3) unilateral strategies driven by strategic integration and trade interests (Contreras, 2024). Globally, the benchmark jurisdictions for AI governance frameworks are the European Union, the United States and the United Kingdom. While the EU has opted for an approach focused on ensuring the safety of these systems throughout their life cycle, the United States has followed a more flexible path and the United Kingdom has chosen a regulation based on principles rather than immediate prescriptive legislation (Ulloa, 2024).

Latin America's regulatory efforts are at an early stage, with uneven and non-linear progress. Some countries have begun to develop specific policies or adapt their existing regulatory frameworks, many influenced by benchmarking approaches and others by multilateral declarations and agreements to which they have subscribed. Among the most important multilateral agreements are the UNESCO Recommendation on the Ethics of AI, published in 2021, and the OECD Principles on AI, to which Argentina, Brazil, Colombia, Costa Rica and Peru subscribed in the framework of the Organization's Ministerial Council Meeting. Both the UNESCO and OECD instruments oriented the first AI strategies in Latin America towards the development and ethical use of this technology (Ulloa, 2024). On the other hand, in 2019, Argentina, Brazil and Mexico signed the G20 AI Principles, and in 2023, through the New Delhi Declaration, the G20 leaders reaffirmed the same principles. Additionally, both the Cartagena Declaration and the Montevideo Declaration have contributed to regulatory harmonization in the region (Ulloa, 2024).

It is worth pointing out that at the last G20, held on November 18th-19th, 2024 in Rio de Janeiro, Brazil, the final communiqué was joined by a joint statement called the "São Luis Declaration" by four G20 engagement groups: Civil 20 (C20), Labor 20 (L20), Think 20 (T20) and Women 20 (W20). This declaration advocates the development and implementation of Artificial Intelligence (AI) in an ethical, sustainable and inclusive manner. It further endorses the reconciliation of the risk-based and rights-based approach and calls on developers and implementers of AI models to publicly report on the capabilities and limitations of AI systems. It also points to the intersectional approach as the theoretical-methodological horizon for addressing the development and implementation of AI, so as to ensure the protection of vulnerable groups, especially girls and women victims of technology-facilitated gender-based violence. Finally, it recognizes the need for a collaborative position on data governance and representative datasets and emphasizes the need to implement open data use policies that promote cultural and linguistic diversity and empower workers (G20, 2024).

Regarding the comparison of AI regulatory approaches and strategies for its incorporation in Latin American countries, it is possible to highlight the case of Brazil, which is one of the countries with the highest AI governance index in the region, since it has a national strategy, institutions with AI competencies and regulatory experimentation alternatives. Also, in mid-2024, Lula da Silva, President of Brazil, released a national AI plan that foresees investments of US$4.1 billion until 2028 (La Nación, 2024). Although Brazil does not have a general AI regulation, it actively participates in international regulation and also has sectoral or specific legislation, such as its regulatory framework on personal data protection (Contreras, 2024; Ulloa, 2024, Vercelli, 2024).

Something similar occurs in Colombia which, although it is true that it lacks a national strategy lacking a national strategy and does not have institutions with defined competencies to take charge of AI, in regulatory matters, it has special laws on data protection and cybersecurity and, in addition, mechanisms for regulatory experimentation (Contreras, 2024). On the other hand, so far Mexico lacks a national AI strategy despite the multisectoral efforts that have been carried out and has specific regulations on personal data protection. However, it presents a case of regulatory experimentation, together with the Inter-American Development Bank, in terms of transparency and explainability of AI (Contreras, 2024). In addition, in October 2024, Mexico City presented an initiative to regulate AI through the Institute of Transparency, Access to Public Information, Protection of Personal Data and Accountability of Mexico City (Hernández, 2024; Riquelme, 2024). But this is not the first initiative. In mid-2023, a draft was presented with the intention of developing a "Mexican Council of Ethics for AI and Robotics" (CMETIAR), which would be responsible for reviewing ethical protocols for AI implementation, monitoring compliance with official Mexican standards for this technology, and submitting annual reports on its oversight (Hernández, 2024).

Finally, Argentina has no experience of regulatory experimentation or a consolidated national strategy, although there are legislative projects underway, as detailed below.

By way of summary,

> *"Colombia is the country that stands out most for its progress in AI regulation when compared to Argentina and Mexico. However, the difference between the three countries is not outstanding, so it can be concluded that AI regulation in Latin America is still in a early stage" (Pedraza Ochoa, et.al, 2023: 509).*

Many regulatory frameworks and legislative proposals in the region have yet to translate into effective regulations. While several countries have implemented national strategies that address common aspects such as ethics, transparency and governance, these efforts remain fragmented and lack consolidation. Furthermore, the approval and implementation of proposed laws depend heavily on the governments in office, often lacking continuity, as seen in Argentina (Ulloa, 2024; Vercelli, 2024).

5. AI regulations in Argentina

In Argentina, political agendas have been present since 2018 and began to accelerate in 2022, particularly after the COVID-19 pandemic, gaining momentum with the advent of the 2023 presidential election year. The country also signed up to the Global Pact on Artificial Intelligence (GPAI) launched in 2020 and to the 2021 Recommendations on the Ethics of Artificial Intelligence (Vercelli, 2024). At the executive level, one of the first initiatives on AI was developed towards the end of Mauricio Macri's government (2015-2019), specifically between 2018 and 2019, and was entitled “National Plan for Artificial Intelligence” (ArgenIA, 2019). Although it bears the name Plan, it is a report on the subject and focuses on the training of human resources, the use of public data, computational infrastructure and ethics in AI. Since it was approved on December 9th, 2019, the last day of the Macrista administration, it lacked administrative structure and budget, falling into oblivion with the change of government (Ulloa, 2024; Vercelli, 2024).

In 2021, during the government of Alberto Fernández, the Artificial Intelligence Program was created within the Secretariat of Strategic Affairs, Resolution No. 90 of November 2021, with the aim of providing support to the Economic and Social Council for the development of activities related to the promotion of artificial intelligence (Secretariat of Strategic Affairs, 2021). This program gave rise to the Argentine Multidisciplinary Center for Artificial Intelligence (CAMIA) presented on April 5th, 2022.

However, it was not until 2023 that teams from the National Agency for the Promotion of Research, Technological Development and Innovation (Agencia I+D+i) and the IDB worked on a $35 million loan to invest in AI to support knowledge economy exports. The agreement included three lines of work: a) the creation of an artificial intelligence center (which could well be CAMIA or its replacement) aimed, among other objectives, at generating capabilities and multidisciplinary projects in AI and developing a regulatory policy agenda in AI; b) financing with non-refundable contributions to the productive sector for the development of AI-based solutions with export potential; and c) strengthening the scientific-technological system through the support of research networks and chairs in AI (Vercelli, 2024; Porta, et. al., 2023).

In 2022, the government announced Argentina's adherence to the Artificial Intelligence Global Compact (Jefatura de Gabinete de Ministros, 2022). The Global Partnership on Artificial Intelligence (GPAI) was launched in 2020 and seeks to comply with the OECD Recommendation on Artificial Intelligence (2019). On its website, the GPAI puts forward "Principles for the Responsible Management of Trustworthy AI": a) inclusive growth, sustainable development and well-being; b) human-centered values and equity; c) transparency and explainability; d) robustness, safety and security; and e) accountability.

In terms of national policies and international cooperation for trusted AI, the GPAI seeks to: a) invest in AI research and development; b) foster a digital ecosystem for AI; c) create an enabling policy environment for AI; d) develop human capacity and prepare for labor market transformation; and e) international cooperation for trusted AI.

Javier Milei's administration has initiated some strategies on an international level. For example, in May 2024 the Argentine government met in California with renowned technology leaders such as OpenAI's Sam Altman, Apple's Tim Cook and Tesla's Elon Musk, thanks to a "mutual interest" in terms of investment and Argentina's promise to provide a "business-friendly regulation and environment". This stance aligns with Milei's government's desire to go for a more flexible and industry-oriented approach (La Nación, 2024; Ulloa, 2024). Milei expects Argentina to emerge as the "fourth pole" of AI globally, after the European Union, the U.S. and China (RT, 2024). In line with this, on June 13th, 2024, the Incentive Regime for Large Investments (RIGI) was approved together with the Bases Law. The RIGI includes high-tech companies among the sectors that will be eligible for tax, customs and exchange incentives for 30 years for investments exceeding US$200 million. According to the latest report by the consulting firm McKinsey, Argentina has "human talent, energy and cold climate" as special characteristics that make it a potential recipient of part of the investments in AI that amounted, worldwide, to 125 billion dollars in 2023 (Risso, 2024).

In addition, December 10th, 2024, Javier Milei and the chief advisor to the Executive, Demian Reidel, presented a new nuclear plan to supply the development of AI. Milei said: "We have a privileged people in human capital, with inhospitable lands at low temperatures throughout our Patagonia, which is a comparative advantage to mount AI servers", "we have abundant energy reserves that are necessary to supply any development" (Secretaria de Prensa, 2024).

On December 17th, 2024, the Science and Technology Committee of the Lower House exchanged views about the nuclear sector in the country. The specialists questioned the paralysation of works in the Argentine nuclear sector, which has more than 70 years of history, and warned about the loss of qualified personnel leaving the activity due to low salaries. They also pointed out the concern that there is a move towards "a privatization of the Argentine nuclear system" (Parlamentario, 2024). As regards the legislative aspect, only on August 6th, 2024 the Science and Technology Committee of the Chamber of Deputies called an informative meeting with specialists in the subject to discuss some bills to regulate it. There are seven projects coming from all the political arc: one from UCR, two from Pro, two from Unión por la Patria, one from *Coalición Cívica* and the seventh from *Democracia Cristiana* (Risso, 2024). In summary, Argentina does not have an AI law that determines risks and impacts. Argentina does not have a regulation that audits algorithms (Porta et. al. 2023).

In this framework, according to Vercelli (2024), both public policies and regulations on AI in Argentina, can be characterized as *"inertial",* since they imitate and follow the solutions proposed by other countries or regions; *"fragmented",* since they address loose, scattered or specific issues, and of *"poor results",* as is the result of the CAMIA initiative. If the absence of a national AI strategy continues in the coming years, it could lead to a waste of resources and irrelevant, dilatory or tangential discussions (Vercelli, 2024).

6. Possible Horizons

Although Argentina does not yet have a consolidated national strategy in terms of regulation or public policy, it has taken important steps toward AI governance through the adoption of ethical principles aligned with international standards, such as those proposed by UNESCO and the OECD. There are also signs of collaboration between public officials, researchers, and technology companies—such as the informational meeting with specialists organized by the Science and Technology Commission of the Chamber of Deputies in August 2024; or between those actors and international organizations, such as the USD 35 million cooperation agreement signed in 2023 between the Agency I+D+i and the Inter-American Development Bank (IDB), aimed at promoting exports in the knowledge economy. Other promising collaborative experiences are led by public universities such as the University of Buenos Aires (UBA), one of the most important universities in Argentina and Latin America and the Caribbean. On February 18th, 2025, the Faculty of Exact and Natural Sciences at UBA signed an agreement with the human rights organization Abuelas de Plaza de Mayo and the tech company Quantity to apply AI to the identification of children who were abducted during the dictatorship (Abuelas, 2025; 0221, 2025).

Although this may seem innovative, "this is not the first time Abuelas has approached AI. In 2023, artist Santiago Barros launched the project Abuelas, using artificial intelligence to generate images of what the disappeared grandchildren might look like today. Additionally, through the Sadosky Foundation, students from across the country have contributed to the digitization of the Abuelas archive through the project Artificial Intelligence for Identity" (0221, 2025). In contrast, there are other cases that may pose a threat to human rights and transparency. One example of AI implementation in public policy in Argentina is the 2024 proposal to deploy a crime prediction system, supported by the creation of the Applied Artificial Intelligence Unit for Security.

The project includes facial recognition software to identify wanted individuals, monitor social networks, and analyse security camera footage in real time to detect activities labelled as "suspicious." Experts and organizations warn that the measure could violate human rights (Barber, 2024). Following Eubanks (2018) analysis, the logic of algorithmic prediction when applied to poor and racialized populations may be presented as a promise of efficiency, but it increases discrimination and reinforces structural surveillance and criminalization—or the criminalization of poverty. Indeed, addressing these issues solely through a risk-based approach may be insufficient. A deeper critique is needed of technological neutrality and the interconnected principles that expose the power dynamics often hidden in the narratives promoting the integration of digital technologies into economic sectors and daily life.

Beyond environmental concerns, as stated by UNESCO (2021), the "precautionary principle" indicates that when there is reasonable doubt that products or processes may pose a threat to human health or the environment, precaution should be applied—even in the absence of conclusive scientific evidence. This principle promotes the consideration of the voices of potentially affected communities, especially in contexts of structural inequality, where the impacts of AI may be profound and difficult to reverse. Other important principles include the "principle of transparency" and the "principle of public participation". The former asserts that the public has the right to know what it consumes, and therefore companies and developers must make public the mechanisms and components of their technologies. This also implies that workers involved in the various stages of digital technology development must have access to the information needed to act in accordance with their own safety (Foladori et al., 2013). As for the latter:

"Public participation in deliberative processes is an essential element of democratic life. All actors and stakeholders must possess the necessary information to act in defence of their rights and interests. Public participation must contribute to policy formation and decision-making, rather than being merely a consumer of events where the government and industry make unilateral decisions" (p. 164).

Based on these three principles and the development of new ones, it is possible to build a theoretical-methodological corpus from the Global South that addresses the implications of AI in the daily lives of communities from a locally grounded perspective. "The active participation of local communities constitutes the crucial foundation for acting in accordance with these principles" (Foladori et al., 2013: 163).

7. Conclusions

The regulation of AI presents unprecedented challenges, not only concerning its incorporation into various economic and social sectors but also regarding the industrialisation of the Global South, which faces renewed forms of colonialism and dependence. At the global level, the paper shows that the approval of the European Union's AI Law constitutes a pioneering model, especially for Latin America, where many countries are opting for risk-based regulations, except in the case of Argentina, which proposes an approach aligned with the market's needs.

In this regard, regulatory perspectives reveal a fragmented landscape: Brazil has made significant progress towards a national strategy aligned with the European Union approach, albeit without specific legislation; Colombia and Mexico exhibit scattered efforts in the absence of a cohesive national strategy; while Argentina demonstrates considerable shifts in its regulatory approach, where strategies and laws depend primarily on the government in power.

Finally, in the Argentine case, the economic measures implemented by Javier Milei to facilitate the country's "insertion" into the global economy represent a reenactment of dynamics of dependence and subordination to global power structures, exposing an openness to colonialism and a departure from an integrated approach tailored to local realities. In practice, regulation in the region has advanced in a disparate and non-linear manner. This study proposes a series of general guidelines to be considered when designing regulations and implementing public policies in artificial intelligence.

Firstly, it is essential to challenge the supposed neutrality of technology from a historical perspective. Far from being objective or impartial, technologies reflect specific interests, priorities, and values. In this regard, in line with Eubanks (2018) and Crawford (2021), the problem cannot be solved solely through better technical regulation. The recognition is required that AI systems, by operating upon unequal social realities, may deepen and consolidate preexisting forms of exclusion. Inequality is not an individual problem—it is a structural condition, and its resolution cannot be delegated to automated processes. On the contrary, it demands a renewed commitment to social justice and a political will to transform the material conditions that sustain it, promoting the well-being and dignity of all people.

Secondly, it is crucial to design and implement digital literacy programmes to bridge the gaps emerging in the new digital phase of capitalism. These programs must be directed at students and educators, the public, and professionals from various sectors. To this end, it is necessary to promote knowledge production and the development of critical thinking from transdisciplinary research approaches that allow us to address AI as a complex phenomenon—not only from a technical perspective but also through the web of its multiple social, political, economic, cognitive, and ethical implications, among others.

Thirdly, regulatory initiatives are needed that amplify the voices of all stakeholders, are grounded in human rights approaches with an intersectional perspective, and prioritise transparency in algorithmic decision-making processes. In this regard, the precautionary principle can guide concrete actions oriented toward social justice.

These elements deserve to be considered when problematizing the rules for the digital economy being negotiated by economic and political actors and international organizations, which are ultimately contributing to the acceleration of these structural changes. Far from reducing inequalities, these governance initiatives that exclude the voices of affected communities and civil society may worsen existing gaps. There is an urgent need for an agenda rooted in a Global South development perspective and a political strategy responsive to the needs of local communities within a global framework.

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Artificial Intelligence in the Management of the US Immigration System

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Abstract

Currently, a migration crisis is unfolding due to natural disasters, armed conflicts, violence, and drug trafficking. Many individuals have been forced to emigrate from their countries in search of asylum in central countries. They have been subjected to restrictive immigration policies and sought ways to circumvent the obligations of host countries to grant refuge. The United States has distinguished itself by intersecting its criminal and immigration policies since 1980, to supervise, persecute, criminalise, and deport migrants, whether irregular or not. The externalisation of immigration controls beyond national borders involves third countries managing mobile populations. More recently, the use of AI, via the CBP-One application, has enabled the extension of administrative borders without third-country intervention. However, CBP-One violates the due process rights of individuals seeking asylum, as well as their rights to security, privacy, and dignity, given that much of the information collected is highly intrusive and the future use of such information remains unknown.

Keywords: asylum system, CBP-One, border externalisation, border internalisation, AI technology.

JEL Codes: F2, F22, O1, O15

1. Introduction

The tendency of central countries to externalise and internalise migratory controls at their borders, thereby restricting access for asylum seekers, has deepened. The COVID-19 pandemic has further exacerbated existing inequalities between central and peripheral countries, significantly impacting asylum seekers. Data from 2024 provided by the United Nations High Commissioner for Refugees (UNHCR, 2025) indicate that, globally, there were 122.6 million forcibly displaced individuals, including 8 million asylum seekers and 37.9 million refugees.

In the United States, the COVID-19 pandemic facilitated the restriction of asylum applications by invoking health concerns and the risk of contagion, under a policy known as Title 42. Although the outsourcing (externalisation) of border migratory controls did not originate in the current decade, it dates back to 1980. Immigration policy has increasingly exhibited acute elements of criminalisation and securitisation, adversely affecting populations in human mobility (Chávez & Aguilar, in press).

In the internalisation and externalisation of the United States' immigration system operations, the intensive use of Artificial Intelligence (AI) has been implemented through the development and deployment of AI systems by private companies. These systems enable the Department of Homeland Security (DHS) to perform functions related to immigration, commerce, and transportation at ports of entry, monitoring the migrant population residing within the country.

The use of AI offers significant advantages in collecting, analysing, and storing large volumes of qualitative and quantitative data. One of the objectives of the DHS in introducing AI systems is to enable the interoperability of information between local, state, and federal law enforcement agencies, as well as the immediate exchange of information with migrant detention centres and the administration of asylum applications. As will be demonstrated in this text, the interoperability of information is also a shared objective among the United States, Mexico, and Central American countries, aiming to access biometric and biographical data of populations involved in human mobility.

As of 11 May 2023, the United States implemented the final rule known as the asylum prohibition. This rule imposes ineligibility on asylum seekers who cross the southwest and border or adjacent coastal borders without authorization after transiting through another country, without having availed themselves of an existing legal process, without being presented at an entry point by appointment made through the CBP-One application or without having been denied asylum in a third country through which they have passed.

The objective of this work is to analyse the policies and practices of the United States in managing its immigration system, as well as the implications of rights violations affecting individuals in mobility and asylum seekers. To this end, the work presents the restrictive trend of asylum policy in the United States in a section. These data demonstrate this trend and describe the operation of the CBP-One application. In a second moment, how AI has been introduced into the immigration system in the country is analyzed. In a third moment, the impacts of AI on the rights of people in mobility and existing regulation are explained. Finally, conclusions are presented.

2. Restrictive Trend of Asylum Policy in the United States of America

In the United States, since the 1990s, immigration and criminal policies have intersected in such a way that policies and practices of persecution, surveillance, and expulsion of minority populations, especially undocumented immigrants, have deepened. Juliet Stumpf called this *crimmigration* (Chávez & Aguilar, in press). In addition to this, immigration policy in the United States changed radically after September 11, 2001, as national security was given priority over labor and immigration issues for humanitarian reasons.

In 2003, the Homeland Security Act (HSA) consolidated 22 agencies related to immigration to create the Department of Homeland Security (DHS), under which the three most important institutions in the conduct of immigration policy work are the United States Citizenship and Immigration Services (USCIS), the United States Customs and Border Protection (CBP) and the Immigration and Customs Enforcement (ICE). The law also established that all agencies must share sensitive information, including private companies with whom contracts were established to provide services that involve managing large amounts of information using AI, under the argument of safeguarding National Security (Dávila & Palacios, 2024).

The crimmigratory policy has been characterized by an increase in surveillance, detention, persecution, removal, and/or expedited deportation from the country, mainly of undocumented migrants or those who have had an encounter with police authorities. The surveillance and persecution that continues to be carried out once the immigrant has entered the country to criminalize is known as the internalization of the border (Menjívar, 2014). In this context, AI stands out in immigration, asylum, removal, or deportation decisions. AI has been beneficial, especially in looking for alternatives in cities and states where law enforcement authorities refuse to collaborate with federal agencies, known as sanctuary cities or states (Dávila & Palacios, 2024).

In 2011, DHS issued the Federal Data Center Consolidation Initiative, which allowed the initiation of contracts with private companies to store consolidated information. In 2017, Executive Order (EO) 13780, “Protecting the Nation from Foreign Terrorist Entry into the United States,” allowed DHS to accelerate the completion and implementation of a tracking system to record an entry/exit through biometric data (Dávila & Palacios, 2024).

Currently, DHS states that immigration agencies use AI following applicable laws in the country: i) Advancing American AI Act (December 2022) and Executive Order 13960 Promoting the Use of Trustworthy Artificial Intelligence in the Federal Government (December 2020), 14110 Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence (October 2023). In addition, since 2022, the DHS has published an inventory of the uses of AI on websites and in their processes annually. This database identifies the uses that may impact people's security and rights and describes how risk situations are handled if this is the case; see Table 1 (DHS, 2024).

Table 1.
Use of AI in the management of immigration policies in the United States

Agency	AI description use
United States Citizenship and Immigration (USCIS) Provides naturalization services, visa applications for immigrants to the United States, and asylum applications.	- It uses AI in 19 processes/cases and in 8 of them it states that its use has implications for people's rights. - Of these 8 cases, 3 of them use facial recognition, which would impact security and privacy issues of users: 1) I-765 - USCIS Face Capture Mobile App 2) I-765 - USCIS Facial Recognition through IDENT (1:1 Face Recognition/Validation)[1] 3) USCIS Consular Consolidated Database (CCD) Facial Recognition (FR) On Demand Report (VISA Only). USCIS uses the AI Risk Classification Assessment System to recommend whether a person should be removed from the country. Analyzes criminal history, history of substance abuse, immigration history and status, family situation, employment situation, among others. (Automated Realtime Global Organization Specialist (ARGOS) for Company Registration Submissions to E-Verify).
United States Customs and Border Protection (CBP) Customs and Border Protection prevents people from entering the country illegally or bringing anything harmful or illegal into the United States. Its top priority is to keep terrorists and their weapons from entering the U.S. while welcoming all legitimate travelers and commerce. Programs related to immigration: - Immigration Inspection Program: Individuals seeking entry into the United States are inspected at Ports of Entry (POEs) by CBP officers who determine their admissibility. - Border patrol is responsible for securing U.S. borders between ports of entry. - National Vetting Center (NVC) is a collaborative, interagency effort to provide a clearer picture of threats to national security, border security, homeland security, or public safety posed by individuals seeking to transit the borders or exploit the immigration system.	- Since 2015, it has used the TECS system, operated by CBP, which stores biographical information from other DHS subsystems. - Contracted Hartsfield-Jackson Atlanta Airport to perform the Departure Information System Test (DIST) to test a new Traveler Verification System (TVS). It hired Delta Airlines to conduct the first full facial recognition test to create automated passenger check-in and check-out. Based on these results, CBP implemented the Traveler Verification Service (TVS), which is a cloud-based comparison service where a single profile is created with the combination of biometric and biographical data. The live scan is completed, and a match is made in the Virtual Private Cloud (VPC), notifications are sent to TECS for agent use. - It uses AI in 16 processes/cases, in all of them it states that its use has an impact on people's rights and one (CBP One) has an impact on people's safety. - Of these 16 cases, 6 use facial recognition for biometric identification: 1) 3rd Party Traveler Identity Verification Services 2) CBP One 3) Semi-Supervised Traveler Identity Verification Services (Traveler Initiated) 4) Supervised Traveler Identity Verification Services (Officer Initiated) 5) Traveler Identity Verification Services (Vetting) 6) Unified Processing/Mobile Intake
Immigration and Customs Enforcement (ICE) Supervises, monitors, detains, deports/removes non-citizens, documented and undocumented. Operates two programs: - Memorandum of understanding program with local and state law enforcement authorities, described in section 287(g) of the IIRIRA. There are two models, one of incarceration of non-citizens with pending criminal charges and another of technical service training so that local and state authorities can serve as immigration officers. - Secure Communities Program seeks to identify foreigners who are in judicial custody using CAP data systems and resources to identify those foreigners who are detained in any judicial or correctional agency and is determined through the review of biometrics and biography if the person is a candidate to be removed from the country.	- Since 2015, it has been used the TECS system, operated by CBP, which stores biographical information from other DHS subsystems. - Hired Thomson Reuters in 2015 to increase information resources. The company maintains Westlaw, the largest legal database in the world. - Hired RELX in 2020 to increase information resources. This company is a subsidiary of the second largest legal database company, LexisNexis. - Both companies acquire information from data vendors who collect information from users on the Internet and then sell access to the aggregated data to interested third parties. - AI is used in 23 processes/cases and in 5 of these it is recognized that its use has an impact on people's rights, and one of them impacts people's safety. - Three of these cases use facial recognition: 1) Biometric Check-in for ATD-ISAP (SmartLINK) 2) Facial Recognition for Investigations of Child Sexual Exploitation and Abuse 3) ICE Mobile Check-in Application

Source: Chávez & Aguilar, in press; Dávila & Palacios, 2024; Amnesty International, 2024; DHS, 2024: n.d.

2.1. Prohibition of Asylum Access: CBP-One

At a global level, developed countries have implemented restrictive policies that do not allow or limit the mobility of migrant populations and/or asylum seekers from peripheral countries towards their nations. In this way, one form that has allowed these migrant populations and people seeking asylum to be limited, discouraged, or denied is the externalization of their borders. Outsourcing/Externalization means:

> *A range of migration management policies focus on shifting the responsibility of providing international protection to refugees and asylum seekers to other countries, or on enlisting source or transit countries in tightening control over their borders. Externalization policies aim to prevent or punish irregular border crossings by refugees, asylum seekers, and migrants, often mobilizing and leveraging international financial aid (Amnesty International, 2023).*

Along with the implementation of this immigration policy, the number of people who migrate and request asylum has increased. Undocumented migration is a good thermometer to demonstrate this. From the second quarter of 2021 to the first quarter of 2024, an average of 750,000 quarterly encounters of the US immigration authority with undocumented migrants on the northern border of Mexico with the United States were documented (BBVA Foundation Mexico & Secretariat of the Interior, 2024:58). The effect of these policies has made travels more dangerous, deaths have increased, and they have put these populations in conditions of greater vulnerability, exposed to kidnappings, extortion, and fraud, whether by state and non-state agents, as well as organized crime in its transit through Mexico (Amnesty International, 2024).

For several years, the United States has been implementing strategies to externalize border control by providing financing to security agencies in Mexico, to a greater extent, and the countries of the Northern Triangle of Central America, to a lesser extent. This measure aimed to improve infrastructure, provide technology to modernize border security, and reform the judicial system. These financings began with the Merida Initiative in 2007 (Paris Pombo, 2022).

Mexican president Felipe Calderón proposed the Merida Initiative to the United States government to cooperate in security matters and include the countries of Central America "to combat the threats of drug trafficking, transnational crime, and terrorism in the Western Hemisphere" (Barreda Vidal, 2014: 50). For 2008, Mexico and the United States agreed on four pillars to implement the initiative:

> *1) dismantling the operational capacity of organized crime; 2) institutionalization of the capacity of the rule of law in security and justice institutions; 3) creation of a 21st-century border structure that facilitates the movement of people and commerce but hinders the flow of drugs, weapons, and illicit money, and 4) creation of strong communities (Barreda Vidal, 2014: 51).*

Within pillar II, USD 2.5 million was allocated for "biometric equipment to capture and store the identity of criminals to secure prison facilities" (Barreda Vidal, 2014: 55). Within the framework of pillar III, "USD 14.5 million was allocated in biometric equipment, which was installed at three points along the southern border of Mexico" (p. 56). In this regard, MIJENTE, National Immigration Project & Immigrant Defense Project (2018) documented that the United States government awarded a contract for USD 75 million to the company CSC Government Solutions (now CSRA, owned by General Dynamics) to create a biometric system to the National Migration Institute (INM) of Mexico in 2017. The intention was to collect biometric data from the population of third countries in the Institute's immigration detention stations.

Additionally, Mexico and the United States signed other collaboration programs to send sensitive and criminal history information: the Criminal History Information Sharing (CHIS) program, Statement of Cooperation (SOC) between DHS and SEGOB's National Migration Institute (INM) for "the exchange of biometric and biographic data between both countries, which seek to exchange identity information on third-country nationals seeking authorization to travel, work or live in Mexico or the United States, or who have been detained by INM" (MIJENTE, National Immigration Project & Immigrant Defense Project, 2018: 40). These cooperation agreements are asymmetrical, given that the information collected from migrants in Mexico and Central America is shared with the United States, but the United States does not share any information with them (Accessnow, 2023). This information will become more relevant when describing how DHS operates biometric information registration and query systems.

Now, some of the most important milestones in the border closure implemented by the United States government to stop the flow of people seeking asylum began in 2018 when the option to request asylum for people who are victims of private violence caused by gangs or someone from the family nucleus was canceled. Between 2017 and 2018, the government made waiting or *metering lists* for asylum seekers at all ports of entry on the border (Paris Pombo, 2022).

In January 2019, the Migrant Protection Protocols (PPM) began, called Stay in Mexico, where Mexico received asylum seekers from third countries who already had an appointment, had their files in English, could present at the ports of entry to appear before a judge (Paris Pombo, 2022).

During the COVID-19 pandemic, in 2020, an Executive Order allowed the DHS to issue Title 42 to block access to asylum in the country; it also facilitated the removal of immigrants at the border with Mexico, either to Mexico or to their countries of origin, with the excuse of stopping the spread of COVID-19. Later, on May 11, 2023, this order was eliminated, but the Circumvention of Lawful Pathways (CLP) final rule was issued, prohibiting asylum access (Dávila & Palacios, 2024; Amnesty International, 2024). This rule imposes ineligibility on asylum seekers who cross the southwest land border or adjacent coastal borders without authorization after transiting through another country,

> Moreover, without having (1) availed themselves of an existing lawful process, (2) presented at a port-of-entry at a **pre-scheduled time using the CBP One app**, or (3) been denied asylum in a third country through which they traveled, are presumed ineligible for asylum unless they meet certain limited exceptions, (Amnesty International, 2024: 2). [Our bolds].

Amnesty International (2024) documented the operation of CBP One through interviews with asylum seekers and decompilation of the code; that is, reverse engineering was carried out to see how the application responds in real terms, starting a session and reserving a quote. Additionally, testimonies were collected about their experience in using the application by asylum seekers.

Table 2.
Problems using the CBP One application

Problem	Description
Digital literacy	- Some people cannot use the application due to poor digital literacy, for example, older adults. - Persons must have an email to register in the application.
Economical	- Not everyone has the latest generation mobile phone. It has been documented that the app works better on newer cell phones, especially the iPhone, which is discriminatory. - Not everyone has access to stable internet. - Persons must provide the address they are going to in the United States and a contact, this has generated a black market and fraud.
Compromises the privacy/security of those who use the application	CBP One app: - Does facial recognition - Trace location using GPS - Creates cloud storage with asylum seeker data, photographs sent to Traveler Verification System (TVS), stored in government databases for up to 75 years - Its use is mandatory if you want to request asylum - Sends sensitive information to private third-party services such as Google Firebase, this is not notified to the user and does not offer a voluntary exclusion option - Requests approval of the privacy policy each time the user logs in, which must be accepted to continue to schedule an appointment - Collects biometric and biographical information on a "voluntary" basis, since if this is not accepted, it is not possible to access an appointment - Stores the information for more than a year in the Cloud East (CACE) of Amazon Web Services (AWS) and does not notify users - Does not alert asylum seekers that their photographs will be matched with facial images of other applicants - It is not known whether your photograph is compared to the arrival image or compared to a larger collection of images. Utah, Vermont and Washington allowed undocumented migrants access to driver's licenses; agents can use this database to do facial recognition searches - CBP does not adequately inform the public how it collects, disseminates or maintains personally identifiable information. Neither is transparent about how the facial comparison technology used works - Information collected may be used for other law enforcement purposes
Depending on the discrimination that already suffers from some racialized populations or minority groups	AI facial recognition technology: - has demographic biases associated with the sex, race and nationality of the people since whoever programs the algorithm may suffer from these biases, even unconsciously - The average time to receive an appointment is 2 to 3 months. - CBP has not increased the number of appointments, even though the number of applicants has been increasing over time. - Paying for a third party to do the registration can lend itself to fraud
Violates due process in the asylum application	- Limiting the exclusive use of CBP One app to have an appointment to request asylum is a violation of the 1951 Convention relating to the Status of Refugees - Appointments can only be made in Mexican territory, from the center to the north of the country. - The risk of asylum seekers increases by having to wait in Mexico to obtain an appointment, whether for reasons of fraud, extortion, kidnapping, etc. - People seeking asylum should have the opportunity to present their application to the authorities, even if they do not have an appointment. - The appointment is assigned by lottery and not by order of registration. - The agents of the National Migration Institute (INM) of Mexico only allow access to the ports of entry to those who have an appointment, this violates the due process of requesting asylum. - Most facial algorithms present biases that can impact the rejection of the asylum application. - Authorities must have mechanisms to compensate for violations of the rights of asylum seekers in failure to comply with due process.
Technical	- Registrations once created cannot be edited, if the person has an error in any data, they must delete the record and start a new one. This implies that the appointment request is deleted and the possibility of receiving it in the next 24 hours. - When there is some type of inconsistency, the application sends the message, in English, of error and fraud. This implies that the person must start their registration all over again. - CBP can delete registrations that appear fraudulent: those that have several records at the same time or those records that exceed 10 people. There have been documented cases in which people seeking asylum may never have an appointment due to inconsistencies in passports, extraordinary situations such as the birth of babies in transit to the border, etc. - In 2023, from January to October the application was updated 16 times. - Lack of assistance to receive support. Assistance is generally via email and in English.
Legal	- Ignorance of the final rule, which would imply that if they decide to cross the border irregularly, they may possibly be deported without the possibility of requesting asylum (which violates international treaties). - It is not clear how the exceptions described in the final rule are determined and it is also not clear whether immigration agents are the ones making this decision

Source: Amnesty International, 2024; Dávila & Palacios, 2024.

CBP One app was launched in October 2020, is available in Spanish, English, and Haitian Creole, and offers 1,450 daily appointments at eight points of entry. CBP One app does not assign appointments on a first-come, first-served basis; instead, it is a lottery, "70% of available appointments are randomly assigned to people who requested an appointment the day before, and 30% are assigned to people who request appointments with the oldest accounts that have been waiting for the longest." (Amnesty International, 2024: 5). In this way, there may be people who will never be able to get an appointment.

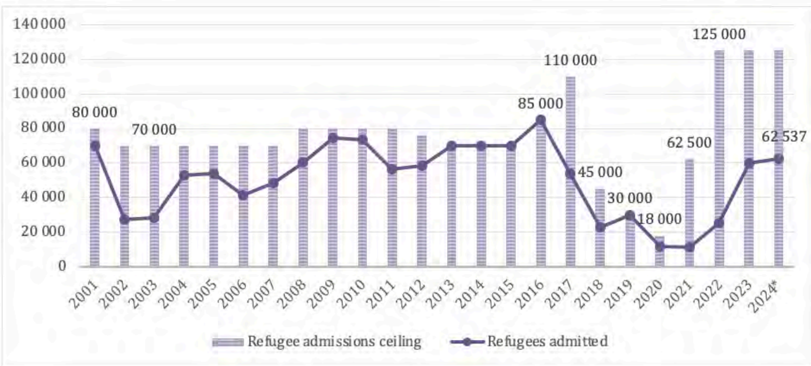
Logging in between 11:00 a.m. and 11:00 p.m. is required to request an appointment, which is done daily until the person schedules one. Once an appointment is assigned, the person has 23 hours to confirm it, which can only be done through a selfie video. If the appointment is not confirmed, it expires, and another must be made. Obtaining an appointment does not mean that an asylum application is submitted; this can only be done before the competent authority (Amnesty International, 2024).

The use of AI tools in border externalization processes is increasingly common. In both crimmigratory policies and the internalization and externalization of border migration controls, invasive technologies that threaten people's privacy and security are used more frequently. This use exacerbates the discriminatory and disadvantaged situations of racialized populations in terms of sex, skin color, race, or nationality.

2.2. Trends in Asylum Applications and Cases

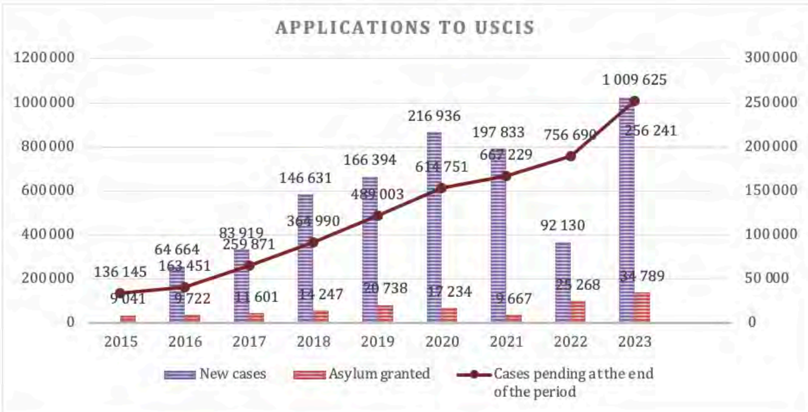
The statistical data in this subsection show the impacts of the restrictive policy in the United States. As seen in Graph 1, the admission of people with refugee status to the United States was the lowest before and during the COVID-19 pandemic (2018, 2018, and 2020). Furthermore, although there has been a recovery in the maximum admissions limit, it has not been achieved. Everything indicates that the policy of externalizing the border through the exclusive use of the CBP One application to request asylum effectively contains the applications. This is reflected in the low number of admissions.

Graph 1.: Persons admitted to the United States with the refugee status, fiscal years 2001-2024 (thousand)



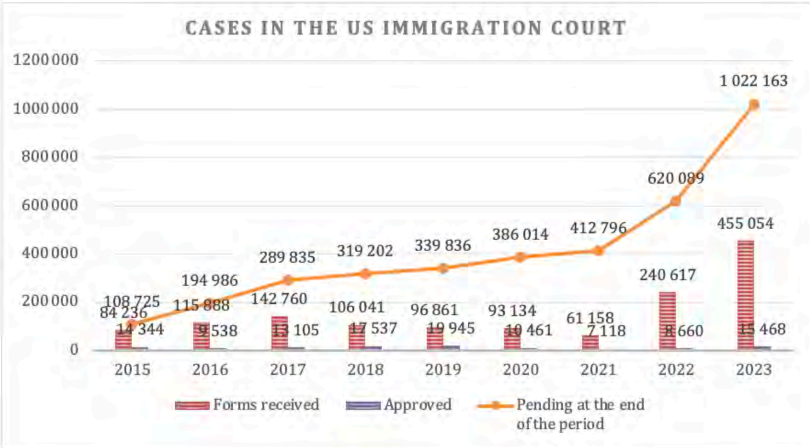
Source: BBVA Foundation Mexico & Secretariat of the Interior, 2024: 60.
*Notes: The information refers to fiscal years from October of the previous year to September of the reference year. *The information for 2024 includes data from October 2023 to May 2024.*

Graph 2.: Applications of Asylum in the U.S., Fiscal Years 2015-2020 (Thousand)



Source: BBVA Foundation Mexico & Secretariat of the Interior, 2024: 61.
Notes: The information refers to fiscal years from October of the previous year to September of the reference year. Each asylum granted by USCIS may correspond to more than one person.

Graph 3.: Cases of Asylum in the U.S., Fiscal Years 2015-2020 (Thousand)



Source: BBVA Foundation Mexico & Secretariat of the Interior, 2024: 61.
Notes: The information refers to fiscal years from October of the previous year to September of the reference year. Each asylum granted by USCIS may correspond to more than one person.

The top ten nationalities of the 62.527 people admitted during the fiscal year 2024 were: Dem. Rep. of the Congo (23.4%), Afghanistan (14.2%), Syria (13.2%), Myanmar (7.4%), Venezuela (7.1%), Guatemala (4.7%), Somalia (4.5%), Nicaragua (2.7%), Eritrea (2.5%) and Sudan (2.3%) (BBVA Foundation Mexico & Secretariat of the Interior, 2024: 60.) Likewise, pending asylum applications and cases totaled just over 2 million at the end of fiscal year 2023, half are in the immigration court and the other in the USCIS (Graph 2 and Graph 3). However, in fiscal year 2023, the immigration court provided 35,000 asylums to people mainly from El Salvador, Venezuela, Guatemala, and Honduras (BBVA Foundation Mexico & Secretariat of the Interior, 2024: 60).

As will be seen in the next section, using the CBP One application violates due process. States have an obligation to provide the conditions for asylum seekers to file their requests. This application also violates rights to privacy, information, and security, promotes discrimination, and violates the right to access asylum.

3. Use of AI in the US Immigration System

3.1. Some Basic Definitions

Before presenting how AI is used in the US immigration system, it is important to present the minimum definitions to understand what we are talking about. As there are multiple definitions of AI, for this writing, we are taking the one set out in the National AI Initiative Act 2020:

> AI means a machine-based system that can, for a given set of human-defined objectives, make predictions, recommendations, or decisions influencing real or virtual environments. Artificial intelligence systems use machine and human-based inputs to
> A. perceive real and virtual environments.
> B. abstract such perceptions into models through analysis in an automated manner and
> C. use model inference to formulate options for information or action.

AI can perform certain tasks or solve problems that surpass a person's performance. However, it cannot write a novel or produce theories that explain or interpret reality. Thus, AI is software used on a computer and does not necessarily need physical assistance. AI and robots are distinguished because the former operates virtually, and the latter operates without AI (Fernández, 2023).

One of the most important distinctions is the algorithm generated using AI compared to software that does not use it. In the conventional algorithm, the programmer manually provides the input data and the rules that must be followed, thus producing an automatic, deterministic result. The algorithm that uses AI, both the input and the output, is introduced in such a way that it creates the rules to solve the problem since it is coded to operate autonomously (Fernández, 2023).

Another important feature of AI systems is that they use machine learning. That is, the system can change its behavior based on experience to improve the performance of what it does. However, they learn by detecting patterns in data to automate complex tasks or make predictions. The two existing machine learning models can be supervised or unsupervised, depending on the degree of intervention of the programmer in the algorithm learning process (Fernández, 2023).

Deep learning is a branch of machine learning that allows computers to perform human activities. It uses algorithms inspired by the structure and function of the human mind, called artificial neural networks. Deep learning is used in facial and iris recognition (Nalbandian, 2022).

The problems associated with using AI are the lack of transparency or black boxes because how the problem was resolved is unknown, and biases since they tend to reproduce trends without considering rights or principles such as equality or equality (Fernández, 2023). It may also be white boxes; this means that the model is entirely interpretable; people can know its behavior, how it made the prediction, and what variables influenced the decision-making (Nalbandian, 2022).

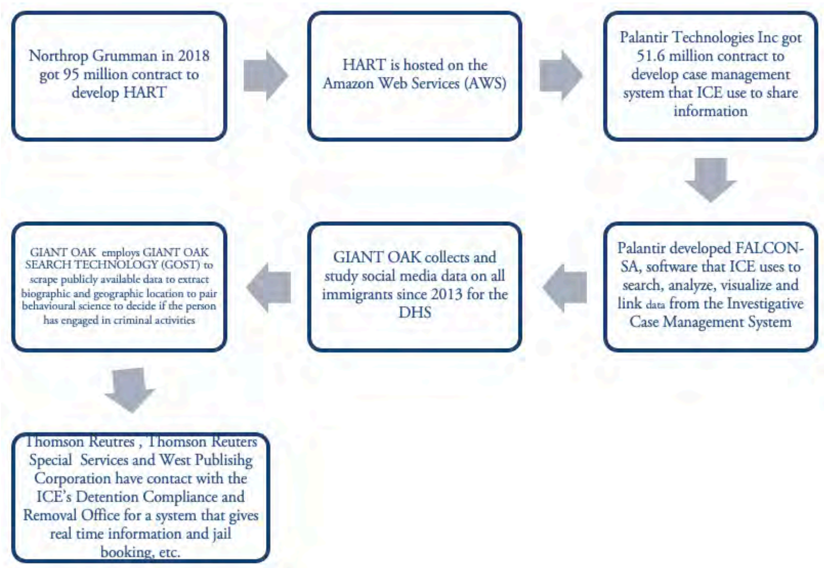
3.2. AI in Immigration Management

The adoption of policies that internalize and externalize migratory controls for crimmigratory purposes, monitoring, supervision, detention, and removal of undocumented or documented migrant populations, minorities, and asylum seekers hides a profitable business on the part of financial consortia such as Vanguard Group and Blackrock. The accumulation of capital is promoted by creating new ways of extracting value from citizens -who, through taxes and public spending, contract private companies for the design, operation, and concentration of large amounts of information- and from the populations who affect said supervision - given that they must access the systems through the latest generation of phones, computers or tablets.

Nalbandian (2022), MIJENTE, National Immigration Project & Immigrant Defense Project (2018), and Investigative (2019) have documented how DHS has outsourced at least seven private Silicon Valley high-tech companies that provide AI services to operate the country's immigration system. This has been possible, as already mentioned, thanks to the laws approved after September 11, 2001, prioritizing national security and defense over the rights of privacy, security, and non-discrimination practices for citizens, migrant populations, and those seeking asylum. Thus, alliances have been created between government agencies, private companies, financial conglomerates, and some universities, which have also developed AI tools and systems.

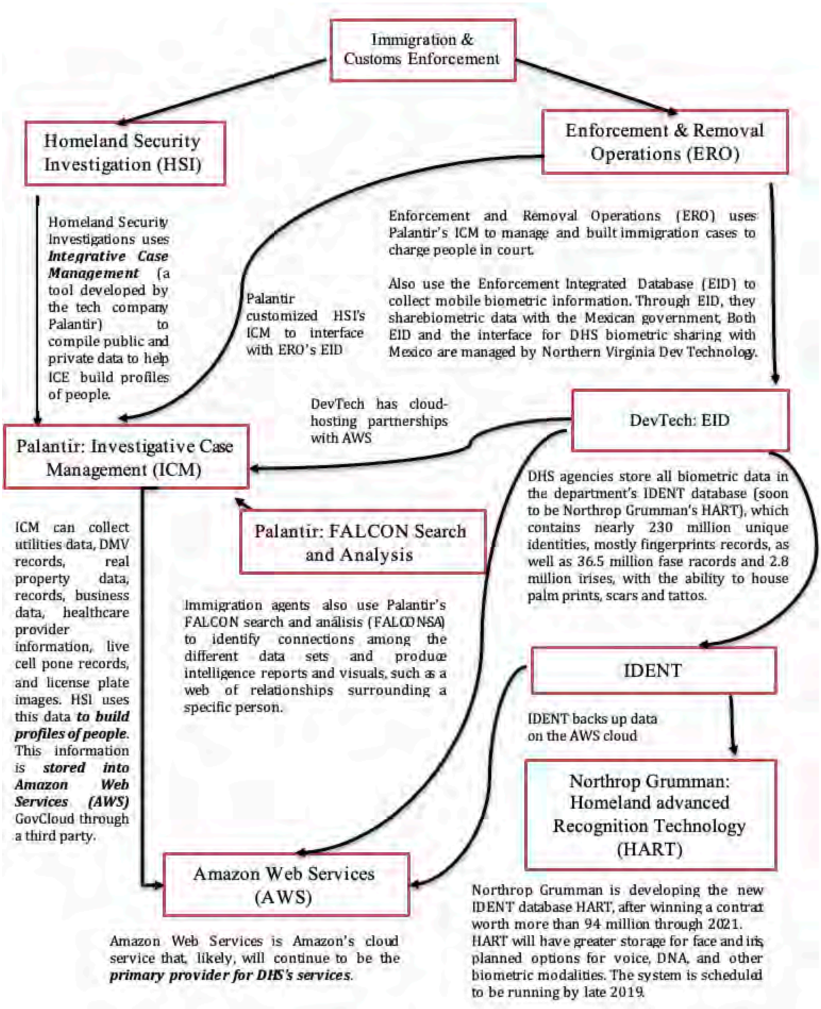
As can be seen, private companies use all information, including public information from Facebook or WhatsApp, for supervision and criminalization purposes. This calls for a significant review to determine whether access to justice and law enforcement should be in the hands of private companies, who seek to profit from data collection, storage, and analysis. The same thing happens with the operation of private companies in migrant detention centers. The fact that there are incentives to charge per bed for the company generates incentives to criminalize populations in vulnerable conditions, such as migrants, racialized groups, etc. (Chávez & Aguilar, in press).

Figure 1: Functioning of seven companies and services that provide USCIS



Note: Nalbandian (2022).

Figure 2: Articulation of AI services provided by private companies to ICE



Source: MIJENTE, National Immigration Project & Immigrant Defense Project, 2018: 4.
Note: The DHS's AI use case inventory of 2024 did not mention the HART database, so it is still in use IDENT.

Nalbandian (2022: 15) and MIJENTE, National Immigration Project & & Immigrant Defense Project (2018: 4) point out how ICE operates in managing AI tools and the services provided by private companies, see Figure 2. What is important to highlight is that Palantir and Amazon are the leading companies that provide data collection, storage, and management services. Although the authorities that apply the law in certain cities or states refuse to have cooperation agreements with ICE, this is solved by ICE because they also use the Palantir system in such a way that every time they use it, they feed it every time they access the system (MIJENTE, National Immigration Project & Immigrant Defense Project, 2018).

In the case of the National Migration Institute (INM) of Mexico, since 2018, it has been warned that the US government has access to the biometric data of undocumented migrants that the INM collects in detention centers. That same year, under the Donald Trump government, the DHS would have given a new contract for $58 million to the CSRA so that the biometric data system that already operates in Mexico could be interoperable and communicate with the FBI system, DHS and the Pentagon. Thus, sensitive data not only of migrants but also of Mexican citizens could be in the hands of the DHS (Esquivel, 2018). The government of Mexico must review the systems that currently operate in social rehabilitation centers, at their ports of entry, and in immigration detention centers to determine if the private company that runs them is related and in direct contact with the DHS.

4. Impacts of AI on the Rights of People in Mobility and Existing Regulation

In general, the Executive Orders issued by Donald Trump were more oriented towards the non-regulation of the use of AI and the promotion of research and use of AI without considering the existing inequalities among the population, which would put a more significant disadvantage on those populations with more precarious conditions. Joseph Biden Jr.'s Executive Orders recognize the risks and negative impacts that the use of AI can have and, therefore, promote more actions to safeguard citizens' civil rights and civil liberties.

However, all these laws and executive orders have two very clear intentions: to promote United States leadership in the design, development, and use of AI in the economy to promote economic growth and to use cutting-edge AI in national security and defense.

The existing regulation in the United States is the following:

i) National AI Initiative Act 2020: This initiative sought to accelerate AI research and applications to promote greater prosperity while improving security. The following points stand out from this law: i) the creation of the National Artificial Intelligence Initiative Office to implement the responsibilities described in the law, ii) designate an Interagency Committee to coordinate federal programs and activities in support of the initiative, iii) National Science Foundation will lead with other agencies a study of the current and future impact of artificial intelligence on the workforce of the United States, iv) General Accountability Office shall conduct a study of artificial intelligence computer hardware and computing to guarantee the US leadership in the area.

ii) Executive Order 13959 Maintaining American Leadership in Artificial Intelligence: This initiative sought to maintain the country's leadership in the research and applicability of AI to promote the economy's growth and improve national security and quality of life. The federal government plays an important role in all aspects of AI research and use; for example, the workforce can use AI in production processes. In that sense, the federal government will coordinate the strategy to sustain and enhance the scientific, technological, and economic leadership position of the United States in AI R&D and its implementation, guided by five principles, among them: i) develop appropriate technical standards and reduce barriers to the safe testing and deployment of AI technologies to create new AI-based industries and the current industries adopt the AI, ii) train current and future American workers so they can develop and apply AI technologies, iii) foster public trust and confidence in AI technologies and, protect civil liberties, privacy, iii) promote an international environment that supports American AI research and innovation but also protect the American advantage in AI.

iii) Executive Order 13960 Promoting the Use of Trustworthy Artificial Intelligence in the Federal Government (December 2020): This executive order established the principles for using AI in the Federal Government for purposes other than national security and defense to ensure that such uses are consistent with our Nation's values and are beneficial to the public. Principles: a) lawful and respectful of our nation's values; b) purposeful and performance-driven; c) accurate, reliable, and adequate; d) safe, secure, and resilient; e) understandable; f) responsible and traceable; g) regularly monitored; h) transparent; and i) accountable.

iv) The White House Office of Science and Technology Policy (OSTP) released a Blueprint in 2022 for an AI Bill of Rights: This blueprint has five principles to guide a better design, use, and deployment of AI and protect citizens' rights and liberties: "a) safe and effective systems; (b) algorithmic discrimination protections; (c) data privacy; (d) notice and explanation; (e) human alternatives, consideration, and fallback," (Fernandez, 2023: 85).

v) Advancing American AI Act (December 2022): This bill promotes using AI in government programs and initiatives to expand the country's competitiveness and strengthen entrepreneurship and innovation capabilities. The adoption of AI by government agencies must follow the country's values, including protection of privacy, civil rights and liberties, etc. Additionally, AI will be tested and leveraged to improve the effectiveness of business practices. The principles that must be considered are those established in Executive Order 13960, the *report entitled "Key Considerations for the Responsible Development and Fielding of AI,"* as updated in April 2021, and the input of other instances related to privacy and civil liberty.

vi) Executive Order 14110 Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence (October 2023): This Executive Order seeks to make AI use responsible because irresponsible use could exacerbate societal harms such as fraud, discrimination, bias, and disinformation, displace and disempower workers, stifle competition,

> and pose risks to national security. Harnessing AI for good and realizing its benefits requires mitigating its substantial risks.

Government agencies' regulation of the development and use of AI in the United States has been essential in the last five years. However, as can be seen, most of the principles for the research, development, and use of AI and its implications or risks in privacy, security, and discrimination are considered in terms of US citizens. This implies that the rights of immigrant and asylum-seeking populations still do not have as many considerations. In this regard, Dávila & Palacios (2024) point out that the United States is "a party to the International Covenant on Civil and Political Rights (ICCPR) and is obliged to protect the human right to privacy of all individuals within its power or control, including asylum seekers and refugees" (p. 8). Thus, the United States should not issue laws violating people's privacy; if they do, they should protect those whose rights have been violated.

Dávila & Palacios (2024) state that the CBP-One application takes advantage of users who have no alternative but to register; otherwise, they would not be able to get an appointment to present their asylum application. CBP One does not provide information on the use of collected data, which agencies and private companies will store and analyze the information. This harms the integrity of users. Also, hiring private companies violates privacy rights because each has different interests and purposes. According to Article 17 of the ICCPR, the United States should use the least intrusive means to achieve the same purpose; this would mean that CBP-One should stop being used until it has been verified that other ways do not compromise people's privacy.

The United States is also part of the International Convention on the Elimination of All Forms of Racial Discrimination (ICERD). Article 5 states "the right to equal treatment before courts and all other bodies administering justice or access to justice" (Dávila & Palacios, 2023: 10). Also, ICERD prohibits profiling populations in terms of race, skin color, or national or origin ethnicity. The International Convention on the Elimination of All Forms of Racial Discrimination, article 2, obliges states to take the necessary measures to eliminate all forms of discrimination (Amnesty International, 2022). It has been documented that CBP-One uses Facial Recognition Technology, which has a discriminatory impact on people with darker skin tones (Amnesty International, 2024; Dávila & Palacios, 2023).

The CBP-One application violates the right to due process in applying for asylum in the United States since under Article 2 of the ICCPR, which says, "States have an obligation to guarantee the human rights of all individuals under their jurisdiction, regardless of their nationality or migration status, including the right to access to justice and due process" (Dávila & Palacios, 2023: 15). Which means that the Final Rule does not comply with international standards.

The CBP-One application, as the only mechanism to request asylum in the United States, violates the rights of people who request asylum, given that it is a pre-condition to access the territory where the request will be made. The final rule also violates the rights of refugees since the immigration status or method of entry into the country cannot impede requesting asylum (Amnesty International, 2024). Therefore, as pointed out by the Convention and Protocol Relating to the Status of Refugees and the Convention against Torture and Other Cruel, Inhuman or Degrading Treatment or Punishment, the principle of *nonrefoulement* must be respected, that is, States are legally obliged not to return or transfer a person to another territory where their life is in danger, or they are exposed to human rights violations or abuses.

5. Conclusion

The United States distinguishes itself as a country at the forefront of knowledge in specific technologies, including AI. Over the past five years, a regulatory and institutional framework has been established to actively promote the incorporation of AI across all sectors involving daily life, work, education, the economy, immigration, law enforcement, and more. One of the aims outlined in US programmes and standards is for the country to lead in the design, use, and application of AI, thereby impacting economic growth and individuals' quality of life.

However, this enthusiasm surrounding the use of AI in federal government functions is overshadowed by potential risks and harm to individuals' civil rights and liberties. This becomes particularly serious when it exacerbates pre-existing inequalities and discrimination already suffered by specific populations based on skin colour, sex, race, or nationality.

As demonstrated, the United States violates the right to due process of individuals seeking asylum. The exclusive reliance on the CBP-One application for securing appointments has been shown to harm the privacy, security, and dignity of its users. At the same time, its benefit can be obtained by other less intrusive means that cause less harm in people's future lives.

It is essential to gain a deeper understanding of how countries such as Mexico, El Salvador, Honduras, and Guatemala use AI at ports of entry and during immigration procedures, whether they share sensitive information with the United States, and what guarantees they offer to individuals from third countries. In the case of Mexico, it must stop acting as another agency of the United States and comply with its obligations to give asylum and to respect the rights of people who are in transit in its territory.

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[1] IDENT (Automated Biometric Identification System) was designed in 1994 to store, match, process, and share biometric and biographic information. For 2018 was the largest biometric repository in the U.S, containing unique identity records for 230 million people and processing on average 350,000-400,000 transactions per day. IDENT was expected to be replaced with a new biometric database called Homeland Advanced Recognition Technology (HART). This system will be built by Northrop Grumman. NEC Corporation will provide face and iris matching algorithms for HART, while Gemalto will provide fingerprint matching technology (Investigate, 2019).

6

Cooperative Collective Action: Digital Platform Drivers' Response to Regulatory Absence in Zacatecas, Mexico

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Abstract

The regulation of labour on digital platforms remains an unresolved challenge in Global South nation-states, where various factors hinder progress towards this goal. Mexico is one such country, notable for being among the regions where digital platforms like Uber have established one of their largest global markets. However, the regulatory initiatives presented before Mexico's Congress of the Union have been hindered by drivers' lack of interest and, consequently, the absence of organisation and mobilisation to promote them. A case study conducted among Uber and Didi drivers in the state of Zacatecas reveals that this situation arises because the labour relationship designed by the platforms discourages behaviours that favour organisation, while the multiplicity of interests inhibits the collective action necessary to promote any regulatory framework. Meanwhile, workers in these companies face informal employment, characterised by strenuous and self-imposed working hours. Their basic needs are not protected under labour law, and reasonable working conditions are denied by both the state and employers.

Keywords: platforms, organization, collective action, regulation, informality

JEL Codes: D74, J40, J51, O33

1. Introduction

Digital platform work is a consequence of technological advances associated with the Fourth Industrial Revolution, which began in the final decades of the 20th century and has disrupted various spheres of life in modern societies—especially labour, the core axis of human coexistence since antiquity. According to Srnicek (2018), platforms are "digital infrastructures that allow two or more groups to interact" (p. 45). These infrastructures are grounded in the capitalist use of data and have enabled formerly physical work activities to transition online, offering advantages such as global reach through internet connectivity without requiring further physical investment.

As a result, these companies can operate globally while avoiding labour and tax regulations—particularly in countries of the Global South. A defining feature of this emerging employment model is its precariousness. In most countries where these platforms operate, workers are classified as independent contractors with flexible schedules and no formal subordination—thus allowing companies to avoid legal labour obligations. As a result, traditional mechanisms for the defence of labour—such as contracts and unions—are not applicable to the capital–labour relationship imposed by these largely transnational corporations.

This article explores how platform workers confront the absence of basic labour rights and the challenges involved in organising to defend them. These difficulties stem from the technological work model itself, the cultural legacy of neoliberal capitalism—such as intensified individualism—and the divisive lobbying practices of platform companies.

In Mexico, labour rights are governed by the Federal Labour Law (LFT), meaning that any legislative reform must be initiated at the federal level through the national Congress based in the capital, not by individual states. This centralisation benefits platform companies, as workers in the states are unable to advocate for change locally and must instead navigate federal mechanisms in the capital—often beyond their organisational reach.

This study draws on Charles Tilly's (1978) theoretical framework of collective action to examine the challenges platform workers face in organising and mobilising. It also investigates how they navigate the absence of key labour rights such as rest days, wages, paid leave, holiday bonuses, and working hour limits as defined by the LFT. To this end, a series of interviews and surveys were conducted with platform workers in Zacatecas, Mexico, as well as with key informants from two major national-level organisations representing these workers.

2. Platform Capitalism and Regulation in Mexico.

Platform capitalism refers to a new economic model that has emerged to address the need to manage and process vast quantities of data (Srnicek, 2018). It aims to maximise production in minimal time and at low cost. The rise of this model has been enabled by technological advancements—particularly the digitalisation of machinery and the computerisation of production processes (Berardi, 2003)—which have profoundly transformed the capital–labour relationship that underpins industrial capitalism.

Among the most emblematic examples of this model are mobility platforms such as Uber—a North American transnational company that emerged in the late 2000s, reshaping the public transport sector and becoming synonymous with platform-based labour.

Uberization has created a model that, while new and based on a novel and unprecedented algorithmic management of labour, builds on previous trends of capitalism: a tendency toward the informalization and casualization of labour, the destruction of labour rights, the exploitation of transnational labour by corporations based in central countries, tax avoidance by large corporations, the private usufruct of infrastructure and public resources, and the design of business formats that function by isolating workers (Radetich, 2022, p. 271).

This situation arises primarily because digital platforms present themselves as technology companies, thereby obscuring the true nature of the labour relations they establish globally. This façade enables them to bypass tax and labour obligations and operate in informal regulatory environments. Uber, for instance, operates in over 10,000 cities worldwide, yet its activities have only been meaningfully regulated in London, France, and the Netherlands. In these jurisdictions, the company is required to provide minimum wage, paid leave, and rest breaks to its drivers (Transport for London, 2022; Bermejo, 2023; Dutch justice rules that Uber drivers are employees, not self-employed, 2021).

In Mexico, between 2019 and 2022, seven legislative proposals aimed at regulating labour relations on digital work platforms were submitted to the national Congress. However, none has succeeded—largely due to corporate resistance and weak stakeholder organisation (Lamas, 2023). As a result, digital platforms continue to operate in opacity, thriving under the protection of unregulated profit.

3. Uber and Didi in Zacatecas, Uncontrolled Operation

Uber and Didi, two prominent ride-hailing platforms, began operations in the state of Zacatecas in 2016 and 2020, respectively. Uber currently operates in the three most populous cities—Guadalupe, Zacatecas City, and Fresnillo—while Didi is limited to Zacatecas City and Guadalupe.

Notably, the expansion of these platforms has not encountered significant regulatory challenges, nor has it generated substantial conflict between platform drivers and traditional taxi drivers. Zacatecas remains one of the few Mexican states where such friction has remained minimal (Cárdenas, 2018; Cabrera, 2017; García, 2016; Méndez, 2016; Stettin, 2019; Azueta, 2023).

Uber's entry into Zacatecas was facilitated by key figures in the local technology sector, particularly Raymundo Ceja González, then Director of the Information Technology Cluster (Ceja, 2016). Resistance from local taxi drivers emerged seven months later, in March 2017, when around 150 drivers formally petitioned the sector authorities to prohibit the platform's operation. They alleged that public officials had exploited Uber's arrival to establish private vehicle fleets for rental purposes (Aguilar, 2017). In June 2017, an additional 500 drivers submitted a document to the State Legislature requesting that any forthcoming Public Transportation Law explicitly ban Uber's legal recognition.

However, between 2018 and 2020, taxi union protests dwindled, with only three demonstrations recorded (Godoy, 2017; Montoya, 2018; Díaz, 2019). In contrast to Mexico City, where authorities have actively pursued regulatory frameworks, Local governments in Zacatecas have shown little initiative to oversee platform operations (Cerbón, 2018; Galaviz, 2023; Mélendez, 2024; Zamarrón, 2022). This inaction reflects the broader economic context of the state, marked by an overreliance on the tertiary sector, widespread informality, underemployment, and persistent labour poverty.

4. Attempt at Regulation

The sole regulatory initiative introduced in Zacatecas was submitted to the local Congress with the intention of reforming the state's Transport, Traffic and Roads Law. The proposed amendments aimed to impose basic regulations on digital ride-hailing platforms, including mandatory credit card payment for services, compulsory registration of companies with the State Registry of Vehicles and Concessions, and the establishment of a fund for administrative and operational purposes.

However, the initiative failed to gain traction and was not actively supported by taxi driver unions—unlike in other states where such groups have pushed for legal reforms compelling platforms to register and pay minimum licensing fees, in an effort to mitigate what they perceive as unfair competition from transnational corporations.

As it stands, the only legal obligations imposed on platform workers in Zacatecas involve compliance with federal tax regulations: Income Tax (ISR) and Value Added Tax (VAT), both enacted in 2019. These taxes apply solely to the drivers' income, while the platform companies themselves remain exempt from local taxation.

4. 1. Weak Economy and Precarious Employment

Zacatecas is characterised by a persistently depressed economy. Its economic activity largely depends on poorly regulated and weakly protected sectors within the tertiary domain, which, despite generating the bulk of employment, have contributed less than 1% annually to the state's GDP over the past 15 years (INEGI, 2024a).

In this context, underemployment and informality rates have consistently exceeded national averages, while poverty levels remain among the highest in the country. Although employment in the informal sector previously remained below the national average, it has shown an upward trend since the COVID-19 pandemic. This shift suggests a growing number of individuals relying on personal assets to generate income outside formal employment structures.

Despite exceeding national averages in most labour-related indicators, Zacatecas consistently reports lower-than-average unemployment rates. This paradox reflects not a healthy labour market, but rather the prevalence of low-quality, informal jobs with insufficient working hours to meet basic consumption needs. As shown in Table 1, Zacatecas exhibits higher rates of informality and underemployment compared to national averages, despite relatively low unemployment rates.

Table 1.: Unemployment, Labour Informality, Underemployment, and Informal Sector Employment Rates in Zacatecas and National Averages (2020–2024)

Year	Unemployment[1] (National/Zacatecas)	Labour Informality[2] (National/Zacatecas)	Underemployment[3] (National/Zacatecas)	Informal Sector Employment[4] (National/Zacatecas)	General Pressure[5] (National/Zacatecas)
2024	2.5% / 2.7%	54.3% / 59.9%	6.8% / 9.2%	27.8% / 24.5%	5.5% / 6.3%
2023	2.7% / 3.4%	55.1% / 60.3%	7.3% / 11.7%	28.2% / 26%	5.8% / 8.1%
2022	3.5% / 2.8%	55.2% / 60%	9.0% / 13.0%	28.3% / 24.2%	6.9% / 6.9%
2021	4.4% / 3.9%	55.1% / 60.6%	13.8% / 18.7%	28.0% / 25.5%	8.1% / 9.7%
2020	3.4% / 3.3%	56.1% / 61.0%	8.5% / 13.7%	27.6% / 22.0%	7.0% / 7.2%

Note. Compiled by the authors using data from INEGI (2020, 2021, 2022, 2023, 2024a).

According to the National Institute of Statistics and Geography (INEGI), Zacatecas has recorded informal employment rates above the national average for

1 Percentage of the economically active population (EAP) not working but looking for work (Inegi, 2024b).
2 Proportion of the economically active population that is the sum, without duplication, of the economically active population that is vulnerable to work due to the nature of the economic unit for which they work, and those whose work relationship or dependency is not recognized by their source of work (Inegi, 2024b).
3 Percentage of the employed population that has the need and availability to work more hours than their current job allows (Inegi, 2024b).
4 Percentage of the economically active population working for a non-agricultural economic unit that operates based on household resources, but without being constituted as a business, so that the income, materials and equipment used for the business are not independent and/or distinguishable from those of the household itself (Inegi, 2024b).
5 Percentage representing the unemployed population plus the employed population looking for work in relation to the economically active population (Inegi, 2024b).

the past five years, indicating that more than half of the workforce remains in vulnerable conditions due to insufficient labour protections. Similarly, underemployment has consistently remained above the national average, suggesting that many individuals work fewer hours than those defined for standard full-time employment. Overall, the data underscore a labour market characterised by precariousness, informality, and insufficient earnings, rather than by stability or quality employment opportunities.

Importantly, although employment in the informal sector had remained below the national average prior to the pandemic, it has shown an upward trend since the COVID-19 crisis. This change highlights a growing number of individuals who increasingly rely on personal assets to generate income outside of formal employment structures. Despite being above the national average in most labour-related indicators, Zacatecas consistently reports lower-than-average unemployment rates. This paradox does not reflect a robust labour market, but rather the prevalence of low-quality, informal jobs with insufficient working hours—inadequate to meet basic consumption needs.

5. Platforms and Collective Action: Theoretical and Methodological Approaches

Srnicek (2018) categorises digital platforms into five types: lean, product, cloud, advertising, and industrial, each with distinct characteristics. This study focuses exclusively on lean platforms, which, according to Srnicek, are defined as those operating without owning physical infrastructure or assets.

Our analysis focuses on lean mobility platforms such as Uber and Didi, which have transformed the global public transport sector by creating an environment of unfair competition. These platforms enable individuals with personal vehicles to provide transport services independently, without requiring formal registration or permits.

Work facilitated by these platforms falls between atypical and non-traditional forms of employment. The International Labour Organization (ILO) defines atypical work as employment that diverges from standard norms, including temporary contracts, part-time work, agency-based jobs, and economically dependent self-employment (ILO, 2024). Similarly, De la Garza Toledo (2009) characterises non-traditional work as lacking conventional salary structures, typically performed outside factory settings, and concentrated in the service sector.

As several studies confirm, this form of employment is often covertly subordinated, posing as independent work while subjecting workers to algorithmic control. Not only is the labour of drivers and couriers exploited, but so too are their personal resources—including vehicles, mobile phones, and maintenance costs—all absorbed into the capitalist cycle (Radetich, 2022; Lamas & Acosta, 2023).

Moreover, the core function of platforms is to act as intermediaries between service providers and clients—whether for transport, deliveries, or accommodation. This intermediary role allows platforms to position themselves as neutral facilitators, distancing themselves from the responsibilities typically associated with employers. Their capitalist success hinges on delivering low-cost, high-speed services driven by consumer demand, often at the expense of the labour force behind them. These exploitative structures are frequently overlooked by governments and users alike, and at times even by the workers themselves, reinforcing a cycle of informality and vulnerability.

This article situates its analysis within this broader context, drawing on Charles Tilly's (1978) theory of collective action. Tilly defines collective action as "the collaborative action of people in pursuit of common interests", which emerges from the dynamic interplay of four fundamental components: interests, organisation, mobilisation, and opportunity (Tilly, 1978, p. 7).

- *Interests* refer to the shared benefits or disadvantages a group seeks relative to other populations.

- *Organisation* denotes the common identity, cohesion, and structured interaction among members.

- *Mobilisation* represents the extent to which collective resources—whether material, symbolic, or human—are coordinated and directed towards common goals.

- *Opportunity* encompasses the external political, economic, or social conditions that affect the feasibility and success of collective action (Tilly, 1978, pp. 54–55).

In this study, the government is understood as the central authority empowered to regulate labour relations and exercise coercive power over the population. Platform workers, meanwhile, are conceptualised as contenders—groups that, during specific moments of opportunity, mobilise collective resources to influence public policy or demand recognition of their rights (Tilly, 1978, p. 51).

To explore this framework, a mixed-methods research design was employed. The research involved 25 surveys and 10 semi-structured interviews with Uber and Didi drivers in Zacatecas and Guadalupe, alongside interviews with representatives of two leading national platform worker organisations. The sampling followed a snowball method, and the interviews addressed the four analytical categories of Tilly's collective action theory.

6. Results

The following data and findings stem from fieldwork conducted with the valuable participation of Uber and Didi platform drivers, who generously agreed to take part in interviews and surveys. Their contributions enabled the reflections and insights presented in this section.

What follows is an analysis structured around the four core analytical categories applied to the study of collective action among platform workers in Zacatecas. Each subsection explores one of these dimensions in depth, shedding light on the social dynamics, motivations, and constraints shaping workers' capacity to organise and mobilise.

6. 1. I Don't Want Rights, I Want Income!: Interests in Conflict

Tilly (1978) notes that group interests are often at odds, as individuals typically prioritise personal gain over collective benefit. He observes: "Each individual actor normally has an incentive to avoid their own contribution to the collective actions that would benefit everyone" (p. 62). This insight is clearly reflected in the case of Uber and Didi drivers in Zacatecas. Drivers join these platforms for various reasons and pursue differing goals—particularly regarding the regulation of their work.

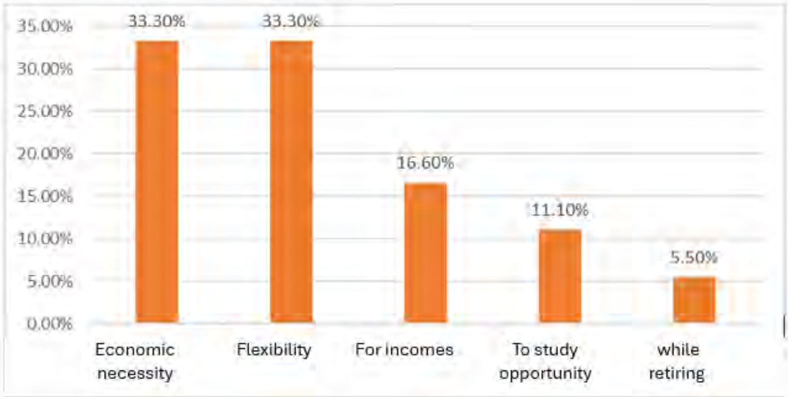
The results show that 33.31% of respondents have a traditional job alongside their work on the platforms. This dual employment status directly affects their interests: for instance, they do not consider it necessary for platforms to provide benefits such as social security, as they already receive these through their primary employment. All drivers in this category stated that their motivation for joining platform work was unrelated to securing labour rights; rather, their reasons included earning extra income, saving, investing, paying off a vehicle, or simply avoiding boredom at home.

All respondents with traditional jobs expressed opposition to regulating platforms under labour laws. They argued that requiring platforms to comply with labour protections would threaten their ability to earn extra income. They feared being tied to fixed schedules that might interfere with their primary jobs, and they also anticipated an increase in tax obligations.

> *"I would not like the job to get regulated because then they would ask for more things, and I wouldn't be able to have another job. Also, if they provide us with insurance and other benefits, the discounts would be bigger. If the app already deducts like this, now if they deducted more for insurance, we would have nothing left. Out of every 100 pesos, between 40 and 45 go to Uber; if they added another discount for insurance, we would be left with just 30 pesos for ourselves." (E2)*

By contrast, full-time platform drivers reported motivations such as financial need (33%), flexible schedules (33%), higher earning potential (16.6%), education costs (11.1%), and supplementing income during retirement (5.5%).

Graph 1.: Motives for Working Full-Time on Ride-Hailing Platforms



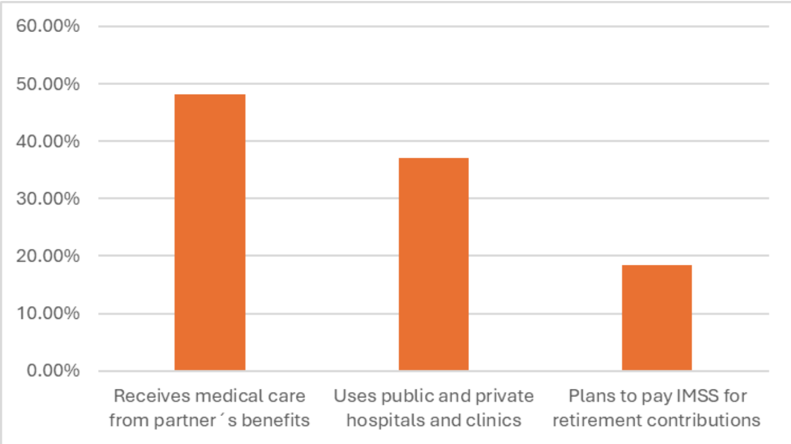
Note: Compiled by the authors using primary data from the fieldwork.

In this regard, E1 explained that his motivations included the flexibility of scheduling his own working hours—even during conventional working times—the opportunity to earn sufficient income more quickly than in traditional employment, and the ability to spend more time with his family:

> *"I started working here because you have a lot of time to do your things, I mean, you can work whenever you want and as long as you want. Before this, I worked at Sabritas, and it was a 12-hour shift—very stressful because it involved sales. I was a delivery man and earned about 3,000 pesos per week. Honestly, with Uber, working just Fridays, Saturdays, and Sundays, I can earn almost the same. Besides, my life quality is better; I have more time with my son. If he needs help with school, has a match, or an assignment, well, I drive him to school and pick him up too." (E1)*

In this context, the pursuit of labour rights takes a back seat to income. Among full-time drivers, 48.14% receive healthcare through a partner, 37% use both public and private services, and 18.51% rely solely on private care. Some also mentioned voluntarily contributing to the IMSS to secure retirement coverage.

Graph 2.: Access to Medical Care for Platform Workers



Note: Prepared by the authors using fieldwork data.

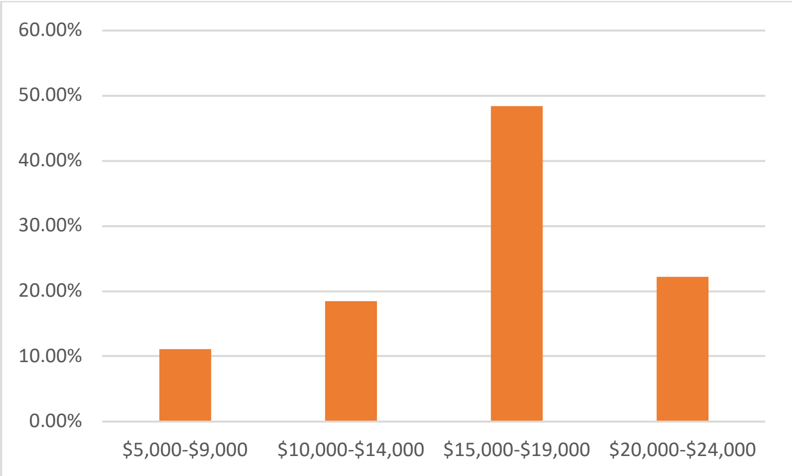
> *"People who are in favour of regulation are the platform drivers who were taxi drivers or those who only work for platforms—and they must be around 70%. But the rest of us believe that if you start working morning to night, it gives you enough to pay for your own insurance." (E5)*

As for benefits such as holidays, interviewees agreed that one of the main advantages of platform work is the ability to take time off without needing approval, though this leave is unpaid. They viewed bonuses—called challenges in Zacatecas and turbos in Mexico City—as informal substitutes for an Aguinaldo (year-end bonus).

> *"Last year, we didn't connect for a day in December because the challenges were not active and trips were really cheap—well, that was our Aguinaldo; we had to do something to pressure the platform." (E1)*

Income levels varied: 22.2% reported earning between $20,000 and $24,000 pesos per month; 48.4% between $15,000 and $19,000; 18.51% between $10,000 and $14,000; and 11.11% between $5,000 and $9,000.

Graph 3.: Average Monthly Net Income (Estimates)



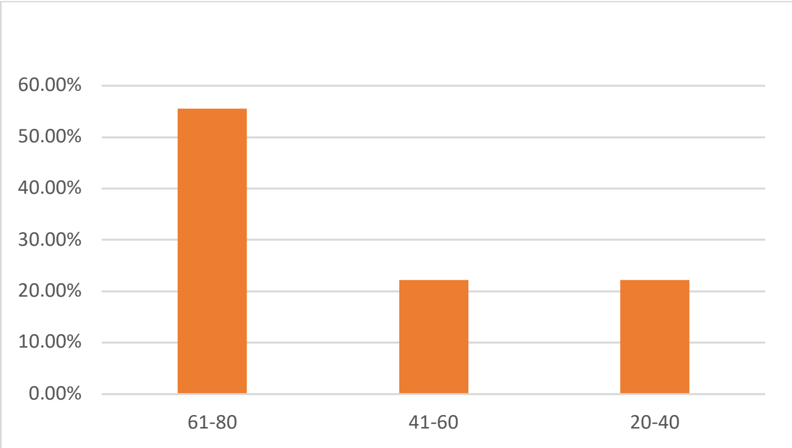
Note: Prepared by the authors using fieldwork data.

Although ride-hailing drivers often earn more than other digital platform workers—for example, delivery drivers average around $10,000 pesos per month (Oxfam, 2022)—they tend to work the equivalent of two full-time jobs per week. This helps explain why many drivers who rely solely on platform work do not support regulation that would impose a standard eight-hour workday, fearing it would limit their earning potential.

This explains why many drivers who work exclusively through platforms resist efforts to impose labour regulations, fearing that such changes would enforce eight-hour workdays similar to traditional employment.

In sum, the diversity of interests among platform workers complicates or even prevents the consolidation of collective demands for labour rights. Most drivers value flexibility and income over legal protections—even at the cost of long hours and personal strain. Although Uber and Didi allow a maximum of 12 consecutive hours online, many drivers rest for only the six hours the app forces them offline before reconnecting.

Graph 4.: Average Weekly Working Hours



Note: Prepared by the authors using fieldwork data.

> *"It's known that here's where the money is—but you've got to work really hard. The good thing is that we can work whenever we want." (E10)*

6. 2. Non-Contentious Organization

If reconciling interests is difficult in traditional jobs, it is even more so in platform work. Still, in Zacatecas, there exists a relatively high degree of organisation among platform drivers—not for contentious mobilisation, but for day-to-day matters like roadside support or protection in the face of criminal violence.

Tilly (1978) argues that a group's organisational strength depends on its internal networks, shared identity, and the time and energy members devote to it. By design, digital platforms use algorithmic management systems that isolate workers from one another. This isolation not only reduces costs but also makes it harder for drivers to build solidarity or form social movements that might challenge the capital interests behind these companies.

In countries like Argentina, more robust forms of organisation have emerged. For example, delivery workers there coordinated a national digital strike in June 2018 against Rappi over abusive practices (Bachoer, 2022). In Mexico, however, worker organisation has remained relatively weak and fragmented. In 2022, two major national collectives of platform workers diverged over how regulation should be framed.

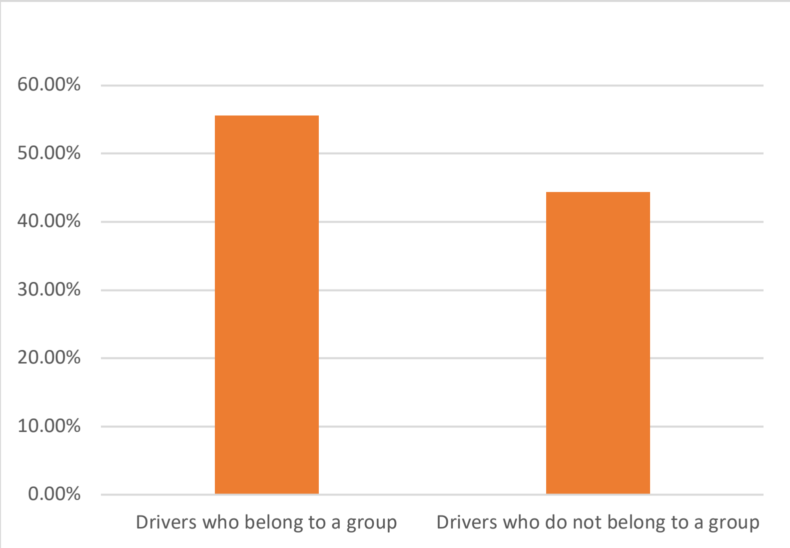
On one side, Ni un Repartidor Menos (NURM) signed a document proposing a regulatory framework that recognises platform workers as service providers, not formal employees. The agreement was co-signed by Uber, Rappi, Didi, and civil organisations like Nosotrxs and Corporativo de Estudios y Asesoría Jurídica A.C. On the other side, the Unión Nacional de Trabajadores por Aplicación (UNTA), acting as a union, signed the Piso Mínimo manifesto with regional groups. This document demands that digital platform workers be recognised as employees under the Federal Labour Law.

This split halted progress in Congress. Without unity, the seven bills introduced on platform labour regulation stalled. The lack of organisation also disrupted the working groups held in the chambers of the Congreso de la Unión.

According to Sergio Guerrero (General Secretary of UNTA, personal interview, May 12, 2024) and Saúl Gómez (NURM spokesperson, personal interview, May 15, 2024), there are no active affiliations or known representatives of these national groups in Zacatecas. Drivers E1 and E7 reported receiving invitations to join national movements but could not specify the names.

Local organisation in Zacatecas has revolved around small-scale goals such as reducing platform commission fees or negotiating fare increases. Communication and coordination occur through roughly 12 WhatsApp groups, each with around 50 members. Drivers identify themselves with stickers of animals or characters on their vehicles, creating informal communities. However, 44.4% of surveyed drivers said they do not belong to any group.

Graph 5.: Participation in Platform Worker Groups in Zacatecas



Note: Compiled by the authors using fieldwork data.

Reasons for avoiding group membership included distrust and a preference for independence. As E3 described:

> *"For a time, I was in a group. They wanted me to put a sticker on my car; nevertheless, I never wanted to do it since I didn't know whether they were up to something good or bad. In fact, there was a member who always posted videos about marijuana use. I wasn't willing to risk it." (E3)*

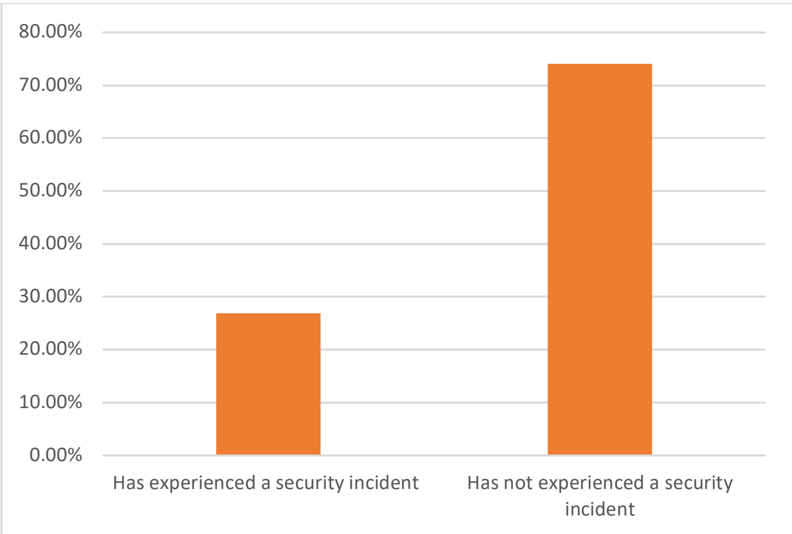
Other reasons for avoiding groups included distrust, a lack of need for social bonds in this kind of work, or prior experiences of being excluded.

> *"I belonged to a group; however, I felt stressed every time, even afraid to go to work. (…) Since there were so many of us, I'm not sure if they were overly dramatic or alarmist, but they would say, 'Don't go to Tierra y Libertad, kidnappings are happening all around the area. Don't go to La Comarca, people*

> *are being killed here.' That didn't help at all. I was just scared, and I preferred to stay home." (E4)*

Conversely, those who remained in the groups cited safety as their main reason. According to INEGI's National Survey of Urban Security (ENSU), Zacatecas cities like Fresnillo and Guadalupe consistently rank among the most dangerous in the country (Lares, 2024).

Graph 6.: Security-Related Incidents Experienced by Platform Drivers in Zacatecas (Past Three Years)



Note: Compiled by the authors using fieldwork data.

Even so, one in four drivers reported experiencing an incident such as assault, abduction, or coercion while working. As E8 recounted:

> *"Nothing has ever happened to me, thank God, but in the group I belong to, we had a small sticker of a rooster. One of the drivers was abducted and told we couldn't use that sticker anymore. We met up for the first time to decide on a new one, and chose a dinosaur—figuring it would be safer." (E8)*

Similarly, E9 described a tragic event in early 2024:

> *"We had never met in person until our colleague was killed. On that occasion, the group administrator suggested that we gather to contribute and support the victim's family. Most attended. It was also decided that we would remove the Batman sticker we'd been using for about 15 days to avoid any problems." (E9)*

In these groups, drivers typically share their real-time location at the start of their shift. If a driver becomes stationary for an unusual length of time, others check on their safety. Toward the end of 2023, several drivers started discussing commission rates and called for a brief strike via a Facebook page called Uber y Didi Zacatecas.

> *"We fought because the retention rate applied by Uber was nearly 50% of the trip fare. This meant that out of every 10 pesos, I was left with only five, from which I had to cover household expenses, fuel, and vehicle maintenance—it simply wasn't enough. There's a Facebook page called 'Uber y Didi Zacatecas.' The admin posted a call to stay offline for a day, and hardly anyone logged in. If we were about 1,000 drivers, maybe 200 stayed online. That was how we got the commission down to 35% and some bonuses too." (E10)*

Despite these efforts, a lack of transparency on how commissions and taxes are calculated has led to confusion and differing views on the effectiveness of the strike.

> *"A lot of us rent our cars, so stopping work hurts us since we still need to pay the rental fees. During the protest, some drivers just took advantage of the surge pricing. There's no unity, no real fairness—it's hard to achieve anything that way." (E8)*

E9 echoed this sentiment:

> *"At the very least, we should have insurance—not just for ourselves, but for our families if something happens. Otherwise, they're left struggling, especially since we usually rent the cars, which leaves them with the debt and no support." (E9)*

6. 3. Mobilization

Mobilization refers to the process by which a group secures and coordinates the necessary resources—whether material, symbolic, or human—to pursue collective goals (Tilly, 1978). In Zacatecas, it is evident that driver groups lack the infrastructure and material capacity required to mobilise effectively. This limitation is largely due to the nature of platform work itself, which discourages social bonding and prevents the formation of cohesive networks.

As mentioned earlier, the few instances of mobilisation that have occurred were confined to private social media channels, mainly used for coordinating short work stoppages in protest against platform commission rates. There have been no attempts to bring these grievances into the public sphere or to participate in broader national movements advocating for regulation. Nor have there been visible efforts to engage with civic organisations or policy bodies to demand improved working conditions.

This absence of sustained mobilisation reflects two critical dynamics: the fragmentation of interests among workers, and the structural barriers imposed by platform capitalism—an economic model that individualises labour to such an extent that coordinated collective action becomes nearly impossible.

This absence of sustained mobilisation reflects both the fragmentation of drivers' interests and the structural barriers imposed by platform capitalism, which collectively limit the potential for long-term collective action.

6. 4. Opportunity

According to Tilly (1978), *opportunity* arises when the interaction between a specific group and external actors creates conditions conducive to collective action in support of the group's interests. In the case of platform drivers, the primary external actor is the government, which possesses the authority to regulate labour relations and enforce labour rights—rights that the companies have thus far refused to acknowledge or implement.

Opportunities for collective action may be subject to repression, tolerance, or facilitation. Repression tends to increase with the scale of mobilisation—defined by the number of participants, duration, geographical scope, degree of organisation, and level of force involved (Tilly, 1978, p. 110). Facilitation occurs when the government allows collective action to proceed without interference, while tolerance denotes a neutral stance in which neither obstacles nor support are provided.

Based on the data gathered, it appears that the collective actions undertaken by platform worker groups in Mexico exist within a space between tolerance and facilitation. Representatives from UNTA and NURM attribute this to the limited number of organised participants, which has hindered the emergence of a critical mass strong enough to attract governmental attention.

Furthermore, the geographic concentration of most actions in Mexico City—coupled with the divergent goals of leading organisations—has significantly restricted the duration and intensity of mobilisations, further weakening their capacity to effect meaningful regulatory change.

7. Conclusions

In Zacatecas, the issue of regulating digital platforms like Uber and Didi appears to be a peripheral concern for most drivers. This attitude stems from the work model itself, which prioritises flexibility and independence while discouraging interpersonal connection and collective identity. Many drivers fear that regulation would mean losing the income flexibility that allows them to sustain themselves in a fragile labour market.

Despite these constraints, platform workers have found ways to form support networks using digital tools such as WhatsApp and Facebook. These networks, however, serve primarily defensive purposes—such as sharing safety information and responding to emergencies—rather than enabling political or labour-based mobilisation. This reflects a form of non-contentious collective action, one that attempts to address unmet needs in the absence of state support or employer accountability.

The Mexican state's passive stance—at the federal, state, and municipal levels—reinforces the informality of platform work. In the face of limited formal employment options, digital labour has become an unofficial safety valve for absorbing underemployment and disguising unemployment statistics.

The analysis of collective action in Zacatecas shows that workers rely heavily on flexible schedules and peer-based communication to cope with the instability of their working conditions. These arrangements allow many to earn incomes that, on paper, seem higher than local averages. But this comes at a high personal cost, including chronic overwork, lack of rest, and absence of basic labour protections.

Interviewees consistently reported working between 60 and 80 hours a week, often with no days off. While the platforms offer performance-based incentives—such as "challenges" or "turbos"—these function as substitutes for legally mandated benefits like holiday pay or bonuses. Time off, while technically available at will, remains unpaid and is rarely taken.

One driver explained: "People are conformists. As long as nothing bad happens, they don't try to change anything. It's all about working, working, working." (E10)

Another said: "At the very least, we should have some kind of insurance—not just for ourselves, but for our families in case we're kidnapped or harmed. Most of us rent our vehicles, so if something happens to us, our families are left with the debt and without us." (E9)

These statements highlight a pervasive sense of resignation among workers, many of whom view themselves not as employees deserving of rights, but as self-employed individuals responsible for their own welfare. This mindset, reinforced by structural precarity and individualistic work dynamics, hinders the formation of a strong labour movement.

In essence, platform work in Zacatecas exemplifies the hallmarks of informal, non-traditional, and precarious employment. Workers' atomised interests, limited mobilisation capacity, and defensive organisational structures reflect a labour force navigating survival in a system that offers flexibility without protection, and income without rights.

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PART III

LABOUR AT THE CROSSROADS: DISPLACEMENT, INNOVATION, RESISTANCE

"Machines were, it may be said, the weapon employed by the capitalists to quell the revolt of specialised labour."
— Karl Polanyi, *The Great Transformation: The Political and Economic Origins of Our Time* (1944), Chapter 14, p. 231.

Industrial intelligence is not merely reshaping labour—it is dislocating workers, concentrating land, and deepening global inequalities. As automation expands and technological innovations transform the structures of production, labour stands at a critical juncture.

But beyond statistics and trends lies a deeper question: **what is labour without agency, without land, without dignity?** In a world where machines extend capital's reach into every factory and field, the future of work becomes a battleground over sovereignty, survival, and justice.

This part delves into the fractured landscape where labour must navigate displacement, innovation, and exclusion. From global indicators of AI-driven labour loss to the uneven adoption of precision agriculture in Latin America, these chapters reveal how technological dependency and capital accumulation reshape livelihoods—and how urgent the need for new solidarities has become.

Labour must either evolve, resist, or radically reimagine itself in a world increasingly ruled by machines.

7 |

Main Indicators of Labour Displacement by Artificial Intelligence Worldwide

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Abstract

After World War II, with the emergence of the first computers, the emergence of high technologies accelerated and, with it, the challenge of strengthening welfare and promoting improved quality of life. Since then, algorithms and programming have been topics of scientific and technological interest, with political, social, and economic implications. Artificial Intelligence (AI) is a concept that has emerged based on the intention to improve the operational, functional, and mathematical processes in the programming of devices of the technological era. AI is understood as the operational form of machines to take optimal decisions using commands and algorithms reducing the possibility of making mistakes. Thus, it would represent the new era in the design, control, and development of new technologies that were not thought possible a couple of decades ago. Technology became especially relevant because it provided a technical solution to the challenge of encouraging capital accumulation. Aside from the benefits that the technological era has brought to some social classes, it is also necessary to mention those sectors that have been violated. The International Monetary Fund (IMF) has warned that 60% of jobs globally are at risk due to the rise of AI and the rapid development of nanotechnology (Martin, 2020). This impending inequality in access to work, goods, purchasing power and social autonomy makes labour displacement an urgent issue that must be addressed in government and labour policies.

Keywords: technologies, artificial intelligence, displacement

JEL Codes: J24, J80, L50, O3

1. Introduction

With the arrival of the technological era and the development of Artificial Intelligences (AI), the labour world has undergone constant changes that have boosted automation and mechanization of repetitive tasks in certain economic sectors, especially in the productive sector. The lack of regularization of AIs has caused several problems in society, especially in labour rights and displacement of the working class. The framework of analysis that has been used for studies of this magnitude alludes to different models and strategies that, under quantifiable metrics, have made explicit different historical trends. Short-term projections, i.e., to 2027 and 2030, have estimated scenarios in terms of social impacts, labour rights and social displacement due to the use of AIs.

The objective of this chapter is to analyse the statistical trends, employment and unemployment rates due to the implementation of AI, in relation to the behaviour of employment at the global level and evaluations of technological adoption that demonstrate the conviction of the use of this technology by industry. This is discussed based on an analytical and historical dissection of the capitalist economic model in which AI has been adopted to accelerate capital accumulation, with the respective contradictions that inherently unfold in the capital-labour relationship.

This paper is divided into four sections: the first is an introduction to the subject and describes the parts of the research; the second is a chronology of the main sectors that were affected by post-industrialist effects during the second half of the 20th century. In turn, the main sectors affected by the monopolistic mechanization derived from automation are presented by way of background. The third section details the current emergency in the face of the overflowing implementation of AI in the labour sector and frames the cases that, internationally, have been most recognized by the media, as well as the analysis of statistics, trends and verifiable consequences in data. In the fourth section, some clarifications are presented in the form of conclusions.

2. The Impact of Technology on the Workplace: A Discussion of Yesteryear.

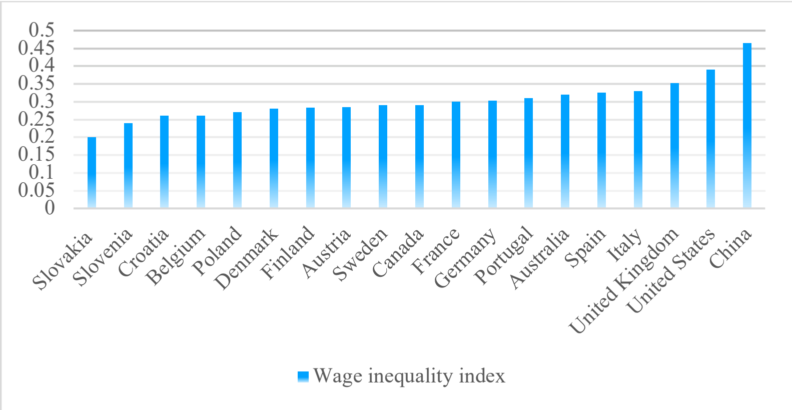
The relationship between binomial technology is not new in the contemporary sense. Its antecedents date back to the first industrial revolution in the 18th century, when the steam engine channelled economic advances by transforming manufactured labour into mass and industrialized production (Villas, 2012). The first industrial revolution, not having globally integrated markets, had a sectoral impact delimited by the economic and geographical environment of the United Kingdom. Its results derived in developments mainly in manufacturing such as cotton textile production, coal steelmaking and the integration of steam power in production processes (Villas, 2012).

In turn, the second industrial revolution documented the first cases of labour displacement due to the establishment of industrial processes. Mechanical production processes, in the first instance, and automation, in the second, led to the increasing generalization of state-of-the-art technologies, especially at the end of the 20th century and the beginning of the 21st century (López & Velasteguí).

This, of course, is not a recent phenomenon. The trend can be traced back to the 1970s, when the insertion of new technologies in production processes was part of what was known as the golden age of capitalism (accelerated global accumulation) (Barciela, 2005), with an impact on the labour, social, political and even cultural spheres. The bourgeoisie as a social class was the great beneficiary of this process.

In contrast, there were a myriad of collateral effects for the world of work; among which wage inequality, high technification of productivity and the elimination of labour-intensive jobs in the high-tech industry stand out. Artigas addressed the phenomenon and established that "this technological evolution is destroying a large number of jobs by replacing humans with robots, and that the jobs that are generated do not cover the demand" (Artigas, 2020, p. 14). Artigas refers especially to the fact that robotization and automation have increased wage inequalities and have had an impact on the rise of forced migration through the claudication of variable capital.

Figure 1.: Wage inequality according to the Gini coefficient for the year 2024.



Note: Own elaboration based on Kaya, 2024 & Statista, 2024.

Figure 1 shows the main wage inequality indicators for countries that are members of the Organization for Economic Cooperation and Development (OECD) and China. The instrument used for this statistic was the Gini coefficient, a tool that quantifies inequality based on numerical categories 0-1. The 0 classification alludes to consolidated equality, while 1 is related to inequality in the metric studied. Under this interpretation, it can be seen that countries such as the USA and China are in the first positions of wage inequality in contrast to those semi-peripheral or peripheral countries in terms of development and technological industry.

Wallerstein (1979) developed the world system theory in which he sought to explain power relations and inequalities in the global economy from a macro-social approach. For this author, countries are categorized into three different groups according to their political, economic and sociocultural position. The first category to which he alluded was that of the central countries, or core countries, countries that have been considered economic powers which have given them control and dominance in international finance, international trade and technologies. Another important characteristic of core countries is the high levels of infrastructure, education and technology they achieve through research advances in fields such as information technology, biotechnology, telecommunications and computer science.

In second place are the peripheral countries, economically dependent and exploited by central countries due to their great financial constraints, indelible industrialization and exploitation for cheap labour and raw materials. Normally, the lack of development in accumulation of knowledge, financing, infrastructure, patents, monopolization of profits and industrial platforms are observed in this type of countries. At the same time, the precarious academic preparation forces the inhabitants to migrate and subject their labour force to very low wages.

However, there is a third class of countries, called semi-peripheral countries, which are characterized by being in an intermediate position by having characteristics of both core and peripheral countries. Some of these characteristics range from gradually growing economies and are usually strategic and political bridges to the core countries. Transnational corporations constantly operate in these countries without jurisdictional responsibilities. Exploitation of natural resources, raw materials, labour and precarious working conditions are seen in this sector, but to a lesser degree compared to peripheral countries. Examples of countries with these conditions in Latin America include Brazil, Mexico, Argentina and Chile.

In recent times, scientific literature on the social studies and impacts of automation has become relevant in the analysis of labour displacement. Advances in production since the 18th century and up to the second decade of the 21st century are directly linked under two concepts: mechanization and automation. Mechanization is a "key and strategic area of development of modern society, synonymous with technological modernization, [...] that allows the generation and application of knowledge and/or technologies to real problems of the environment" (Reyes, Cid & Vargas, 2013, p. 3). On the other hand, the word mechatronics derives mainly from (mechatronics), whose meaning is mechanism wick and (tronics) in relation to electronics. It appeared in July 1969 in a Japanese report by Tetsuro Mori, when he introduced his Kaizen technique, which consisted in the use of machines and quality systems to solve operating problems that partially supplanted human labour.

Automation, in turn, represented "the substitution, in technical processes, of human tasks by mechanical, electrical, electronic equipment or systems, in order to optimize the use of existing resources and the continuity of processes" (Aguilar et al., 2013, p. 107). Automation embodied a scenario in conjunction with mechanization, since the latter was only limited to closed and punctual commands in the development of functions. With the arrival of automation, an infrastructure was defined that made it possible to cover all phases of a production process (Aguilar et al., 2013)

The internet, big data, nanotechnology, artificial intelligence, cyborg are just some of the references of the trendy so-called industry 4.0 which "is preceded by a change not only in technology, but also in the economic development models of countries, mainly in the case of emerging economies and their participation in the market" (Fernandez, 2017, p. 369). These technologies emerged based on the intention of perfecting the operational, functional and mathematical processes in the programming of the devices of the technological era. AI, defined as "the ability of machines to make optimal decisions [...] minimizing the possibility of making an error in each decision" (Caiafa & Lew, 2017, p. 1), would represent, then, the new era in the design, control and development of new technologies that were not thought possible a couple of decades ago.

This transition is grounded in the form of manipulation of controlled processes at tiny scales through sensors, the so-called Nano Electromechanical Systems (NEMS) that are possible from the nanometre scale. NEMS derive from nanotechnology, which is the technology responsible for investigating and analysing the manipulation of data, materials and processes at nanometre levels; that is, "at a dimension equivalent to 10 to the -9 meter" (Álvarez, Arbeláez, Acevedo & Lee, 2009, p. 76). Thus, the manufacture of new materials would aspire to more flexible properties, prolonged durability, strength and artificial reasoning capacity thanks to manoeuvres at microscopic scales that would alter the physical state of the materials for better performance (Álvarez et al., 2009).

In 2018, the International Monetary Fund (IMF) stated that 60% of jobs globally would be at risk due to the establishment of AI and the rapid development of nanotechnology (Martin, 2020). Given the imminent inequality in access to work, goods, purchasing power and social autonomy, labour displacement should be a priority issue in government and labour policies since "phenomena less than

30 years old today seem characteristics of a new normality" (Martin, 2020, p. 132). Only in the analysis by McKinsey Global Institute, the food industry and accommodation services obtained 66% with a tendency to be automated in the short term, followed in second place by the manufacturing industry with 64% (Artigas, 2020). At the international level, the COVID-19 pandemic consolidated the need for rapid responses in health, because it was the sector with the highest demand. AI was used both for the manufacture of vaccines and for the management of information that required special care (Aguilar & Terán, 2021). Automation, apart from having solved one problem, generated another: the reduction of human presence in labour responsibilities.

In the same sense, the World Economic Forum (WEF) in 2020, diagnosed through international scales, that by 2025, 50% of the productive force would be driven by AI (Lockhart, 2020). In fact, by 2018 "companies had 71% of the workforce made up of humans while the rest, 29% was made up of robots" (Artigas, 2020, p. 21). This premise concluded in that the short-term estimate for 2025 was that the human workforce, on average, was 48%, while the remaining was awarded to AI.

In the year 2023, according to the Future of Jobs Report (2023) alluded that the implementation of AI in companies caused a 25% turnover of labour personnel around the world (Universitat Oberta de Catalunya, 2023). That figure supported previous reports and gave support to estimates made by other studies, such as McKinsey Global Institute in 2018. The above statistics correlate with the results of the Future of Jobs survey report (2020) where the conclusions showed that "almost half of business tasks (47%) would be automated in the next 5 years" (Universitat Oberta de Catalunya, 2023, p. 7). If we add to this the fact that 75% of the businessmen and women surveyed expressed their willingness to implement AI in their operational and production processes, we are potentially talking about "two thirds of current jobs being exposed to some degree of automation [...] and replacing up to a quarter of current work" (Universitat Oberta de Catalunya, 2023, p. 7). The first crises of job displacement due to the insertion of AI have already been foreseen.

For example, in May 2023, the actors' union SAG-AFTRA went on strike in Hollywood with two manifestos in its petition: better working conditions and the demand for a program to regulate the use of AI in the entertainment industry.

This is because films such as The Safe Zone and The Frost were produced both in script, scenery and acting with high-end digital media (Gandini, 2023). SAG-AFTRA positioned its uncertainty about the use of AI in the creation of digital replicas of actors, as well as the cloning of their voices without guarantee of labour rights for the use of their image. After 3 months the strike ended and some agreements were reached, among which stand out; that the industry could not use digital media in the creation of scripts or in the replication of original texts under adaptive purposes, the right to monetary guarantees for actors when cloning voices and image and the limitation of intelligent tools (Gandini, 2023).

Crises such as the one described above represent political and labour contradictions when it is understood that this context occurred in a central country. On the contrary, peripheral and semi-peripheral countries are in a degree of subordination to the interests of the imperialists. As an example of this, the theory of dependency proposed by Andre Gunder Frank alludes to the fact that the global economic structure is intertwined to empower those who have monetary, political and even arms resources over those who lack the same (Frank, 1978).

In current contexts, Mexico has been categorized as a peripheral country, from Gunder Frank's point of view, for different reasons. In principle, its economy is stable thanks to its industrial sectors such as automotive, electronics, manufacturing and agriculture; however, much of that strength is dependent on foreign investment, especially from the United States, which is considered a central country and a global power, due to its geographical proximity and political relations. In fact, it is no coincidence that Foxconn, a Taiwanese multinational company dedicated to the assembly and manufacture of semiconductors, is about to build a plant in the city of Guadalajara, Mexico.

Taiwan ranks as the top semiconductor producer, as 92% of the most advanced semiconductors were manufactured there in 2021 alone (Kanklunen, 2022). However, Taiwan does not keep all the semiconductors it manufactures since approximately 60% of its production is invested in the United States for upgrading and improvement of the American military industry. This has opened the possibility of generating intellectual property clauses and patents, which limits other countries to compete with this leadership.

The fact that a Taiwanese company dedicated to the production of nano sensors and nano semiconductors is about to set up in Mexico would not be due, then, to the desire to strengthen the Mexican economy, much less to increase the percentage of employability, but to increase the route of the capitalist production chain and the theory of dependence, This installation is due to the geostrategic location of Mexico with the United States, which, through cheap labour, exploitation of natural resources, labour precariousness and the economic dependence of a dependent country on a central country, such as the United States, facilitates the progressive increase of capital accumulation for the core country.

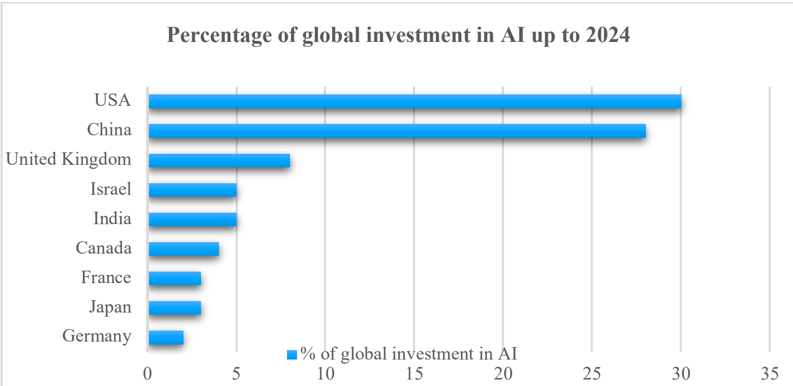
3. The Replacement of Labour by Machines: A Critical Approach

The increasingly globalized relations between countries and theoretical currents such as the critique of political economy make it possible to dissect concrete reality from a dialectical analysis by building analytically from the abstract. In this case, data from a concrete reality and the geopolitical context of a territory can be defined by "its population, its class division, branches of production, exports, imports, production, annual consumption, etc." (Marx, 1975, p. 49). Previously, the practice of labour was exclusively human, which led to give it a value, but this premise has been disarticulated by the advent of AIs, where the latter are able to cover most of the labour activities traditionally performed by human beings.

The results of the McKinsey Global Institute showed that leading countries in accumulation based on technical progress, such as the United States and China, maintain hegemonic power in implanted technology, while peripheral countries have cemented their role as suppliers and maquilas (disguised) of high-tech exports. Thus, "cities of knowledge [...] seek to embed state-of-the-art technology in peripheral spaces that combine socio-technical spheres with technology of greater or lesser complexity with employees à la carte: available, disorganized, needy and precarious" (Márquez, 2021, p. 12).

The Figure shows the percentage of investment of the 10 leading countries in financing technological innovation. However, the list only shows the leadership of centralized countries with a wide advantage over mostly semi-peripheral countries. If we talk about global accumulation, the theory of the world system provides unavoidable aspects on why the power of capital, the circulation of IAs and labour infrastructure is a trigger for semi-peripheral and peripheral countries. In the case of semi-peripheral countries, the main triggers lie in institutional weaknesses such as education and investment to achieve significant advances in industry, socioeconomic disparities and dependence on access and research resources.

Figure 2.: Percentage of global investment among the top 10 countries in the world 2024



Note: Own elaboration based on Artigas, 2020.

With this chronology and under the hegemonic epistemological model of the social division of labour that promotes capitalist accumulation, we can apply the logical principle of social construction addressed by Carnap (1928) in virtue of the fact that labour relations are altered by predictive systems of labour displacement, as happened with the establishment of steam power, cotton textile production and the iron and steel industry of mineral coal. In other words, these models are replicable, because if we go back to the second industrial revolution, the same process of transformation to mechanization and promotion of large corporatist companies not only ended up displacing workers, traders and native people, but also the artisanal forms of production, and, in some cases, even affecting natural ecosystems.

Therefore, it is necessary to argue the fundamental role of the State in authorizing and distributing patents. Patents in AI are considered key information sources, database and permissions for their legal research and analysis; in other words, "a patent is a temporary and spatial monopoly right over a process or product, granted by the State to an inventor to explore his invention" (Robles et al., 2016, p. 204). Patents have been related to economic systems in a strategic way and are divided into 4 general fields.

The first is the origin of the patent, which indicates whether the patent obeys a specific sector such as a chemical laboratory or an engineering application. The second refers to the conversion of that patent into a physical product; consequently, the third applies to that product and, finally, the fourth is the collection of data from the three previous phases for the study and interpretation of the effectiveness of the patented product. In this mechanism, the State plays an important role in determining the laws and regulations to be followed to obtain a patent.

Table 1.: Breakdown of number of nanotechnology patents by country 2023.

Country of origin of patent application	**Number of patents (thousands)**	**Position**
USA	69,100	1
Japan	11,440	2
South Korea	11,224	3
Taiwan	7,305	4
China	7,032	5

Note: Own elaboration based on Statnano, 2023.

Therefore, if the State becomes the main protagonist of permits, legal norms and promotion of innovation, it should also be responsible for resolving the secondary effects that impact on the rule of law. In Latin America there are the Patent Cooperation Treaty (PCT) and the Agreement on the Aspects of Intellectual Property Rights (TRIPS). However, the most recognized for its history and influence has been the International Patent Classification (IPO), which has been in place since 1971 and houses a large number of patents from more than 100 countries (Robles et al., 2016).

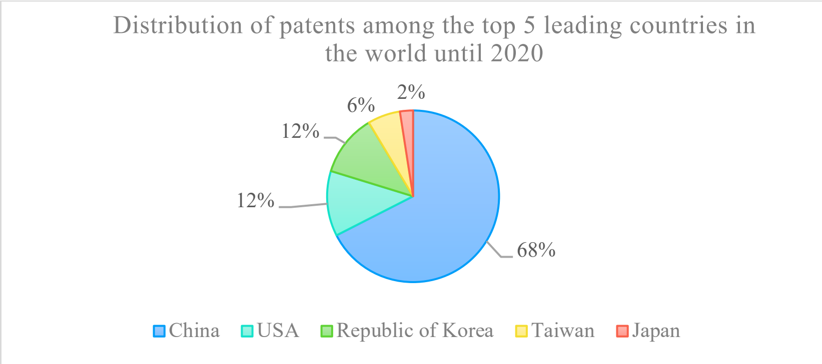
Analysts estimate that AI patents and, to a greater extent, those related to nanotechnology will increase 10-fold between 2000 and 2023 globally. However, patent registration has not been proportional. The current leading countries in patent registration for AI innovation and development are the United States, Japan, South Korea, Taiwan and China (Statnano, 2023).

Hence, according to the report issued by the World Intellectual Property Organization, for 2020, the leading countries for patents and patent applications were: 1) USA, 2) China, 3) Japan, 4) South Korea, 5) Germany, 6) United Kingdom and 7) France. The USA alone registered more than 135 000 patent applications followed by China with just over 125 000 (World Intellectual Property Organization, 2019). The trend in patents and the monopoly in their distribution can be corroborated by observing that, within the first 20 positions in the ranking of universities and public research organizations, 17 are from China, and the remainder from the Republic of Korea.

With this data analysis, it is possible to break down the concept of underdevelopment defined by André Gunder Frank by stating that underdevelopment is not the previous phase of development, but a direct consequence of the inequality of peripheral countries in the capitalist system. Gunder Frank's strongest argument is that the central countries extract wealth and knowledge from the periphery, or rather, from peripheral and semi-peripheral countries as seen from Wallerstein's theory. Therefore, by visualizing that countries such as the United States, Japan and China concentrate most patents globally, the accumulation of wealth and hegemonic monopoly control is established in this circle of power, which makes it difficult for countries in Latin America, Africa and some parts of Asia to lag behind in the advancement of patents and, consequently, in infrastructure and financing (Kay, 2022).

Moreover, the fact that dependence "conforms a certain type of social structures whose legality or dynamism is given by the condition of dependence" (Dos Santos, 2015, p. 29) leads to the strengthening of segregationist political and social organizations subordinated to the interests of imported capital and monopoly chains of central countries. This explains the particularity of dependence of a semi-peripheral or peripheral country in relation to a central one, since the central economy becomes more specialized and technical, asserting greater control, profitability and production with the use of resources such as AI and industry.

Figure 3.: Patent Distribution Scheme Among the Top 5 Leading Countries in the World 2020..



Note: Author's elaboration based on data from the World Intellectual Property Organization, 2019.

The concentration of patents within core countries reinforces global asymmetries and underscores the deepening technological divide inherent in the global capitalist system.

In addition, Benedikt (2019) presented a trend of professions and occupations at risk from the impending integration of AI into industrial, commercial, and administrative sectors the U.S. economy. Jobs with the highest rate of risk to displacement include fishing, agriculture, construction, transportation of materials, culinary, sales, and administrative and clerical responsibilities. In second place, with a lower degree are activities performed by law firms, health care services, financial operations, engineering and business. Finally, the education, science and technology, mathematics, computer science and technical health care sectors were ranked as the fields at the lowest risk of being displaced according to the same author.

First, he highlighted the degree of biases and subjectivities that involve human decisions, since modern work, digital security, the cloud, business applications, devices and hybrid learning are advances that facilitate productivity processes, but also represent inequality, discontinuity and labour displacement. Based on the evolution of world systems theory, Chase Dunn & Tomas Hall define that the growth of one capitalist sector represents the crisis and collapse of another. If we qualify their view of inequality, we can see how the polarization of the labour market is redefined by automation and the use of AIs, specifically in jobs categorized for the middle class.

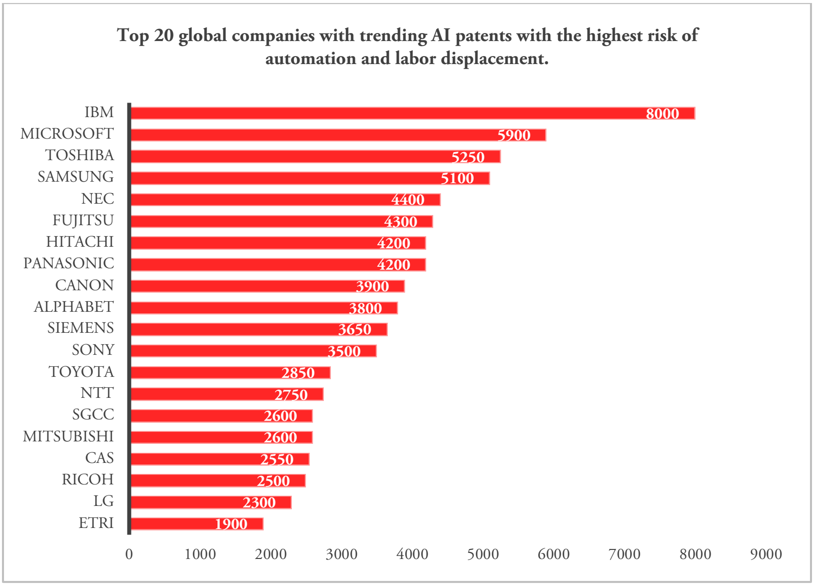
Table 2.: Percentage of industrial employment exposed to AI-driven automation in Europe 2023.

Category	Percentage
Administrative support staff	45%
Specialized professionals	34%
Technicians and professional assistants	31%
Managers	29%
Armed forces workers	22%
Agriculture, fishing and forestry	21%
Sales Services	15%
Elementary works	8%
Machine operators and assemblers	7%
Artisans	4%

Note: Author's elaboration based on Hatzius, Briggs, Kodnani and Pierdomenico, 2023.

Table 2 shows that the limited decrease in administrative, accounting and clerical personnel accelerates the growth of the underclass by displacing them in functions that can be replaced by IAs. Hence, statistics show that the productive underclass is increasing and with it, the quality of life by perceiving less guarantees; however, the increase in demand for jobs specialized in high technologies such as developers and programmers has been strengthening. These data reflect what Dunn & Hall (1997) called structural transition, in which a determining factor, in the conception of work, generates an expansion and a crisis, the expansion, in this case directed to the technologist elites, controlled by central countries, in contrast to the crises and collapses due to the declines of the working class.

Figure 4.: Concentration of the main international brands tending to automate and generate labour displacement.



Note: Author's elaboration based on data from the World Intellectual Property Organization (2019).

Once again, it is corroborated that most of the listed companies belong to central countries with patent and investment capacity for technological innovation, since they are entirely dedicated to the production and distribution of electronic equipment, telecommunications and software applications; they have also benefited from the institutions mentioned in Figure 2 and that only Japan has more than 12 companies on this list, unlike the United States, which only registered 2 companies. However, these two companies represent the two corporations with the most patent families: IBM (8,920 patents) and Microsoft (5,930 patents) (World Intellectual Property Organization, 2019).

Arrighi's (1994) well-founded hypothesis on cycles of accumulation, hegemony and inequality can be broken down under this heading. He speaks of a new cycle in the capitalist economic model that was fortified after a pandemic, this rise symbolizes the reconfiguration of a new order for capital accumulation and a new definition for hegemony and distribution of power. AIs have come to promote new tensions in the labour market, eventually permeating the unequal conditions of a society that increasingly lags in the absence of regulatory policies, training programs and the inclusion of the concept of equal opportunities for all social classes.

4. Conclusions

There is an overwhelming trend for the automation and improvement of industrial, economic and labour processes at the international level. Innovation and the development of AIs represent the beginning of a new era in the form of capitalist production that will eventually affect more than 50% of professions and labour occupations according to the international indicators reviewed in this article. In Latin America, some situations of labour displacement and precariousness have been detected due to the establishment of IAs; however, in Europe, conflicts arising from the violation of labour rights have been more constant.

Events such as labour displacement, migration of native people, productive processes dependent on automation and mechanization of AI are constant problems that have been observable at different times in history. From the first and second industrial revolution to the second decade of the 21st century, even more so after the devastation caused by the COVID-19 pandemic. There are international indicators that have already estimated possible scenarios due to the lack of regulatory policies on the utility given to AI in key sectors for social development such as the economy and production.

The scarce or almost non-existent government policy for the use and regulation of high-end technologies further complicates the situation, since efforts have so far been directed at improving production processes through the permanent establishment of AIs to replace labour responsibilities. One of the main difficulties lies in the distribution and authorization of patents for research in innovation and development of new technologies. The imbalance between the unbridled introduction of AIs, automation and intelligent mechanization over policies of regulation, protection and control of AIs has been a constant that has been growing over the last few years. During and after the COVID-19 pandemic, the nearshoring modality was strengthened, which ultimately came to empower platform capitalism.

The number of companies dedicated to research in innovation and development of AIs are few at the international level and are in developed countries of the first world. The strategic distribution of patents, especially in nanotechnology, has been given to companies and entities for geopolitical purposes and not for the development of the population. Consequently, the participation of the State in the legislative, governmental and political spheres will be transcendental in the maintenance of new forms of work and the permanence of citizens' rights.

Finally, issues such as labour displacement involve an in-depth study based on empirical and quantifiable evidence to assess the implications of potential problems and possible solutions in the short and medium term.

Potential risks such as a redefinition of work would be transcendental in the way of life as we know it now, because from an objective point of view, the digital era began a few decades ago, but with the updates achieved its consolidation in the capitalist productive world is imminent and the main disadvantage would be that, given the high demand and technological advances, automation would be consolidated in the processes of development and execution, which would contribute to the figures for labour displacement would be potentiated.

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Precision Agriculture in the Age of Artificial Intelligence and Nanotechnology: Global Trends and Latin America's Transition[1]

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Abstract

This paper examines the evolution of agricultural technologies by tracing their development across successive industrial revolutions. It then focuses on precision agriculture (PA), which relies on key technological pillars from Industry 4.0 (I4.0), with particular emphasis on Artificial Intelligence (AI) as the integrator of technical operations, and nanotechnologies as enablers of such integration. The paper highlights that precision agriculture seeks to improve crop production efficiency by increasing productivity and optimising resource use. This is achieved through the accurate assessment of plant needs, effective information processing, and the automation of diverse operational tasks. Among the central innovations in this domain are nanofertilisers and nanopesticides, underscoring the significant role that AI plays in driving these transformations. Moreover, the paper explores the global technological landscape, identifying the countries leading the development of these technologies and analysing how Latin America is transitioning towards PA. This shift's economic and technological implications for the region are also considered. In sum, the paper offers a critical perspective on the ongoing transformation in agriculture, underlining its significance and impact on both productive and social structures.

[1] Note: This text is part of the research project Ciencia de Frontera #304320 funded by the Consejo Nacional de Humanidades, Ciencia y Tecnología (CONAHCYT) of Mexico.

Keywords: Precision agriculture (PA), artificial intelligence (AI), nanotechnologies, Industry 4.0 (I4.0), crop management, Latin America.

1. Introduction

Agriculture is a human activity that, through the cultivation of land, enables the production of essential resources needed to sustain material life by generating food for the population—making it one of the indispensable activities for the survival of the species. From the agricultural revolution that began at least 12,000 years ago, when the first plants and animals were domesticated, to the present day—characterised by the use of information technologies, Artificial Intelligence (AI), robotics, biochemistry, genetics, and nanotechnologies—agriculture has evolved to ensure sufficient production to meet the needs of each historical moment.

The development of agricultural production techniques has always been linked to the broader transformation of humans and their tools. These tools, once rudimentary, have evolved into machinery and, more recently, into software systems, satellite-based signals, and automated networks. Throughout history, food production has intersected with broader technological progress in other sectors, thereby contributing to the evolution of agricultural systems. This includes the development of biochemical and physical models that have modified crops, as well as significant improvements in the machinery and equipment used in agricultural production.

Nevertheless, beyond the technical evolution of agriculture, it is essential to incorporate a social analysis. As productive capacities evolve, so too do the corresponding social relations (Marx, [1867] 2008). This perspective helps to explain why, today, sufficient food production often takes a back seat to the economic issue of access. In other words, it is not enough to produce adequate food if the most vulnerable populations lack the economic means to access it.

Within this context, it becomes necessary to examine the evolution of agricultural technologies in close relation to industrial and technological revolutions, with the aim of understanding Precision Agriculture (PA) as a system integrated with Industry 4.0 technologies. Simultaneously, a social perspective must be maintained—one that reveals the asymmetries in the adoption of this technological package in Latin America, particularly in relation to the dominance of certain countries in its production.

The analysis also seeks to underline the limitations faced by the region: insufficient infrastructure, lack of training among agricultural labourers, economic constraints on accessing this technology, and ongoing issues surrounding data ownership—all of which affect both developing and underdeveloped countries.

In the process of adopting PA, there is a risk of reproducing patterns of technological dependence on developed nations, along with unequal and highly polarised access to these tools in Latin American economies. This may lead to outcomes such as the concentration of agricultural land and the displacement of less skilled agricultural workers.

This research adopts a critical development theory perspective and employs a qualitative, exploratory, and analytical methodology. It draws on an extensive review of academic literature to examine the historical evolution of agricultural technologies within the framework of industrial revolutions and to contrast global and regional technological development. It also includes technical reports and case studies related to precision agriculture and the enabling role of nanotechnologies, thereby framing the social and economic implications of adopting these technologies in Latin America.

Some limitations were encountered, including the limited availability of up-to-date data on the adoption of PA across the region, as well as challenges in measuring workforce displacement or obtaining accurate data on technology imports specific to precision agriculture.

2. The Evolution of Agricultural Technologies and their Intensification Linked to the Industrial Revolutions

Under capitalism, the development of productive forces is associated with processes of technological innovation, considered fundamental pillars of economic growth and development. Consequently, economic sectors with lower levels of technological adoption are usually classified as laggards, facing significant productivity challenges. Technological innovation becomes a key element to generate new market opportunities, becoming a determining factor for profitability and competitiveness expectations. It should be noted that these technological revolutions were initially aimed at transforming the industrial sector and subsequently permeated other sectors of the economy.

Thus, technological development in the agricultural sector has been associated with the industrial revolutions, which gave rise to the era of industrial capitalism, with the appearance of the steam engine at the end of the 18th century. This revolution allowed the mass production of goods using steam-driven engines. In the agricultural sector, ploughs were modified, and the first chemical fertilisers were developed in the early 19th century (AGRO, 2020).

The second industrial revolution occurred approximately a century later and was characterised by the development of the internal combustion engine and the use of hydrocarbons and electricity as energy sources. In the agricultural sector, significant transformations occurred with the advent of motorisation. In the United States, innovations such as the cotton stripper, steel ploughs, and mechanical threshing machines emerged. These advances, coupled with significant developments in chemistry, led to the production of more advanced chemical fertilisers, insecticides, and fungicides (Ciro, 1994).

The third technological revolution marked the beginning of the digital era, characterised by the rise of the internet and information and communication technologies (ICTs). It occurred during a crucial moment in capitalism—the post-war period of the mid-twentieth century (Ampudia Mello, 2013). This revolution coincided with two significant agricultural transformations: the Green Revolution of the mid-twentieth century and the development of agricultural biotechnology in the latter quarter of that century.

The Green Revolution was marked by the development of agricultural techniques and high-yielding crop varieties, primarily targeting wheat and rice production in low- and middle-income countries (Karunarathne et al., 2020). Advancements in biology and chemistry led to the development of hybrid plants, such as wheat seeds modified to bypass natural germination inhibitors, thereby enabling the deseasonalisation of crop cycles (Molina, 2021). This period also saw the emergence of synthetic agrochemicals, including fertilisers and highly hazardous pesticides such as parathion and endrin, which contributed to increased productivity at substantial environmental and health costs (Karunarathne et al., 2020).

Although productivity and profitability in the agricultural sector increased, the sustainability of the Green Revolution was quickly questioned. Its adverse effects included the disruption of cultivated ecosystems and, in some cases, threats to human health (Molina, 2021). Organisms developed resistance to pesticides, prompting the creation of even more toxic alternatives. The Environmental Protection Agency (EPA) and the Agency for Toxic Substances and Disease Registry (ATSDR) have classified parathion as highly toxic. It has since been banned due to its negative impacts on both the environment and human health, including effects on the human nervous system such as blurred vision, gastrointestinal distress, respiratory difficulties, convulsions, and in severe cases, death. Long-term exposure among agricultural workers has led to its classification as a possible human carcinogen (ATSDR, 2021).

Agricultural biotechnology emerged with the promise of enabling more productive and sustainable farming practices. According to the International Food Information Council[2] (IFIC, 2000), this innovation aimed to increase food production with less land, offering tastier, fresher, and healthier products, safer animal feed, and enhanced environmental protection (Parks, 2005, p. 414). However, market realities reveal a different priority—corporate profitability. Examples include herbicide-resistant crops, such as Monsanto's *Roundup Ready soybeans,* and *Bacillus thuringiensis* (Bt) crops, genetically modified to produce their own insecticides (Altieri, 2009, p. 102).

The global market for transgenic crops expanded rapidly. In 1999, genetically modified crops were planted across 40 million hectares (Larach, 2001); by 2019, this figure had risen to 71.5 million hectares (ArgenBio, 2024), including maize, soybeans, cotton, alfalfa, sugar beet, potatoes, and papayas. In 1999, genetically modified crops were planted across 40 million hectares (Larach, 2001); by 2019, this figure had risen to 71.5 million hectares (ArgenBio, 2024), including maize, soybeans, cotton, alfalfa, sugar beet, potatoes, and papayas. China began

[2] International Food Information Council (IFIC) is a non-profit educational organization with a mission to effectively communicate science-based information about sustainable food systems, with a focus on food security and nutrition, based in Washington DC (IFIC, 2025).

producing genetically modified crops in 1992, but the United States soon took the lead, planting 20 million hectares by 1999 (Larach, 2001).

Genetically Modified Organisms (GMOs), whose DNA is altered through genetic engineering, pose potential risks to both human and environmental health. In the United States, three agencies—the Food and Drug Administration (FDA), EPA, and Department of Agriculture (USDA)—oversee GMO regulation. However, the primary regulatory framework—the FDA's Voluntary Plant Biotechnology Consultation Programme—is optional. Producers may choose whether to engage with the FDA to assess food safety before marketing new GMOs (FDA, 2022). This voluntary nature is influenced by economic interests: in 2023, the US exported 54.6 million tonnes of maize and approximately 49 million tonnes of genetically modified soybeans (FIRA, 2024; Statista, 2024).

Transgenic products remain central to global debate. Genetic engineering is largely dominated by multinational agrochemical and pharmaceutical corporations, highlighting its profitability for major capital interests. By the late twentieth century, major producers of genetically modified seeds included DuPont-Pioneer and Monsanto, which together controlled 20% of the global market, followed by Novartis (Switzerland) and Limagrain (France) (Larach, 2001). As of 2017, market consolidation had intensified, with Monsanto–Bayer controlling 24.5%, DuPont–Dow 19.5%, Syngenta–ChemChina 18%, and BASF 6% (Gonzalez, 2020, p. 23).

Earlier agricultural technological revolutions—prior to the era of Precision Agriculture (PA)—generated high expectations but often failed to deliver on their promises. This recurring pattern highlights a systemic prioritisation of profitability over the resolution of social and ecological issues. It is therefore legitimate to question whether PA will follow a similar trajectory, as long as science and technology remain subservient to capitalist interests.

The Fourth Industrial Revolution, commonly referred to as Industry 4.0 (I4.0), emphasises automation, robotics, nanotechnologies, and Artificial Intelligence (AI) (World Economic Forum, 2022). Nanotechnologies, which manipulate matter at the atomic and molecular scales, offer unique physical, chemical, and biological properties; however, their long-term toxicological effects remain uncertain (Royal Society, 2003). Nanotechnology constitutes a core foundation of Industry 4.0 (I4.0). As Foladori and Ortiz-Espinoza (2021, p. 68) explain, connectivity lies at the heart of I4.0 and depends on the opto-micro/nano-electronics industry, which in turn relies on devices requiring atomic and molecular manipulation—namely, nanotechnologies."

3. Precision Agriculture and I4.0

The International Society of Precision Agriculture defines Precision Agriculture (PA) as a management strategy that collects, processes, and analyses temporal, spatial, and individual data. This information is then combined with other inputs to support management decisions based on estimated variability, thereby improving resource-use efficiency, productivity, quality, profitability, and sustainability in agricultural production (ISPA, 2024). Such a strategy requires I4.0 technologies such as global positioning systems (GPS), geographic information systems (GIS), remote sensors, yield and application monitors, and intelligent machinery (Maohua, 2001).

Say et al. (2017, p. 41) classify these technologies based on their functions within the production process. They categorise these into three groups: (1) data collection technologies such as soil sampling, mapping, yield monitoring, GPS, remote sensing, and crop scouting—often conducted via drones equipped with nanosensors; (2) data processing tools including GIS, agricultural mapping software, economic analysis, geostatistics, and modelling; and (3) decision-making and application technologies, such as variable-rate input spraying using drones, GPS guidance systems, and agricultural robotics.

The core functionality of PA is underpinned by two cross-cutting technologies: nanotechnology and artificial intelligence (AI). Nanotechnology enables the development of smaller and more precise components, which are essential for nanosensors used in data collection. It also facilitates the creation of nanofertilisers, nanopesticides, nanoherbicides, and nanomaterials that enhance nutrient delivery in crops (Lira Saldivar et al., 2018).

Moreover, nanotechnology supports digital connectivity by underpinning the opto-micro/nano-electronics industry (Foladori & Ortiz-Espinoza, 2021). AI plays a central role by processing large volumes of cloud-based data to generate actionable knowledge, which in turn supports decision-making in agricultural production (Saiz-Rubio & Rovira-Más, 2020).

The key objectives of Precision Agriculture (PA) are to enhance productivity, improve product quality, and strengthen crop resilience. These goals are achieved by monitoring critical variables such as temperature, humidity, soil moisture, and pH levels, while also reducing the use of pesticides and fertilisers to increase production efficiency and quality (Sharma et al., 2023). The overarching aim is to increase profitability in agricultural markets by minimising financial risks and maximising returns.

Despite these benefits, PA also presents potential social and environmental risks. From a social perspective, the incorporation of nanotechnology raises concerns, as studies have warned about the toxic effects of nanomaterials (NMs) on both environmental systems and human health (Vázquez Núñez, 2022). Excessive use of nanofertilisers—whether accidental or deliberate in the pursuit of crop yield maximisation—can result in nitrogen pollution, which poses serious ecological threats (Angus, 2016).

The application of nanomaterials in soils can alter soil structure and disrupt the rhizosphere, the zone surrounding plant roots where microbial life thrives. These substances also influence physicochemical properties of the soil, such as pH and dissolved organic carbon content (Pérez-Hernández et al., 2024, p. 23), thereby reducing nutrient availability and enzymatic activity (Zhou et al., 2012). Numerous studies have demonstrated that high concentrations of nanomaterials can induce toxicity and cause physiological and genetic alterations in plants (Rico et al., 2015).

In this context—where technological innovation is often shaped by the interests of capital seeking to dominate the market and extract technological rent (Echeverría, 2005)—the potential risks associated with nanotechnology have sparked global regulatory debate, particularly within the European Union (EU) and the United States (USA).

4. Global Dynamics of Precision Agriculture and Adoption in Latin America

Precision agriculture (PA) has become a central topic in the global primary sector, and Latin America is no exception. However, its development in the region is shaped by distinctive characteristics associated with the agricultural sector in underdeveloped economies. Historically, Latin America has been integrated into the global economy primarily as a supplier of raw materials and agricultural goods, a role it continues to play. According to the Food and Agriculture Organization (FAO, 2021), the region accounts for approximately 14% of global agricultural exports. Yet, the degree of PA adoption varies across countries and regions, depending on technological infrastructure, investment capacity, and the educational level of farmers.

The United States leads the implementation of PA, followed by the European Union, Australia, and Canada. Within Latin America, Brazil and Argentina demonstrate the most substantial progress in adoption, while uptake in other countries remains nascent (Bongiovanni et al., 2006; Oksen & Tabrizi, 2023). In parallel, countries like China and India have begun producing PA-related technologies and expanding the use of such systems domestically.

Brazil stands out with an estimated 67% of its agricultural land incorporating PA technologies, such as GPS-guided automated machinery, drones, and soil sensors (Cherubin et al., 2022). These tools are most widely employed in the cultivation of soybeans, maize, cotton, beans, sugarcane, oats, and coffee (Borghi et al., 2016). Brazilian agritech firms, such as Agrosmart, now offer comprehensive PA solutions and maintain a presence in Latin America, the United States, and Israel (Cook & O'Neill, 2020, p. 5).

In Argentina, the adoption of PA has primarily centred on yield monitoring, especially in the Humid Pampa region. This technology is predominantly used in soybean and maize production (Bongiovanni & Lowenberg-DeBoer, 2006). Chile, on the other hand, has promoted PA to enhance fruit and wine production. Notably, by 2005, more than 40% of vineyard land—around 60,000 hectares—was already employing PA techniques to improve water efficiency (Best, 2006, p. 228).

Other countries, including Mexico, Colombia, Paraguay, Peru, and Uruguay, are progressing more slowly in PA adoption. In Colombia, PA is being introduced in coffee and sugarcane production, while in Mexico, it is expanding in horticulture, garlic, sugarcane, and avocado farming. Nonetheless, multiple barriers persist, including limited access to technology, high initial costs, and insufficient technical expertise—particularly in rural areas and smaller economies.

The productivity gains and cost reductions associated with PA are well-documented and difficult to dispute. For instance, in Argentina, PA has led to a 25% reduction in nitrogen fertiliser application, thereby decreasing nitrous oxide emissions significantly (INTA, 2022). In Chile, the implementation of precision irrigation has reduced water usage in vineyards by approximately 18% (Asquez, 2025). Despite these benefits, the widespread adoption of PA in Latin America remains constrained by structural barriers and carries social implications that merit further exploration.

In Latin America, the adoption of precision agriculture (PA) technologies has been hindered by the region's territorial diversity and the complexity of land tenure systems. Most agricultural operations are small to medium-sized and run by low-income producers, making substantial investment in technological upgrades particularly challenging.

The agricultural structure across Latin American countries shares certain traits that further complicate PA implementation. In Paraguay, over 85% of producers are smallholders with landholdings under 20 hectares, yet they represent less than 10% of arable land. In contrast, just 1% of producers—those with holdings over 1,000 hectares—control 70% of the country's arable land (CAN, 2022). Despite agriculture contributing 20% to GDP and 80% to exports, the sector grapples with foreign competition and food dependence, although subsectors like fruits and vegetables are seeing export growth.

In Mexico, agriculture accounts for 4% of GDP and employs 24% of the economically active population, but most producers operate on plots averaging only 5.9 hectares (INEGI, 2023). Moreover, just 5.8% of agricultural units have access to credit, and while educational levels are improving, there is still a significant deficit in technical training required for PA adoption.

Brazil exhibits similar inequality. According to its 2017 agricultural census, properties under 50 hectares make up 81.4% of rural economic units but occupy just 12.8% of rural land, while holdings over 2,500 hectares—only 0.3% of total units—account for 32.8% of land (Cherubin et al., 2022). These patterns reflect broader regional trends, underscoring one of the main structural challenges to adopting advanced agricultural technologies.

Rural infrastructure limitations also impede PA uptake. In many areas, connectivity remains poor, despite being critical for PA technologies. Another barrier is the lack of contextual knowledge regarding which technologies are most suitable for specific crops or regions (Oksen & Tabrizi, 2023). Without intervention, such challenges may exacerbate inequality or even lead to the exclusion of producers unable to integrate these technologies (ECLAC et al., 2020, p. 92).

According to indicators compiled by ECLAC on digital technology access and usage in rural Latin America and the Caribbean, the situation is dire. Electricity access ranges from 65% to 98% depending on the country, while only 37% of the rural population has internet access and a mere 17% can access 4G networks (ECLAC et al., 2020, p. 95). These statistics point to an urgent need for public investment and planning to improve infrastructure and ensure equitable PA adoption.

Rural poverty remains a key obstacle, with 45.7% of rural populations living below the poverty line. In terms of education, urban residents aged 15 and older average 10.5 years of schooling, compared to just 6.9 years in rural areas (ECLAC et al., 2020, pp. 40–41). This educational gap limits the qualification of the rural workforce for PA technologies, placing them at a disadvantage.

Addressing these disparities requires robust policies to support investment in both public and private goods. This includes expanding rural services, improving internet and telecommunications infrastructure, and strengthening educational strategies that equip rural populations with essential technical knowledge (ECLAC et al., 2020, p. 43). Otherwise, rural labourers risk exclusion in the face of increased mechanisation.

Throughout the 20th and 21st centuries, governments have launched public policies and programmes to promote technological integration in agriculture. For example, Argentina's National Institute of Agricultural Technology (INTA) launched the Manfredi Precision Agriculture Programme to train farmers and adapt foreign technologies through university and private sector partnerships. Despite these efforts, limited investment in infrastructure and research continues to hinder their effectiveness (Bongiovanni & Lowenberg-DeBoer, 2006, pp. 212–213).

In Chile, the National Institute of Agricultural Engineering (INIA) has spearheaded PA development, focusing on fruit and wine sectors. Paraguay has similarly promoted PA through institutions such as the Cooperative Programme for Technological Development (PROCISUR) and the Regional Centre for Agricultural Research (CRIA) (Best, 2006, p. 228).

Mexico has adopted PA within broader rural modernisation programmes via the Ministry of Agriculture and Rural Development (SADER). Efforts include pilot projects using drones, remote sensors, and GIS in maize, wheat, and fruit production, alongside credit schemes for equipment modernisation (SADER, 2025).

Despite these initiatives, public policies have not ensured equitable access to PA technologies. Long-term planning is essential to capitalise on Latin America's agricultural potential while addressing structural inequalities.

The primary risks associated with PA adoption in the region include rising inequality, power imbalances among stakeholders, exclusion of low-skilled workers—particularly women—and data misuse. Land concentration is also a concern, as advanced technologies may lead to the absorption of small and medium holdings by large, capital-intensive enterprises (ECLAC et al., 2020; Say et al., 2017). A considerable gap remains between advanced digital machinery and rudimentary tools (Santos Valle & Kienzle, 2020).

Additional risks include the environmental externalities associated with Industry 4.0 technologies (Foladori, 2022) and the unknown long-term effects of certain nanomaterials on ecosystems and human health.

Lastly, automation in agriculture could displace unskilled workers, exacerbating inequality and poverty in developing countries. Those most at risk include women, youth, indigenous people, and migrants—groups already vulnerable to job loss due to technological change (ECLAC et al., 2020, p. 25).

5. Concentration of Capital and Mastery of Technological Production

The replacement of conventional agriculture with farming practices aligned with capitalist modernity opened significant pathways for the expansion of large economic corporations. It has become evident that these corporations have benefited the most from the provision of modern machinery and agricultural inputs (Wolford, 2021).

The PA perspective differs between developed and peripheral countries, primarily due to underlying structural inequalities. PA technologies are largely developed by transnational capital, with notable contributions from countries such as China, the United States, Israel, and several European nations, including Germany, France, and Switzerland (Emergen Research, 2024; Sargiotto, 2024; Wackwitz et al., 2024). Furthermore, the development of nanotechnology in agriculture is heavily influenced by major multinational corporations that dominate research, development, and commercialisation. Companies such as Bayer-Monsanto, ChemChina-Syngenta, and DuPont-Dow have consolidated control over the production of pesticides and nanotechnology-based products, including nanoplagicides and nanofertilisers.

The global market for agricultural drones is primarily led by the United States and China, followed by several European countries, India, and Brazil, as shown in Table 1. China holds a dominant position in the global drone market through companies such as DJI and XAG, both of which have established a significant presence in Latin America. DJI, in particular, has a strong foothold in the Mexican market. Meanwhile, the United States generates considerable revenue from the export of precision technologies and related services. It is also worth noting that some Chinese technology firms collaborate with U.S.-based capital enterprises to enhance their market reach.

Table 1.: Countries producing Drones for precision agriculture

Country	Main companies	Remarks
United States	AgEagle, Agribotix, Altavian, Anzu Robotics, Autel Robotics, AV (AeroVironment), Blue Skies, DroneDeploy, EAvision, PrecisionHawk, Rotor Technologies, Sentera, Trimble	The U.S. leads in revenues thanks to innovation and exports.
China	DJI, EHang, HEISHA, Jifei, JOUAV, MMC, SZ DJI, TT Aviation, XAG	China dominates global manufacturing of agricultural drones.
France	Delair, Parrot	Significant revenues from high-precision technology.
Germany	Microdrones, Volocopter	Recognized for its alliances with major brands.
Japan	Terra Drone, Yamaha	Specialization in unique hybrid and agricultural drones.
Israel	Heven, Tevel	Advances in autonomous technologies.
Spain	Hemav	Local companies with an impact in Europe.
India	IdeaForge	Recent growth in emerging markets.
Brazil	XMobots	Innovation in agricultural mapping and surveying.
Slovenia	C-Astral	Specialized drone manufacturing.
Switzerland	SenseFly	Drones for mapping and agriculture.

Note: own elaboration with data from (Axayacatl, 2023a; Sargiotto, 2024).

Since 2014, the International Finance Corporation (IFC) has invested over 60 million USD in agricultural technology companies, alongside more than ten indirect investments through accelerators, seed funds, and venture capital initiatives (Cook & O'Neill, 2020, p. 7). These investments clearly reflect a strategy driven by profitability, with the primary objective being the maximisation of economic returns. Regarding the development and control of other essential forms of machinery, it is in the field of intelligent agricultural equipment that North American companies particularly excel.

Table 2.: Companies producing intelligent machinery for precision agriculture.

Company	Key Innovation
Deere & Company (John Deere) (U.S.)	GPS-guided tractors and harvesters,
Trimble, Inc. (U.S.)	Hardware, software and data analysis for precision agriculture.
Antelliq (French)	RFID technology for animal monitoring.
Topcon Positioning Systems (Japanese)	Integration of AI, IoT and GPS for precision agriculture.
Nexus Corporation (United States)	Smart sensors and IoT devices with AI and ML.
Heliospectra (Sweden)	Intelligent LED lighting for indoor growing.

Note: own elaboration with data from (Axayacatl, 2023b; Emergen Research, 2024).

Companies that develop precision agriculture (PA) technologies operate across multiple domains, including connectivity, software, and satellite systems. It is therefore necessary to analyse which actors dominate each segment of the market. The tables referenced above illustrate the dominant sources of capital and the countries from which these technologies originate, with the United States and China emerging as clear leaders.

The rapid rise in venture capital investment in agricultural technology companies in recent years signals a growing global interest in this sector. A substantial proportion of these investments originate from U.S.-based firms, and a significant share targets companies that integrate artificial intelligence (AI) into agricultural applications. Notably, agri-tech companies employing AI attracted 6.7 billion USD in venture capital, of which 1.9 billion USD was received in 2018 alone (Cook & O'Neill, 2020, p. 2). While such investments undoubtedly foster innovation and technological progress, they are also fundamentally driven by the pursuit of profit. The primary motivation behind these financial flows is not to alleviate global issues such as hunger or food insecurity, but rather to capitalise on the profit potential of precision agriculture.

For Latin American countries, the technological dependency on external actors—particularly those producing these technologies—risks being further entrenched and intensified unless the region develops its own technological alternatives. This dynamic reflects a broader trend of capital concentration and accumulation within the global economic system.

Although the adoption of these technologies in Latin American agriculture remains at an early stage, their expansion over time appears inevitable. Therefore, it is crucial to continue monitoring and analysing this evolving phenomenon.

6. Conclusions

Reflecting on the adoption of *Precision Agriculture (PA)* in Latin America reveals a core reality: within the capitalist system, profitability remains the overriding priority in all production sectors. Other considerations—including environmental and social risks—are often relegated to secondary status, or rendered invisible when potential profit margins dominate the agenda.

Previous technological revolutions within agriculture demonstrate that economic gains have consistently taken precedence over known and documented risks. These risks have not disappeared; rather, they continue under the current wave of agricultural innovation, bringing renewed concerns such as social exclusion, rural displacement, land concentration, and the ongoing dominance of capital interests. These dynamics perpetuate technological dependency and also raise serious health and environmental issues, particularly regarding the deployment of nanomaterials in PA.

Among Latin American countries, Brazil leads in both the adoption and policy development related to PA, followed closely by Argentina. Brazilian institutions, especially the Brazilian Agricultural Research Corporation (*Embrapa*), have played a pivotal role in advancing PA technologies—particularly in soybean, maize, and sugarcane production. The private sector has also made substantial investments in this domain.

Argentina has similarly achieved a high level of PA integration, particularly in soybean and maize cultivation. The National Institute of Agricultural Technology (*INTA*) has promoted research and developed extensive training programmes for farmers. Other countries—including Chile, Uruguay, Paraguay, Peru, Mexico, and Colombia—have also integrated *Industry 4.0 (I4.0)* technologies into their agricultural systems, though progress varies significantly across the region.

Despite these advancements, the implementation of PA remains prohibitively expensive for those without access to capital. It demands not only financial resources, but also supporting infrastructure, technical expertise, and reliable connectivity. As it stands, PA in Latin America largely reflects a model of capitalist precision agriculture that remains inaccessible to the majority of the region's small- and medium-scale producers.

The adoption of this technological model faces multiple challenges. In this context, the state must play a proactive and strategic role—supported by universities and research institutions capable of generating region-specific knowledge and innovation. These efforts are essential to mitigate the social and environmental consequences of technological expansion.

To foster inclusive access, Latin American governments should adopt policy frameworks that prioritise social inclusion, environmental sustainability, and technological sovereignty. Public investment is needed to improve rural infrastructure, enhance credit opportunities for smallholder farmers, and build effective public–private partnerships to broaden the accessibility of precision agriculture across the region.

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PART IV

SOCIETAL TRANSFORMATIONS: HEALTH, ENVIRONMENT, AND TECHNOLOGY

"The machine does not isolate man from the great problems of nature but plunges him more deeply into them."
— Antoine de Saint-Exupéry, Wind, Sand and Stars (1939), Chapter III, p. 67.

The technological revolution reaches far beyond economies—it touches the very core of life: our health, our environment, our survival. Yet what if technology, far from liberating us, binds us tighter to the crises we seek to escape? Each new promise of progress entangles us more deeply in nature's enduring dilemmas, exposing the fragile balance between innovation and integrity.

This part explores the paradoxical role of AI and technological solutions in critical sectors. From the transformative but ethically fraught applications of AI in healthcare, to the measured success of green taxation in environmental governance, to the extractivist risks embedded in AI's use in Mexico's mining sector, these chapters chart the difficult terrain where technology can both heal and harm.

In the shadow of innovation, a more vital question endures: not whether we will advance—but what, and whom, we will choose to protect.

9

Artificial Intelligence in Healthcare: Transformative Applications, Ethical Challenges, and Future Pathways

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Abstract

Artificial intelligence (AI) has emerged as a transformative force within the healthcare sector, enhancing diagnostic precision, enabling personalised care pathways, and optimising operational efficiency. Leveraging technologies such as machine learning (ML), natural language processing (NLP), computer vision, and robotics, AI enables early disease detection, advances precision medicine, enhances operational workflows, and supports real-time clinical decision-making. These advancements address critical challenges, including escalating healthcare costs and systemic resource inefficiencies, while enhancing patient outcomes and satisfaction. The integration of AI into healthcare services fosters advancements in diagnostic imaging, virtual health assistants, and predictive analytics, significantly strengthening patient engagement and clinical decision-making workflows. This chapter systematically explores AI's transformative role in healthcare, critically evaluating its applications while addressing associated ethical, operational, and technical challenges. It provides a comprehensive foundation for researchers, policymakers, and practitioners aiming to foster a more efficient, patient-centred, and sustainable healthcare ecosystem. This chapter uniquely synthesises technological applications with stakeholder-centric perspectives, providing a roadmap for the ethical and sustainable integration of AI into healthcare ecosystems.

Keywords: artificial intelligence, AI-driven tools, healthcare, healthcare chatbots, healthcare integration

JEL Codes: I11, 138, O14

1. Introduction

Artificial intelligence (AI) is increasingly recognised as a transformative technology capable of reshaping healthcare systems worldwide. It offers innovative solutions to improve the quality of healthcare services, streamline operational processes, and advance medical research. AI empowers healthcare professionals to make more informed decisions, enhancing diagnostic precision and facilitating the development of tailored, personalised treatment plans. When fully integrated, AI can optimise operational efficiency, improve patient outcomes, and enable more effective, patient-centric healthcare delivery, thereby enhancing the sustainability and resilience of healthcare systems.

Although the convergence of AI and healthcare is not a recent phenomenon—with early systems like Dendral demonstrating its potential—today healthcare stands as one of the most dynamic and rapidly evolving sectors for AI applications (Adadi & Berrada, 2020). According to Verified Market Research (2024), the global market value of AI-powered healthcare solutions is projected to surge from $19.37 billion in 2024 to approximately $306.8 billion by 2031, reflecting the increasing dependence on AI across hospitals, laboratories, and research centres. Investment trends underscore AI's strategic importance, with major technology firms such as Google, Microsoft, and IBM making significant investments in AI-driven healthcare innovations.

Innovations such as robotic-assisted surgery, virtual nursing assistants, and AI-based fraud prevention solutions demonstrate substantial potential for creating economic and clinical value within the healthcare sector. For instance, robotic-assisted surgeries alone contribute an estimated $40 billion annually by enhancing surgical precision and expanding procedural capabilities. The COVID-19 pandemic further accelerated the adoption of digital health solutions, reinforcing AI's indispensable role in modern healthcare.

Against this backdrop, this chapter aims to critically evaluate the transformative impact of AI on the healthcare sector, bridge existing knowledge gaps, and propose a strategic roadmap for sustainable integration. By systematically analysing applications across diagnostics, drug discovery, patient interaction, and clinical decision-making, the chapter highlights how emerging AI technologies can foster a more resilient, equitable, and innovative healthcare ecosystem.

Furthermore, this study adopts a stakeholder-centred perspective, acknowledging that AI's transformative influence extends beyond clinicians and researchers to encompass patients, administrators, and broader public health ecosystems. Throughout, particular emphasis is placed on ethical, legal, and operational challenges, providing a comprehensive framework for the responsible and sustainable deployment of AI in healthcare.

Table 1.: Potential Annual Value of AI Applications in Healthcare and Their Contributions

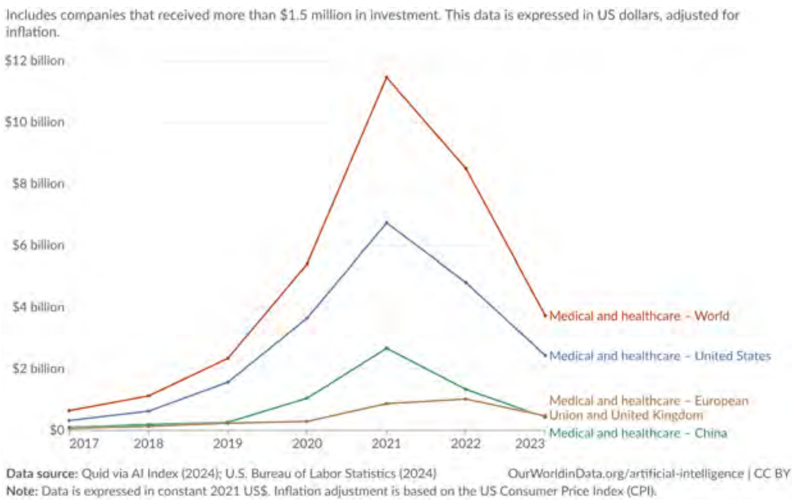
Application	Estimated Annual Value	Key Benefits
Robotic-Assisted Surgery	$40B	Expands the range of surgeries performed.
Virtual Nursing Assistants	$20B	Mitigates shortages in medical staff.
Administrative Workflows	$18B	Enhances integration with existing systems.
Fraud Prevention	$17B	Identifies and prevents sophisticated fraud.
Medication Dosage Accuracy	$16B	Reduces the risk of dosage-related errors.
Connected Medical Devices	$14B	Facilitates the growth of interconnected tools.
Clinical Trial Enrolment	$13B	Leverages extensive datasets for research.
Initial Diagnosis Support	$5B	Improves the precision of preliminary diagnoses.
Imaging Analysis	$3B	Optimizes data storage and retrieval.
Cybersecurity Solutions	$2B	Protects sensitive health information.

Note: Bekbolatova et al. (2024)

Table 1 summarises the estimated annual economic contributions of key AI applications in healthcare, highlighting their potential to enhance clinical efficiency and reduce systemic costs. Robotic-assisted surgery alone accounts for an estimated $40 billion annually, driven by its capacity to expand surgical options and enhance procedural precision. Virtual nursing assistants contribute approximately $20 billion per year by alleviating healthcare workforce shortages and improving patient support services. Streamlining administrative workflows generates around $18 billion annually, primarily through enhanced integration with existing healthcare information systems. AI-driven fraud detection technologies contribute approximately $17 billion annually by identifying and preventing sophisticated fraudulent activities in healthcare billing and claims.

Systems designed to minimise medication dosage errors are estimated to yield $16 billion annually, while connected medical devices—enabling seamless data exchange across platforms—generate an additional $14 billion in value. Leveraging large-scale datasets to optimise clinical trial enrolment contributes $13 billion per year, while AI-driven initial diagnostic support adds $5 billion, advanced imaging analysis $3 billion, and cybersecurity measures $2 billion to annual healthcare value. Collectively, these applications demonstrate AI's ability to simultaneously drive economic efficiency, reduce operational waste, and improve patient outcomes across the healthcare continuum. Moreover, this chapter introduces a structured model—the AI-Driven Healthcare Transformation Framework (AI-HTF)—to conceptualize the evolutionary phases of AI integration in healthcare, providing strategic insights for sustainable and ethical deployment.

Figure 1.: Annual Private Investment in AI, by Focus Area, Medical and Healthcare



Note: Our Word in Data (2025).

Figure 1 depicts the evolution of private investments in AI across the healthcare and medical sectors globally—including key regions such as the United States, the European Union, the United Kingdom, and China—between 2017 and

2023. The investment dynamics showcased in Figure 1 underscore AI's emergence as a strategic priority at both regional and global levels, reinforcing its pivotal role in driving healthcare innovation. The notable investment peak in 2021 is largely attributable to the accelerated demand for digital health innovations spurred by the COVID-19 pandemic. As illustrated in Figure 1, private investment in AI exhibits a sustained upward trajectory, reflecting both heightened technological enthusiasm and the demonstrable impact of AI innovations on healthcare delivery. The breadth of AI applications outlined in Table 1—including innovations in diagnostics, treatment planning, and operational optimisation—further substantiates the investment patterns depicted in Figure 1. Together, the trends captured in Figure 1 and the applications detailed in Table 1 illustrate an emerging paradigm wherein AI is no longer a supplementary tool, but a fundamental driver of systemic transformation in healthcare.

2. AI Applications Revolutionizing Healthcare

Artificial intelligence (AI) is driving a profound paradigm shift across the healthcare sector, transforming diagnostic procedures, therapeutic strategies, patient engagement models, and clinical decision-making processes. By deploying advanced algorithms and machine learning models, AI facilitates the analysis of vast volumes of medical data, delivering rapid, accurate, and personalised solutions. These capabilities are elevating the scope and quality of healthcare services, contributing to a more efficient, proactive, and patient-centred healthcare model.

This section systematically evaluates AI's transformative impacts, focusing on its applications in diagnostic imaging, drug discovery, virtual health assistants, and clinical decision support systems, while also exploring emerging trends and future pathways.

2.1. AI-Driven Innovations in Diagnostic Imaging

AI has revolutionised diagnostic imaging, significantly enhancing the speed and precision of medical diagnoses. AI-powered diagnostic tools facilitate the rapid analysis of imaging data, promoting early disease detection and improving prognostic outcomes (Chaturvedi et al., 2025). In oncology and cardiovascular medicine, machine learning algorithms accurately detect pathological patterns, enabling earlier interventions and improving survival rates (Ardila et al., 2019).

Moreover, AI systems expand diagnostic capabilities in resource-limited settings, enhancing healthcare access globally (Becker et al., 2017). AI's integration into medical imaging not only expedites diagnosis but also strengthens clinical decision-making by assisting healthcare professionals in interpreting complex datasets (Sandeep Ganesh et al., 2022).

The transformative role of AI is particularly evident in cancer diagnostics. Machine learning models trained on extensive imaging datasets identify lesions and abnormalities with remarkable accuracy, facilitating earlier treatment initiation (Kahn et al., 2024). AI's proactive healthcare capabilities extend further: AI systems can detect diseases at asymptomatic stages, enabling preventive interventions that improve clinical outcomes and healthcare system sustainability (Adadi & Berrada, 2020).

Beyond detection, AI optimises personalised treatment planning by integrating genetic, environmental, and behavioural factors into therapeutic decisions (Abbasi et al., 2023). High-resolution dataset analysis empowers AI models to enhance diagnostic precision across radiology, pathology, and ophthalmology specialties (Rana & Shuford, 2024).

While efforts to integrate AI into clinical workflows began decades ago, contemporary advancements have significantly elevated its reliability and impact (Bekbolatova et al., 2024). Today, AI-supported imaging technologies reduce diagnostic errors, decrease hospital readmissions, and support early interventions for chronic conditions, reinforcing AI’s critical role in modern healthcare.

2.2. Transforming Drug Discovery and Development Through AI

Drug discovery and development are traditionally prolonged, costly, and fraught with high attrition rates. AI offers transformative solutions by accelerating research timelines, improving predictive accuracy, and optimising clinical trial design.

Machine learning algorithms streamline early-stage discovery by predicting toxicity profiles, identifying promising compounds, and prioritising targets for development (Adadi & Berrada, 2020). Pharmaceutical companies increasingly integrate AI into target identification, biomarker discovery, molecular modelling, and clinical trial management (Sandeep Ganesh et al., 2022).

Abbasi et al. (2023) highlight that AI reduces the risk of failure by refining compound selection and optimising trial enrolment processes. AI-driven computational biology platforms analyse clinical data, scientific publications, and molecular databases to discover novel therapeutic pathways (Olawade et al., 2024).

AI's contributions extend to drug repurposing: during the COVID-19 pandemic, AI platforms rapidly identified potential antiviral agents, accelerating therapeutic development. By constructing a network-based model, Zhou et al. (2020) identified potential therapeutic candidates for COVID-19, demonstrating how AI and computational biology can rapidly support drug repurposing initiatives." Adaptive clinical trial designs enabled by AI facilitate real-time patient monitoring and improve study flexibility (Esteva et al., 2021).

Despite these significant advancements, critical ethical concerns—such as data transparency, algorithmic bias, and equitable data utilisation—must be rigorously addressed to ensure responsible, fair, and socially beneficial drug development. Overall, AI is fundamentally reshaping pharmaceutical research and development (R&D), opening new frontiers for faster, safer, and more effective therapeutic innovation, while demanding robust ethical oversight.

2.3. Revolutionizing Patient Interaction: Virtual Health Assistants and Chatbots

AI has fundamentally transformed patient engagement through the deployment of virtual health assistants (VHAs) and chatbots. These tools enhance healthcare accessibility, streamline administrative processes, and foster patient-centred care.

Virtual health assistants, powered by natural language processing and machine learning, provide real-time support, automate routine interactions, and deliver personalised guidance (Alowais et al., 2023). Chatbots have become widespread across healthcare facilities, assisting with appointment scheduling, medical queries, and triage support (Inbenta, 2025; Smart Medical History, 2025). AI-driven chatbots offer several key benefits:

- 24/7 accessibility
- Reduced patient waiting times
- Rapid information delivery
- Enhanced support for vulnerable populations
- Cost reductions through operational efficiency
- Improved patient satisfaction via personalised interactions

As Smart Medical History (2025) notes, chatbots outperform traditional methods in terms of speed, accuracy, and patient engagement. Nevertheless, concerns persist regarding potential misdiagnoses, data security vulnerabilities, and the need to preserve the human elements of care (Coherent Solutions, 2024).

Despite these challenges, the chatbot market in healthcare is poised for rapid expansion, reflecting an increasing demand for scalable digital health solutions. VHAs and chatbots thus represent an essential component of future patient engagement strategies.

2.4. Empowering Clinical Decision-Making with AI Support Systems

AI-powered clinical decision support systems (CDSS) are reshaping clinical practice by enhancing diagnostic accuracy, improving operational workflows, and personalising treatment strategies.

AI systems analyse complex clinical datasets—including patient histories, lab results, and genomic information—to support healthcare professionals in delivering accurate and timely care (Yu et al., 2018). These systems enhance healthcare access, particularly in underserved regions, by providing critical decision support where expertise is limited.

Shaheen (2021) categorises AI contributions into clinical, operational, and consumer decision-making, each contributing to improved healthcare responsiveness and efficiency. In emergency medicine, AI-driven tools enable early detection of critical conditions, improving intervention outcomes (Alowais et al., 2023). Table 2 compares traditional methods with AI-driven chatbots, highlighting clear operational and experiential advantages.

Table 2.: Comparison of Traditional Methods and AI-Driven Chatbots in Healthcare

Aspect	Traditional Methods	AI-Driven Chatbots
Data Collection Time	Lengthy process	Rapid and efficient
Accuracy	Susceptible to mistakes	Highly accurate
Patient Satisfaction	Relatively lower	Significantly higher
Human Error Rate	Considerably high	Minimal
Availability	Restricted to operational hours	Accessible 24/7
Integration with Health Systems	Challenging and time-intensive	Smooth integration with Electronic Health Records

Note: Smart Medical History, 2025.

Real-time clinical insights generated by AI, such as remote patient monitoring and predictive modelling, reduce hospital admissions and optimise chronic disease management (Rana & Shuford, 2024; Bekbolatova et al., 2024).

Moreover, the application of AI in emergency medicine has proven critical, with real-time decision support tools facilitating the early detection of life-threatening conditions and enabling prompt and effective interventions (Alowais et al., 2023). AI-driven systems also significantly contribute to resource management by predicting patient demand, optimising staff deployment, and managing emergency department wait times.

In the domain of remote patient monitoring, AI-enabled technologies track vital signs, detect anomalies early, and trigger timely interventions, thereby reducing hospital admissions and improving the management of chronic diseases (Rana & Shuford, 2024). Predictive modelling further enhances the ability to anticipate patient needs and allocate resources effectively. Bekbolatova et al. (2024)

highlight that AI algorithms can detect subtle patterns in complex datasets, while Ramirez (2024) underlines the role of AI in streamlining clinical workflows and supporting evidence-based decision-making.

However, successful CDSS implementation hinges on ensuring data quality, system interoperability, and clinician trust. Transparent, explainable AI models are crucial for fostering confidence among healthcare providers (Amann et al., 2020).

In conclusion, AI-powered decision support systems are critical enablers of precision medicine, operational efficiency, and equitable healthcare delivery. Their applications in real-time emergency decision-making, remote patient monitoring, and predictive modelling further reinforce their pivotal role in enhancing healthcare responsiveness and proactive patient care. Sustainable integration demands continuous investment in technological innovation, clinician education, and ethical governance frameworks.

3. Technological Pillars of AI in Healthcare

The integration of artificial intelligence (AI) into healthcare is revolutionizing service delivery, patient outcomes, and operational efficiency. This transformation is built upon four core technological pillars: machine learning (ML), natural language processing (NLP), computer vision, and robotics. These foundational technologies empower healthcare systems to analyze vast datasets, enhance diagnostic precision, streamline workflows, and support personalized medicine initiatives. Each of these pillars contributes uniquely to reshaping modern healthcare landscapes, fostering a new era of data-driven, patient-centered care.

3.1. Harnessing the Power of Machine Learning and Predictive Analytics in Healthcare

Machine learning, a subfield of AI, enables systems to improve task performance through data and experience without explicit programming (Chaturvedi et al., 2025). It underpins predictive analytics, allowing healthcare providers to anticipate risks, personalize treatments, and optimize resource allocation.

Ramirez (2024) highlights those predictive analytics, driven by ML, facilitates early diagnosis, proactive intervention, and enhanced patient care. By mining historical and real-time data, these models identify risk patterns, forecast clinical events, and guide timely responses.

Chaturvedi et al. (2025) and Maddox et al. (2019) emphasize ML's critical role in predicting hospital readmissions and managing chronic diseases. Olawade et al. (2024) demonstrate how predictive models applied to large datasets, such as electronic health records (EHRs)- can effectively stratify patient risks and personalize care strategies.

Furthermore, ML enables treatment stratification by identifying patients most likely to benefit from specific therapies (McNemar, 2021). In oncology, ML models enhance early cancer detection, risk assessment, and targeted therapy development (Bekbolatova et al., 2024). In summary, machine learning and predictive analytics are essential enablers of precision healthcare, promoting early intervention, personalization, and operational efficiency across the healthcare continuum.

3.2. Revolutionizing Communication with Natural Language Processing (NLP)

Natural language processing (NLP) enables computers to interpret, analyze, and generate human language, bridging the gap between structured computational logic and the nuances of human communication (Alowais et al., 2023). Khan et al. (2024) emphasise that NLP is crucial for analyzing unstructured clinical data such as physicians' notes, patient narratives, and research articles. By extracting key insights from these sources, NLP enhances decision-making and streamlines clinical workflows.

NLP systems automatically summarize clinical documentation, identify high-risk patients, and support administrative tasks (Ramirez, 2024). These capabilities reduce clinician workload and enhance the accuracy and accessibility of healthcare information (Davenport & Kalakota, 2019). NLP also strengthens patient-centered care. By analyzing patient narratives, NLP algorithms uncover hidden health indicators and enable more personalized treatment plans (Bekbolatova et al., 2024).

Moreover, integrating NLP into electronic health records (EHRs) facilitates real-time data capture and retrieval, improving clinical documentation and supporting rapid responses to patient needs. However, addressing linguistic variability, semantic ambiguity, and cultural context remains critical for ensuring the reliability and inclusivity of NLP systems. In conclusion, NLP is a transformative force in healthcare, enhancing communication, decision support, and administrative efficiency while advancing personalized and preventive care models.

3.3. Advancing Diagnostics: Computer Vision and Medical Imaging

Medical imaging is a cornerstone of modern diagnostics, and the integration of computer vision, an AI branch focused on image interpretation, has profoundly enhanced diagnostic capabilities. Yu et al. (2018) identify automated image diagnosis as one of AI's most successful applications in healthcare. Computer vision systems, trained on vast medical datasets, detect subtle pathological changes, enabling earlier and more accurate diagnoses across radiology, ophthalmology, dermatology, and pathology.

Olawade et al. (2024) emphasize that AI-powered imaging systems enhance diagnostic precision, support personalized treatment planning, and reduce diagnostic errors. In orthopedics, AI aids radiographic analysis, surgical planning, and risk assessment, leading to improved surgical outcomes (Bekbolatova et al., 2024). In oncology, computer vision models enhance tumor detection and prioritize critical cases for radiological review. These systems also standardize imaging assessments, minimize inter-observer variability, and alleviate clinician workload, contributing to more consistent, high-quality care delivery.

However, the successful implementation of AI in medical imaging necessitates transparent, bias-free models and rigorous clinical validation to ensure clinician trust and patient safety. In summary, computer vision technologies are reshaping diagnostic practices by improving accuracy, reducing errors, and facilitating earlier, more effective interventions.

3.4. Transforming Surgeries and Care with Robotics

Robotic technologies represent one of the most advanced intersections of AI and healthcare, offering enhanced surgical precision, reduced invasiveness, and improved patient outcomes. Shaheen (2021) notes that AI-powered robotic systems guide surgical instruments with unparalleled accuracy, supporting surgeons before and during operations. These systems enable minimally invasive techniques across disciplines such as gynecology, urology, and cardiothoracic surgery (Davenport & Kalakota, 2019).

While full automation remains rare, robotic-assisted surgeries, such as those enabled by the da Vinci Surgical System, significantly enhance surgical capabilities without displacing surgeon expertise (Yu et al., 2018). Innovative systems like the Smart Tissue Autonomous Robot (STAR) demonstrate AI's potential to surpass human precision in delicate procedures (Bekbolatova et al., 2024). Beyond surgery, robotics also contributes to rehabilitation and elderly care. Robotic exoskeletons assist patients in mobility and recovery, while humanoid robots provide therapeutic support for individuals with complex needs (Olawade et al., 2024).

Robotic-assisted procedures have reduced hospital stays, lowered complication rates, and accelerated recovery times, leading to substantial clinical and economic benefits (American Hospital Association, 2024). Nevertheless, the successful integration of robotics into healthcare demands careful attention to regulatory compliance, clinician training, cost management, and ethical considerations. Ensuring that these technologies augment human expertise, rather than replace it, is critical for maintaining patient trust and safety. In conclusion, robotics, powered by AI, is transforming surgery and patient care, driving advances in precision medicine, rehabilitation, and healthcare accessibility.

4. Transformative Applications of Artificial Intelligence in Healthcare for Diverse Stakeholders

Artificial intelligence (AI) is transforming healthcare by addressing the diverse needs of patients, clinicians, administrators, public health officials, and researchers. Each stakeholder group benefits uniquely from AI's capabilities, which enhance service delivery, optimize decision-making, and drive innovation across the healthcare ecosystem.

4.1. Patients and Families: Empowered Self-Management and Proactive Care

AI-powered tools—such as wearable devices, mobile health applications, and telehealth platforms—facilitate continuous health monitoring, early disease detection, and proactive disease management. These technologies have proven particularly impactful in managing chronic diseases, supporting mental health, and aiding rehabilitation.

Solutions that promote medication adherence, encourage healthier lifestyles, and deliver accessible support services empower patients to engage actively in their care journeys. By offering real-time insights and personalized interventions, AI fosters improved health outcomes and greater patient autonomy.

4.2. Clinician Care Teams: Enhanced Diagnostics and Personalized Treatment

Clinicians benefit significantly from AI-driven innovations that augment diagnostic precision, assist surgical procedures, and tailor treatment plans. AI-powered imaging analysis systems, robotic surgery platforms, and precision medicine tools enable earlier detection of diseases, minimize surgical risks, and facilitate evidence-based decision-making. Machine learning models help identify disease patterns, optimize therapy choices, and predict clinical outcomes, enabling clinicians to deliver more targeted, effective, and patient-centric care.

4.3. Public Health Managers: Strengthening Population Health Surveillance

Public health officials leverage AI to monitor population health trends, manage disease surveillance, and optimize healthcare resource allocation. Deep learning models and geospatial analytics tools track environmental health risks, detect infectious disease outbreaks, and identify vulnerable populations. These capabilities support targeted interventions, inform public health policy, and enhance the resilience and responsiveness of healthcare systems to emerging challenges.

4.4. Healthcare Administrators: Optimizing Operations and Safeguarding Resources

Administrators deploy AI to enhance operational efficiency, ensure financial integrity, and automate administrative tasks. AI-driven fraud detection tools identify irregular billing patterns and unlicensed practices, protecting healthcare funding streams. Machine learning algorithms automate medical record coding and billing compliance, reducing administrative burdens and minimizing human error, thereby streamlining organizational workflows.

4.5. Researchers: Accelerating Biomedical Innovation

Researchers harness AI to advance genomics analysis, disease prediction, and drug discovery. Integrated cognitive computing systems facilitate tumor profiling, interpret genetic datasets, and support the discovery of novel therapeutic compounds. AI accelerates research timelines, broadens the frontiers of biomedical innovation, and enables a more rapid translation of discoveries into clinical practice.

4.6. Cybersecurity: Protecting Sensitive Health Information

AI also plays a critical role in cybersecurity by safeguarding sensitive health information. Machine learning algorithms continuously monitor healthcare information systems for anomalies, enabling the early detection of potential breaches and ensuring compliance with data privacy regulations. Robust AI-driven cybersecurity frameworks are essential for maintaining trust and protecting patient data in increasingly digital healthcare environments. Table 3 summarizes key AI applications across stakeholder groups, highlighting their respective technological foundations and healthcare contributions.

Table 3.: AI Applications Across Stakeholder Groups in Healthcare

User Group	Application Category	Examples of AI Applications	Technologies
Patients & Families	Health Monitoring	Wearable devices, mobile apps, health metrics tracking	ML, NLP, Chatbots, Speech Recognition
	Disease Prevention & Management	Obesity control tools, diabetes management, mental health support	Conversational AI, NLP, Speech Recognition
	Medication Adherence	Medication tracking systems, telehealth robots	Robotics, Automated Reminders
	Rehabilitation	Robotics-assisted stroke recovery tools	Robotics
Clinician Care Teams	Diagnostics & Early Detection	AI tools for cardiac, oncological, and ophthalmic diagnostics	ML
	Surgical Assistance	Robotic surgery platforms, AI-generated surgical plans	Robotics, ML
	Precision Medicine	Personalized chemotherapy regiments	Supervised Learning, Reinforcement Learning
Public Health Managers	Population Health Monitoring	Elderly care tracking, pollution and water safety monitoring	Deep Learning, Geospatial Analytics
	Disease Surveillance	Detection of waterborne microbes, air quality monitoring	Geospatial Data Mining, Deep Learning
Business Administrators	Fraud Detection	Identification of billing fraud and unlicensed practitioners	Supervised & Unsupervised ML
	Medical Record Automation	Automatic coding of health records for billing compliance	ML, NLP
Researchers	Genomics Analysis	Tumor analysis, genetic profiling	Integrated Cognitive Computing
	Disease Prediction	Neural networks predicting cancer and other conditions cancer	Neural Networks
	Drug Discovery	AI-driven drug synthesis and formulation	ML, Computer-Assisted Synthesis
Cybersecurity	Data Protection	Safeguarding personal health information	NLP, ML

Note: Roski, et al. (2022).

Lämmermann et al. (2024) emphasise that while AI's transformative potential is immense, successful implementation requires robust management strategies. Seamless information exchange, careful governance of data flows, and the establishment of supportive organisational frameworks are critical to preventing task ambiguity and maximising AI's benefits.

In conclusion, AI's applications span all levels of healthcare, offering opportunities to improve patient outcomes, strengthen system resilience, and accelerate scientific innovation. However, realising these benefits necessitates coordinated efforts to manage technological, ethical, and organisational complexities responsibly.

5. AI-Driven Healthcare Transformation: A Three-Stage Model

Artificial intelligence (AI) is no longer a supplementary tool within healthcare; it is fundamentally reshaping the structure, processes, and delivery of services. To conceptualise this dynamic evolution, we propose the AI-Driven Healthcare Transformation Framework (AI-HTF), which classifies healthcare transformation into three progressive stages: Integration, Augmentation, and Restructuring.

5.1. Integration Stage

In the Integration Stage, AI technologies are incorporated into existing healthcare systems primarily as operational support tools. Rather than altering the core of healthcare delivery, AI enhances workflows, improves administrative efficiency, and streamlines basic operations (Davenport & Kalakota, 2019).

Examples include appointment scheduling chatbots, automated triage systems, fraud detection mechanisms, and workflow optimisation platforms. At this stage, human professionals retain full decision-making authority, with AI serving as an auxiliary aid to assist and expedite routine tasks (Olawade et al., 2024).

Key characteristics of the Integration Stage include:

- Enhancement of operational workflows.
- Automation of administrative and repetitive tasks.
- Minimal influence on clinical decision-making.
- Human expertise remains central to patient care.

5.2. Augmentation Stage

The Augmentation Stage marks AI's transition from a supportive tool to an active collaborator in clinical and operational decision-making. AI applications, such as advanced diagnostic tools, predictive analytics platforms, and robotic-assisted surgeries, exemplify this phase (Yu, Beam, & Kohane, 2018).

Machine learning models assist clinicians by identifying complex disease patterns, optimising treatment pathways, and forecasting patient outcomes (Ramirez, 2024). Although human judgement remains paramount, it is now significantly enhanced by AI's analytical capabilities, resulting in greater diagnostic accuracy, operational efficiency, and improved patient satisfaction (Rana & Shuford, 2024).

Key characteristics of the Augmentation Stage include:

- AI functions as a collaborative decision-making partner.
- Substantial improvements in diagnostic precision and operational performance.
- Expansion of predictive analytics and personalised care planning.
- Enhanced clinician support without replacing human oversight.

5.3. Restructuring Stage

The Restructuring Stage represents a paradigm shift where healthcare systems are fundamentally redesigned around AI capabilities. In this visionary model, AI orchestrates integrated, personalised, and predictive healthcare ecosystems (Chaturvedi, Chauhan, & Singh, 2025).

In the restructuring phase:

- Autonomous clinics leverage continuous remote patient monitoring.

- Real-time, data-driven diagnostics and dynamic treatment adjustments become standard practice.
- Administrative and many clinical functions are increasingly automated.
- AI assumes primary roles in managing tasks traditionally reserved for healthcare professionals.

While human oversight remains critical for ethical governance, AI emerges as a central agent, shifting from reactive to proactive, preventive healthcare models.

Key characteristics of the Restructuring Stage include:

- Fully data-driven, autonomous healthcare ecosystems.
- Continuous patient monitoring and real-time care adaptations.
- Emphasis on preventive rather than reactive healthcare strategies.
- Reimagining healthcare structures around AI orchestration.

5.4. Implications of the AI-HTF Model

The AI-Driven Healthcare Transformation Framework (AI-HTF) illustrates that the impact of AI on healthcare is both dynamic and cumulative, intensifying with each successive stage. As systems evolve through the Integration, Augmentation, and Restructuring stages, addressing challenges such as data privacy, algorithmic bias, transparency, and clinician trust becomes increasingly critical (Kiseleva, Kotzinos, & De Hert, 2022).

Governance frameworks must evolve in parallel with AI capabilities to ensure ethical deployment and sustain public trust. Policymakers are urged to design adaptive regulatory strategies that safeguard patient rights while encouraging technological innovation.

Healthcare providers must commit to continuous education and foster multidisciplinary collaboration to enhance AI literacy and bolster clinician engagement. Empowering healthcare professionals to understand, critique, and guide AI systems is essential for their effective and ethical utilisation.

Technology developers bear the responsibility of prioritising transparency, explainability, fairness, and user-centred design principles in AI systems. Prioritising the development of Explainable AI (XAI) is essential for fostering clinician trust and supporting responsible clinical decision-making.

Additionally, cross-sector collaboration—uniting healthcare institutions, technology companies, regulatory bodies, and patient advocacy groups—is vital to ensure that AI integration serves human needs ethically and sustainably.

In conclusion, the AI-HTF model offers a strategic roadmap for comprehending and navigating AI's evolving role in healthcare. Its successful implementation demands coordinated efforts across technical, ethical, and regulatory domains to balance innovation with responsibility and equity.

Figure 2: AI-Driven Healthcare Transformation Framework

Integration Stage
• Operational AI support (e.g., administrative automation)
↓
Augmentation Stage
• Clinical and operational decision support (e.g., diagnostics, predictive analytics)
↓
Restructuring Stage
• AI-centric healthcare ecosystems
(e.g., autonomous clinics, personalised medicine)

The AI-Driven Healthcare Transformation Framework (AI-HTF) provides a structured roadmap for understanding AI's evolutionary trajectory within healthcare. It highlights that AI's influence is not static but cumulative, demanding nuanced governance, sustained technological innovation, and inclusive stakeholder engagement at each stage. Moving forward, empirical research is crucial to validate the AI-HTF model across diverse healthcare environments. Future work should refine strategic pathways to ensure that AI adoption remains equitable, ethical, and oriented toward enhancing global healthcare resilience.

6. Conclusion

Artificial intelligence (AI) has firmly established itself as a catalyst for transforming healthcare delivery, operational efficiency, and patient outcomes. However, despite the breadth of its transformative applications, critical gaps persist in understanding the nuanced challenges of AI integration, including issues of transparency, ethical risks, and trust deficits.

This chapter provides a comprehensive analysis of AI's multifaceted contributions to healthcare, emphasizing its applications in diagnostics, drug discovery, patient engagement, clinical decision-making, and operational management. By leveraging foundational technologies, such as machine learning (ML), natural language processing (NLP), computer vision, and robotics, AI enables the analysis of vast medical datasets, supports personalized treatment approaches, and streamlines healthcare workflows. Moreover, the chapter underscores the stakeholder-centered nature of AI's impact—patients, clinicians, public health officials, administrators, and researchers each experience distinct benefits and face unique challenges as AI becomes increasingly embedded within healthcare ecosystems.

Nevertheless, addressing critical challenges is essential for the sustainable and ethical integration of AI. Data privacy concerns, algorithmic biases, accountability gaps, and the "black-box" nature of many AI systems pose significant obstacles to widespread trust and adoption. Robust governance frameworks, rigorous regulatory oversight, and transparent, explainable AI (XAI) models are urgently required to safeguard patient rights and promote equitable healthcare innovation.

Looking ahead, research should prioritize the development of XAI technologies, conduct robust clinical validation studies, and foster interdisciplinary collaboration among healthcare providers, technologists, ethicists, and policymakers. AI can only fulfil its promise of creating more efficient, equitable, and patient-centered healthcare systems globally through strategic, ethically grounded implementation.

In conclusion, artificial intelligence holds transformative potential for healthcare; however, realizing its promise requires a deliberate and ethically conscious approach to its development, integration, and governance. Future efforts must balance innovation with responsibility, ensuring that AI serves as a tool for human empowerment rather than a source of unintended harm. This study contributes uniquely by offering an integrated, stakeholder-focused framework for the ethical and strategic deployment of AI in healthcare.

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Examining the Effects of Green Taxes on Environmental Pollution in Central Europe

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Abstract

The objective of this study is to empirically investigate the impact of green taxes on the reduction of environmental pollution in 10 Central European countries such as: (Austria, Croatia, Czech Republic, Germany, Hungary, Lithuania, Poland, Slovak Republic, Slovenia and Switzerland), for a 13-year period from 2010 to 2022. This research uses secondary data from the World Bank Database and The Global Economy Database. The models included in the econometric analyses are: Ordinary Least Squares (OLS), Fixed Effect (FE), Random Effect (RE) and the Hausman-Taylor (HTH) model. The results provide support for the alternative hypothesis, that increasing green tax rates has a positive impact on reducing environmental pollution in Central European countries. The findings show that the increase in production, the increase in carbon dioxide and the increase in the standard of living expressed in per capita income have a positive impact on the increase in pollution predicted by the variable PM2.5. Therefore, an increase in green taxes leads to an average decrease in the PM2.5 index, presenting a statistically significant coefficient at the 1% level (P=0.001). The green growth index variable also has a negative but statisticaly insignificant impact. These results provide support for the use of coercive policies by European countries, as they play a crucial role in improving environmental conditions and green development, which are the contemporary challenges for policymakers.

Keywords: Central European countries, environmental policies, green taxes, green technologies, reduction of environmental pollution

1. Introduction

Since a clean environment plays an essential role in the development of life on Earth, special attention should be given to environmental pollution, which continues to escalate with its effects on global climate conditions. The negative effects of environmental pollution primarily endanger nature and greenery, health and life, as well as the function of economies and the development of many countries. Ghorani-Azam et al. (2016) assert that exposure to poor air quality is a major factor in increasing disease and mortality rates such as cardiovascular and respiratory diseases. Therefore, the measures for its reduction are the main parameters of the economies of many countries of the world, which, through the incentives of green policies, aim to reduce these negative effects on the environment. Moreover, the main focus of the countries is to make people aware of a healthy and green lifestyle in the long term through various instruments such as green taxes. The reduction of greenhouse gases and the rational use of energy are an undisputed incentive for economic growth, resulting in effective management of environmental policies. Key contributing factors to environmental degradation include population growth and increasing energy demands driven by modernization and technology use. And this increased demand for energy carries the cost of rational and effective management, as poorly designed green policies can exacerbate environmental harm on global warming and environmental pollution or damage. Therefore, today the policies of many countries are directed to the results of sustainable development, through renewable energy and maintaining the balance of greenhouse gas reduction on the one hand and modern technology innovations on the other.

The study by Peng et al. (2025) finds that green taxes and fees are tools that can influence environmental, social and corporate governance (ESG) performance, for green economic transformation and sustainable development. The empirical findings of the paper showed that green taxes and fees significantly increase the ESG performance of enterprises. The research confirmed that green taxation has achieved positive results in environmental policy management. Murad et al. (2025) analysed the impact of environmental taxes on CO_2 emissions in 38 OECD countries, accounting for cross-sectional dependence, non-stationarity and heterogeneity. The paper confirmed that there is a long-run negative relationship between environmental taxes and CO_2 emissions. The paper supports the hypothesis of the Environmental Kuznets Curve (EKC) in high-income countries.

Zhang and He (2025) confirmed that the tax system plays a crucial role in promoting corporate green transformation and high-quality development. The paper examined the impact of the Environmental Protection Tax Law (EPTL) of the People's Republic of China on the quality of corporate development, based on data from corporations on the Shanghai and Shenzhen stock exchanges during the period 2014 to 2021. The findings confirmed that the law promotes the quality of corporate development by stimulating green innovation, improving Environmental, Social and Governance (ESG) performance, and reducing managerial myopia.

Gehring (2016) states that developed countries increasingly apply contemporary legal standards and regulations, which serve as crucial instruments to fulfill long-term economic development goals and explore possible legal and political remedies. The importance of studying the impact of green taxes in reducing environmental pollution is the focus of this paper. The paper analyses how important and necessary this intervention policy is on the part of Central European countries, through regulatory and legal policies. The purpose of the paper is that interested stakeholders should rely on the study's findings, taking as a basis how appropriate this implementation will be from one country to another, adapting to their economies and regional specifics. Through this paper we aim to offer the approach to green taxes and the impact of this paper is to raise awareness that every step taken in this field is in favor of reducing the negative effects of environmental pollution and promoting a healthier environment.

The main objective of this paper is to analyse the impact of green taxes on reducing environmental pollution in Central European countries, basing the research on empirical statistical analysis through secondary data.

The research question of this paper is:

What is the impact of green taxes in reducing environmental pollution in Central European countries?

The research hypotheses are:

H0: Increasing green tax rates has no impact on reducing environmental pollution

H1: Increasing green tax rates has a positive impact on reducing environmental pollution

This paper aims at the importance of the application of taxes as a measure of economic and ecological benefit, in reducing environmental pollution in Central European countries and encouraging behavioural change to mitigate environmental harm economically. Through this paper, we aim to balance the value of the decision to apply taxes, which is dedicated to polluters, and the awareness that any measure taken in this area is a reduction of the negative effects of the global climate, with an environment with a lower level of pollution. Quantitative methodology with secondary data was used for the analysis of the paper. The models included in the econometric analyses are: Ordinary Least Squares (OLS), Fixed Effect (FE), Random Effect (RE) and the Hausman-Taylor (HTH) model. For the comparison of the results, the Hausman Taylor test was used, where from the results of this test, the model with fixed effects is the most appropriate model for the analysis of the results of this paper.

This paper is divided into several sections, the following section presents the literature review, the third section explains the methodology and data collection, the fourth section presents the empirical results, the fifth section presents the discussions. And the last section presents the conclusion and recommendations.

2. Literature Review

Numerous studies have highlighted the role of green taxes in reducing pollution, especially focusing on the inclusion of many instruments and environmental policies related to the reduction of Co2 and their implementation, which in different regions can result in different effects. An example of the implementation of environmental policies that mitigate the effects of environmental degradation and environmental taxes on gas emissions and the impact of the strictness of these policies in Central Europe and Western Europe, it turns out that the strictness of environmental policies depends on the specifics of countries and economic factors emphasize (Dmytrenko et al., 2024). Koziuk et al. (2020) analyzed data from European countries and found that the effectiveness of environmental taxes depends on the design of environmental taxes and this varies from one country to another depending on their implementation. According to Štreimikienė (2015), the impact of environmental taxes is direct on the sustainable development of energy, through which it affects the reduction of the use of fossil fuels and their replacement with cleaner fossil materials such as natural gas.

Furthermore, Koval et al. (2022) assert that the promotion and protection of the environment is one of the most urgent tasks of the European environmental policy, as well as the reduction of greenhouse gases and the development of clean technologies in production, depends on the impact of environmental taxation. Cansino et al. (2010) conclused that not all available technologies are promoted, arguing that many European countries use tax incentives to promote green energy, constituting another difficulty to the EU's objective to provide a framework of renewable energy policy. Dogan et al. (2023) emphasizes that renewable energy, although with high costs, is the solution to reduce environmental pollution and high energy consumption which is related to the development of many countries in Europe. Streimikiene et al. (2018) strongly emphasize that most European countries have taxes as the most important tool for reducing the environmental impacts of various economic activities. Xu et al. (2024) concluded that the main obstacle to the sustainable growth of the regional economy of European countries is environmental pollution. Kotlán et al. (2021) have found that high levels of corruption can become an obstacle in limiting long-term sustainable development policies alongside the advantages of environmental taxes. Moreover, Krass et al. (2013) emphasize the use fixed cost subsidies and consumer rebates related to environmental taxes as motivation in choosing green technologies. Tchapchet-Tchouto et al. (2022) concluded that economic growth worsens with increasing environmental taxes. Maier & Ricci (2024) claim that due to austerity measures, tax changes, transport taxation and energy consumption in the period 2010-2019, consumption taxes have increased in the vast majority of EU member states. Cooke (2015) emphasizes that the countries of Central and Eastern Europe have a large energy force of greenhouse gas emissions, which are important in global climate change and that every action taken from them constitutes an important step regarding the global climate. Andersen et al. (2006) in their paper addressed the topic of primary renewable energy sources and their conversion, in particular renewable energy sources to produce energy in the form of electricity. First of all, stop the transport from using fossil fuels and enable the transition to the use of electricity in transport vehicles. Khan et al. (2023) claimed that CO2 emissions can be reduced through the implementation of environmental taxes, eco-innovations, the use of renewable energy sources and the increase of energy efficiency. Bovenberg (1999) analyzed the impact of environmental tax reforms on welfare, income distribution and employment. Another analysis by Chenget al. (2024) point out that higher environmental taxes favor cleaner energy alternatives and greener infrastructure. The authors Esen et al. (2021) in their analysis conclude that if environmental taxes are well designed, they have the potential to reduce environmental problems, that is, if the implementation of policies such as tax exemptions, refunds or tax allowances that limit their impact is excluded. According to Ghazouani et al. (2021) a tool recommended by economists and environmental scientists in European economies is environment-related taxes, carbon and energy taxes. Turner et al. (1998) point out that if environmental taxes are poorly conceived, they can be harmful and can have effects on reducing the quality of the environment, increasing costs and undesirable social consequences. According to Cheng et al. (2022) green taxes have positive effects contributing to green policies, more so for large firms, state-owned firms and firms with high analyst following. Thus, green taxation promotes carbon emission efficiency by accelerating the incentive of capital investment assert the authors (Zhou et al., 2022). Li et al. (2021) point out that the application of green taxes has positive effects in reducing pollutant emissions. But according to them, policymakers should consider the promotion of tax rates in areas with low tax rates and tax incentives to stimulate firms in reducing pollutants. According to Guan et al. (2025) Among the essential factors for achieving balance and advancing the Sustainable Development Goals (SDGs) are environmental taxes (ET), green finance (GF), and cultivating a skilled workforce dedicated to achieving sustainable development. Su et al (2025) confirmed that promoting a regional green economy and reducing negative environmental externalities is possible through designing optimal tax policies and strengthening cooperation between regional governments. Another study by Huang et al. (2025) analyzed the impact of environmental tax reform on corporate green behavior and ESG performance. Through empirical analysis, the paper found that the adoption of environmental tax significantly enhances corporate ESG performance. The paper confirmed that tax reforms affect corporate green behavior by increasing environmental investment, accelerating green technological innovation, and improving financial conditions through tax-related financial incentives. Authors Zhou and Su (2025) using data from Chinese companies explored the relationship between environmental protection taxes, management efficiency, and green technology innovation. The findings show that the implementation of environmental protection taxes has a positive impact on the rate of green technology innovation within corporations, and improved managerial efficiency escalates it. Another study by Roy (2025) concluded the effectiveness of carbon taxation in promoting the production, consumption and exchange of green goods. The paper highlights that heterogeneity in the causal effects of carbon taxation is observed across different groups of countries and time periods. Qamruzzaman (2025) analyzes green finance, environmental taxes, and green innovation in China, claiming that green finance and investment are among the factors influencing China's transition to a sustainable economy. The paper further points out that efforts to reduce CO2 emissions through environmental taxes and incentives, and collective efforts with strong government support for research and development in low-carbon technologies, can help put China on a sustainable economic path. Anjun (2022) in his analysis of taxes and corporate social responsibility (CSR) emphasized that there is a positive relationship between environmental taxes and CSR. The greater the intensity of environmental taxes, the positive relationship will improve with the increase in the degree of CSR. Wang (2022) points out that promoting the sustainable development of enterprises is done by tax equity and this is achieved by increasing corporate green innovation. The paper claims that tax equity of tax reforms has different effects on the sustainable development of enterprises at different stages of the life cycle. Sabău-Popa et al. (2024) asserts that green taxes are an instrument of environmental policy and that they contribute to sustainable development. The paper further emphasizes that total green taxes and energy taxes are closely related to the variation of GDP and primary energy consumption as important indicators of sustainable development, showing a positive and significant correlation.

3. Research Methodology and Data

This study employs secondary data analysis to measure the impact of green taxes on reducing environmental pollution, processed using STATA programme.

The data for these countries were obtained from the World Bank Database and The Global Economy database, covering a period of thirteen years, from 2010 to 2022. The research includes 10 Central European countries (Austria, Croatia, the Czech Republic, Germany, Hungary, Lithuania, Poland, the Slovak Republic, Slovenia and Switzerland). The main objective of the study is to examine the role of green taxes in mitigating environmental pollution in Central

European countries. The results of this study are expected to provide significant positive effects for decision-makers and policy-makers in meeting economic and taxation objectives by reducing pollutant emissions in the environment.

The econometric analyses comprised several models: ordinary least squares (OLS), Fixed Effect (FE), Random Effect (RE), and the Hausman-Taylor (HTH) model. The Fixed Effect model was chosen because allows for the examination of within-group variation over time, making it well-suited for studying changes within specific entities or groups while controlling for their inherent characteristics. Additionally, the FE model is robust to certain forms of endogeneity and can provide reliable estimates even in the presence of correlated omitted variables, offering researchers a powerful tool for analyzing panel data with a focus on individual-level dynamics. To compare the results, the Hausman Taylor test was used, where based on the results of this test, the model with fixed effects is the most suitable model for research.

The model is defined as follows:

$$Yit = c + \beta 1\ (GT) + \beta 2\ (GGI) + \beta 3\ (MAN) + \beta 4\ (CO2) + \beta 5\ (PSI) + \beta 6\ (GDPC) + uit \quad (1)$$

Where yit is the dependable variable, which in this case is PM2.5, i = 1….10 (countries), t = 2010…2022 (years); c is constant; GT (Green Tax); GGI (Green Growth Index); CO2 (Carbon Dioxide); PSI (Political Stability Index); MAN (Manufacturing); GDPC (GDP per Capita) and uit is the exogenous disturbance.

Table 1.: Definition of variables

Nr	Variable	Abbreviations	Unit
1	Particles that are 2.5 microns or less in diameter	PM2.5	micrograms per cubic meter of air
2	Green Tax	GT	% of Tax
3	Green Growth Index	GGI	Index
4	Carbon Dioxide	CO2	Metric Tons per Capita
5	Manufacturing	MAN	Percent of GDP
6	Political Stability Index	PSI	Index
7	GDP per Capita	GDPC	US $

3.1. Descriptive Statistics

The data in table 2 offers insights into various economic indicators for Central European Countries the period of 2010-2022.

Beginning with environmental indicators, the mean concentration of fine particulate matter (PM2.5) at 94.06 micrograms per cubic meter reflects the average air quality in terms of particle pollution, indicating potential health risks associated with air pollution sources like vehicle emissions and industrial activities. Additionally, the mean carbon dioxide (CO2) emissions of 6.3 metric tons per capita highlight the average individual carbon footprint, pointing towards the region's contribution to global greenhouse gas emissions and its environmental impact.

Shifting towards economic indicators, the mean Green Tax (GT) of 4.7% signifies the average percentage of tax levied on activities with environmental implications, showcasing the region's approach towards incorporating environmental considerations into fiscal policies. Furthermore, the mean manufacturing contribution (MAN) to the Gross Domestic Product (GDP) at 18.01% underscores the sector's significance in driving economic output, indicating the level of industrialization and employment opportunities within the economy. Complementing this, the mean Gross Domestic Product per capita (GDPC) of $38,109.18 reflects the average economic well-being and standard of living enjoyed by individuals in the region.

Table 2.: Descriptive Statistics of Variables

Variable	Obs	Mean	Std. Dev.	Min	Max
PM25	130	94.06	12.07	46.22	100
GT	130	4.70	1.20	2.12	7.31
GGI	130	69.93	4.54	61.24	78.32
MAN	130	18.01	2.57	12	24.03
CO2	130	6.30	1.96	3.42	10.9
PSI	130	.90	.21	.49	1.42
GDPC	130	38109.18	15190.47	11933.38	71949.32

Lastly, in terms of political indicators, the mean Green Growth Index (GGI) score of 69.93 highlights the region's average level of green growth, suggesting the extent to which economic development is aligned with environmental sustainability objectives. Furthermore, the mean Political Stability Index (PSI) score of 0.9 indicates the average level of political stability within the region, influencing factors such as investment confidence, economic growth, and overall societal well-being.

4. Empirical Results

This chapter contains the empirical results, where initially in table 3 the results of the correlation analysis are presented. Based on the results of this analysis, the green tax variable has a negative relationship with the dependent variable (PM2.5) with a correlation coefficient of r= -0.25. Thus, an increase in green taxes is negatively associated with a reduction in the PM2.5 index. Meanwhile, the increase in production has a positive relationship r=0.05 and the increase in carbon dioxide also has a positive relationship with the PM2.5 index (r=0.21), these results show that the increase in production and the increase in carbon dioxide have an impact on the increase in pollution predicted by the variable PM2.5.

Table 3.: Correlation Results

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) PM25	1.000						
(2) GT	-0.253	1.000					
(3) GGI	-0.533	-0.078	1.000				
(4) MAN	0.050	-0.092	-0.067	1.000			
(5) CO2	0.217	-0.150	0.018	0.579	1.000		
(6) PSI	-0.423	0.035	0.479	-0.082	-0.016	1.000	
(7) GDPC	-0.713	0.184	0.533	0.299	0.204	0.443	1.000

Table 4 presents the summarized results of the econometric models, where four econometric models were implemented; Ordinary Least Squares (OLS), fixed effects method (FE), random effects method (RE) and Hausman Taylor method (HTH). Based on the results of the Hausman test (P=0.0.1117) presented in the appendix, we consider that the most suitable model for the interpretation of the results is the model with the fixed effects method, so the detailed results of this model are presented in table 5.

Table 4.: Summary Results of Econometric Models

Variable/Model	OLS	FE	RE	HTH
GT	-0.906	-4.256***	1.485	-0.142
	(-1.63)	-3.4	-1.64	(-0.30)
GGI	-0.452*	-0.822	-0.589	-0.399
	(-2.50)	(-1.39)	(-1.59)	(-1.80)
MAN	0.202	1.231	0.505	0.0665
	-0.63	-1.68	-0.92	-0.24
CO2	1.946***	5.509***	3.032***	0.343
	-4.97	-4.28	-3.76	-0.69
PSI	-1.947	-4.498	4.107	-1.493
	(-0.56)	-0.9	-0.94	(-0.73)
GDPC	-0.531***	0.906**	-0.640***	-0.16
	(-9.08)	(-3.32)	(-4.85)	(-1.86)
PM25_lag				0.817***
				-22.57
CountryId				-0.362
				(-0.72)
_cons	136.0***	105.1*	120.8***	51.52**
	-9.57	-2.2	-4.24	-2.86
N	130	130	130	129

Note:t statistics in parentheses
*Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$*

Based on the results presented in table 5, where the regression results using the fixed effects model are presented, the coefficient of determination (R-squared=0.733) shows that the model has a high explainability with 73.3% of the variation of the dependent variable, whereas the F-statistic =9.48 P=0.000 shows that the model is statistically significant.

According to the presented results of the coefficients, the green tax variable has a negative impact on environmental pollution (B= -4.25), so for every 1% increase in green taxes, the PM25 index decreases by 4.25 on average, this coefficient is statistically significant at the 1% level (P=0.001). The green growth index variable (B= -0.82) also has a negative impact, but without a significant impact.

The increase in production has a positive impact on environmental pollution (B=1.23), so for every 1% of gross local production increase in production, the PM2.5 index increases by 1.23 on average, the coefficient is statistically significant at the 10% level (P =0.095). Carbon dioxide emissions also have a strong positive impact on pollution (B=5.5), where for every 1 unit increase in carbon dioxide emissions, the PM2.5 index increases by 5.5. on average, the coefficient is statistically significant at the 1% significance level (P=0.000).

The increase in the standard of living expressed in terms of income per capita has a positive impact on environmental pollution (B=0.90), thus, for every one-dollar increase in income per capita, the PM2.5 index increases by 0.90 on average, the coefficient is statistically significant at the 1% significance level (P=0.001).

Table 5.: Results from Fixed Effect Model

PM25	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
GT	-4.25	1.25	3.40	.001	1.77	6.73	***
GGI	-.82	.59	-1.39	.167	-1.99	.34	
MAN	1.23	.73	1.68	.095	-.21	2.68	*
CO2	5.50	1.28	4.28	.000	2.95	8.06	***
PSI	-4.49	5.01	0.90	.372	-5.44	14.43	
GDPC	.90	0.01	-3.32	.001	-.01	0.04	***
Constant	105.12	47.88	2.20	.030	10.27	199.97	**
Mean dependent var	94.06		SD dependent var		12.07		
R-squared	0.73		Number of obs		130		
F-test	9.48		Prob > F		0.000		
Akaike crit. (AIC)	830.21		Bayesian crit. (BIC)		850.28		

*Note: *** p<.01, ** p<.05, * p<.1*

5. Discussion

The results of the econometric analysis regarding the effectiveness of green taxes in reducing environmental pollution in Central European countries are consistent with previous research findings. Firstly, the significant negative impact of green taxes on environmental pollution is consistent with the conclusions of authors such as Dmytrenko et al. (2024), who highlighted the role of environmental policies, including green taxes, in mitigating CO2 emissions. Similarly, Štreimikienė (2015) emphasized the ...

The positive association between economic activities like manufacturing and GDP per capita with environmental pollution, as indicated by positive coefficients in the analysis, is consistent with findings from studies such as those by Tchapchet-Tchouto et al. (2022) and Maier & Ricci (2024). These studies discuss how economic growth can exacerbate pollution levels, emphasising the challenge of balancing economic development with environmental sustainability, a theme echoed in the current discussion.

However, the lack of statistical significance for the coefficient of the green growth index variable regarding its impact on pollution levels diverges from some existing literature. While the current study suggests a potential link between green economic development and reduced pollution, this finding contrasts with research such as that by Khan et al. (2023), which emphasizes the effectiveness of environmental policies, including eco-innovations and renewable energy adoption, in reducing CO2 emissions. This discrepancy suggests the need for further exploration into the specific components of green growth and their influence on environmental outcomes to reconcile these differing perspectives.

While the positive coefficient for income per capita aligns with the environmental Kuznets curve hypothesis, indicating that higher standards of living may initially lead to increased pollution levels, the statistically significant positive relationship underscores the complexity of addressing pollution solely through income growth. This finding corresponds with discussions by authors like Esen et al. (2021) who emphasize the importance of well-designed environmental taxes alongside income growth to effectively reduce environmental problems, indicating a need for multifaceted approaches to achieve environmental sustainability in Central European countries.

Null Hypothesis (H0): Increasing green tax rates has no impact on reducing environmental pollution ($B = 0$)

Alternative Hypothesis (H1): Increasing green tax rates has a positive impact on reducing environmental pollution ($B < 0$)

Given the coefficient for the green tax variable ($B = -4.25$) and its associated p-value ($P = 0.001$), we can perform a hypothesis test using the conventional significance level of 0.05.

Since the coefficient is negative (-4.25), it suggests that there is a negative relationship between green taxes and environmental pollution, which aligns with the alternative hypothesis of a positive impact on reducing pollution.

The p-value (P = 0.001) is less than the significance level (0.05), indicating that the coefficient for the green tax variable is statistically significant.

Therefore, we reject the null hypothesis and conclude that there is evidence to support the alternative hypothesis: increasing green tax rates has a positive impact on reducing environmental pollution in Central European countries.

6. Conclusion

To promote sustainable development and a resilient economy, policymakers should support the implementation of economic and tax policies that reduce pollutant emissions in the environment. The research highlights that any increase in green tax rates in Central European countries has a positive impact on reducing environmental pollution and favours the green economy in general. This paper analyzed the impact of green taxes to create certain policies that help reduce the environmental pollution of these countries. Indicating that as the percentage of green taxes increases, the PM2.5 index decreases, reflecting ipmroved air quality. Average air quality is reflected through the dependent variable (PM2.5), which represents the potential health risks associated with sources of air pollution such as vehicle emissions and industrial activities. Among other important indicators we have: average carbon dioxide emissions carbon (CO2), average green tax (GT), average production contribution (MAN) to Gross Domestic Product (GDP), average Gross Domestic Product per capita (GDPC), Green Growth Index (GGI) and Index of Political Stability (PSI).

The analysis highlights results that show that the increase in production, the increase in carbon dioxide and the increase in the standard of living expressed in per capita income have a positive impact on the increase in pollution predicted by the PM2.5 variable. Thus, the green tax variable negatively affects environmental pollution, where a 1% increase leads to a decrease in PM25 by 4.25 on average, with a statistically significant coefficient at the 1% level (P=0.001). The green growth index variable also has a negative impact, but without a significant impact.

The result of the Political Stability Index shows the average level of political stability within the region, influencing factors such as confidence in investments, economic growth and general social well-being, where the average value of this index 0.90 indicates that the countries of the study demonstrate a stable political environment which enables investments and economic development.

The results of the analysis of the econometric models complement the results of the literature and are consistent with the findings from previous studies that the increase in green tax rates affects the reduction of environmental pollution in Central European countries. Based on the analysis, we conclude that there is a positive relationship between economic activities such as production and GDP per capita with environmental pollution, as shown by the positive coefficients in the analysis, and economic growth can worsen pollution levels, highlighting the challenge of balancing economic development with environmental sustainability.

Stakeholders in the region and policymakers can use these findings to design fiscal policy strategies aimed at reducing environmental pollution, development and promotion for sustainable economic growth and addressing environmental challenges. The study highlights the necessity of regional cooperation and knowledge sharing to ensure effective policymaking for sustainable economic growth and environmental well-being in Central Europe.

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APPENDIX

Table A1 - Hausman (1978) specification test

Hausman Test	Coef.
Chi-square test value	14.954
P-value	0.1117

11 |

The Use of Artificial Intelligence: The Challenge of Environmental Protection in México

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Abstract

This article addresses the normalised problems of pollution, dispossession, and extractivism carried out by mining companies in Mexican communities. It analyses the importance of applying artificial intelligence (AI) to streamline exploration and extraction processes with fewer resources, greater profit, and potentially less impact on the environment. At the same time, it reflects on whether this technological application could shift the current extractive logic or simply become another tool to increase disproportionate and unconscious extractivism. The discussion focuses on whether AI can genuinely contribute to environmental care or if it risks exacerbating damage to nature and the health of the inhabitants of the communities surrounding the activities of mega-mining.

Keywords: mining, extractivism, imperialism, artificial intelligence

JEL Codes: L72, O14, O32, Q51

1. Introduction

Mining dates back to antiquity and has indisputable socio-economic importance within contemporary capitalism. Today, it remains a profit-generating activity of considerable importance, particularly for transnational capital. However, it also produces serious, and in some cases irreversible, environmental contamination that significantly affects the health and development of inhabitants in the communities where such activities occur.

From this context, several pressing questions emerge: Is it possible to reverse the environmental harm generated by mining? Can the economic benefits be balanced with a reduced environmental footprint? Should ecological care take precedence over economic development? The most immediate responses tend to polarise: some advocate halting all mining activities in defence of the environment, while others support the continuation of mining for its economic benefits and the sources of income it sustains.

In the mineral extraction process, multiple actors converge: society, the State, companies, the environment, and non-governmental organisations. Each of these groups holds distinct interests and perspectives on development and the common good. Those with economic and legislative power tend to promote a hegemonic model rooted in extractivism, prioritising growth from a market-driven viewpoint. In contrast, others—often with fewer resources and limited institutional access—struggle for environmental justice through prolonged, uneven efforts grounded in communal and ecological understandings of development.

Technological investment in the mining sector is substantial. Open-pit mining, for example, offers high and often rapid returns, despite heightened risks of ecological harm As a potential alternative, the use of artificial intelligence (AI) is proposed to support more precise territorial exploration and to assess environmental impacts. By aiding in the detection of deposits, analysing geological and geophysical data, and optimising extraction techniques, AI may reduce the spatial and temporal costs associated with mining. However, the challenge remains to ensure that such technologies serve the integrity and development of affected populations.

AI has already been adopted to enhance mineral extraction through real-time monitoring, targeted exploration, and systematised data analysis—thereby improving profitability and efficiency. Nevertheless, its implementation has so far aligned more with the goals of resource exploitation than environmental protection. As such, the central question persists: can AI function as a bridge between mining activity and environmental stewardship, or does it risk reinforcing the dynamics of extractivism and the degradation experienced by the inhabitants of the communities surrounding the activities of mega-mining?

Recognising the broader context of a capitalist system marked by asymmetries in power and ownership, this paper suggests that technological advancement should not merely be guided by the imperatives of capital. Rather, it argues for innovation grounded in sustainability and human well-being—offering pathways to mitigate environmental harm while preserving the resources vital for future generations.

2. Capitalist Hegemony and Environmental Care

For a better understanding of the dynamics of imperialist mining companies, it is necessary to consider different factors that converge directly in the process of mineral extraction—such as the participation of society, the State, companies, the environment, and environmental activists—each with their own interests and interpretations of development and the common good.

In this configuration, legal instruments, police forces, and the military are often utilised to safeguard these interests. Through representative democracy, the ruling class legitimises its power by portraying it as the will of the people, thereby concealing the class-based nature of political dominance. This gives rise to the concept of cultural dominance which reflects how prevailing belief systems are standardised and presented as a just and unalterable social order. These belief systems are disseminated through education systems, media channels, and other cultural institutions.

This control operates not only in the economic dimension but also in shaping power structures, ideological frameworks, and social norms. By holding the means of production, the ruling class is able to configure social reality to its advantage, defining what is deemed just, legitimate, and acceptable. In contrast, opposing views are frequently characterised as unjust, uninformed, or socially detrimental.

However, this structure is not always readily perceived, given that the material and social conditions experienced by individuals often hinder deep reflection on their lived realities. Immersed in daily routines, many people lack access to critical perspectives on the systems that constrain them. As they are caught in repetitive cycles of labour, consumption, and adaptation, these structures—though artificial—are internalised as natural. In doing so, the belief systems underpinning capitalism are presented as objective truths, naturalising inequality and authoritarian control, and reinforcing the notion that the existing order is the only viable one.

Thus, dominant belief systems tend to frame alternative ways of life or thought as inherently subversive or threatening. Anything that deviates from bourgeois standards is rapidly labelled as immoral or harmful, contributing to the maintenance of the prevailing system. Political ecology, in this sense, serves as a tool to delve deeper into these socio-environmental dynamics and propose pathways toward genuine sustainability and justice.

The incorporation of technology—including AI—into mining must therefore be approached critically. From this standpoint, research must transition from superficial to complex analyses, capturing all aspects of the issue. Social inquiry must likewise account for transformations over time, including shifts in cultural values, normative structures, and technological developments, as this paper aims to do.

3. Use of AI in Mining Extraction

The main characteristics of AI are its capacity to function without rest, analyse large volumes of data, exhibit lower error rates, and perform tasks involving learning and decision-making. These attributes make AI highly efficient and effective in scenarios that demand continuous processing or the management of complex information.

However, it is important to acknowledge that despite its advanced capabilities, AI is not fully autonomous. Its functionality depends on prior human input, including accurate data and carefully developed algorithms. The quality of AI outputs is directly related to the quality of the information provided and the mathematical models employed.

Furthermore, although AI can adapt to new circumstances via machine learning algorithms, it still requires human supervision and calibration to ensure that its actions remain ethical and aligned with established objectives. Hence, AI acts as a complement to human activity rather than a replacement.

Regarding its application in mining, AI is proposed through the following methodology:

> *to obtain operational pushbacks for open pit mines that maximise the NPV of the project while respecting operational and design constraints. This integrated approach is achieved through the combined application of a genetic algorithm and a clustering algorithm (K-means). A genetic algorithm is defined as a heuristic search inspired by the theory of evolution and a clustering algorithm (K-means). These techniques provide efficient solutions to complex optimization problems and are described in the following sections (Loor Cárdenas, 2020, p. 3).*

In other words, it is the integration and grouping of geological and subsurface data, with the purpose of respecting the operability and increasing and efficient extraction of minerals and metals, as well as profits.

> *methodology that helps to improve VASEH using satellite imagery and deep learning systems, focusing on generating tools that are as automatic as possible and independent of third parties. The new approach, when integrating remote sensing and A.I., allows 3 main improvements with respect to the algorithm that has been used to classify images in the GEA research projects: (i) updated information is used with respect to the spatial and temporal component; (ii) CNNs are used, which are more powerful algorithms with respect to classical machine learning techniques; and (iii) a proprietary framework is used to make the entire classification process, from start to finish, be carried out in the same environment, thus making the process more agile and simple for the user (Pardo Calvache, et al, 2023, p. 70).*

The implementation of AI has also been proposed to obtain information about the Earth from remote sensors, such as satellites. This technology makes it possible to generate land cover maps, which analyse changes in land cover over time to identify areas impacted by human activities and quantify changes, considering biophysical, social, and economic aspects.

Therefore, it is observed that the implementation of technology and, in particular, the use of AI is applied to make both material and human resources more efficient in the process of exploration and extraction of minerals and metals, with an initial and slight intention of caring for the environment, which already at the time of application the impetus of imperialist extractivism leaves it aside, and the environmental damage is only accentuated.

4. Dispossession as a Means of Livelihood for Mining Imperialism

4. 1. Dispossession

The dispossession is not only characterised by its violent nature but that this coercion presents itself in multiple and varied ways. In many cases, it can take indirect forms, which are difficult to identify at first glance, in which power dynamics are masked behind agreements that appear to be mutually beneficial.

This facade of collabouration can blur the reality of exploitation or abuse that underlies such social relations. Moreover, in certain situations, this coercion is endorsed or supported by the state, adding complexity to the social dynamics.

This support is seen in the laws and regulations that are issued; for example, in the Political Constitution of the United Mexican States, Article 27 in its second paragraph reads as follows: ... *"Expropriations may only be made for reasons of public utility and by means of compensation. The nation shall always have the right to impose on private property the modalities dictated by the public interest. Paragraph amended DOF 06-02-1976, 10-08-1987, 06-01-1992*" (Political Constitution of the United Mexican States, 2024, *translated by authors*).

Therefore, in its regulatory law, which is the Mining Law, Article 6 mentions which activities are considered to be of public utility: "The exploration, exploitation and benefit of the minerals or substances referred to in this Law are of public utility; their purpose is to contribute to the equitable distribution of public resources guarantee the protection of the environment, achieve the balanced and sustainable development of the country and improve the living conditions of the population. Paragraph reformed DOF 08-05-2023" (Mining Law, 1992, translated by authors)

Although it mentions that environmental protection must be guaranteed, the reality of the situation is different. The State's background in advancing the interests of capital always benefits the bourgeoisie by prioritizing the safeguarding of private property, the increase of profit, and extensive and intensive collabouration to increase the resources of the owners of the means of production.

The dates of the modification of the constitutional paragraphs, executed between 1992 and 2023, illustrate the priority of the neoliberal reforms that have been lived in Mexico under this logic. Therefore, the intervention of the State in benefiting extractivism and dispossession is evident from the supreme law that governs the country, the Constitution, and how it seeks to blur this impartiality, to mention the intention of safeguarding the environment. However, it remains only on paper.

For this paper, we will address the dispossession of a community or village, which we will understand as the dispossession of common goods, which means, according to Navarro: "the dispossession of common goods is always, at the same time, a dispossession of the political capacities of the community that owns and uses the resources taken from it" (Navarro Trujillo, 2015, p. 31).

The multiple dispossession: the effect is not only on one person or one family but also on society, a community, a group of families, and individuals. In other words, multiple dispossessions arise from the incessant aggregation of capital from a common resource in a population. Consequently, when glimpsing the relationship between capital aggregation dispossession and coercion there are different scopes, as Navarro Trujillo (2015) argues:

> *The process of accumulation between capital and its relationship with non-capitalist forms of production is marked without any disguise by violence, deceit, oppression and rapine (Luxemburg, 1967, p. 224). In analysing the imperialism of the late nineteenth and early twentieth centuries, Luxemburg reflects on the destructive advance of the current forms of capital accumulation at the expense of natural and peasant economies. In this sense, she points out that "violence, deceit, oppression and pillage" -although disguised under legal forms and covered by the ideologies of progress, modernization and development- have been the privileged mechanisms to achieve this goal. And the fact is that "capital has (...) no other solution than violence, which constitutes*

> *a constant method of capital accumulation in the historical process, not only in its genesis, but at all times, until today" (ibid.: 180). The violent method is, here, the direct result of the clash of capitalism with the formations of natural economy that hinder its accumulation (Navarro Trujillo, 2015, p. 35).*

Today, in 2025, the 21st century, this violent process of capital aggregation which began two centuries ago, continues, and its social and developmental effect is essentially destructive. This destruction is evident and palpable, both for society and for the environment, which has been damaged and devastated as capitalism, in its extractivist configuration, increases its activity. With all the above, the question arises as to why, if capitalism's coercion damage, and deceit are so evident, it continues to generate and support its development and extension. Although not entirely, this can be elucidated with the following reflection.

> *Underlying the language of dispossession is a false dichotomy between "development" versus "poverty," in that the former is presumed to be capable of eradicating the latter. At least two dominant senses of "poverty" are contained in this approach: on the one hand, the one that understands it as the lack of progress and lack of willingness of the poor to modernise and integrate into the system, which is expressed in the need of capital to incorporate non-Western or considered pre-capitalist modes of consumption and production to the process of value valorisation; and on the other hand, the one that conceives it as a predatory force of nature, which can be mitigated through the market and its mechanisms of optimal allocation, putting order to the "disorganisation" with which the community sphere is viewed (Navarro Trujillo, 2015, p. 60).*

Through this process, we can see how the accumulation of capital is fuelled by practices that, far from being transparent and ethical, are based on the violent dispossession of land and resources with the participation or approval of the State. Companies resort to deception and manipulation, presenting themselves as agents of development and progress for the communities where they are installed and carry out their extractive activities. This discourse, which apparently promises well-being, development, and progress to society, hides the actual consequences of their activities.

This perpetuates a cycle of exploitation that damages the natural environment and undermines the health and development of the local population. While extractivism is commonly understood as extracting material or raw resources, it is crucial to clarify that these resources must be exported from their original location:

> *Extractivism is the export of unprocessed or poorly processed natural resources, from which it becomes necessary to specify this condition. For this purpose, we take as a frame of reference the criteria of the United Nations Statistics Division (widely used in Latin America by ECLAC). Therefore, the condition of limited or absent processing refers to the set of so-called "primary products" (Gudynas, 2013, p.4).*

Therefore, the extractvism should be observed from a globalised perspective, in which the raw material and the merchandise move from one territory to another from its extraction, processing and sale, likewise, it should be emphasised the:

> *the coexistence and specific combination of two forms of capitalism, one based on the capital-labour relation, or the exploitation of surplus labour force coming from agriculture, and the other sustained on the appropriation of naturalisation - the extraction and exploitation of natural resources to be exported in primary form (extractivism) (Veltmeyer & Zayago Lau, 2019, p. 46).*

With the above, a critical point is added in which the relationship between the extraction of natural resources from the territory of origin and the society that inhabits that territory can be glimpsed. This link is manifested in a particularly significant way through the exploitation of the labour force. This is made possible by the overt action of the State in its role as guardian of capital. Extractivism not only involves the direct intervention of natural resource extraction but also profoundly impacts local communities social and economic structure. Companies operating in these regions often use local labour, which may appear beneficial in employment.

However, in many cases, this relationship is characterised by precarious working conditions, low wages, a lack of fundamental labour rights, and irreparable damage to the health of both workers and community inhabitants. The relationship between the extraction of natural resources from the territory of origin and the society inhabiting that territory can be glimpsed, and it is the exploitation of the labour force.

Finally, the concept of extractivism refers to the process of extracting natural resources from a specific territory to process and commercialise them in other markets. This phenomenon not only implies the physical extraction of resources but also involves the exploitation of the local labour force, which is often subjected to precarious and unequal working conditions.

Extractivism manifests through various forms of land rents, where companies obtain significant economic benefits while local communities receive little in return. Moreover, public policies often play a crucial role in this process, as they are often designed to favour the interests of corporations rather than protect the rights and welfare of affected populations. These policies may include the relaxation of environmental regulations, tax incentives, and the promotion of foreign investments that ignore extractive activity's social and ecological effect.

In this way, extractivism becomes a process of systematic dispossession, where communities are stripped of their resources, their land, and, in many cases, their culture. This dispossession not only has economic consequences but also generates a deep social fracture as communities face the loss of their identity and autonomy.

5. Imperialism and Capital Expansion

To begin to define imperialism,

> *Therefore, this extension of domination is accompanied by force, it is not a peaceful acceptance or an honest transition, it is accompanied by deception, very similar to what was observed in dispossession. As for the concept of imperialism as previously observed it has an intimate relationship with capitalism however, they are not the same, they are related in the sense that for imperialism to develop a capitalist economic system is necessary. "Lenin theorized imperialism as the highest form of capitalism, a manifestation of its fundamental laws of development" (Veltmeyer & Petras, 2019, p. 12).*

Therefore, for imperialism to be established, the economic structure of the host country must be adapted to the impositions of the imperialist country. This requires, in the first place, state power since the governmental institutions of the host country must be willing to accept and facilitate external influence, often through enacting laws and policies that favour the interests of the empire. The

State becomes a facilitator of the extractive processes on behalf of the transnational capitalist class and, therefore, with the complacency of the local bourgeoisie, an indispensable element in the extractivist configuration.

In addition, the imperialist country's intervention usually involves the use of military force, either to subdue local resistance or to protect the empire's economic and political interests in the region. The presence of armed forces can be crucial to guaranteeing the stability of the new imposed order, avoiding revolts, and ensuring control over the natural resources extracted from the territory.

> *At least four central aspects of the Marxist theory of imperialism can be distinguished that contributed in a novel and rigorous way to the understanding and explanation of the capitalist mode of production: the tendency towards concentration, centralization, export and worldwide geographic expansion of capital; the progressive division of the globe into "advanced" and "backward" nations; the division of the world by the powers and their domination over peripheral regions and economies, and the role of the latter in the development of the capitalist world system (Martínez Álvarez, 2024, p. 168).*

From the above, it is important to highlight the four aspects: concentration, centralization, export and expansion. In these we can see, at a glance, how an imperialist country calling itself "advanced" takes advantage of an imperialist country over another called "backward."

The imperialism seeks to establish a system that allows it to continuously extract resources and wealth from territories where they are abundant or have not been exploited, maximising profit and obtaining a greater accumulation of capital. To achieve this, it dispossesses local populations of their lands and resources, transforming their traditional economies and way of life.

6. Mega-Mining in Mexico: A Case of Zacatecas

We understand that the capitalist mining system uses dispossession as a source of subsistence and that the hegemony exercised over society does not allow them to glimpse or oppose the excessive extractivism that they carry out day by day.

The central issue in the Mexican context is the situation experienced daily by inhabitants of mining communities. The direct influence of imperialism in the dispossession of territory for the incessant and disproportionate accumulation of capital through neoliberal policies and reforms that, under the mask of progress, gave open and strong passage to capitalist companies is palpably and directly observed.

> *In the Mexican mining sector, parastatal mining companies were privatised during the first three years of the Carlos Salinas government (1988-1994) and were sold with little transparency, at prices well below their market value, to certain Mexican businessmen (Delgado-Wise and Del Pozo, 2002). Among the most important are Jorge Larrea, father of Germán Larrea, current owner of the mining company Grupo México; Alberto Bailleres, owner of Industrias Peñoles; and Carlos Slim, whose business emporium includes the Frisco mining company, which is involved in the mining conflict in Salaverna, Mazapil in Zacatecas state (Uribe Sierra, Gómez Alonso, & Tetreault, 2020).*

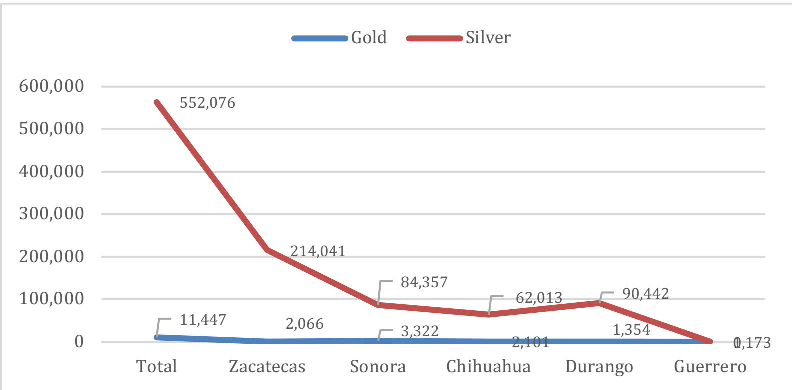
In addition, to solve the direct interference of the State partially and benefit the transnational capital, specific laws were created to facilitate the extraction permit and the extraction of the deposits for derisory times that, for example, revolve around the time of life of a person, with the possibility of extending for other years to appropriate and exploit the natural resources, causing irreparable damage to the ecological system and health of the nearby inhabitants.

> *The year 1992 was a key year for extending neoliberal reforms to the mining sector in Mexico. In that year, the government of Carlos Salinas made changes to the Political Constitution of the United Mexican States and to the agrarian, mining and other laws to give private and foreign capital greater access to land, minerals, water and other natural resources. Thus, the 1992 Mining Law, which is still in force, was enacted to completely open the sector to private and foreign investment, extend the term of mining concessions from 25 to 50 years and establish that mining will have preference over any other productive use of land (Uribe Sierra, Gómez Alonso, & Tetreault, 2020).*

It is worth mentioning that the extraction process destroys the soil and contaminates the water and the air, thus affecting the local flora and fauna. Likewise, contamination not only stays in one place but expands to miles away from its origin, thus magnifying and amplifying its devastating reach. This neoliberal process continued with a excessive increase, according to Aleida Azmar and Isidro Tellez *"(2013-2018) 4.1 million hectares were granted in new concessions, an area almost three times larger than that delivered during the period 1982-2000, when a total of 1,481,694 hectares were granted. [...] However, by that time mining concessions totaled 36.3 million hectares*" (Azamar-Alonso and Téllez-Ramírez, 2022; Semarnat, 2022, p.17).

In 2015, mining extraction reached the state with the largest concession territory in Sonora, and the amounts of extraction were as shown in the following table, figures in kg.

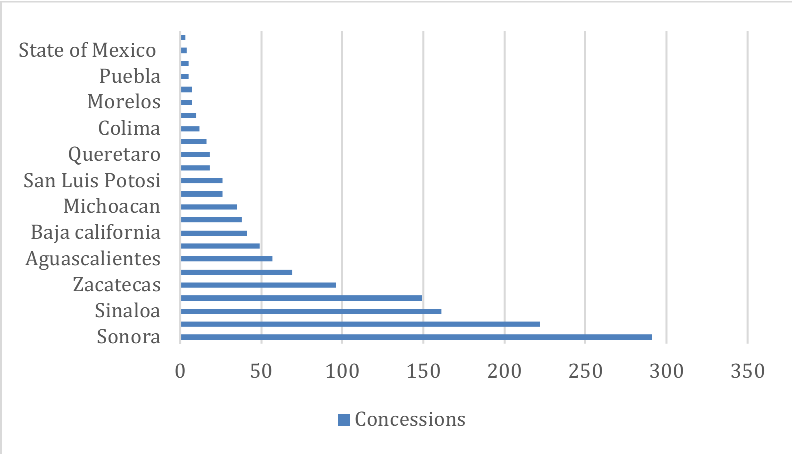
Graphic 1. Mining and metallurgical industry data



Own creation based on statistics of the mining and metallurgical industry (December 2024).

The latest gold and silver mining report (SGM, 2024, p.14,15) was 128.50 million ounces of gold and 233.99 million ounces 2023 of silver in 2023. Notably, 1,609 mining concessions operate in 68 of the 142 terrestrial Natural Protected Areas (NPAs). There are 1.5 million hectares under concession in these areas, corresponding to 7.7% of the protected land area. (Azamar-Alonso and Téllez-Ramírez, 2022; Semarnat, 2022, p.12).

Graphic 2. Mining concessions in México



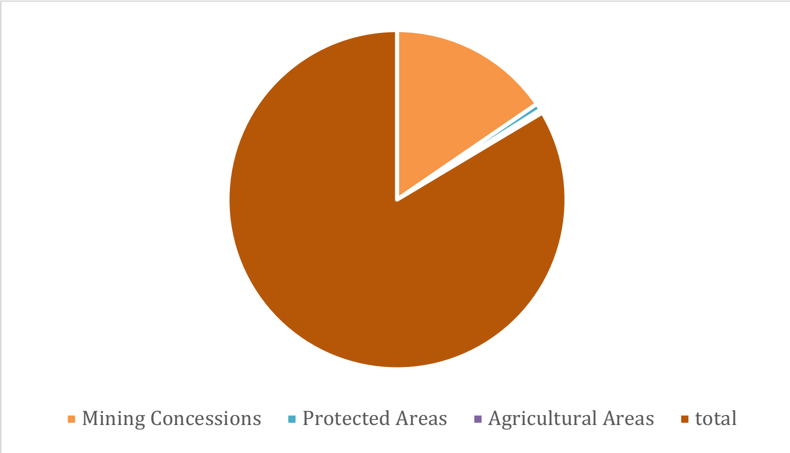
Own research with data from https://geocomunes.org/

The territory in which activities are carried out and the extraction of metals and minerals have been increasing year by year, covering a considerable percentage of the national territory. The total area of Mexican territory is 196 437 500 hectares (INEGI, 2017), for agricultural and forestry production units in Mexico totalled 473 484, and its agricultural area totalled 801 100 hectares (INEGI,2023). Mining concessions totalled a surface area of 36.3 million hectares (Azamar-Alonso and Téllez-Ramírez, 2022; Semarnat, 2022, p.17).

In the state of Zacatecas, Mexico it is one of the most outstanding activities, both in the economic and cultural areas, since it is so deeply rooted in society as an activity that generated the founding of the state and its growth. This argument seeks to hide the reality and its irreparable consequences.

> *according to the National Institute of Statistics and Geography (2013), exports in mining increased in nominal terms from 262.6 million dollars in 2007 to 1'796.2 million dollars in 2012, with a growth in real terms of 557.8% (Guzmán López, 2015, p. 112).*

Graphic 3. Territory



Own research with data from (INEGI, 2017), ((INEGI,2023), (Azamar-Alonso and Téllez-Ramírez, 2022; Semarnat, 2022, p.17).

As previously analysed, capitalist imperialism invades territories through physical or economic violence, with the support of the State that generates legislation in favour of its interests in the search for maximum profit, dispossessing the inhabitants of that place of their territory, activities, and development. This dispossession is so visible that it has relegated almost to disappearance as the main activity in Zacatecas in recent years. The small and medium mining, local and articulated to the Zacatecas society, has been displaced, which for many years fed and supplied the bulk of the local family, avoiding starvation, disease or death, changing it for the enrichment of a few outside the Mexican territory.

> *Environmental impacts caused by open-pit mining megaprojects in the state of Zacatecas, Mexico 22.72%, while for the year 2012 it decreased to 6.8%. In the opposite direction, mining reported an increasing trend for the same period; in 16 years of the period, the contribution of mining production to the state GDP increased almost nine times; a situation that has recently worsened, if we consider that in 1997 the contribution was 4.42% and increased 38.3% by 2012 (Guzmán López, 2015, p. 114).*

Therefore, it is evident that the dispossession that began in the 1990s continues with devastating force over Zacatecas society. In only 30 years, the State and its inhabitants are already facing the consequences of the overexploitation of its natural resources, manifested in the contamination of water, the destruction of the soil, the pollution of the air, and the increase of diseases.

> *It is carried out regardless of the devastation of the territory, the obstruction of the responsible care and use of common goods, as well as the systematic violation of human rights and the deepening of a crisis of human insecurity, the latter understood as the loss of people's standard of living and quality of life, which "reduces the person to a human commodity" (Márquez et al. 2012, p. 35). For Zacatecas, this is the effect of the neoliberal development model, in which territory, common goods and life are commodified, and which generates victims excluded from the benefit of the surpluses generated in the entity (Guzmán López, 2015, p. 116).*

Although the concession time has not yet been extended, if this trend continues, by the time the 50-year legal concession period is reached, the territory will be devastated. Society will suffer from serious health problems, precariousness, and poverty. It is crucial to address these issues urgently, promoting sustainable resource management and ensuring the well-being of the affected communities.

7. Conclusion

In the hegemonic capitalist system, in its contemporary imperialist version, where mining capital is concentrated in extracting natural resources from developing countries, as they call them, the technological frontiers have moved forward. In this regard, Mexico began with constitutional reforms and the creation of the mining law, representing a watershed that gave way to the concessions of territory for mining activities disproportionately.

The analysis in this paper shows how metal extraction and the territory consumed by mining increase year by year, even when the granting of new mining concessions has stopped. Implementing new technologies plays an important role in this phenomenon, aimed at reducing exploration time, increasing profits, and increasing automation processes such as A.I. This technology, therefore, accelerates the extraction processes and makes more efficient use of the resources available for large-scale mining.

In observing the catastrophic and disastrous damage caused by mega-mining activities, we seek to reduce the industry's impact, including damage to the environment. However, there is a structural tension between technological progress and ecological damage. It is assumed that the development of new technologies brings with it an intrinsic ecological benefit, but this is not an objective under the mercantile and capitalist system, where profit and competitiveness are subordinated to any other objective.

Consequently, it is crucial that counter-hegemonic arguments, those that seek to dismantle power structures and propose new forms of social organisation, be sustained in a solid, logical, and formal manner. Only through a well-founded argumentation, well-articulated and supported by concrete evidence, is it possible to effectively confront bourgeois hegemony and open the way to a fundamental transformation in social and production relations, which are the ones that determine or influence environmental impact. The struggle against hegemony is fought at the economic and ideological levels, where the ideas that induce structural changes and social relations are the real protagonists of social change.

The big question is whether it is possible to integrate technology, mining, and sustainability in a way that strikes a balance between economic development and environmental preservation under the conventions of the current production system. Suppose technology is oriented toward sustainability based on an adjustment in social relations. In that case, it can become a powerful tool to reduce the ecological footprint of mining, promote the regeneration of ecosystems, and ensure that local communities do not suffer the adverse effects of excessive extractive activity.

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PART V

WAR WITHOUT HUMANS: ETHICS, AI, AND THE FUTURE OF DEMOCRATIC LEGITIMACY

In recent decades, warfare has increasingly moved away from direct human engagement toward a domain dominated by machines, algorithms, and autonomous systems. The integration of Artificial Intelligence (AI) into unmanned combat vehicles (UCVs) represents not only a technological leap but a fundamental shift in how war is conceived, conducted, and justified. This part of the book delves into the ethical dilemmas and political consequences of this transformation, where the presence of human judgment is progressively sidelined by automated decision-making.

As military operations become more "efficient" through the use of AI-driven platforms, the traditional boundaries of accountability, legality, and civilian oversight begin to blur. The ease with which states can now initiate and sustain conflict—without parliamentary approval, public scrutiny, or clear attribution of responsibility—poses a critical threat to the democratic foundations of modern governance. Through the case of unmanned aerial systems and AI-enhanced warfare, this section explores how emerging technologies can erode democratic legitimacy by shifting power from public institutions to opaque techno-military complexes.

This final part challenges readers to confront a stark question: in a world where war can be waged without humans, what becomes of our most human values—ethics, responsibility, and democratic control?

12

The Dehumanization of Warfare: The Role of Unmanned Combat Vehicles and Artificial Intelligence in Modern Conflict

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Abstract

As unmanned combat aerial vehicles (UCAVs) have become a reality in both interstate and intrastate conflicts, states that have witnessed their effectiveness in conflict zones have increasingly invested in other types of unmanned combat vehicles (UCVs), such as unmanned ground vehicles (UGVs), unmanned surface vehicles (USVs), and unmanned underwater vehicles (UUVs). The competition between states in the development and deployment of unmanned systems has led to the emergence of a substantial industry within the military–industrial complex. The final stage of this process is the integration of Artificial Intelligence (AI) into these platforms. While the integration of AI offers strategic advantages for technologically advanced states, it also introduces unforeseen risks that may fundamentally transform the nature of war and conflict. Within this framework, the present study aims to examine the negative and positive consequences of the dehumanisation of warfare. It first analyses the proliferation of UCAVs, followed by the integration of AI into these vehicles. The study argues that while UCVs provide certain benefits—such as reducing the number of human casualties—their widespread use has also led to increased civilian deaths and injuries. Although AI integration offers the possibility of reducing collateral damage, it fails to resolve issues of political accountability and the depoliticisation of war.

Keywords: unmanned combat vehicles, artificial intelligence, warfare, conflict

1. Introduction

Technological advancements have historically shaped the nature and conduct of warfare. Innovations such as gunpowder, mechanised warfare following the Industrial Revolution, the development of nuclear weapons during the Cold War, and the integration of digital systems into military operations have all significantly transformed conflict dynamics. While war continues to serve as a means for political actors to pursue their objectives, technological evolution has profoundly changed its character. These changes have also altered how political entities conceptualise security, requiring them to address threats stemming from ongoing technological progress.

Two contemporary innovations with transformative potential are:

1) the deployment of unmanned combat vehicles (UCVs) across land, air, and sea; and

2) the incorporation of Artificial Intelligence (AI) into such systems.

These advancements reduce human involvement in warfare—a trend often referred to as the dehumanisation of conflict. The rapid evolution of military technologies since the early 2000s highlights this shift. While the promise of lower political, economic, and humanitarian costs is often cited, such technologies also raise complex ethical and strategic concerns.

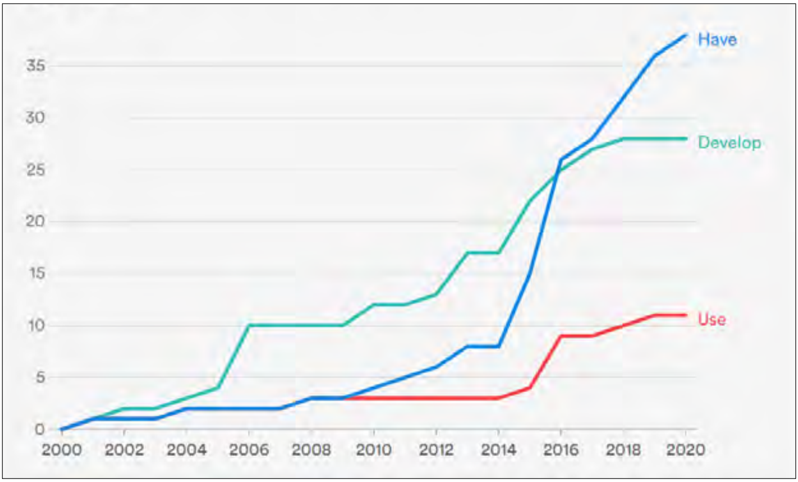
This study explores the implications of dehumanised warfare. It begins by examining the spread of UCAVs, focusing on their role since the early 2000s. It then analyses the inclusion of AI within national security strategies, as well as the risks it poses. Finally, the study assesses the advantages and disadvantages of AI-integrated UCVs, particularly in terms of their impact on international humanitarian norms and political accountability.

2. Proliferation of Unmanned Combat Vehicles

While efforts to develop unmanned vehicles date back many decades, the 2000s marked a pivotal moment in the deployment of UCVs. UCAVs, in particular, have become a hallmark of modern conflict zones. Today, numerous actors possess the capability to develop or use UCAVs. Modern UCAV technology, initially introduced by the United States (US) after 2001 during the fight against global terrorism, has since evolved into a critical security tool and a strategic foreign policy instrument for many states.

Israel was among the first countries to follow the US in adopting UCAV technology, emerging as one of the few nations to have and develop this capability in the early 2000s. By 2010, Iran had also entered the field, employing reverse engineering to develop UCAVs as part of its strategy to counter both direct and indirect threats from Israel and the US (Lendon, 2014). This development positioned Iran as a significant player in UCAV technology and its proliferation. During the 2010s, the use of UCAV technology expanded dramatically. It was no longer limited to states; armed non-state actors also began using these vehicles in conflict zones, further altering the landscape of modern warfare.

Figure 1.: Number of States Developing, Having, and Using UCAVs between 2000-2020



Note: New America, 2020a.

As illustrated in Figure 1, no state possessed UCAV technology in 2000. The US was the first to develop and use it in 2001. By 2004, four states had UCAV technology, though only two used it in conflict zones. By 2010, 12 states were capable of developing UCAVs, four had them, and three actively used them in conflict. The 2010s witnessed a steady increase in the number of states involved in having, developing, and using UCAVs. By 2015, 22 states could develop UCAVs, 15 had the technology, and four used it in conflict zones. By 2020, these figures surged, with 28 states capable of producing UCAVs, 38 having them, and 11 using them in conflicts. The number of states capable of accessing UCAV technology rises each year. By 2024, it is estimated that at least 42 states possess UCAV technology, either through domestic development or imports from other countries. Moreover, at least 11 additional states are expected to acquire this technology in the near future (Drone Wars, 2024). When including armed non-state actors, it becomes evident that UCAVs have become indispensable in modern warfare. The list of states with UCAV technology spans major powers like the US, China, and Russia; middle powers such as Pakistan, Turkey, and Iran; and smaller powers like Burkina Faso, Georgia, and Iraq (New America, 2020b).

Several factors have driven the proliferation and widespread use of UCAV technology since 2000. Key factors can be summarized as the increasing number of states capable of producing UCAVs, the acceleration of technology transfers, and the frequent use of UCAVs in conflict zones. States producing UCAVs often share this technology with allies, sell it as part of diplomatic agreements, or engage in commercial transactions. Declining production costs have made UCAVs accessible to economically weaker states, such as Ethiopia, Togo, and Sudan. For example, while the US-origin Reaper UCAV costs an estimated $28 million, the Turkish TB2 UCAV is priced at approximately $5 million (Atherton, 2023). The lower costs of commercial UAVs and simpler UCAVs have also attracted armed non-state actors, further fueling their proliferation in international conflicts.

Emerging conflict zones have also significantly contributed to the widespread use of UCAVs. These areas serve as testing grounds for technology, solidifying its strategic importance for both state and non-state actors. For instance, the US global war on terrorism heavily influenced the use of UCAVs. During the Bush administration, the US conducted 48 UCAV strikes in Pakistan, a figure that surged to 363 under the Obama administration, totaling 414 strikes (New America, 2023a). Yemen similarly became a key site for UCAV operations, with the US executing 378 strikes by 2023 (New America, 2023b). In Somalia, an undeclared war zone, the US carried out 355 UCAV strikes after 2003 (New America, 2023c). Libya became another major theater for UCAV operations following NATO's 2011 intervention, with the US conducting 550 airstrikes, 513 of which occurred in 2016, heavily relying on UCAV technology (New America, 2020c).

Ongoing conflicts in the Middle East have further accelerated UCAV proliferation. Israel has been the regional leader in utilizing UCAVs to address threats. Over time, however, anti-Israeli actors acquired UCAV technology and began employing it against Israel. In this context, Iran and its conflicts with Israel have played a pivotal role in spreading UCAV technology throughout the region. Iran developed its first UCAV in 2010 (Black, 2010) and conducted its first operational UCAV attack in 2016, targeting northern Syria (Gettinger, 2020, p. 181). In April 2024, Iran launched over 100 drones in retaliation for Israeli airstrikes (Al Jazeera, 2024a). Iran has also supplied UCAVs to Hezbollah, Hamas, Houthi forces in Yemen, and Shiite militias in Iraq (Hanna, 2021; Loveluck et al., 2021). Iran's role extends beyond the Middle East, as it has reportedly sold UCAVs to nations such as Venezuela, Ethiopia, Tajikistan, Sudan, and Russia (Nada, 2023). Turkey has also deployed its UCAVs in various conflicts in the Middle East, targeting PKK positions in Iraq (Reuters, 2023), YPG forces in Syria (Daily Sabah, 2020), and even Russian-backed Syrian Armed Forces in Syria (Urcosta, 2021). These operations underscore Turkey's increasing reliance on its domestically developed UCAV technology to address both domestic and international security challenges.

In addition to Israel, Turkey, Iran and its allies, other armed non-state actors in the Middle East have increasingly employed UCAVs in conflict zones. For example, ISIS has carried out numerous UCAV attacks in Iraq and Syria (Al-Moghedi & Aljuhani, 2023:8), Al-Qaeda began weaponizing UAVs in 2013 and the PKK has launched UAV attacks from northern Syria targeting Turkey, particularly in 2017 (Habertürk, 2019). These cases underscore that UAV and UCAV technologies are becoming frequently used tools in the region's conflicts by various armed non-state actors.

Recent international conflicts, such as the Nagorno-Karabakh War and the Russia-Ukraine War, have underscored UCAVs' strategic importance. In the Second Nagorno-Karabakh War, which erupted between Azerbaijan and

Armenia in 2020, Turkey provided UCAV technology to Azerbaijan. It is widely claimed that the UCAVs supplied by Turkey significantly boosted Azerbaijan's offensive capabilities against Armenia, playing a key role in Azerbaijan's military success (Martins et al., 2023:1). Turkey's UCAV technology has also been prominent in the ongoing Russia-Ukraine conflict. Turkey began selling UAVs to Ukraine in 2019, which Ukraine has actively deployed against Russia. Turkey has also signed agreements for additional UAV deliveries to Ukraine and committed to joint production initiatives (Farooq, 2022). In addition to Turkey's contributions, Iran has supplied UCAVs to Russia for use in the conflict against Ukraine. This has prompted the US and the European Union to impose sanctions on Iranian companies, research centers, and individuals linked to the production and supply of these Iranian-origin UAVs (U.S. Department of Treasury, 2022). Moreover, events during the Russia-Ukraine war provide an important case study in the use of AI-enabled unmanned surface vehicles (USVs) (Aksu, 2024, p. 4) and even this war was defined as the 'war of drones' (Balmforth, 2023).

The proliferation of UCVs, particularly UCAVs, signifies the dehumanization of warfare. These vehicles enable states and non-state actors to mitigate the economic, political, and humanitarian costs of conflict. Specifically, national armies can minimize casualties and protect soldiers' lives during engagements. In this context, the integration of AI underscores the diminishing human involvement in conflict zones while simultaneously reducing the direct costs associated with wars and conflicts.

3. Artificial Intelligence and Modern Warfare

AI technology has not yet entered the combat arena in a significant way, but experts predict its potential impact on the future of warfare. This influence depends on several factors, including the rate of commercial investment, competition among global powers, advancements in AI research, the military's acceptance of AI applications, and the development of AI-specific warfighting strategies (Sayler, 2019:34). This section will examine early attempts by leading states to integrate AI into national security strategies and the potential effects of AI on modern warfare.

3.1. Artificial Intelligence and National Security

AI technology became a prominent reality for states during the 2010s, with almost every nation seeking to integrate it into their national security strategies. These strategies extend beyond military applications, encompassing AI use in cybersecurity, information security, economic and financial statecraft, defense, intelligence, homeland security, diplomacy, and humanitarian missions (Horowitz et al., 2018).

Major actors in international politics are particularly focused on long-term plans to incorporate AI into national security strategies. For example, in July 2017, China's State Council issued the 'New Generation Artificial Intelligence Development Plan' (AIDP). This document, along with 'Made in China 2025' released in May 2015, forms the foundation of China's AI strategy (Allen, 2019:3). The AIDP is a pivotal indicator of China's commitment to AI as a strategic tool, emphasizing international competition, economic growth, and social governance. It represents as a transformative policy aimed at securing China's influence in global competition (Erdoğdu, 2021:6).

Similarly, the US acknowledges the importance of AI in military affairs. 'The US National Defense Strategy' released in January 2018 identified AI as a critical technology for ensuring the nation's ability to win future wars (Sayler, 2019:1). Reflecting this priority, the US Department of Defense (DoD) increased its unclassified investments in AI from over $600 million in 2016 to $927 million in 2020, and further to $1.1 billion in 2023, maintaining over 685 active AI projects (Harris, 2023:6). Russia also recognizes AI's strategic significance. In 2017, President Vladimir Putin declared, "Whoever becomes the leader in this field will rule the world" (Congressional Research Service, 2020). By the early 2020s, over 50 nations had adopted AI strategies as part of their national policies (Erdoğdu, 2021:6).

3.2. AI Integration to Modern Warfare and Unmanned Combat Vehicles

AI integration into modern warfare emphasizes cognitive warfare, autonomous weapon systems, and enhanced military capabilities. The concept of 'smart warfare' highlights the role of AI in improving information processing, decision-making, and overall effectiveness in conflict (Aksu, 2024:4). AI primarily influences two key areas of military operations: decision-making in conflict zones and warfighting capabilities. AI technologies enable military forces to collect and analyze vast amounts of data from surveillance systems, satellites, UCVs, and sensors. This data facilitates actionable insights and improves situational awareness, enhancing battlefield decision-making. Additionally, automating certain tasks reduces the burden on human operators, allowing them to focus on strategic planning and critical decisions. For instance, AI-integrated UCVs can operate autonomously, learning and adapting to battlefield conditions (Petrovski, Radovanović, & Behlic, 2022:92). Today, AI-integrated autonomous 'suicide drones' can pursue targets such as enemy radar, ships or tanks based on preprogrammed targeting criteria and launch an attack when its sensors detect an enemy's air-defense radar. These drones use AI technology to shoot down incoming projectiles faster than a human operator and can remain in flight for far longer periods than human-operated vehicles (Johnson, 2020:28).

Beyond autonomous vehicles, AI also holds the potential to transform military command structures, which are currently dominated by human decision-makers (Allen, 2019:6). The US DoD, among others, is developing AI applications for intelligence collection, logistics, cyber operations, command and control, and semiautonomous systems (Sayler, 2019:1). In this way, AI integration could significantly enhance military decision-making by enabling autonomous operations, improving information synthesis, and accelerating the speed of military actions (Sayler, 2019:1). For example, the US DoD defines the AI-integration process as "decision advantages in a competitive condition" and expects AI to strengthen the warfighting decision-making process. As part of these decision advantages, the DoD plans to improve "battlespace awareness and understanding, adaptive force planning and application, fast, precise, and resilient kill chains, resilient sustainment support, and efficient enterprise business operations" (Hicks, 2023). Similarly, the US Air Force's Multi-Domain Command and Control system aims to centralize operations across air, space, cyberspace, land, and sea with the help of AI (Sayler, 2019:12). All branches of the US military are incorporating AI into platforms such as fighter aircraft, drones, ground vehicles, and naval vessels, and AI has already been deployed by the US in operations in Iraq and Syria (Sayler, 2019:1).

China, too, has advanced its military AI capabilities. In 2019, it sold its Blowfish A2 UCAV to the UAE. This AI-integrated UCAV can autonomously execute complex combat missions (Allen, 2019:6). Moreover, China and Russia try to incorporate AI not only into UAVs and but also into unmanned underwater vehicles (UUVs) for swarming missions infused with AI machine-learning technology (Johnson, 2020:30).

These examples illustrate how AI-enabled military technologies are already being deployed in conflict zones and are becoming commercially available to international buyers. All these processes even started to create a kind of a new global arms race based on AI among the major actors of international relations and the US, China, and Russia rush to weaponize AI (Simonite, 2017).

4. Effects of the Dehumanization of War

The increasing use of UCVs and AI in combat zones has both advantages and disadvantages. This section discusses the main benefits of dehumanizing war, such as reducing human, political, and economic costs and minimizing human error. It also explores the potential risks, including the role of the military-industrial complex, ethical concerns, diminished democratic oversight, and reduced political and military accountability.

4.1. Advantages of the Dehumanization of War

AI-integrated UCVs offer significant benefits to actors in conflict zones. First, these systems, whether autonomous or semiautonomous, reduce human costs by eliminating the need for human operators within combat vehicles. Their widespread adoption is expected to lower casualty rates in large-scale conflicts. Removing humans from direct combat roles can enhance the management of modern battlefield complexities and speed (Brose, 2019:131). In this regard, the primary utility of AI-driven UCVs lies in saving lives and reducing human suffering.

Moreover, AI integration can help reduce civilian casualties, or 'collateral damage.' The use of UCAVs in the US global war on terrorism has faced criticism for civilian casualties. Official US government reports acknowledged 64 to 116 civilian deaths across 473 drone strikes in Pakistan, Yemen, Somalia, and Libya from 2009 to 2015. However, independent investigations, such as those by the Bureau of Investigative Journalism, estimate the toll to be between 380 and 801 civilian deaths (Serle, 2016). Advanced AI systems are expected to improve strike accuracy and minimize such casualties, reducing human error and saving civilian lives.

Second, AI enhances battlefield effectiveness. As combat accelerates and information processing surpasses human cognitive capacities, AI becomes indispensable. Autonomous systems operating at machine speed can act independently on the battlefield, processing information and relaying commands faster and more precisely than humans. AI also helps commanders adapt to rapidly changing environments, potentially shortening conflict durations and increasing the precision of military actions (Horowitz et al., 2018:10). Moreover, improved accuracy and efficiency in UCVs may help shorten the duration of armed conflicts between warring parties. Even some AI proponents contend that although humans will be present, their role will be less significant, and the technology will make combat 'less uncertain and more controllable,' as machines are not subject to the emotions that cloud human judgment (Sayler, 2019:35).

The third potential benefit of dehumanized warfare is the reduction of economic costs. As the costs of UCAVs decrease, both powerful and less powerful states can access this technology. Advanced UCAV technology offers various options tailored to different security needs, from micro, mini, and small UCAVs to medium-sized tactical UCAVs (Class I), medium-altitude long-endurance UCAVs (Class II), and high-altitude long-endurance UCAVs (Class III) (Haider, 2021:14). These systems are now accessible not only to major powers but also to smaller states such as Somalia, Libya, Ethiopia, Togo, and Sudan. This process contrasts with the exclusivity of nuclear weapons and allows more states to enhance their security and defense capabilities. A similar trend is expected with AI-integrated UCVs.

Currently, defense-producing states have begun exporting AI-equipped UCVs. For example, China has already exported many of its advanced military UCAVs to countries in the Middle East, including Saudi Arabia and the UAE. China has also announced plans to export next-generation stealth drones as they become available. While many current-generation drones are remotely operated, Chinese officials expect future models to incorporate increasing levels of AI and autonomy. Chinese manufacturers are already selling UCAVs with substantial combat autonomy (Allen, 2019:6). In summary, while the proliferation of AI-integrated UCVs promises to lower the costs of war in various dimensions, the dehumanization of conflict introduces new risks and opportunity costs for the actors involved.

4.2. Risks of the Dehumanization of War

One of the critical questions regarding the potential negative effects of the proliferation of UCVs and the integration of AI is the economic influence of this process and its impact on the trajectory of political, economic, and military outcomes. AI-integrated military technologies do not arise solely from the national security needs of states but also from the historical and expanding relationship between the military and the private sector (Hall & Coyne, 2014:446). In this context, the relationship between military/security and industrial concerns is central to these discussions. The demands of the military-industrial complex have always been part of military affairs, and UCVs and AI technologies are not exempt from these demands.

For example, in the US, domestic manufacturers of drones strongly pressure the government to relax many of the rules currently prohibiting combat drone sales abroad (Hall & Coyne, 2014:446). The US Air Force, Army, Navy, and Special Forces all use UCV technology and collaborate with private contractors to research, develop, and test new UCVs for domestic and international use. A similar situation exists in other drone-producing countries like China and Turkey, where manufacturers play a significant role in driving the adoption and proliferation of UCAVs. These countries rely on private actors for production, further intertwining public and private interests.

AI technology has an even greater impact on public-private linkages because it is largely developed by and for the commercial sector. Within a short period, the evident potential of AI for military applications has led armed forces worldwide to experiment with AI-enabled defense systems to determine their effectiveness in combat tasks (Layton, 2021). Consequently, the proliferation of these technologies in military affairs does not always reflect public interest but can instead align with the incentives of political institutions or the private sector.

Ultimately, public-private linkages influence each other and, in doing so, shape the trajectory of defense policy and production (Hall & Coyne, 2014:446).

Another significant area of discussion regarding fully autonomous UCVs is accountability for their actions. With advancements in AI, UCVs may become capable of independently causing deaths by carrying and deploying weapons without human intervention (Ak, 2018:115). International law, including the law of war and the law of armed conflict, clearly defines the legal use of force, distinguishes between combatants and civilians, and outlines the responsibilities and rights of both in wartime and peacetime. For instance, killing an enemy soldier during wartime is not classified as a crime or murder. Crimes committed by combatants are addressed under international law, with potential offenders facing national or international trials, often in military courts. However, fully autonomous military systems raise complex questions about accountability for potential crimes. If AI-integrated autonomous military systems harm civilians, determining responsibility becomes a matter of legal and ethical debate.

By removing direct human intervention, these systems introduce new ethical dilemmas, especially regarding the dehumanization of warfare (Aksu, 2024:4). The evaluation of UCVs as new weapons and their integration with AI as a method of warfare are significant topics under international law (Ak, 2018:115). Both UCVs and AI integration in military operations require updated legal regulations within the framework of the law of war. Another critical concern is the dehumanization of warfare due to UCVs and AI, which may undermine scrutiny and democratic checks and balances. In democratic countries, parliamentary approval for deploying soldiers or declaring war plays a central role. However, the dehumanization of war through UCVs enables governments to circumvent parliamentary oversight.

For example, in the US, while the president has significant authority over decisions such as troop movements and combat strategies, the US Constitution also gives considerable authority to Congress including the power to provide for the common defence, declare war, raise and support an Army and Navy, make rules and regulations for the military, and purchase land for military bases (Stennis Center for Public Service, n.d.). However, the US government has conducted significant military operations while bypassing Congress's oversight in undeclared war zones like Yemen, Somalia, or Pakistan thanks to the UCAV technology. (The Bureau of Investigative Journalism, n.d.). Similarly, in Turkey, the Turkish Constitution requires the Grand National Assembly's authorization to deploy the armed forces abroad (Uslu, 2021). However, drone strikes do not necessitate such approval, allowing the executive branch to bypass democratic scrutiny. Moreover, while some states take a cautious approach to developing a drone-use doctrine, others, like the US, formulate doctrines only after extensively using the technology. Democratic values have sometimes been set aside in the name of short-term efficiency by some states (De Swarte, Boufous & Escalle, 2019:294) and prioritizing efficiency over the development of a well-defined doctrine creates new ethical and democratic deficiencies. The lack of international or national regulations governing the law of armed conflict further complicates these issues.

Another major risk is the lowering of the threshold for military action by enhancing conflicts with increased range, accuracy, mass coordination, intelligence, and speed (Johnson, 2020:36). States may be more inclined to engage in conflict with AI military systems because these systems reduce the risk of human casualties (Allen, 2019:5). Lower costs of war make decisions to initiate conflicts easier. This reduced cost undermines efforts to find peaceful solutions, as the absence of significant losses diminishes incentives for diplomacy. Decreasing the costs of war, combined with limited public and democratic scrutiny, makes military action more accessible to decision-makers. As a result of this, war instead of being "a mere continuation of policy by other means" as Clausewitz's quota, turns into a technical issue decided by the limited number of decision-makers and even by technocrats. This process does not only symbolize the dehumanization of war but also depoliticization of war.

5. Conclusion

The relationship between technology and warfare is bidirectional: technological advancements influence military affairs, and military developments, in turn, drive technological innovation. Two significant developments since 2000 exemplify this interaction: the proliferation of unmanned combat vehicles (UCVs) and the integration of artificial intelligence (AI) into military affairs. The widespread use of unmanned combat aerial vehicles (UCAVs) began with the US global war on terrorism after 9/11, where the technology was extensively deployed in declared and undeclared war zones. Israel also pioneered UCAV technology, utilizing it against regional adversaries. However, this triggered a security dilemma, prompting nations like Iran to reverse-engineer UCAVs and share this technology with allies. Over time, inter-state conflicts such as the Russia–Ukraine war, as well as smaller skirmishes, accelerated the use of UCAVs. Today, due to declining production costs and the proliferation of UCV technology, both state and non-state actors have UCVs, including UCAVs, unmanned ground vehicles (UGVs), unmanned surface vehicles (USVs), and unmanned underwater vehicles (UUVs).

The second critical development is AI integration into military affairs. Although the private sector leads in AI innovation, states have recognised its strategic importance and incorporated AI into national security strategies, addressing both military and non-military affairs. In military applications, AI holds two prominent roles. First, it enhances the concept of 'smart warfare' by improving the performance of AI-integrated UCVs, reducing human error during active conflict. Second, AI significantly improves decision-making processes in combat, potentially minimising mistakes and enhancing operational efficiency.

Both UCAVs and AI technologies embody the broader trend of dehumanising warfare, wherein human involvement in conflict is reduced. This dehumanisation carries both advantages and risks. On the positive side, UCAVs can reduce casualties by limiting the deployment of soldiers to conflict zones. Instead, these technologies allow states to conduct operations while safeguarding human lives. Additionally, AI integration may improve the accuracy of strikes, mitigating civilian casualties that have plagued traditional UCAV use. Beyond saving lives, dehumanisation can reduce the economic costs of war, as falling production costs make these technologies accessible even to economically weaker states. Advanced systems also enhance military efficiency, potentially shortening the duration of conflicts.

However, dehumanising warfare presents significant risks. A key concern lies in the relationship between the private sector and the military. The motivations of private companies involved in developing unmanned systems and AI may diverge from state interests, with the military–industrial complex exerting a profound influence on defence strategies. Another major risk is the erosion of democratic scrutiny. In democratic nations, decisions to deploy troops or declare war often require parliamentary approval. However, advanced technologies enable governments to conduct military operations, including in undeclared war zones, without such oversight. For example, US drone operations in Pakistan, Yemen, and Somalia circumvented Congressional authorisation, and this process highlights gaps in national and international legal frameworks that fail to address these emerging technologies. Ethical challenges also emerge as the dehumanisation of war reduces direct human involvement. Autonomous systems diminish the accountability of political and military leaders for actions taken during conflicts, creating new legal and moral dilemmas. Additionally, the lowered costs of war make the use of force more attractive, increasing the likelihood of conflict. Instead of seeking peaceful resolutions, parties may resort to violence more readily due to the ease and efficiency provided by these technologies.

Ultimately, the dehumanisation of warfare risks turning war into a depoliticised, technical endeavour, detached from its traditional role as an extension of political or social struggles. Addressing these challenges requires robust international norms, legal frameworks, and democratic oversight to balance the advantages of these technologies against their profound ethical and political implications. Moreover, to mitigate these risks, international legal frameworks must evolve to address AI and autonomous warfare, ensuring accountability and ethical considerations in conflict.

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IJOPEC PUBLICATION
London ijopec.co.uk Istanbul

ISBN 978-1-913809-51-5

ARTIFICIAL INTELLIGENCE & THE FUTURE OF HUMANITY

EDITED BY
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EDGAR ZAYAGO LAU
ARMIDA CONCEPCIÓN GARCÍA

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