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Novel Legal Issues of IoT and DLT in Smart Contracts, Constitutional Limits, Civil Liability and the Quest for a European Governance

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Abstract

Digital interconnection of "smart" devices (IoT) and the rise of distributed-ledger technology (DLT) have enabled self-executing agreements, *smart contracts*, capable of acting without human oversight.

Celebrated for their potential to enhance efficiency, these technologies also press against foundational legal principles. This thesis investigates the tension between code-driven contracting and European constitutional guarantees, including legal certainty, individual autonomy, and effective judicial protection, while also unsettling classical doctrines of civil liability.

Building on a comparative doctrinal analysis across Italy, Germany, the UK, and the US, and an empirical mapping of key EU legislative initiatives (GDPR, Data Act, MiCA, AI Act, Cyber Resilience Act), this thesis interrogates three core questions:

1. **Constitutional compatibility**: Do immutable DLT records and autonomous IoT-driven performance threaten the right to privacy, due-process values or separation of powers?
2. **Attribution & liability**: How should deterministic vs. non-deterministic AI agents embedded in smart contracts be allocated fault within existing tort and product-liability regimes?
3. **Regulatory design**: What model of EU governance, hard law, regulatory sandboxes or transnational technical standards, best balances innovation and rights-protection?

A mixed-method framework combines (i) legal-theory reconstruction, (ii) case-law analytics on EU and Member-State judgments, and (iii) scenario testing with prototype automated-contract code.

Findings reveal a growing "accountability gap" where constitutional principles are formally preserved yet practically eroded by code-based automation. To bridge this gap, a two-tier liability matrix is proposed, distinguishing *code authorship risk* (strict) from *oracle-data risk* (fault-based). This offers clear guidelines for distinguishing between code authorship risk and oracle-data input risk.

These recommendations offer legislators a path towards a harmonised, innovation-friendly, and constitutionally sound digital-contract ecosystem. Specifically, this thesis recommends the adoption of a model EU Regulation on Critical Autonomous Contracting Systems, coupling mandatory human-override clauses with a default distributed-liability fund. Additionally, it proposes a two-tier liability matrix, offering clear guidelines for allocating responsibility in AI-driven smart contract ecosystems

***Keywords*:** AI, automated contracting, deterministic & non-deterministic AI, smart contracts, blockchain, IoT, civil liability, constitutional law, EU tech-governance.

Declaration

I, **Sharmin Nisar Chougule**, hereby declare that the present thesis is my original work carried out between July 2022 and June 2025 under the supervision of Prof. Lucia Ruggeri at the University of Camerino. Except where specific reference is made, all sources used are acknowledged. The thesis has not been submitted for any other degree or qualification at this or any other institution. I accept responsibility for the content and confirm that the similarity index complies with the Faculty's regulations.

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This work is dedicated to all of you!

List of Abbreviations

Abbreviation	Full Forms
AI	Artificial Intelligence
ANN	Artificial Neural Network
CRA	Cyber-Resilience Act
DLT	Distributed-Ledger Technology
GDPR	General Data Protection Regulation
IoT	Internet of Things
MiCA	Markets in Crypto-Assets Regulation
ML	Machine Learning
NFT	Non-Fungible Token
SVM	Support-Vector Machine
XAI	Explainable Artificial Intelligence

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Introduction

A. Research Background

The coming together of the Internet of Things (IoT), Distributed Ledger Technology (DLT), and Artificial Intelligence (AI) is transforming how contracts are formed, executed, and enforced in the digital age. We have defined and explained IoT and DLT later in this dissertation. AI systems, ranging from simple deterministic algorithms to complex machine learning models, add an autonomous decision-making layer to this mix. Together, these technologies allow *automated contracting* processes in which IoT sensor inputs can trigger blockchain-based smart contracts, potentially with AI components interpreting data or negotiating terms. For example, a sensor in a smart vehicle (IoT) might automatically communicate with a blockchain-based insurance contract to execute a payment or adjust terms based on driving behaviour, without direct human oversight. This blending of physical devices, code-based agreements, and intelligent automation fundamentally "bridges the gap between the physical and digital realms of legal agreements" and lies at the frontier of modern contract law.

Such technological conjunction, while promising unique efficiency and innovation, also raises novel and complex legal questions. Traditional legal frameworks for contracts and civil obligations assumed human decision-makers and clear *loci* of control; by contrast, IoT- and AI-driven smart contracts distribute agency among devices, algorithms, and platforms. Automated contract formation by electronic agents is no longer theoretical, it is becoming common in sectors like finance, supply chains, and smart consumer services. Recognising this trend, international bodies and regulators have begun to respond. For instance, the United Nations Commission on International Trade Law (UNCITRAL) has recently developed a draft Model Law on Automated Contracting (2024) to provide legal certainty for contracts formed by automated systems, including those deploying AI.[1] Notably, the UNCITRAL framework acknowledges that automated systems may operate in either a deterministic or non-deterministic manner, an important technical and legal distinction. A deterministic system is governed by pre-defined, rule-based logic that ensures a consistent and reproducible output for a given input. This predictability aligns with traditional legal constructs, particularly in contract law, where foreseeability and clarity are essential for establishing intent and binding obligations. In contrast, a non-deterministic system, typically powered by artificial intelligence and machine learning algorithms, may yield different outputs from the same input due to its reliance on probabilistic models, context-sensitive variables, or continuously evolving datasets. Such systems are inherently adaptive and data-driven, learning from past interactions and modifying behavior over time, which can lead to stochastic or unpredictable outcomes.

From a legal standpoint, this distinction is critical. It raises foundational questions about whether the outputs generated by a non-deterministic AI system can be attributed to a human or organisational will, as required for the valid formation of a contract. In other words, if an AI-enabled platform autonomously negotiates or executes contractual terms with another system, can this process genuinely reflect a **"meeting of the minds"** or mutual consent, as traditionally understood in contract doctrine? The indeterminacy of AI-driven outputs complicates the identification of intention, offer, and acceptance, thereby challenging the enforceability and legal validity of such agreements. These concerns strike at the core of contract law and demand a re-examination of attribution, agency, and consent in the age of algorithmically negotiated contracts.

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[1] United Nations Commission on International Trade Law, *UNCITRAL Model Law on Automated Contracting with Guide to Enactment* (United Nations Publication, Sales No. E.25.V.4, 2024) https://uncitral.un.org/sites/uncitral.un.org/files/2424674e-mlautomatedcontracting-ebook.pdf

Beyond contract formation, the *enforcement* of obligations through code (so-called "self-enforcing" contracts) and the delegation of decision-making to AI challenge established legal safeguards. IoT devices acting upon smart contract commands could, for example, automatically disable a leased machine or lock a smart home's door when a payment is missed. While efficient, this kind of automated enforcement may bypass traditional remedies and protections (like court oversight or grace periods), raising concerns under fundamental legal principles of due process and proportionality. At the same time, the ubiquity of IoT sensors means that vast amounts of data, much of it personal or sensitive, are continually processed and recorded, often on immutable ledgers. This reality brings into play constitutional law considerations, notably the rights to privacy and data protection enshrined in the EU Charter of Fundamental Rights and related instruments. Indeed, reconciling blockchain's transparency and immutability with data protection laws (like the "right to be forgotten" under Article 17 GDPR) has emerged as a key challenge. Likewise, the use of AI in decision-making triggers concerns about transparency, accountability, and potential bias, which implicate principles of equality and fair process.

By "constitutional limits," this thesis examines how IoT-DLT systems and AI-driven smart contracts strain the fundamental rights protections enshrined in the EU Charter of Fundamental Rights (CFREU) and the European Convention on Human Rights (ECHR). Specifically, this thesis interrogates tensions with: Article 7 (Right to Private and Family Life), Article 8 (Data Protection), Article 17 (Right to Property and Rectification), and Article 47 (Right to Fair Trial and Effective Remedy). These constitutional protections rest on the assumption of human agency, judicial oversight, and the ability to challenge automated decisions, yet autonomous code, by design, operates without such intermediaries. Additionally, the thesis examines the Rule of Law principle and legality requirements: can pre-programmed, immutable code fulfill the constitutional guarantee that legal obligations are clear, accessible, and subject to proportionate enforcement? When a smart contract automatically locks a consumer's asset due to a payment delay, without notice or remedy, does this respect the due process safeguards that constitutional law demands? The tension is acute because DLT's cardinal feature, immutability, directly conflicts with constitutional rights like rectification (CFREU Article 17) and data erasure (GDPR Article 17). Similarly, AI components in smart contracts raise questions of human dignity (CFREU Article 1): can autonomous algorithms make binding decisions affecting legal rights without human review? This thesis argues that these tensions are not merely technical puzzles but substantive constitutional challenges requiring reforms to ensure that innovation in contracting does not erode foundational legal protections.

The background against which this research is set is one of rapid technological evolution that is outpacing traditional legal concepts. The intersection of IoT, DLT, and AI in smart contracting creates a *lacuna* in our understanding of how existing legal frameworks apply and where new legal doctrines or adaptations are needed. This dissertation responds to that gap by examining the novel legal issues that arise in this context, with a focus on European Union law and its Member States' responses. While prior scholarship has explored smart contracts or IoT in isolation, this thesis uniquely examines their convergence with AI under a constitutional and civil liability lens, proposing concrete reforms including a dual-tier liability framework and a model EU Regulation.

B. Importance of IoT, DLT & Smart Contracts in Modern Legal Systems

IoT, DLT and smart contracts (augmented increasingly by AI) are not only technological innovations but socio-economic drivers that modern legal systems must urgently grapple with. These technologies

are now at the forefront of digital transformation in economies worldwide.[2] By the end of 2025, tens of billions of IoT devices will be in operation globally, permeating sectors from healthcare and transportation to smart homes and cities. This proliferation of connected devices is leading to an exponential growth of data and a new level of interdependence between cyber and physical domains. The ability of IoT networks to automatically trigger actions and transactions has significant benefits, for instance, optimising supply chains, enabling real-time responses in critical infrastructure, and creating new consumer conveniences. Smart contracts running on blockchain infrastructure add the element of trust-minimisation: they allow secure, automated execution of agreements without relying on a central authority or traditional intermediaries. This can reduce transaction costs and fraud in areas like finance (consider the rise of decentralised finance protocols) and trade logistics (e.g. self-executing insurance or payment when a shipment condition is verified by sensors). AI, in turn, enhances these systems by enabling more sophisticated decision-making and predictive capabilities, such as dynamic contract terms that adjust based on AI analysis of incoming data streams.

The importance of these converging technologies to law is evidenced by the increasing attention of policymakers and jurists. In the European Union, a *flurry of legislative and regulatory initiatives* has been launched to address aspects of IoT, blockchain, and AI. The EU's General Data Protection Regulation (GDPR), effective since 2018, directly tackles personal data flows ubiquitous in IoT ecosystems and imposes obligations (like privacy by design and strict consent requirements) that profoundly affect how IoT-based smart contracts can be designed. Building on fundamental privacy rights, the GDPR has become a global benchmark, underscoring the legal significance of controlling data in smart environments. More recently, the Data Act (Regulation (EU) 2023/2854) was adopted to create harmonised rules on fair access to and use of data generated by IoT devices.[3] The Data Act addresses issues of *data ownership* and sharing obligations in IoT contexts, seeking to balance innovation with fairness in digital markets. Its provisions will, for example, empower users of connected products to access and port the data they generate, and will regulate the terms of smart contracts used for data sharing.[4] This emphasis on data governance highlights that control over IoT-generated data is now recognised as a key legal and economic issue for modern societies.

Likewise, the European Union is finalising a landmark Artificial Intelligence Act,[5] which will establish comprehensive rules for the development and use of AI systems, including those embedded in IoT devices or services. The proposed AI Act adopts a risk-based approach, imposing stricter requirements (such as transparency, human oversight, and safety features) on AI systems deemed high-risk, for instance an AI that manages critical infrastructure or makes decisions with legal effects on individuals. Once enacted, the AI Act will directly impact the deployment of AI in automated contracting, for example, an AI that automatically negotiates contract terms or decides on contract performance might be classified and regulated as a high-risk system if it could significantly affect someone's rights. This reflects an important normative choice: to ensure that even as we automate, human rights and values remain safeguarded in algorithm-driven interactions. Complementing this, the EU has also moved to update its liability frameworks. Although a dedicated AI Liability

[2] European Commission, 'Europe's Internet of Things Policy' *(Shaping Europe's Digital Future)* digital-strategy.ec.europa.eu accessed 1 June 2025.

[3] European Commission, 'Data Act' *(Shaping Europe's Digital Future)* digital-strategy.ec.europa.eu accessed 1 June 2025; DLA Piper, 'Data Act' *(Insights, Topics)* dlapiper.com accessed 1 June 2025.
Entered into force: 11 January 2024, Becomes applicable in full: 12 September 2025

[4] Ibid. DLA Piper.

[5] Entry into force: 1 August 2024 (20 days after publication). General applicability: Two years later, i.e., from 2 August 2026. Some provisions apply earlier: Bans on prohibited AI: 6 months after entry into force from 2 February 2025. Codes of practice and general-purpose AI (GPAI) obligations: 12 months after entry into force from 2 August 2025.

Directive[6] was proposed to ease victims' ability to sue for AI-caused harm, consensus faltered and the proposal was withdrawn in 2025.[7] Nevertheless, the policy debate it ignited underlines how crucial accountability is in the age of autonomous systems. Efforts continue via revisions to the Product Liability regime, aiming to clarify that producers of software, AI and IoT devices can be held liable for defects causing damage, even when AI "black boxes" are involved in the chain of events. In parallel, sector-specific regulations have targeted the blockchain domain: notably, the Markets in Crypto-Assets Regulation (MiCA) was adopted in 2023 to establish a harmonised EU framework for crypto-assets and their service providers.[8] MiCA, while focused on digital assets and not directly on smart contracts generally, enhances legal certainty for blockchain-based transactions (e.g. by setting rules for token issuance and exchange) and thus supports the broader ecosystem in which smart contracts operate.

Furthermore, recognising the security risks inherent in a world of ubiquitous connectivity, the EU has introduced the Cyber Resilience Act (CRA), a new law on cybersecurity requirements for products with digital elements (including IoT devices).[9] Adopted in late 2024, the CRA mandates that manufacturers of connected hardware and software ensure baseline cybersecurity (e.g. protection against unauthorised access, secure updates, no default passwords) throughout a product's lifecycle.[10] This regulation is poised to directly influence IoT contract ecosystems by reducing vulnerabilities that could be exploited to manipulate sensor data or smart contract triggers. Together, instruments like the GDPR, Data Act, AI Act, MiCA, and CRA illustrate the multifaceted regulatory response required to integrate IoT, DLT and AI into the legal order. Modern legal systems are essentially being recalibrated to address questions of trust, privacy, security, and liability arising from these technologies. The importance of our subject matter, therefore, lies in its pervasive impact: it touches fundamental rights (privacy, property, non-discrimination), core private law principles (contractual freedom and liability), and broader policy goals (innovation, consumer protection, cybersecurity). For legal scholarship, this convergence prompts a re-examination of doctrines that were developed for a very different world. It challenges scholars and practitioners to interpret age-old concepts, like consent, fault, or even the notion of a "contract" itself, in light of autonomous machines and immutable code. In short, IoT, DLT

[6] We can indeed refer to the EU Artificial Intelligence Act (AI Act) in your discussion on liability in AI and IoT-enabled contracts. The AI Act, formally known as Regulation (EU) 2024/1689, establishes a comprehensive legal framework for AI within the European Union. It classifies AI systems based on risk levels—unacceptable, high, limited, and minimal—and imposes corresponding obligations on providers and users. For high-risk AI systems, which include many AI/IoT applications, the Act mandates strict requirements such as conformity assessments, transparency, human oversight, and post-market monitoring to ensure safety and accountability. However, it's important to note that while the AI Act sets out these obligations, it does not directly address liability issues. Liability for damages caused by AI systems is being considered separately under proposed legislation like the AI Liability Directive and the revised Product Liability Directive. These proposals aim to adapt existing liability frameworks to address the unique challenges posed by AI technologies, such as assigning responsibility when AI systems cause harm. Therefore, in your discussion, you can reference the AI Act to highlight the EU's approach to regulating AI systems and ensuring their safe deployment. For discussions specifically about liability, it would be more appropriate to refer to the proposed AI Liability Directive and the revised Product Liability Directive, which are designed to address accountability and compensation for damages caused by AI systems.

[7] Caitlin Andrews, 'European Commission withdraws AI Liability Directive from consideration' *(International Association of Privacy Professionals, 12 February 2025)* iapp.orgiapp.org accessed 1 June 2025.

[8] Greenberg Traurig LLP, 'New Rules for Crypto-Assets in Europe' *(Insights, 30 September 2024)* gtlaw.com- accessed 1 June 2025. Also see, Greenberg Traurig LLP, 'Regulatory & Compliance' *(Overheard on the Block(chain))* https://www.gtlaw-overheardontheblockchain.com/category/regulatory-compliance; accessed 1 June 2025.

[9] Council of the European Union, 'Cyber Resilience Act: Council adopts new law on security requirements for digital products' *(Press Release, 10 October 2024)* consilium.europa.eu accessed 1 June 2025.

[10] Ibid. consilium.europa.eu Look at key elements of the new regulation: "The regulation will apply to all products that are connected either directly or indirectly to another device or to a network. There are some exceptions for products for which cybersecurity requirements are already set out in existing EU rules, for example medical devices, aeronautical products, and cars."

and smart contracts represent a architype shift for the law, one that is already underway and demanding attention at the highest levels of law-making and jurisprudence.

C. Objectives & Research Questions

Given the background and importance outlined above, this dissertation sets out to investigate the novel legal issues that emerge from the interplay of IoT, DLT, and AI in the domain of smart contracts, with particular emphasis on European constitutional principles and civil liability frameworks. The central research objective is to develop a comprehensive legal analysis of how these technologies disrupt or strain existing legal norms, and to propose how law and regulation should adapt in order to address the challenges without unduly hindering technological innovation. In pursuing this objective, the study aims to fill gaps in current legal scholarship by bringing together insights from contract law, data protection law, technology law, and fundamental rights discourse, areas that have often been treated separately despite the convergent nature of the technologies in question.

To structure this inquiry, the research addresses several key questions:

1. **Convergence and Conceptual Framework:** *What are the defining features of IoT, DLT, and AI-enabled smart contracts, and how do they converge to create an automated contracting ecosystem?* This question sets the stage by clarifying the technical and conceptual landscape, for example, distinguishing *deterministic* smart contract processes (where outcomes are pre-defined by code) from *non-deterministic* or AI-driven processes where outcomes may vary. It asks how these features fit (or misfit) within traditional legal definitions of contracts and obligations.
2. **Validity and Formation of Automated Contracts:** *How do traditional legal requirements for contract formation and validity (such as offer and acceptance, intent to create legal relations, and certainty of terms) apply to agreements formed and executed by IoT devices and AI agents on DLT platforms?* Within this, a crucial sub-question is whether and how the "will" or intent of parties can be ascertained when an autonomous system concludes the contract.[11] For instance, if an AI algorithm autonomously decides to enter a micro-transaction based on sensor data, can that decision be attributed to a human principal under existing contract law doctrines? This part of the research probes doctrinal concepts like agency, mistake, and consent in the context of algorithmic contracting.
3. **Constitutional and Fundamental Rights Implications:** *What constitutional or fundamental rights issues are raised by the deployment of IoT- and AI-driven smart contracts, particularly under EU law?* This question examines how rights to privacy and data protection (e.g. implications of ubiquitous data collection by IoT sensors and ledger transparency) are impacted. It also explores the extent to which the use of autonomous systems in private ordering might engage principles of human dignity, equality, or procedural fairness. For example, does an individual have a right to a human review or due process if a smart contract or AI denies them a service or executes a penalty (as reflected in GDPR's restrictions on purely automated decisions with legal effects)? The research evaluates existing safeguards and identifies potential constitutional tensions when code-based decisions replace or pre-empt traditional legal processes.

[11] United Nations Commission on International Trade Law (UNCITRAL), 'UNCITRAL Model Law on Automated Contracting with Guide to Enactment' *(United Nations Publication, 2025)* uncitral.un.org accessed 1 June 2025. See remarks on Article 8.

4. **Civil Liability and Risk Allocation:** *How are liability and legal accountability addressed when IoT devices malfunction, smart contract code errs, or AI systems cause harm in the execution of contracts?* This question focuses on private law remedies and risk allocation. It considers scenarios such as: a software bug in a smart contract that leads to financial loss, a faulty IoT sensor that triggers a detrimental action, or an AI recommendation system that results in discriminatory contract outcomes. The analysis covers contract law remedies (voidability, damages for breach, etc.), tort law (negligence or product liability for defective devices or software), and emerging statutory frameworks. A critical aim is to determine whether existing laws, for example, the EU Product Liability Directive and national tort laws, are adequate to cover these situations, and how forthcoming changes (such as extended producer responsibility for digital features or strict liability for certain AI applications) might fill the gaps.
5. **Regulatory and Governance Response:** *How are current and proposed European legal instruments addressing the above issues, and what further reforms or governance mechanisms might be necessary?* Here, the dissertation surveys the landscape of EU legislation and policy (GDPR, Data Act, AI Act, MiCA, CRA, etc.) to identify their contributions and limitations. It interrogates whether these instruments form a coherent framework or if significant regulatory *lacunae* remain, for example, in cross-border IoT scenarios or in governing the use of decentralized autonomous organizations (DAOs) that deploy smart contracts. This question also invites a normative discussion: how should law-makers strike the balance between fostering innovation (e.g. smart contracts improving efficiency) and protecting societal values (consumer rights, security, fairness)? Recommendations are developed in response to this inquiry.

By addressing these research questions, the dissertation aims to paint a detailed picture of the legal landscape for IoT- and DLT-based smart contracting, highlighting points of tension and suggesting ways forward. The questions are interrelated: findings on contract formation feed into the discussion on liability, and insights on fundamental rights inform the evaluation of regulatory sufficiency. Through this structure, the research maintains a clear focus on the central theme, *the novel legal issues arising from smart contracts in an IoT and AI environment*, while exploring its facets from multiple angles.

D. Scope and Methodology

1. Scope

This study is primarily situated in the context of **European Union law, and then specifically in Italy, Germany, and less specifically or rather only in use cases in France,** with selective comparative references to other jurisdictions, notably the United States, United Kingdom, and Singapore, to illuminate different approaches for comparison with common law. The emphasis on EU law is justified by the EU's proactive regulatory stance on digital technologies, as seen in its recent legislative acts and proposals. Within EU law, the dissertation engages with both *supra-national* instruments (regulations, directives, and the EU Charter of Fundamental Rights) and their interplay with *national laws* of Member States. For example, while data protection and digital market rules are largely set at the EU level (GDPR, Data Act, etc.), contract law and civil liability rules still largely derive from national civil codes and jurisprudence, thus the analysis will frequently reference principles from Italian civil law (as a representative civil law system) and compare them with other jurisdictions' solutions. The subject matter is inherently interdisciplinary, but the legal scope is

focused on constitutional and private law dimensions rather than criminal law or purely technical discussions. Issues of constitutional law (in the European sense) addressed include privacy rights, the legality principle, and the rule of law as it relates to automation. On the civil side, the scope encompasses contract formation and validity, interpretation of smart contract terms, and liability in contract and tort (including product liability for defective devices or software). While the technology of IoT, DLT, and AI will be described to the extent necessary for legal analysis, the work does not purport to make novel technical contributions; rather, it assumes the technologies as given and examines their legal implications. Importantly, this dissertation does not seek to cover every possible use of IoT or blockchain, but is delimited to their use in or alongside smart contracts and automated transactions. For instance, general issues of cryptocurrency regulation or AI in employment decisions are beyond our scope except insofar as they directly inform the contracting context. The time frame of legal materials considered is up to mid-2025, capturing the most recent developments (such as the final text of the Data Act 2023 and the emerging case law or guidance available by that date).

2. Methodology

The research methodology is fundamentally doctrinal and analytical, rooted in legal scholarship traditions. It involves a thorough analysis of legislation, regulatory proposals, case law, and academic commentary. Given the fast-paced development of this field, the methodology also includes an element of policy analysis, examining preparatory legislative documents, regulatory impact assessments, and soft law instruments (like guidelines from data protection authorities or standard-setting bodies) to glean the intent and direction of legal change. A key part of the method is interpretative: applying established legal principles to hypothetical and real scenarios involving IoT and AI-driven smart contracts, in order to test how the law would respond. For example, to explore liability, the thesis may dissect a scenario of an autonomous vehicle (IoT device with AI) executing a smart contract that results in an accident, and analyze it under existing tort law doctrines. Comparative methodology is also employed in a targeted way. By looking at jurisdictions outside the EU (such as U.S. state laws on IoT security, or Japan's recognition of blockchain records in court), the research draws lessons and highlights alternatives, enriching the analysis of EU law and potentially suggesting best practices or cautionary tales. The theoretical framework combines elements of law and technology (examining how code-based architecture can regulate behavior, the "code is law" debate) with classic legal theory (questions of autonomy, intent, and responsibility). This blend allows the dissertation to consider not only black-letter law, but also underlying legal *values* and *policies*.

Throughout the research, an effort is made to maintain a balance between *descriptive* and *normative* approaches. The descriptive aspect maps out the current legal landscape: identifying which rules apply to IoT/DLT smart contracts and where ambiguities or gaps lie. The normative aspect engages in reasoned argument about how those ambiguities should be resolved, for instance, whether new legal definitions are needed for autonomous agents, or how liability should be apportioned to maintain both innovation incentives and protection of the public. Sources include primary legal texts (statutes, regulations, international conventions), case law (where available, e.g. court decisions that have touched on smart contracts or automation), and a broad range of secondary literature from legal scholars, technologists, and ethicists. Notably, policy reports and expert group findings (such as reports by the EU Blockchain Observatory or the European Data Protection Board) are used to shed light on emerging consensus or points of contention in the field.[12]

[12] D Bhumichai and others, 'The Convergence of Artificial Intelligence and Blockchain: The State of Play and the Road Ahead' (2024) 15(5) *Information* 268 mdpi.com accessed 1 June 2025. See specifically section 4.1 of the paper.

In terms of structure, the dissertation is organised to reflect the layered approach of the analysis. Following this Introduction, the next chapter provides a technological and conceptual primer on IoT and DLT in smart contracts, ensuring that legal readers understand how these systems function (Chapter 1). Subsequent chapters delve deeper into specific aspects: Chapter 2 traces the evolution of the smart contract notion and its relationship with traditional contract law; Chapter 3 examines the role of AI in automated contracting, differentiating deterministic versus learning-based systems and their implications for autonomy and control; and discusses the legal issues arising in such autonomous contracting systems, including data governance, validity of contracts, and liability concerns; Chapter 4 offers a comparative analysis of how different legal frameworks (within Europe and internationally) are responding, including analysis of EU instruments like GDPR, MiCA and national initiatives; finally, Chapter 5 looks ahead to future trends and formulates recommendations for legal and policy reform. The methodological approach in each chapter is to integrate doctrinal analysis with illustrative examples and hypothetical case studies, providing a grounded understanding of abstract issues. By the Conclusion, the study synthesises the findings to answer the research questions and highlights the contributions made to the scholarly discourse on law's adaptation to emerging technology.

This doctrinal and comparative methodology informs the chapter structure. Through this structured and comprehensive methodology, the dissertation ensures a clear, well-reasoned examination of the novel legal issues at hand. The approach is designed to be rigorous in legal analysis while remaining attuned to the practical realities of how IoT devices, blockchains, and AI systems operate. This will enable the work not only to critique and clarify the law as it stands, but also to offer meaningful insights for legislators, courts, and stakeholders as they navigate the challenges of integrating these transformative technologies into the fabric of modern legal systems.

Chapter 1: Internet of Things (IoT) and Distributed Ledger Technology (DLT) in Smart Contracts; Real-World Use Cases; and Emerging Technical and Legal Challenges

1.1. Introduction

The coming together of the IoT and DLT is transforming how contracts are formed, executed, and enforced in the digital age. IoT refers to networks of interconnected "smart" devices embedded with sensors and software, commonly defined as a global infrastructure enabling connectivity and data exchange among physical and virtual "things" through the Internet.[13] DLT, most prominently exemplified by blockchain provides decentralised and tamper-resistant databases, as initially conceptualised in Satoshi Nakamoto's seminal whitepaper on Bitcoin[14] and subsequently elaborated upon by EU-level strategies on digital innovation[15] that can host self-executing code (smart contracts) and transaction records.[16] Together, these technologies enable **smart contracts** that automatically respond to real-world events, bridging the gap between the physical and digital realms of legal agreements. The proliferation of IoT devices (projected to exceed 29 billion globally by the end of 2025), according to recent estimates by the International Telecommunication Union and Statista)[17] and the maturation of blockchain platforms has made this interface increasingly relevant.

This chapter provides a foundational overview of IoT and DLT, their core architectures and functions, and illustrates their synergy in contractual settings through real-life use cases.

1.2. IoT Technologies: Definitions, Architecture, and Role in Smart Contracts

1.2.1. Defining IoT

The Internet of Things is commonly defined as a global network infrastructure enabling connectivity and data exchange among physical and virtual "things" (devices, sensors, objects) through the Internet.[18] In simpler terms, IoT devices are everyday or industrial objects embedded with sensors, computing power, and network connectivity that allow them to sense their environment, communicate, and act on instructions. Examples range from consumer gadgets (smart thermostats, fitness wearables, voice assistants) to industrial systems (networked factory machines, smart grid meters, connected vehicles). By 2008, the number of connected devices worldwide had already exceeded the human population (IoT devices surpass people),[19] and this number has grown exponentially since. The hallmark of IoT is the autonomous, continuous exchange of data between

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[13] International Telecommunication Union, "Overview of the Internet of Things," ITU-T Y.4000 series, 2012.

[14] Nakamoto, Satoshi, *"Bitcoin: A Peer-to-Peer Electronic Cash System"* (2008), self-published whitepaper, introducing the blockchain concept of a decentralized, tamper-resistant ledger, available at bitcoin.org (last visited 25 April 2025). (origin of blockchain/DLT concept).

[15] European Commission, 'Blockchain Strategy', Digital Single Market Policy, 2020, available at https://digital-strategy.ec.europa.eu/en/policies/blockchain-strategy (last visited 10 April 2025).

[16] S. Nakamoto, 'Bitcoin: A Peer-to-Peer Electronic Cash System', Bitcoin.org, 2008, available at https://bitcoin.org/bitcoin.pdf (last visited 10 April 2025).

[17] Statista, *"Number of IoT connected devices worldwide, 2019–2030 (in billions)"* (2023), forecasting ~30 billion IoT devices globally by 2025, available at Statista (last visited 25 April 2025). (IoT adoption statistics).

[18] International Telecommunication Union, supra n 1. See also European Commission, 'Internet of Things: An Action Plan for Europe', COM(2009) 278 final. See also, International Telecommunication Union (ITU), *Recommendation ITU-T Y.2060: "Overview of the Internet of Things"* (2012), Geneva: ITU, defining IoT as a global infrastructure for the information society (enabling connectivity among physical and virtual "things"), available at ITU (last visited 25 April 2025).

[19] Evans, Dave (Cisco), *"The Internet of Things: How the Next Evolution of the Internet Is Changing Everything"* (2011), Cisco White Paper, noting that by 2008 the number of connected devices exceeded the world's population, available at Cisco (last visited 25 April 2025).

devices, often called machine-to-machine (M2M) communication, which enables automation and intelligent control in diverse domains. The International Telecommunication Union succinctly describes the IoT as "the networked interconnection of everyday objects",[20] facilitating ubiquitous computing in which devices weave themselves into the fabric of daily life.[21] The European Union defines IoT as "an infrastructure of interconnected objects, people, systems and information resources together with intelligent services to process and react to information from the physical and virtual world."[22]

1.2.2. Core Architecture of IoT

IoT systems typically have a multi-layered architecture comprising:

1.2.2.1. Devices (Sensors and Actuators): Physical collect data from the environment (sensors measuring temperature, location, biometrics, etc.) or perform actions (actuators that open locks, adjust temperatures, etc.). For example, GPS trackers and temperature sensors in a supply chain or a smart home illustrate this layer.[23]

1.2.2.2. Connectivity: Network technologies that transmit data to and from devices. Depending on use, this can include wireless protocols (Wi-Fi, Bluetooth, Zigbee), cellular networks (LTE/5G), or low-power wide-area networks (e.g. LoRaWAN).[24] Reliable connectivity is essential for IoT devices to communicate with servers or with each other.[25]

1.2.2.3. Edge and Cloud Computing: The data collected by IoT devices is processed either locally at the "edge" (on or near the device) or in the cloud. *Edge computing* analyses data close to the source to enable real-time responses with minimal latency, for instance, a factory sensor might shut off a machine immediately upon detecting an anomaly.[26] *Cloud computing* provides large-scale data storage and more intensive analytics, aggregating device data to derive insights or run machine learning algorithms.[27]

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[20] International Telecommunication Union (ITU), *ITU Internet Reports 2005: "The Internet of Things"* (2005), ITU, describing the IoT as "the networked interconnection of everyday objects" enabling ubiquitous computing, available at ITU (last visited 25 April 2025).

[21] International Telecommunication Union, 'The Internet of Things', *ITU Internet Reports*, 2005, available at https://www.itu.int/net/wsis/tunis/newsroom/stats/The-Internet-of-Things-2005.pdf (last visited 10 April 2025). See also International Telecommunication Union, 'Overview of the Internet of Things', ITU-T Recommendation Y.2060, June 2012.

[22] European Commission, 'Advancing the Internet of Things in Europe', SWD(2016) 110 final, 19 April 2016, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016SC0110 (last visited 10 April 2025). Also see, Sundmaeker, Harald, Guillemin, Pascal, Friess, Peter, & Woelfflé, Sylvie (eds.), *Vision and Challenges for Realising the Internet of Things* (2010), European Commission (CERP-IoT Cluster), p. 34, defining IoT as "an infrastructure of interconnected objects, people, systems and information resources together with intelligent services to process and react to information from the physical and virtual world," available at EU IoT Cluster (IERC) (last visited 25 April 2025).

[23] J. Gubbi et al, 'Internet of Things (IoT): A vision, architectural elements, and future directions' 29(7) Future Generation Computer Systems, 1645–1660 (2013).

[24] IEEE Communications Society, "Low Power Wide Area Networks for IoT," 2020.

[25] P. Middleton et al, 'Forecast Analysis: Internet of Things - Endpoints Worldwide, 2021 Update', Gartner Inc., 2021, available at https://www.gartner.com/en/documents/4001904 (last visited 10 April 2025).

[26] Gartner, "Edge Computing: A Primer," 2018.

[27] W. Shi and S. Dustdar, 'The Promise of Edge Computing', 32(5) Computer, IEEE, 78–81 (2016).

1.2.2.4. Data Analytics and AI: IoT deployments often leverage analytics or AI to make sense of the vast streams of data, enabling predictive maintenance, trend analysis, or smart decision-making.[28]

1.2.2.5. User Interface: Finally, IoT systems present information or controls to users through dashboards, mobile apps, or other interfaces, allowing human monitoring and intervention. In summary, IoT is an ecosystem where sensors gather data, networks transmit it, and computing systems process and act on it, all with minimal human involvement, creating a seamless integration of the physical world into digital systems.[29]

These architectural features, while technical, create legal challenges, for example, decentralised connectivity complicates attribution of fault, and edge computing raises data sovereignty issues. These implications are explored in later chapters.

1.2.3. Constitutional Implications of IoT Data Architecture

The multi-layered architecture of IoT systems, while enabling powerful automation, creates constitutional vulnerabilities that merit explicit analysis. **Continuous data collection by sensors raises privacy concerns** under CFREU Article 8 and GDPR. IoT devices are designed for ubiquitous monitoring, smart meters track energy use in real-time, wearables record health data continuously, connected vehicles log location and driving behavior. While individually justified (e.g., network optimization, user personalization), the cumulative effect is pervasive surveillance. From a constitutional standpoint, the right to privacy includes the right to anonymity and freedom from constant observation; the European Court of Human Rights (ECtHR) has recognized that even lawful data collection can infringe privacy if disproportionate (S. and Marper v. UK, 2008).

When IoT data feeds into smart contracts on immutable DLTs, a second constitutional tension emerges: **the conflict between DLT transparency and data protection rights**. Blockchain's immutability means data, once recorded, cannot be deleted or corrected. Yet GDPR Article 17 (Right to Erasure) and CFREU Article 17 (Right to Rectification) grant individuals the right to request deletion or correction of personal data. If a sensor malfunction records incorrect health data on a blockchain, the data subject has a constitutional right to erasure, but DLT architecture makes this impossible without compromising ledger integrity. This is not merely a technical constraint; it is a constitutional conflict. The EDPB has acknowledged this tension in its guidance on blockchain and GDPR (EDPB Opinion 05/2018), suggesting that immutable systems may be incompatible with privacy rights unless specific safeguards (pseudonymization, consent) are employed.

Furthermore, the **edge computing layer raises issues of jurisdictional data sovereignty and due process**. When IoT devices process data locally (at the network edge) before transmitting to central systems, the question arises: which legal regime applies? If an IoT device in Italy processes personal data from an individual in Germany, does Italian law, German law, or GDPR (as supranational law) govern? From a Rule of Law perspective (a core constitutional principle), individuals must know which legal authority has power over their data and rights. Decentralized IoT architectures blur these lines, potentially leaving individuals without clear recourse or transparent legal authority, violating the constitutional requirement of legal certainty and accessibility.

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[28] M. Mohammadi and A. Al-Fuqaha, 'Enabling Cognitive Smart Cities Using Big Data and Machine Learning: Approaches and Challenges' (2018) 56 *IEEE Communications Magazine* 94, 94–101. See also McKinsey Global Institute, 'The Internet of Things: Mapping the Value Beyond the Hype', June 2015.

[29] A. Zanella et al, 'Internet of Things for Smart Cities', 1(1) IEEE Internet of Things Journal, 22–32 (2014).

1.2.4. **IoT's Function in Smart Contracts**

The data and connectivity provided by IoT greatly enhance the functionality of smart contracts. Smart contracts (addressed in detail in Chapter 2) are self-executing pieces of code on a blockchain or other DLT that automatically perform actions when predefined conditions are met. However, on their own, blockchains have no native knowledge of off-chain events, they require trustworthy data inputs from the outside world, often referred to as *oracles*. IoT devices serve as natural oracles by feeding real-time, verifiable data from the physical environment into digital contracts. This marriage of IoT and smart contracts in the real world, then does Y" logic to be executed autonomously. For example, in a smart logistics contract, IoT sensors attached to a shipping container can monitor the location and environmental conditions of goods in transit. The smart contract (programmed with the shipment agreement terms) will automatically release payment to the supplier once the sensor data indicates the goods have arrived at the destination in acceptable condition (e.g. within the required temperature range). In an automotive insurance contract, a vehicle's telematics IoT device might continuously record braking patterns, mileage); a smart contract can adjust the driver's insurance premium dynamically or trigger rewards/penalties based on that tel. Indeed, "IoT devices provide real-time updates on shipment location, condition, and status" and if a monitored parameter deviates from an agreed range, the IoT sensor can immediately alert the smart contract to take corrective action or enforce a contingency.[30] This integration reduces the need for manual verification or intermediaries: the contract trusts the sensor data. The benefits are considerable, automation (contractual performance is executed automatically without human administration), accuracy (minimised human error or fraud by relying on sensor data), and speed/cost efficiency (instantaneous execution and removal of middlemen).[31] In essence, IoT acts as the eyes and ears of smart contracts, bringing situational awareness that allows contracts to be event-driven and self-enforcing in response to the physical world.

1.2.5. **Technical Challenges in IoT Integration**

While promising, the fusion of IoT with smart contracts also raises technical challenges. One major issue is interoperability, the IoT landscape is fragmented across many manufacturers and standard protocols, making it difficult to ensure different devices and platforms can communicate in a unified manner.[32] A smart contract may not easily ingest data from heterogeneous IoT systems unless common data standards or middleware are in place. Another concern is data integrity and reliability: smart contracts will only be as good as the data they receive. If an IoT sensor reports incorrect or tampered data (whether due to malfunction or cyberattack), the smart contract could misfire, for instance, releasing payment for a shipment that was never delivered or was spoiled. Ensuring that IoT data is accurate, secure, and tamper-proof is thus critical.[33] Techniques like digital signatures on device data, redundant sensors, or consensus from multiple IoT sources are being explored to bolster

[30] T.M. Fernández-Caramés and P. Fraga-Lamas, 'A Review on the Use of Blockchain for the Internet of Things', 6(3) IEEE Access, 32979-33001 (2018); see also Chainlink Labs, 'Connecting Smart Contracts to the Real World', Chainlink Whitepaper (2017). See also Accenture, "The Rise of Smart Contracts Powered by IoT," 2021.

[31] K. Christidis and M. Devetsikiotis, 'Blockchains and Smart Contracts for the Internet of Things', 4(2) IEEE Access, 2292-2303 (2016); see also Deloitte, 'Smart Contracts in the Blockchain World: Contractual Conditions in Code', Deloitte Insights (2016). See also IBM Blockchain, "How Smart Contracts Work with IoT," White Paper, 2020.

[32] World Economic Forum, "IoT Guidelines for Interoperability," 2020. See also International Organization for Standardization (ISO), 'Internet of Things (IoT), Interoperability for IoT Systems, Part 1: Framework', ISO/IEC 21823-1:2019; see also European Commission, 'Advancing the Internet of Things in Europe', SWD(2016) 110 final.

[33] ENISA, "Security and Resilience of Smart Home Environments," 2022. See also E. Oriwoh and M. Conrad, 'Things in the Internet of Things: Towards a Definition', 4 International Journal of Internet of Things, 1-5 (2015); also see ENISA, 'Baseline Security Recommendations for IoT', ENISA Report (2017).

reliability. Scalability is another issue: enterprise deployments might involve thousands or millions of devices streaming data, handling this volume on a blockchain can be impractical due to throughput limitations and costs.[34] Careful architecture (such as off-chain aggregation of data or layer-2 networks) is needed to make IoT-blockchain systems scalable. Lastly, security vulnerabilities in IoT pose a threat to smart contracts. IoT devices are infamously susceptible to hacking if not properly secured; a hacker who compromises an IoT sensor could feed fraudulent inputs to a smart contract. The Mirai botnet attack of 2016, where malware took over hundreds of thousands of IoT cameras and routers with default passwords to launch a massive DDoS attack, demonstrated the systemic risks of insecure IoT devices.[35] A corrupted IoT device in a smart contract scenario could similarly cause automated transactions to execute under false pretenses. These challenges that while IoT augments smart contracts with powerful capabilities, robust technical and legal safeguards are needed to realize their full potential. The following sections will examine how DLT provides a platform to mitigate some issues (like data tampering through immutability) even as other risks persist.

1.3. DLT: Blockchain Basics and Smart Contract Support

1.3.1. Defining DLT and Blockchain

The European Blockchain Services Infrastructure (EBSI) defines DLT[36](s) as "replicated, shared, and synchronized digital data geographically spread across multiple sites, countries, or institutions, with no central administrator or centralized data storage."

Distributed Ledger Technology refers to a digital database that is consensually shared and synchronized across multiple sites or institutions, with no central administrator or centralised data storage.[37] Each participant (node) in a DLT network holds a copy of the ledger, and updates are propagated to all copies via a consensus protocol. Blockchain is the most well-known type of DLT, distinguished by structuring data into blocks that are cryptographically linked in chronological order. A key feature of blockchain and similar DLTs is decentralisation**:** control over the ledger is distributed among participants rather than residing with a single authority. For example, Bitcoin's blockchain is maintained by thousands of independent nodes worldwide, making it resilient to single points of failure or control.[38] Another fundamental property is immutability**:** once data (such as a transaction) is added on the ledger and confirmed by the network, it becomes extremely difficult to alter or delete.[39] Cryptographic hash linking and consensus rules ensure that any attempt to tamper with a past record would be evident and rejected by the network. This permanence lends a high degree of trustworthiness to records on DLT, they can serve as verifiable proof of what occurred and when.[40]

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[34] V. Buterin, 'A Next-Generation Smart Contract and Decentralized Application Platform', Ethereum Whitepaper, 2014; see also European Union Blockchain Observatory & Forum, 'Scalability, Interoperability and Sustainability of Blockchains', EU Blockchain Observatory Report (2019).

[35] Krebs, B., "The Democratization of Censorship: Mirai Botnet Attack," Krebs on Security, 2016. See also A. Kolias et al, 'DDoS in the IoT: Mirai and Other Botnets', 50(7) IEEE Computer Magazine, 80-84 (2017); see also FBI, 'Alert Number I-101316-PSA: Cyber Actors Increasingly Exploit the Internet of Things', 13 October 2016.

[36] EBSI, "What is Distributed Ledger Technology?", European Blockchain Services Infrastructure, available at: https://ec.europa.eu/cefdigital/wiki/display/CEFDIGITAL/Blockchain+Infrastructure; See also, European Blockchain Services Infrastructure (EBSI), "DLT Definitions and Infrastructure Principles," European Commission, 2021.

[37] European Commission, "Blockchain and the EU: Trusted Digital Services," Digital Strategy, 2020.

[38] Nakamoto, S., "Bitcoin: A Peer-to-Peer Electronic Cash System," 2008.

[39] Supra note K. Christidis and M. Devetsikiotis (2016).

[40] Ibid.

DLTs are also typically transparent (at least to the participants of the network): all parties can inspect history, which fosters trust through verifiability.[41] To reach agreement on ledger updates, DLT networks use consensus mechanisms, protocols that allow distributed nodes to validate transactions and agree on the next state of the ledger. Common consensus algorithms include Proof of Work (used by Bitcoin and originally by Ethereum), which requires solving computational puzzles (ensuring security at the cost of high energy consumption), Proof of Stake (used by modern networks including Ethereum post-merge), which relies on economic stakes and is more energy-efficient.[42] In permissioned enterprise DLTs, variants of *Byzantine Fault Tolerance* algorithms (like Hyperledger's PBFT) are used to achieve fast agreement among a fixed set of known nodes.[43]

The new Italian legal definition of DLT encapsulates these features, describing DLT as a system based on a shared, distributed ledger, "structurally decentralized" and secured by cryptography, where data (whether encrypted or clear) can be registered, validated and Continuing from the earlier analysis of DLT fundamentals:

Immutable and *verifiable by each participant*, which cannot be altered or modified without consensus.[44] This definition, from Italy's 2019 legislation, mirrors EU-level guidance on blockchain and cryptoassets,[45] showcasing a harmonized understanding across European jurisdictions.[46] In sum, a DLT like blockchain provides an **append-only ledger** secured by cryptography and consensus, where trust arises from the network's design rather than a central intermediary.

From a legal standpoint, the immutability of blockchain raises questions around data rectification and deletion rights under GDPR (explored in Chapter 4), and consensus models affect enforceability and auditability of automated contracts.

1.3.2. Types of DLT: Two broad categories of DLT networks are often distinguished:

1.3.2.1. Public (Permissionless) Blockchains

Open networks like Bitcoin and Ethereum where anyone can run a node, read the ledger, and (in principle) submit transactions or create smart contracts.[47] These maximise decentralization and transparency, every participant can verify every transaction, but at the cost of performance. Public blockchains have faced challenges with throughput and latency, processing only a limited number of transactions per second (e.g., Ethereum handled ~15 TPS in its early years) which can lead to network congestion and high fees during peak demand.[48] They also rely on incentives (like mining rewards) to

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[41] Ibid.

[42] Ethereum Foundation, 'Ethereum Proof-of-Stake (PoS) Overview' (2022).

[43] Hyperledger Foundation, "Understanding Byzantine Fault Tolerance in Fabric," Technical Guide, 2021. See also, Hyperledger, 'Understanding Byzantine Fault Tolerance', Hyperledger Architecture White Paper, 2019.
The Hyperledger Foundation explains Byzantine Fault Tolerance (BFT) in Fabric as a mechanism to ensure system reliability even when some nodes act maliciously or fail, highlighting its evolving role in permissioned blockchain consensus.

[44] Law Decree No. 135/2018 (converted with amendments by Law No. 12/2019), Art. 8-ter, Italy.

[45] Decreto-legge 14 dicembre 2018, n. 135, converted with amendments by Legge 11 febbraio 2019, n. 12, art. 8-ter, introducing definitions of "technologie basate su registri distribuiti" and "smart contract" into the Italian legal framework, published in *Gazzetta Ufficiale* n.36 del 12 febbraio 2019.
Decreto-legge 14 dicembre 2018, n. 135, conv. in legge con modificazioni dalla L. 11 febbraio 2019, n. 12, art. 8-ter (*G.U.* n.36 del 12 febbraio 2019).

[46] European Commission, 'Report on the Legal, Governance and Interoperability Aspects of Blockchain Infrastructures' (2020), available at https://digital-strategy.ec.europa.eu.

[47] Wood, G., "Ethereum: A Secure Decentralised Generalised Transaction Ledger," Yellow Paper, 2014.

[48] Buterin, V., "Scalability and the Blockchain Trilemma," Ethereum Blog, 2018.

maintain security. Public blockchains are the backbone of decentralized finance (DeFi) and open smart contract ecosystems, but their permissionless nature can raise compliance questions in regulated industries due to their open nature and pseudonymity.[49]

1.3.2.2. Private/Consortium (Permissioned) Blockchains

Networks like Hyperledger Fabric or R3 Corda pre-selected or authorized (e.g., a group of banks or supply chain partners).[50] These typically employ more centralized consensus algorithms (or even a trusted leader to order transactions) enabling much higher speed (thousands of TPS) and lower latency. They sacrifice some degree of decentralization and openness for efficiency and access control. Because participants are known, permissioned chains can incorporate legal identities and may fit more easily under existing legal frameworks (e.g., participants can be held accountable, and data can be restricted to certain parties for confidentiality) Permissioned blockchains are often preferred for enterprise use.[51] Hybrid models also exist, blending elements, for instance, a consortium blockchain that periodically anchors its data to a public chain for added immutability, or a public network with permissioned sub-networks.

For legal analysis, permissioned DLTs are generally more compatible with EU accountability requirements, while permissionless DLTs challenge traditional jurisdictional and enforcement models.

1.3.3. DLT's Synergy with Smart Contract forms (like Ethereum, Tezos, or newer ones such as Avalanche or Cardano) were specifically designed to host smart contracts, code that executes on the DLT itself, binding parties through self-enforcing logic. The key advantages of using DLT for contracts include:

1.3.3.1. Trustless Execution

Parties do not need to trust each other or a central arbitrator; they trust the code and the network. Once a smart contract is deployed, its code will execute deterministically as written, without one party being able to cheat or alter terms unilaterally. Funds or assets locked in the contract will only be released per the agreed conditions, providing inherent escrow-like security.[52] This dramatically reduces the need for traditional intermediaries (e.g., agents, clearinghouses), lowering transaction costs and friction.[53][54] A legal contract that might have required multiple verifications and a notary can, in theory, be replaced by a smart contract that auto-executes (though, as later chapters will explore, *legal* validity and enforceability of such code is a separate issue).

1.3.3.2. Security and Integrity

DLT's cryptographic security ensures that once a contract is recorded, it cannot be tampered with, and every action it takes (each transaction) is indelibly logged. This audit trail is valuable for legal

[49] European Securities and Markets Authority (ESMA), 'Advice on Initial Coin Offerings and Crypto-Assets', ESMA50-157-1391 (2019).
[50] Hyperledger Foundation, "Introduction to Hyperledger Fabric," Technical Documentation, 2021.
[51] R3 Corda, 'Corda for Financial Institutions', White Paper (2020).
[52] Antonopoulos, A. M., and Wood, G., "Mastering Ethereum: Building Smart Contracts and DApps," O'Reilly Media, 2018.
[53] Tapscott, D., and Tapscott, A., "Blockchain Revolution: How the Technology Behind Bitcoin is Changing Money, Business, and the World," Penguin, 2016.
[54] N. Szabo, 'Smart Contracts: Building Blocks for Digital Markets', (1996).

compliance[55] and dispute resolution, if a smart contract executed, say, a payment or a transfer of property, that transaction is provable and timestamped.[56] Moreover, blockchain's resistance to outages or data loss (due to replication across nodes) means the contract's operation is resilient. However, security is a double-edged sword: *bugs* in smart contract code can lead to unintended behavior that is just as immutable, notorious incidents like the 2016 "DAO hack" on Ethereum, where flaws in a smart contract were exploited to siphon funds of USD 60 million worth of Ether,[57] underscore the need for rigorous code audits and perhaps legal standards for coding practices.

1.3.3.3. Automation and Efficiency

Smart contracts can perform complex conditional logic instantly, e.g., releasing a shipment title document when payment is received AND an IoT sensor confirms delivery. This streamlining can reduce multi-step workflows to a single code trigger, saving time. It also can reduce litigation over performance because the code either executes or not, leaving less room for subjective interpretation (again, this is a simplification; in practice, smart contracts often need to be linked with legal prose to cover exceptions, recourse, etc.). Still, industries from finance to real estate are piloting DLT for automated settlements, for example, real-time gross settlement systems in banking using permissioned DLT, or property registries on blockchain for near-instant title transfers (as seen in projects in Sweden and Georgia).[58]

1.3.3.4. Transparency and Auditability

Especially in permissioned enterprise contexts, all stakeholders having access to the "single source of truth" ledger can reduce discrepancies. In supply chains, the entire provenance of a product, where it was made, shipped, stored, can be recorded on a blockchain visible to all participants.[59] For regulators or auditors, read-only access to such ledgers provides real-time oversight of compliance (e.g., tamper-proof logs of pharmaceutical supply chain conditions, or automated tax collection via smart contracts on commercial transactions).[60]

However, there are challenges and limitations to note: Scalability remains a concern for many DLTs, high-profile networks have experienced slowdowns and prohibitive fees during usage spikes (for instance, the surge of interest in DeFi in 2020-21 caused Ethereum transaction fees to skyrocket, making small-value smart contract operations uneconomical).[61] The industry is addressing this via "Layer 2" scaling solutions (like the Lightning Network for Bitcoin or rollups and sidechains for Ethereum),[62] and new consensus algorithms, but the risk of congestion is something a legal framework must consider (e.g., what if a contract fails to execute timely due to network backlog?). Energy

[55] G. Peters and E. Panayi, 'Understanding Modern Banking Ledgers through Blockchain Technologies: Future of Transaction Processing and Smart Contracts on the Internet of Money', in D. Lee (ed), *Handbook of Digital Currency* (Elsevier, 2015), 239–278.

[56] Szmigiera, M., "Smart Contracts and Auditability in Blockchain Systems," Statista Insights, 2022. [27] IBM, "Food Trust: Enhancing Traceability and Trust in the Supply Chain," White Paper, 2020.

[57] J. Clark and A. Essex, 'Commitment Issues in Blockchain Smart Contracts', *International Conference on Financial Cryptography and Data Security* (2017).

[58] Swedish Land Registry, 'Blockchain for Land Registration', 2019.

[59] IBM, "Food Trust: Enhancing Traceability and Trust in the Supply Chain," White Paper, 2020.

[60] Council of the European Union, *Cyber Resilience Act: Council Adopts New Law on Security Requirements for Digital Products* (10 October 2024) available at https://www.consilium.europa.eu/en/press/press-releases/2024/10/10/cyber-resilience-act-council-adopts-new-law-on-security-requirements-for-digital-products/ (last accessed 22 May 2025).

[61] BitInfoCharts, 'Ethereum Average Transaction Fee' (2021).

[62] M. Al-Bassam et al., 'Rollup Solutions for Ethereum: A Comparative Overview', 2022.

consumption was a major criticism of early blockchains using Proof of Work (Bitcoin's annual energy use was compared to a small country). Ethereum's shift to Proof of Stake in 2022 cut its energy use by ~99%, and many newer DLTs are energy-efficient, but environmentally sustainable design is now part of the regulatory conversation (the EU has debated carbon footprint disclosures for blockchain projects). Legal recognition is another challenge: while Italy and a few jurisdictions now legally equate blockchain records or smart contracts (with proper authentication) to written contracts,[63] many countries still lack explicit laws. Questions arise such as: can a purely digital contract satisfy form requirements (e.g., a notarial deed)? How to handle jurisdiction if nodes are globally distributed? These uncertainties form a significant part of "novel legal issues" explored in this thesis. We will look at legal challenges in detail in chapter 3. Governance of decentralized networks is also has the authority to update a smart contract code if a bug is found? Could a majority of nodes collude to alter the ledger (a 51% attack) and would that invalidate past contract executions? Such issues straddle technology and law, requiring interdisciplinary solutions.

In summary, DLT provides the infrastructure for robust, self-executing contracts and trustworthy record-keeping, which complements IoT by offering data integrity and automation. Yet, to harness these advantages in legally sound ways, one must navigate the nuanced technical constraints and evolving legal frameworks, which we will continue to unravel.

1.3.4. Constitutional Challenges of DLT Immutability and Transparency

Immutability, blockchain's defining feature, creates a direct constitutional conflict with fundamental rights. **Immutability vs. Right to Rectification (CFREU Article 17)**: When data is recorded on a blockchain, it becomes permanent. A data entry error, false sensor reading, or erroneous transaction cannot be deleted or corrected without forking the ledger (splitting it into two versions), which is technically disruptive and legally questionable. Yet Article 17 CFREU and GDPR Article 17 guarantee individuals the right to request correction or erasure. Consider a concrete scenario: an IoT sensor records that Party A failed to deliver goods on time, triggering a smart contract penalty. The sensor was faulty; the goods arrived on time. Under traditional law, Party A can petition a court to correct the record. On blockchain, the incorrect record is permanent. This immutability violates the individual's constitutional right to have accurate records and to seek correction, a protection rooted in human dignity and due process.

Blockchain's transparency means all network participants can see all transactions and data recorded (in public blockchains; permissioned networks restrict visibility but maintain immutability). This radical transparency conflicts with constitutional privacy rights. Consider an automated insurance contract recorded on blockchain: the contract terms, claims data, and payout amounts are visible to all network participants. This transparency may reveal sensitive personal information (health status, financial capacity, behavioral patterns) to third parties without meaningful consent. The EU Court of Justice (Schrems II, Case C-311/18) has emphasized that privacy rights require limits on data access and visibility; individuals must retain control over who sees their personal information. Blockchain's default transparency undermines this control, raising questions about whether DLT systems can ever

[63] Agenzia per l'Italia Digitale (AgID), *Guidelines on Smart Contracts and Blockchain Technologies* (2022) available at https://www.agid.gov.it/en/designers-developers/blockchain-and-smart-contracts (last accessed 22 May 2025). Also see, Art. 8-ter, *Decreto-legge* 14 dicembre 2018, n. 135 (converted with modifications by Law 11 February 2019, n. 12), on the legal validity of technologies based on distributed ledgers and smart contracts, available at https://www.normattiva.it (last accessed 22 May 2025).

be reconciled with CFREU Article 8 without substantial architectural modifications (encryption, access controls).

A foundational constitutional principle, the Rule of Law, requires that legal obligations and consequences be subject to scrutiny and correction. Laws must be clear, accessible, and fairly enforced. When a smart contract's outcome is immutable, individuals cannot challenge the execution of the contract through traditional legal channels without also unraveling the entire chain of transactions that depend on it. If a faulty smart contract executes an unlawful penalty, the immutability of DLT means the penalty is technically irreversible unless the community agrees to fork the ledger, an extraordinary measure that violates expectations of legal certainty and accessible justice. The European Court of Justice has held (Case C-465/00, Österreichischer Rundfunk) that the right to effective remedy (CFREU Article 47) requires meaningful access to courts and ability to challenge administrative action. Immutable code that auto-executes may preclude meaningful access to remedy if reversal is technically impossible.

1.4. Real-World Use Cases Integrating IoT and DLT

IoT and DLT are not merely standalone technologies; rather, their convergence creates a distinct legal category that challenges traditional contractual frameworks. These are not separate regulatory domains; instead, their intersection in automated contracting demands a unified legal approach balancing innovation, privacy, and liability. Numerous pilot projects and emerging solutions demonstrate their combined power in practical scenarios. Below we explore several domains where smart contracts, powered by IoT data and secured by blockchains, are reshaping traditional processes. Each use case highlights benefits as well as legal considerations that arise.

1.4.1. Supply Chain and Logistics

1.4.1.1. Scenario: A global supply chain involves multiple parties, manufacturers, shippers, insurers, customs, buyers, and often suffers from paperwork inefficiencies, lack of transparency, and trust issues. IoT sensors can track shipments in real time (location via GPS, conditions via temperature/humidity sensors, shock sensors for mishandling, etc.). By feeding this data into a blockchain platform, all parties gain a **shared, tamper-proof view** of the goods in transit. Smart contracts can automate responses: e.g., release payment from buyer to seller once an IoT device on the container signals the goods have arrived at the buyer's warehouse and remained within agreed condition parameters throughout.[64] If conditions deviate (say the container temperature exceeds a threshold indicating possible spoilage), the smart contract could notify the parties and trigger an inspection or dispute resolution process automatically.

1.4.1.2. Example: TradeLens (IBM/Maersk):[65] One often-cited implementation was the TradeLens platform, a collaboration between IBM and Maersk, which used a permissioned blockchain to record

[64] European Union Agency for Cybersecurity (ENISA), *Distributed Ledger Technology & Cybersecurity: Improving Information Security in the Financial Sector* (December 2019) 25–27, available at https://www.enisa.europa.eu/publications/dlt-cybersecurity (last accessed 22 May 2025).
Also see, M. Saberi, M. Kouhizadeh, J. Sarkis and L. Shen, 'Blockchain Technology and Its Relationships to Sustainable Supply Chain Management' (2019) 220 *International Journal of Production Research* 1, 2–3, available at https://doi.org/10.1080/00207543.2019.1651947 (last accessed 22 May 2025).

[65] A.P. Moller-Maersk & IBM, *TradeLens: Blockchain-Enabled Shipping Solution, Press Release* (August 2018), announcing the TradeLens platform to digitize global trade using DLT (with over 90 organizations participating by 2018), available at Maersk Press (last visited 25 April 2025). *(DLT use case in global shipping supply chains).*

shipping events and documents. While TradeLens[66] primarily focused on digitising documents and reducing customs clearance times, it also integrated IoT inputs like vessel GPS data and container status. At its peak, Tradehipping events involved 8+ customs authorities, demonstrating the scalability of DLT in a complex supply chain. Although Maersk announced in late 2022 that it would discontinue TradeLens (citing a lack of full industry adoption), the project proved the feasibility of blockchain to provide end-to-end visibility. On the IoT side, companies like **DHL** have used IoT sensors for pharmaceuticals in transit and coupled it with blockchain to ensure provenance. A DHL-Accenture prototype tracked drugs from manufacture to patient, writing each handoff to a blockchain; IoT tags on packages ensured that any temperature excursions or tampering attempts were logged immutably.

1.4.1.3. Benefits. Transparency and trust are greatly enhanced, as all participants have access to the same data, thereby reducing opportunities for fraud.[67] For example, it becomes nearly impossible to forge shipping records or alter timestamps. Automation via smart contracts enables streamlined logistics and automatic payment settlements upon delivery, helping to mitigate cash flow issues.[68] Counterfeit prevention is also a key advantage: for high-value goods such as pharmaceuticals or luxury items, an unbroken blockchain record from source to consumer helps verify authenticity,[69] and the Internet of Things (IoT) can ensure, for instance, that a sealed container has not been opened en route, using tamper-evident IoT seals that log any breach.[70] Regulatory bodies (such as customs or food safety agencies) benefit as well, as such systems allow for more efficient compliance monitoring. For example, in a pilot project involving mangoes, Walmart reported that it was able to reduce the time required to trace a package's origin from seven days (using manual methods) to just 2.2 seconds by using blockchain-based systems.[71] This represents a dramatic improvement with implications for both consumer safety and regulatory responsiveness.

1.4.1.4. Challenges/Legal Issues: Data on a blockchain is tamper-proof, but *garbage in, garbage out* still applies: if an IoT sensor is faulty or compromised and feeds incorrect data (intentionally or not), the blockchain will faithfully record it, raising the stakes for data integrity and auditability of IoT devices.[72] Legal agreements need clauses on what happens if an automated payment triggers wrongly due to sensor error. Liability attribution is tricky: if a smart contract misfires, is the IoT device manufacturer at fault, the coder of the contract, or some participant who provided an oracle service?[73] Also, jurisdiction can be murky: a global supply chain blockchain might be run by nodes in many countries, which law governs the validity of the electronic records or the conclusion of smart contracts embedded in this system?[74] The UK Jurisdiction Taskforce, for instance, in its 2019 *Legal Statement on Cryptoassets and Smart Contracts*, opined that smart contracts can be seen as contracts under English law and that an English court can recognize them, but each situation will depend on

[66] TradeLens, "Digitizing Global Trade," IBM and Maersk, archived at: https://www.tradelens.com

[67] S. Saberi, M. Kouhizadeh, J. Sarkis and L. Shen, 'Blockchain Technology and Its Relationships to Sustainable Supply Chain Management' (2019) 57 International Journal of Production Research 2117–2135.

[68] F. Casino, T.K. Dasaklis and C. Patsakis, 'A Systematic Literature Review of Blockchain-Based Applications: Current Status, Classification and Open Issues' (2019) 36 Telematics and Informatics 55–81.

[69] N. Kshetri, 'Blockchain's Roles in Meeting Key Supply Chain Management Objectives' (2018) 39 International Journal of Information Management 80–89.

[70] H. Treiblmaier, 'The Impact of Blockchain on the Supply Chain: A Theory-Based Research Framework and a Call for Action' (2018) 23 Supply Chain Management 545–559.

[71] R. Kamath, 'Food Traceability on Blockchain: Walmart's Pork and Mango Pilots with IBM' (2018) 1 Journal of the British Blockchain Association 1–12.

[72] S. Pearson, M. Fraser and D. Greenwood, 'Accountability in the Internet of Things Era' (2021) 23 *Computer Law & Security Review* 105–121.

[73] A. Finck, 'Smart Contracts as a Form of Private Ordering: A Comparative Perspective' (2019) 67 *American Journal of Comparative Law* 637–676.

[74] P. De Filippi and A. Wright, *Blockchain and the Law: The Rule of Code* (Harvard University Press 2018).

connecting factors.[75] Data privacy is another factor: IoT devices may collect personal data (e.g., if tracking individual products to end consumers, or workers' interactions with goods). Under GDPR, personal data on an immutable ledger raises concerns, since data generally cannot be altered or erased ("right to be forgotten"), how do we reconcile that with blockchain?[76] Techniques like hashing or off-chain storage with on-chain references are used to mitigate direct storage of personal data on blockchain, but legal guidance (like the EU's 2019 guidelines on blockchain and GDPR) is still evolving on this front.[77] Lastly, interoperability and standards: from a legal view, if an industry adopts a blockchain system, will there be a single standard or multiple competing ledgers? The EU has supported projects like the *European Blockchain Services Infrastructure (EBSI)* to create common, cross-border DLT services, which could include supply chain notarization, ensuring any records (and smart contracts) are admissible and recognizable across member states.[78]

1.4.2. Smart Energy Grids and Environmental Systems

1.4.2.1. Scenario: In the energy sector, the rise of prosumers (households or businesses that both produce and consume energy, e.g., via solar panels) has led to interest in *peer-to-peer (P2P) energy trading*. Instead of selling excess solar power back to a utility at fixed rates, what if neighbors could directly trade energy among themselves at market-driven rates? IoT devices like smart meters can measure energy production and consumption in real-time at each household. A blockchain can serve as a decentralized marketplace where prosumers publish offers or automatically trade energy via smart contracts, using the meter readings as inputs.

1.4.2.2. Example, Power Ledger:[79] In Australia, blockchain-based platform for energy trading, creating local marketplaces for renewable energy.[80] IoT smart meters at each participant's site feed usage data to the platform; smart contracts then reconcile who sold how many kWh to whom and handle payments (often in tokens or via fiat gateways). The blockchain ensures transparency (participants can verify the energy origin, useful for guaranteeing renewable sources) and quick settlement. Another project, *Energy Web Foundation*, uses enterprise Ethereum to let devices (like electric vehicles or smart appliances) interact with the grid in sophisticated ways, for instance, an IoT-controlled water heater could be turned on or off via a smart contract that balances grid load, with the blockchain recording the user being compensated for letting the grid control their device at peak times.[81] Beyond electricity, blockchains are tracking carbon credits and renewable energy certificates, often with IoT sensors ensuring that, for example, a carbon capture device's output is as claimed.

1.4.2.3. Benefits: Decentralization here has ideological and practical appeal, reducing the dominance of big utilities by empowering communities to manage energy democratically. Smart contracts enable

[75] UK Jurisdiction Taskforce, *Legal Statement on Cryptoassets and Smart Contracts* (LawTech Delivery Panel, November 2019), available at https://lawtechuk.io/reports/ukjt-legal-statement-on-smart-contracts accessed 25 April 2025.

[76] European Data Protection Board (EDPB), *Guidelines 05/2020 on Consent under Regulation 2016/679*, version adopted on 4 May 2020.

[77] European Commission, *Blockchain and the GDPR* (2019), available at https://ec.europa.eu/newsroom/article29/item-detail.cfm?item_id=612053 accessed 25 April 2025.

[78] European Commission, *European Blockchain Services Infrastructure (EBSI)* (2023), available at https://digital-strategy.ec.europa.eu/en/policies/ebsi accessed 25 April 2025.

[79] Google Cloud (Power Ledger case study), *"Power Ledger: Facilitating Peer-to-Peer Energy Trading with Blockchain"* (2019), describing the Australian start-up Power Ledger's blockchain-based platform for decentralized renewable energy trading and settlement, available at Google Cloud (last visited 25 April 2025). (DLT use case in energy trading).

[80] Power Ledger, 'Power Ledger: P2P Energy Trading Platform' (2022), available at https://www.powerledger.io accessed 25 April 2025.

[81] Energy Web Foundation, 'Decentralized Operating System for the Energy Sector' (2023), available at https://www.energyweb.org accessed 25 April 2025.

real-time microtransactions, an IoT device could literally do a transaction every 15 minutes matching supply and demand, far beyond the billing cycles of traditional utilities. This can also improve energy efficiency and grid stability: price signals could encourage IoT thermostats to use power when it's cheapest/greenest, smoothing out demand peaks. Environmental sustainability is promoted by validating green energy sources; for instance, charging an electric car via a smart contract that ensures the energy came from a solar IoT station could carry a premium token reward or a certified carbon offset on blockchain. Europe has been exploring such concepts; the EU's *Horizon* programs have funded pilots in blockchain energy trading in countries like the Netherlands and France, aligning with the EU's broader climate goals.

1.4.2.4. Challenges/Legal Issues: Energy markets are heavily regulated. Any P2P trading platform must navigate local regulations on energy resale, grid safety, and consumer protection. In some jurisdictions, only licensed utilities can sell power, does a prosumer using a blockchain become an "unlicensed utility"? Regulators like *Ofgem* in the UK or state Public Utility Commissions in the US are watching these experiments; some have created regulatory sandboxes to allow limited trials of P2P trading. Data from smart meters is also typically considered personal data (it can reveal patterns of living), thus protected under laws like GDPR, so consent and privacy-preserving designs are necessary (e.g., perhaps aggregating data or anonymizing participants on the public ledger). Cybersecurity is crucial: if IoT devices control critical infrastructure like the electric grid, they become targets for attack, so the system must fail-safe (e.g., default to a stable state if the blockchain or IoT network fails). The EU's *Cyber Resilience Act* 2024 squarely addresses this: it imposes cybersecurity requirements on any product with digital elements (IoT hardware and software included) to ensure they're secure by design and patched throughout their lifecycle.[82] A compromised smart meter could not only defraud the system but also destabilize grid operations if misused en masse (imagine an attacker turning off thousands of IoT heat pumps at once via a malicious contract). Liability for such events is a gray area: manufacturers might be liable under product liability law if a device was insecure, but if the user failed to update firmware, or if the attacker exploited the blockchain's logic itself (say, spammed the network to delay contract execution), it becomes complex. Insurance products for such cyber-physical risks are evolving accordingly.

Additionally, contractual enforcement is interesting here: energy trades executed by code, are they recognized as binding contracts? Most likely yes if the participants agreed to the platform's terms, but what if something goes wrong (a software bug causes an unfair charge)? Legal redress mechanisms (arbitration or courts) need to be available beyond the code's own dispute logic. We will see in Chapter 4 how liability and dispute resolution are being approached in automated contracting.

This case illustrates the challenge of attributing liability when smart contracts rely on potentially compromised sensor data, a core issue for Chapter 3.

1.4.3. Automotive and Mobility Ecosystems

1.4.3.1. Scenario: Modern vehicles are essentially computers on wheels with extensive IoT capabilities (sensors, connectivity, even V2X communication). There are several angles where IoT and blockchain intersect in this sector:

[82] European Commission, *Proposal for a Regulation on Horizontal Cybersecurity Requirements for Products with Digital Elements (Cyber Resilience Act)*, COM(2022) 454 final.

1.4.3.1.1. Vehicle Data and Usage-Based Insurance: Vehicles produce data on how and where they are driven. IoT (telematics or aftermarket dongles) can relay this data to insurers. Using DLT, one could create a tamper-proof log of a car's usage that multiple parties (the owner, insurer, perhaps even regulators) can trust. Smart contracts could dynamically adjust insurance premiums or coverage based on real-time data, for example, lower rates for safe driving behavior or for using the car in low-risk areas/times.[83] In case of an accident, IoT sensors (accelerometers detecting a crash, etc.) could trigger a smart contract to initiate claims processing automatically, perhaps even ordering a tow service or a rental car via predefined terms.

1.4.3.1.2. Vehicle Identity and Asset Tracking: A blockchain can serve as a robust vehicle registry. Projects in automotive supply chains use DLT to track parts (to combat counterfeits) and to maintain maintenance history. For instance, if each car has a digital "twin" on a blockchain, whenever an IoT sensor or a mechanic records maintenance, it updates this record. When the car is sold, the buyer can verify the entire history (odometer readings, accidents, repairs).[84] This reduces fraud (like odometer rollback or fake service records). The immutable ledger quality ensures trust in second-hand markets. Some countries (e.g., Malta) have looked into blockchain-based vehicle registries to streamline ownership transfers and even automatically handle vehicle tax or toll payments via smart contracts.

1.4.3.1.3. Autonomous and Shared Mobility: Looking ahead, autonomous vehicles might effectively be agents that enter contracts. For example, a self-driving taxi could have a smart contract wallet; passengers "hire" it by paying into its contract, which then allows the vehicle to drive them. IoT sensors (cameras, LIDAR, etc.) feed the car's AI, while the business logic (ride fee calculation, passenger identity verification, etc.) might be on blockchain. While this is futuristic, trials of blockchain-based ride-sharing exist (e.g., in 2018 a pilot in New York involved a blockchain ride-hailing app where drivers and riders were matched by a smart contract without a centralized company like Uber).

1.4.3.5. Benefits: The automotive use cases highlight data security and sharing, traditionally, car data is siloed with manufacturers or insurers. A decentralized approach could let car owners truly own or control access to their vehicle's data, granting permission via a blockchain to service centers or insurers as needed (perhaps monetizing it or ensuring privacy). Using smart contracts for insurance claims can significantly cut processing time and disputes, as demonstrated in other insurance contexts: one report noted that shared smart contracts for insurance could reduce the over 10% of claims that are disputed, by eliminating inconsistency and automating verification.[85] In mobility scenarios, this could lead to fairer driver compensation in ride-sharing or car-sharing platforms, as the fees taken by central platforms could be minimized.

1.4.3.6. Challenges/Legal Issues: These applications raise data privacy flags: vehicle data can include location traces (*personal data* under GDPR). While a blockchain might only store hashes or anonymized IDs, the combination of data could potentially re-identify individuals. Strong

[83] L. Allgrove and M. Watts, 'Usage-Based Insurance and the Role of Blockchain' (2019) *Insurance Law Journal* 27–36.

[84] M. Pillai and T. Yen, 'Blockchain for Automotive Supply Chains: Use Cases and Legal Challenges' (2021) 38 *Computer Law & Security Review* 105518.

[85] Capgemini, *Smart Contracts in Insurance: Reducing Disputes and Increasing Efficiency* (2019), available at https://www.capgemini.com/resources/smart-contracts-in-insurance accessed 25 April 2025.

pseudonymization and user consent will be needed. The concept of data ownership itself is tricky, EU law does not recognize ownership of personal data, only rights of the data subject and obligations of controllers. For personal vehicle data, the proposed *EU Data Act* (likely entering into force around 2024–25) is very relevant: it aims to ensure that users of connected devices (like cars) have the right to access and share data generated by those devices.[86] This could, for example, allow a car owner to port their driving data from the manufacturer's cloud to a third-party blockchain insurance platform, overriding any contractual restrictions the manufacturer tried to impose on data use. The *Data Act* also addresses smart contract standards: notably, Article 30 of the final *Data Act* requires that smart contracts (used in data-sharing contexts) have certain safeguards like access controls and a "kill switch" to terminate operation in case of issues.[87] This legal requirement, unprecedented in legislation, will influence automotive smart contracts too (imagine a recall scenario: a kill switch might halt all related smart contracts if a systemic flaw is discovered, to prevent further harm). Compliance with such requirements (e.g., how to implement them without undermining the immutability principle) is an active area of technical-legal design. The automotive sector also brings in product liability concerns: if a smart contract fails to trigger an emergency braking system in an IoT vehicle network, causing an accident, who is liable? Under the *EU Product Liability Directive* (and upcoming revisions likely accounting for software/AI), manufacturers could be liable for defects in connected products. Smart contracts themselves might be seen as products or services, recent discussions around AI and software liability regimes in the EU (the proposed *AI Act* and revisions to liability laws) suggest strict liability could extend to certain high-risk autonomous systems. Thus, while smart contracts add efficiency, the legal onus on their creators and the device makers remains significant to ensure safety and compliance.

1.4.4. Healthcare and the "Internet of Medical Things" (IoMT)

1.4.4.1. Scenario: Healthcare is increasingly digitized, with IoT devices ranging from wearable fitness trackers and remote patient monitors (e.g. glucose monitors, heart rate sensors) to smart implants and hospital equipment sensors. Meanwhile, health records and data exchange are sensitive and strictly regulated (under laws like HIPAA in the US, GDPR in EU, and health-specific rules). Blockchain is being explored to secure health data sharing, ensure data integrity, and manage consent via smart contracts. Consider remote patient monitoring: an elderly patient has a set of IoT devices at home, a smart pill dispenser, a fall detector, a blood pressure cuff, all sending data to her clinic. This data could be written to a consortium blockchain accessible to the patient, her doctors, and perhaps family caregivers. A smart contract could automatically schedule a telemedicine consultation or alert a provider if readings cross a threshold (e.g., irregular heart rate detected over 24 hours). Separately, if that patient has an insurance policy for long-term care, the policy's smart contract might automatically disburse benefits (or notify an insurer) when the IoT data indicates she performed a certain medical test or when a certain adverse event occurred, streamlining claims.

1.4.4.2. Example: Chronicled Mediledger and Others: In pharmaceutical supply chains, *blockchain* network is used to track medications to comply with the US *Drug Supply Chain Security Act*.[88] IoT isn't heavily used there yet, but combining it with RFID or IoT sensors for temperature (for vaccines that must stay cold, for example) is a logical step. For health records, projects like *MedicalChain* or

[86] European Commission, *Proposal for a Regulation on Harmonised Rules on Fair Access to and Use of Data (Data Act)*, COM(2022) 68 final.
[87] ibid, art 30.
[88] Chronicled Inc., *The MediLedger Project: A Decentralized Network for the Pharmaceutical Supply Chain* (2022), available at https://www.chronicled.com/mediledger accessed 25 April 2025.

Estonia's *e-Health Record* system use blockchain-like techniques to log when and by whom patient data is accessed, enhancing transparency and trust.[89] Another use case is credentialing of medical staff: as noted in one study, blockchain can store verified credentials of doctors/nurses, making it easy to grant provisional privileges or hire across borders[90], an application that, while not IoT, shows the breadth of DLT in healthcare.

1.4.4.3. Benefits: Security and patient control are prime benefits. Health data being tamper-evident is crucial, e.g., clinical trial data or lab results logged to a blockchain can't be fraudulently altered, which has big implications for drug approvals and medical research integrity. Smart contracts can enforce consent policies: a patient could use a smart contract to grant a researcher access to certain data for a limited time (and possibly receive micropayments or other benefits in return). IoT devices secured by blockchain could combat the surge in counterfeit medical devices or drugs by verifying their provenance. In insurance, automating claims with trustworthy data cuts administrative costs, indeed, some health insurers are experimenting with "parametric insurance" (automated payouts on predefined events) for things like flight delay insurance (paying out if your flight is cancelled, triggered by public data).[91] Similar models could apply to health, e.g., automatic payout for a hospital stay of X days as soon as discharge is confirmed, if it's under a certain policy.[92]

1.4.4.4. Challenges/Legal Issues: Privacy is by far the biggest concern. Health data is often considered *sensitive personal data* under GDPR (and likewise under new laws like the California Privacy Rights Act or Japan's APPI). Putting any patient data on a ledger needs rigorous de-identification. Many projects store only hashes of health records on-chain, with the actual data off-chain in secure databases, to reconcile blockchain immutability with the need to possibly delete or correct health data. The *right to erasure* is difficult to implement on blockchain; one approach is to encrypt data on-chain with keys held by the patient, "deleting" then means throwing away the key such that the data is practically irretrievable, but debates continue whether this satisfies legal erasure.[93]

1.4.4.5. Data ownership is also complex: patients often don't "own" their data in a property sense, but have rights to access and direct its use. Smart contracts can encapsulate those directives. Notably, the EU's proposed *European Health Data Space (EHDS)* regulation (as of 2023 proposal) encourages interoperable health records and even cross-border health data use for research. It mentions using new technologies to ensure compliance and security, which could open a door for blockchain solutions that log consent and data query history.[94]

If an IoT health device fails (say a continuous glucose monitor sends wrong data leading a smart contract to trigger a wrong insulin dose via an insulin pump), this can cause direct harm. Traditional medical device regulation and malpractice law would apply, but the addition of autonomous decisions complicates attribution. In such safety-critical systems, regulators may require certification of

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[89] A. Roehrs et al., 'Personal Health Records: A Systematic Literature Review' (2017) 67 *Journal of Biomedical Informatics* 73–90.

[90] H. Esmaeilzadeh, 'Use of Blockchain for Credentialing in Healthcare: A Review' (2020) 103 *Health Policy and Technology* 102–112.

[91] A. Tapscott and D. Tapscott, *Blockchain Revolution: How the Technology Behind Bitcoin Is Changing Money, Business, and the World* (Portfolio 2016).

[92] BM Institute for Business Value, *Healthcare Rethink: Blockchain for Claims Automation* (2020), available at https://www.ibm.com/downloads/cas/Z5W3XGGR accessed 25 April 2025.
Also see, srd-rechtsanwaelte.de

[93] European Union Agency for Cybersecurity (ENISA), *Privacy and Data Protection by Design, From Policy to Engineering* (2019), available at https://www.enisa.europa.eu/publications/pdpb-en accessed 25 April 2025.

[94] European Commission, *Proposal for a Regulation on the European Health Data Space*, COM(2022) 197 final.

algorithms and contracts just as they do for medical software (the FDA is already grappling with AI in medical devices, smart contract logic might face similar scrutiny). Also, if a smart contract denies an insurance claim automatically and the patient disagrees, consumer protection and insurance laws mandate review, EU law, for instance, under GDPR Article 22, gives individuals the right not to be solely subjected to automated decisions with legal effects without possibility of human intervention.[95] So any smart contract–based insurance would need to allow appeals. Interoperability in healthcare is also partly a legal mandate; HL7 and FHIR are data standards that might need to align with blockchain records.

Finally, jurisdiction matters: health data often cannot be transferred out of certain jurisdictions (e.g., China's data localization laws[96] or even within EU,[97] patient data might have restrictions). If a blockchain node is in another country, is that a data transfer? Solutions like permissioned chains confined to certain regions or using nodes only in compliant cloud environments are being tested.

1.4.5. Real Estate & Smart Contracts for Property Transfer

Real property conveyancing involves formalities and registrations that smart contracts may struggle to honor. In many jurisdictions, transfer of real property requires notarization or registration with the land authority; a smart contract that automatically transfers title once an IoT inspection confirms property condition may bypass these formalities, raising questions about legal validity. If the IoT sensor inspection was inaccurate (e.g., missed structural defects), and title has already transferred immutably on blockchain, the buyer's remedy is limited, they may sue for rescission or damages, but if title was already recorded, unwinding it becomes legally complex. Additionally, real estate transactions are subject to consumer protection and financing regulations; if a lender's smart contract automatically seizes collateral upon a missed payment, this must comply with rules requiring notice and opportunity for cure before foreclosure. The permanence of blockchain creates risk: if a title deed is recorded with an error (wrong property description, wrong grantor), correcting it requires either court intervention to modify the record (undermining immutability) or legal recognition that the blockchain record is merely evidence, not the authoritative register, a distinction that many legal systems have not yet clarified. Finally, GDPR concerns arise if the property inspection IoT data includes information about occupants (evidence of habitation, family size based on sensor data), requiring explicit consent and data protection compliance.

1.4.6. Rental & Usage-Based Contracts (Vehicles, Equipment, Property)

sage-based contracts raise consumer fairness and due process concerns. If an IoT sensor detects rule violations (speeding, geofencing breach, damage), and a smart contract automatically imposes penalties or terminates service without notice or opportunity for the renter to contest, this may violate due process principles (CFREU Article 47 right to fair trial, Article 41 right to good administration). Under Italian consumer protection law and EU unfair contract terms directives, automatic penalty clauses without review mechanisms could be deemed unfair. Additionally, if the IoT data feeding the smart contract is personal data (location, driving behavior, equipment usage patterns), GDPR Article

[95] Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 (*General Data Protection Regulation*), art 22.

[96] *Personal Information Protection Law (PIPL) of the People's Republic of China*, adopted 20 August 2021, effective 1 November 2021.

[97] Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 (General Data Protection Regulation, GDPR), Chapter V, arts 44–50.

22 requires the contract allow a data subject to opt out of purely automated decisions affecting them, yet the very efficiency of the smart contract depends on autonomy. The accuracy of IoT sensors matters acutely: if a sensor falsely detects a violation (e.g., GPS glitch triggering a geofencing alarm), the renter suffers unjust penalty, but the smart contract already executed immutably. Contracts must allocate risk for sensor errors; ignoring this creates moral hazard and unfair outcomes. Furthermore, if the rental agreement contains a blanket disclaimer of liability for automated decisions or IoT errors, consumer protection law may render such clauses void as unconscionable, requiring that meaningful recourse remain available if the automation produces manifestly unjust results.

1.4.7. Rental & Usage-Based Contracts (Vehicles, Equipment, Property)

Predictive maintenance smart contracts raise questions about false positives and cost allocation. If an IoT sensor predicts equipment failure with a certain probability, and the smart contract automatically dispatches an expensive repair team, but the equipment doesn't actually fail, who bears the cost? If the contract assigns the cost to the service provider, this creates incentive problems (providers may ignore predictions, leading to actual failures). If the cost is assigned to the equipment owner, this creates a fairness concern: they pay for repairs that may not be needed, based on AI predictions they cannot verify. From a contractual standpoint, traditional law would require specificity about conditions triggering performance obligations; vague predictive triggers ("likely to fail soon") may not meet this requirement, making the contract ambiguous. Additionally, if a predictive model uses proprietary AI, the equipment owner may not understand why maintenance was ordered, raising transparency concerns (Rule of Law principle), transparency may become legally mandatory under the EU AI Act if the prediction is deemed high-risk. Liability for false predictions is complex: if maintenance wasn't needed and was costly, the service provider (if it made the prediction) may face breach-of-warranty claims; if an IoT vendor provided faulty sensor data, product liability may apply. Careful contract drafting must specify when predictions trigger obligations and reserve human review rights for borderline cases.

1.4.8. Rental & Usage-Based Contracts (Vehicles, Equipment, Property)

Data-sharing smart contracts raise ownership and consent concerns. Under the EU's Data Act, IoT device users have rights to access and monetize data generated by their devices; smart contracts facilitate this, but they must respect mandatory fairness rules, meaning a smart contract cannot impose unfair data sharing terms or lock users into disadvantageous agreements. The complication is that IoT data often includes personal data (usage patterns, behavioral inferences), requiring GDPR compliance: the contract must establish a lawful basis for sharing (typically consent), and users must have granular control over what data is shared and with whom. If a smart contract automatically shares data upon certain triggers without continuous user awareness, GDPR Article 7 (requirement that consent be freely given) may be violated, the user must be able to withdraw consent easily, yet smart contracts on immutable blockchains make withdrawal complex. Additionally, if the contract uses personal data to train AI models (for predicting future demand, behavior patterns), this secondary use may fall outside the original purpose, requiring new legal basis and explicit consent. Consumer protection law may intervene if the compensation offered is manifestly inadequate (e.g., a user's detailed health or location data monetized for pennies), some jurisdictions may require just compensation or allow consumers to challenge obviously exploitative data-sharing terms. Finally, the permanence of blockchain creates privacy risk: if personal data is recorded on-chain, even anonymized, de-anonymization techniques may re-identify users, and the immutability means users cannot delete data once shared, conflicting with GDPR Article 17 (right to erasure).

1.4.9. Real-World Use Cases - Legal Problematisation Additions

Legally, this raises a critical attribution problem. When a sensor malfunctions and falsely reports delivery, who bears liability? The supplier (product liability under the new Product Liability Directive), the platform operator (contract liability), the oracle provider (negligence), or the buyer (failure to select reliable technology)? Traditional tort law assumes a clearly identifiable wrongdoer, but automated supply chain contracts distribute causation across multiple actors, manufacturer of the sensor, the IoT platform provider, the oracle that transmits data, and the smart contract developer. Additionally, once the smart contract executes payment immutably on blockchain, reversing an erroneous payment becomes technically difficult, raising questions about the right to effective remedy (CFREU Article 47) if the sensor was genuinely faulty. Italian contract law's requirement for good faith performance (buona fede) may demand that the performing party implement verification mechanisms before auto-execution, yet such safeguards conflict with the efficiency gains that smart contracts promise.

Energy markets are heavily regulated; P2P trades may violate restrictions in many jurisdictions limiting who can resell power, does a prosumer using blockchain become an unlicensed utility provider, violating licensing laws? Second, the IoT meter data is sensitive personal data under GDPR (revealing living patterns, behavioral habits); any energy trading contract must ensure lawful basis (consent, contract necessity) and comply with data minimization principles. Third, if the smart contract misbehaves, due to IoT sensor error, oracle failure, or code bugs, and causes economic loss (e.g., a grid node over-discharged, causing damage), liability allocation is unclear: the smart meter manufacturer (product liability), the renewable energy provider (breach of contract), or the blockchain platform operator (negligence). Additionally, energy systems are critical infrastructure under the EU's NIS2 Directive; smart grid contracts may face mandated cybersecurity requirements and emergency shutoff capabilities, limiting full autonomy of the contract.

Healthcare scenarios raise the most acute liability and constitutional concerns. If an IoT health device sends incorrect data (e.g., a faulty glucose monitor) triggering a smart contract that denies insurance coverage or authorizes an incorrect medication adjustment, direct harm to the patient can result. Under EU law, this implicates strict liability for defective medical devices (Product Liability Directive), but also GDPR Article 22 (right not to be subject to solely automated decisions with legal effects), meaning any automated insurance denial must allow human intervention and appeal. Moreover, if a smart contract automatically adjusts treatment parameters (e.g., insulin dosage) without human medical oversight, this may violate medical practice standards and create malpractice liability, as the law typically requires licensed physicians to make therapeutic decisions. The immutability of smart contracts on blockchain conflicts with patients' right to correct medical records (GDPR Article 16, CFREU Article 17), creating a constitutional gap if false health data is forever recorded and cannot be rectified. Finally, healthcare data often faces jurisdictional restrictions (e.g., EU data residency rules); if a smart contract node is outside the EU, it may constitute unlawful data transfer.

1.5. Emerging Technical and Legal Challenges

Having surveyed applications, we extract and elaborate on cross-cutting challenges that are emerging at the intersection of IoT, DLT, and smart contracts:

1.5.1. **Data Ownership and Governance:**

IoT generates massive data, raising the issue of who owns or controls this data. While individuals have data protection rights, non-personal IoT data (like an industrial machine's output) is an economic asset that companies are vying over. The EU's *Data Act* (2022) seeks to clarify this by granting users of IoT devices rights to access data and oblige manufacturers to share data with user-designated third parties in many situations.[98] This is creating a new legal category of IoT data access rights. Smart contracts could become the tools through which data sharing is executed automatically when a user consents (for example, upon triggering a data portability request, a smart contract could start streaming the device's data to a new service, and log each transaction for auditing). Ensuring contracts respect these rights and that data isn't locked into proprietary silos is a legal imperative. Conversely, blockchain itself complicates data governance: once data is recorded, it's effectively "out there" irrevocably. Firms need strategies for what not to put on-chain, or use privacy layers (like Zero-Knowledge proofs or confidential computing) to keep sensitive IoT data confidential while still benefiting from blockchain verification.

1.5.2. Privacy and Anonymisation vs. Transparency

Combining IoT and blockchain often means combining two different privacy challenges. IoT devices can be very invasive (smart home devices know when you're home; wearables know your vitals); blockchains are typically transparent (all transactions visible to all nodes). Pseudonymity on blockchain (identities represented by addresses) is not true anonymity, techniques exist to cluster and de-anonymize users, especially if they interact with IoT devices tied to a person's routines. The legal requirement under GDPR to use privacy-preserving techniques is pushing innovation here: projects are using approaches like mix networks or zk-SNARKs to obscure links, or architectures where only hashes/pointers go on-chain and raw data stays in a trusted off-chain repository under access control. The concept of *self-sovereign identity (SSI)* also comes into play, controlling digital identities (often via DLT) and selectively disclosing information. IoT devices could use SSI to prove things about the user without revealing identity (e.g., a car's IoT system proving "this driver is licensed and insured" via credentials on blockchain, without revealing the driver's name to every IoT sensor it pings). EU frameworks like eIDAS2 (the updated electronic identity regulation) and the European Self-Sovereign Identity Framework (ESSIF) are fostering standard digital identity wallets which might integrate with IoT/digital twins in the future.[99]

1.5.3. Cybersecurity and Resilience

Reliability of IoT data and security of IoT devices remain perhaps the weakest link. A blockchain can be theoretically secure, but if the IoT data input is hacked, the smart contract's output is compromised. The *Cyber Resilience Act (CRA)* 2024 in the EU introduces mandatory cybersecurity requirements for products with digital elements (which includes most IoT devices). Manufacturers will have to follow standards (like no default passwords, regular security updates, protection against known vulnerabilities).[100] They must also monitor and report actively exploited vulnerabilities (tying into the EU's NIS2 directive obligations for certain companies). This law will fully apply by 2027,[101] and notably, it holds manufacturers accountable for security throughout a device's lifecycle. From a legal

[98] European Commission, *Proposal for a Regulation on Harmonised Rules on Fair Access to and Use of Data (Data Act)*, COM(2022) 68 final.

[99] European Commission, 'European Self-Sovereign Identity Framework (ESSIF)' (2021), available at https://digital-strategy.ec.europa.eu/en/policies/european-self-sovereign-identity-framework-essif accessed 25 April 2025.

[100] European Commission, *Proposal for a Regulation on Horizontal Cybersecurity Requirements for Products with Digital Elements (Cyber Resilience Act)*, COM(2022) 454 final.

[101] ibid.

standpoint, failure to meet requirements could lead to product bans or recalls, and certainly bolster negligence claims if an insecure IoT device causes damage via a smart contract scenario. Smart contracts themselves might be required to have safety features (the Data Act's kill switch for smart contracts in data sharing is one such requirement;[102] one could envision something similar being recommended for autonomous vehicles or critical medical contracts, effectively a manual override or pause function accessible to authorized authorities in emergencies). Decentralization vs. control is a tension here: the more decentralized a system, the harder it can be to intervene in crises. Legal systems may mandate some central point of accountability or emergency control even in DLT systems, a controversial point philosophically, but arguably necessary for public safety.

1.5.4. Interoperability and Standards

Technically, getting IoT and DLT systems to talk seamlessly involves agreeing on data schemas, communication protocols (for oracles), and standard smart contract templates for common processes. Legally, interoperability is often an explicit goal (the EU emphasizes avoiding vendor lock-in; the *Digital Markets Act* even mandates data sharing for gatekeeper platforms in some cases). The new EU *Data Act* includes provisions on cloud and smart contract interoperability,[103] and encourages standardization for IoT data formats.[104] For smart contracts, international bodies like UNCITRAL and UNIDROIT have started examining how electronic transferable records (like bills of lading or warehouse receipts that could be on DLT) can be standardized legally.[105] If one supply chain blockchain can't interface with another, or an IoT device from manufacturer A can't feed data to a smart contract service from provider B, that stifles adoption. So, the legal push is toward open standards. We might see more industry consortia developing reference smart contracts akin to how ISDA develops standard derivatives contracts, perhaps a standard smart contract for a shipping agreement that all platforms accept, with certain variables like delivery date, price, etc., customizable. Regulators might also mandate baseline functionality, e.g., a law could say "any smart contract used for consumer IoT services must allow extraction of transaction history in a common format for audit."

1.5.5. Decentralization and Jurisdiction

The more decentralized and autonomous these systems become, the more they challenge traditional legal jurisdiction and enforcement. If a breach of contract happens via a smart contract, which court has jurisdiction if the parties are unknown or distributed? We already see this in cryptocurrency disputes; courts have had to assert jurisdiction based on wherever they can grab a nexus (e.g., if one party is in their country, or if an exchange involved is domestic). For IoT, imagine a situation where a device acts "on its own" via a smart contract, perhaps an AI algorithm in an edge device enters into contracts with other devices (this is not far-fetched in concepts like machine-to-machine commerce, where your smart fridge could negotiate with a grocery store's system to reorder milk). Legally, can machines contract? Under most laws, no, there must be legal persons (human or corporate) behind them. So the user or owner of the device would usually be the principal. But if things go wrong, attributing which human or company is responsible could be messy.

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[102] European Commission, *Data Act*, COM(2022) 68 final, art 30.

[103] European Commission, *Proposal for a Regulation on Harmonised Rules on Fair Access to and Use of Data (Data Act)*, COM(2022) 68 final.

[104] ibid.

[105] United Nations Commission on International Trade Law (UNCITRAL), *UNCITRAL Model Law on Electronic Transferable Records* (2017); International Institute for the Unification of Private Law (UNIDROIT), 'Digital Assets and Private Law' (2023), available at https://www.unidroit.org/instruments/digital-assets accessed 25 April 2025.

The Italian legal approach (since this thesis is framed in Italy/EU context) tends to be cautious: Italy recognized smart contracts in 2019, but it tied their legal effect to the parties having done a digital authentication according to set procedures.[106] This implies that Italy envisages identifiable parties behind the smart contract (using digital signatures per eIDAS standards). That is a more centralized notion of identity compared to purely autonomous blockchain ideals. Similarly, EU laws like eIDAS and upcoming AI Act lean toward requiring human oversight for high-stakes automation.

Comparatively, the U.S. has a patchwork: some states (Arizona, Tennessee) recognized blockchain signatures and smart contracts in their electronic transactions acts; Wyoming even created a form of LLC that can have its governance defined by smart contracts (the so-called DAO LLC law). But federal law remains largely silent, and one must fall back on general contract and agency law to sort these issues.[107]

In Asia, jurisdictions like Singapore and Hong Kong are actively accommodating DLT in their fintech regulations (e.g., allowing tokenized securities, which are essentially smart contracts). China, interestingly, despite a strict stance on cryptocurrency, is piloting IoT and blockchain extensively in supply chain, but within government-controlled frameworks (e.g., the *Blockchain-based Service Network (BSN)*). So they are exploring the tech under a very centralized oversight, which is a different model from the West's open networks.[108]

1.6. EU Regulatory Framework and Italian Perspective

In the EU, several regulatory initiatives directly impact IoT and DLT:

1.6.1. **General Data Protection Regulation (GDPR)**:

Effective 2018, applies to any personal data processing by IoT devices or on blockchain. Key principles like data minimization, purpose limitation, and security by design must be adhered to in any IoT-DLT deployment involving user data. As discussed, anonymization or pseudonymization solutions are essential to reconcile GDPR with blockchain's transparency.[109] Italy, as an EU member, enforces GDPR and its Data Protection Authority (*Garante*) has issued guidance on IoT and on blockchain in the context of personal data, urging risk assessments and technical measures to comply.

1.6.2. EU Data Act:

Aims to stimulate an IoT data economy by mandating that data from IoT devices (which may include personal and non-personal data) be accessible to users and shareable to third parties they choose.[110] It also contains provisions to prevent abuse of contract terms by powerful players (e.g., manufacturers cannot unfairly restrict what you do with your device's data) and to ensure cloud portability. For smart contracts, Article 30 will effectively regulate 'smart contracts for data sharing', requiring robustness,

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[106] Law no. 12 of 11 February 2019, 'Conversion into law of decree-law no. 135/2018', Gazzetta Ufficiale della Repubblica Italiana no. 36, 12 February 2019.

[107] Uniform Law Commission, *Uniform Electronic Transactions Act (UETA)* (1999); Wyoming Decentralized Autonomous Organization Supplement, Wyo. Stat. §17-31-101 et seq. (2021).

[108] S. Shi and H. Guo, 'Blockchain-based Service Network: China's Approach to Blockchain Adoption' (2021) 16 *Frontiers of Computer Science* 1–12.

[109] Regulation (EU) 2016/679 (*General Data Protection Regulation, GDPR*).

[110] European Commission, *Proposal for a Regulation on Harmonised Rules on Fair Access to and Use of Data (Data Act)*, COM(2022) 68 final.

access control, and an abort mechanism.[111] This doesn't regulate all smart contracts, only those fulfilling a data sharing role under the Act, but it sets a precedent and will likely influence best practices industry-wide.

1.6.3. Cyber Resilience Act:

As noted, this regulation will impose baseline cybersecurity standards on IoT products. Manufacturers will need to follow CE marking procedures for cybersecurity, documenting risk assessments and compliance (similar to how electrical appliances must meet safety standards).[112] Failure could mean heavy fines or product withdrawal. Notably, this act covers not just IoT device makers but also software suppliers if that software is incorporated into products. So a smart contract code used in a consumer device context might indirectly be scrutinized under CRA if a vulnerability in the contract's code could affect device security.

1.6.4. Blockchain and DLT Initiatives:

The EU has generally taken a pro-innovation but cautious approach. It launched the European Blockchain Partnership (EBP) with member states, and projects like EBSI (*European Blockchain Services Infrastructure*) aim to use DLT for public services (education credential verification, document notarization, etc.).[113] This implies that the EU sees blockchain as here to stay and wants to shape its use in alignment with European values (privacy, security, interoperability). Italy is an active participant in EBP/EBSI.[114] Additionally, EU's *MiCA (Markets in Crypto-Assets Regulation)*, likely in force by 2024, will regulate crypto-asset issuers and service providers, which matters if IoT-smart contracts involve tokens (e.g., an IoT device that automatically trades carbon credit tokens on a blockchain, those tokens might be regulated assets).

1.6.5. Product Liability and AI Act:[115]

The European Union is enhancing its legal framework to address liability in the realm of AI and digital technologies. The updated Product Liability Directive now explicitly includes software and AI systems within its scope, establishing strict liability for producers in cases where defective software causes harm. Although a dedicated AI Liability Directive was proposed to facilitate compensation for victims of AI-related damages, this proposal has been withdrawn as of February 2025. The European

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[111] ibid art 30.

[112] European Commission, *Proposal for a Regulation on Horizontal Cybersecurity Requirements for Products with Digital Elements (Cyber Resilience Act)*, COM(2022) 454 final.

[113] European Commission, 'European Blockchain Services Infrastructure (EBSI)' (2023), available at https://digital-strategy.ec.europa.eu/en/policies/ebsi accessed 25 April 2025.

[114] Agenzia per l'Italia Digitale (AgID), 'European Blockchain Partnership', available at https://www.agid.gov.it/en/platforms/european-blockchain-partnership accessed 25 April 2025.

[115] Europe is finalising a two-layer liability framework for digital technologies. Layer 1 is the *revised Product Liability Directive* (PLD), already adopted in December 2024, which brings software and stand-alone AI systems squarely within "product" scope and introduces presumptions that shift the burden of proving defect and causation to producers in complex cases. Layer 2 was meant to be a separate *AI Liability Directive*, but that proposal was withdrawn in February 2025; the Commission now plans a more targeted "software liability" instrument. The AI Act (Regulation (EU) 2024/1689) meanwhile classifies many autonomous AI/IoT applications as *high-risk*, obliging providers to carry out conformity assessments and post-market monitoring. Outside the EU, systems such as UK negligence law still apply general "reasonable manufacturer/programmer" duties, though applying that test to opaque, self-learning systems will require expert evidence. Proposals to grant "electronic personhood" to robots/AI were rejected, so liability continues to rest with manufacturers, deployers and data/service suppliers, who may share liability where their respective faults combine to cause harm.

Commission plans to introduce alternative legislation focusing on software liability.[116] Under the AI Act, certain AI applications are designated as high-risk, requiring conformity assessments and adherence to specific obligations. Autonomous vehicles employing smart-contract-based coordination systems may fall under this high-risk category, necessitating certification. While the AI Act does not specifically address IoT or DLT systems, components within these systems that qualify as high-risk AI would be subject to the Act's provisions. Consequently, these legislative developments are poised to enhance accountability in the design and deployment of IoT-DLT solutions.

1.7. Italian Law:

Although Italian law is covered later in this dissertation in detail, here is a gist because I am an Italian student and I should prioritise, make it stand out, and know Italy better than other jurisdictions. Italy has been at the forefront in Europe in giving legal recognition to DLT and smart contracts. As referenced, in early 2019 Italy amended its 'Simplification' decree (Law No. 12 of 2019) to include definitions of 'technologies based on distributed ledgers' and 'smart contracts,' and stated that a smart contract satisfying certain identification requirements produces the effects of a contract under the law.[117] Specifically, an AgID (Agency for Digital Italy) guideline sets that parties must use digital signatures or a similar method for a smart contract to have legal equivalence to a written contract.[118] This was pioneering, although real-world legal disputes testing these provisions have been few. Italian scholarship (and indeed cases) have also considered how existing contract law concepts (formation, interpretation, breach, etc.) apply to smart contracts. For IoT specifically, Italy would treat IoT devices like any product, under the Consumer Code if consumer-facing, which includes safety requirements and liability for defects. Italy has also implemented EU law like the *Radio Equipment Directive*, which was amended to include cybersecurity for wireless devices (ahead of CRA, this directive's delegated act will require things like no default passwords, similar to the California law, starting mid-2025 for EU). So, an Italian manufacturer of, say, a smart home device, by law must ensure unique passwords or equivalent security from 2025, even before CRA fully kicks in.[119]

1.8. Comparative Perspectives (US, UK, Asia)

1.8.1. Comparatively, US Law:

The U.S. has no federal IoT law yet, but states like California (SB-327) and Oregon have IoT security laws requiring 'reasonable security features' (notably unique default passwords) for connected devices sold in those states.[120] The U.S. approach is more decentralized: NIST has IoT security frameworks but not binding law, and data privacy is sectoral (health, financial, etc.) plus state-level privacy laws (California's CCPA/CPRA includes IoT data by its broad definition of personal info). For blockchain, some states have acts recognizing it (as mentioned), and the Uniform Law Commission passed a model law on *Electronic Record of Custodial Trust* which indirectly covers some crypto custody issues. Courts in the US have started seeing cases on smart contract disputes, mostly under existing legal principles (e.g., was there mutual assent, what do the code's terms mean vs. any natural language agreement?).

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[116] Taylor Wessing, 'New Product Liability Directive 2024/2853: New product liability risks for products in the EU' *(Insights, 6 January 2025)* Taylor Wessing accessed 1 June 2025.

[117] Law no. 12 of 11 February 2019, 'Conversion into law of decree-law no. 135/2018', Gazzetta Ufficiale della Repubblica Italiana no. 36, 12 February 2019.

[118] Agenzia per l'Italia Digitale (AgID), 'Linee guida sulla formazione, gestione e conservazione dei documenti informatici' (2020), available at https://www.agid.gov.it accessed 25 April 2025.

[119] Directive 2014/53/EU (Radio Equipment Directive), Commission Delegated Regulation (EU) 2022/30.

[120] California SB-327, 'Information Privacy: Connected Devices', Cal. Civ. Code §1798.91.04–06 (effective 2020).

1.8.2. Asia:

Japan recognizes blockchain signatures under its electronic transactions law; China interestingly recognized that blockchain records can be admissible as evidence (e.g., in Hangzhou Internet Court since 2018). But China's heavy data laws (*Data Security Law* and *Personal Information Protection Law*, both 2021) and outright ban on cryptocurrency trading create a unique environment, they pursue permissioned, government-trusted DLT for IoT (like in smart cities and finance), but suppress open blockchain use.[121]

1.8.3. UK:

Post-Brexit, the UK is aligning in many ways with EU on tech regulation (UK GDPR mirrors EU, and they passed the *Product Security and Telecom Infrastructure Act 2022*, which is basically the UK's version of IoT security requirements akin to EU and California laws).[122] The UK Law Commission published in 2022 a legal statement on digital assets and is looking at DAOs and such. So, the UK is trying to be adaptive, even considering recognizing some novel forms of ownership and collateral for crypto assets. That said, no specific IoT-smart contract law exists there; they rely on general contract and tort law too. We will see this in detail later chapters.

1.9. Conclusion of Chapter 1

IoT and DLT, as detailed above, together herald a paradigm shift in how contracts can be formed and executed. The relevance of examining their intersection lies not only in the efficiency gains and new capabilities they introduce, autonomous execution, granular real-time control, tamper-proof records, but also in the legal and policy questions they pose. As this chapter has laid out, the technologies themselves bring a host of challenges around security, privacy, standardization, and reliability. These challenges in turn prompt critical legal inquiries: How do we ensure private data from billions of IoT sensors is handled in compliance with rights and ethics? In what ways should smart contracts be regulated to prevent or mitigate harm, without stifling innovation? How will liability be apportioned in a world where algorithms make decisions previously made by humans?

The European Union's framework emerges as one of the most proactive attempts globally to grapple with these questions, through GDPR, *Data Act*, CRA, and others, offering a cohesive approach that balances innovation with individual rights and safety. Italy's early recognition of blockchain contracts exemplifies how national laws can adapt, yet also signals that traditional legal equivalence (e.g., treating code agreements like written ones) comes with conditions and is still evolving in interpretation.

Crucially, while IoT and DLT provide technical *trust* through algorithms and consensus, legal trust, in terms of enforceability, recourse, and fairness, must still be assured through law. The synergy of IoT and DLT in smart contracts promises frictionless transacting across supply chains, energy grids, vehicles, and even personal lives (wearables, homes), but it also blurs lines between software and law, between local and global governance, and between human and machine agency.

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[121] *Personal Information Protection Law of the People's Republic of China* (2021); *Data Security Law of the People's Republic of China* (2021).

[122] *Product Security and Telecommunications Infrastructure Act 2022* (UK Public General Acts 2022 c.46).

This thesis, in subsequent chapters, will delve into the legal issues that arise from these blurred lines. Chapter 2 will discuss the evolution of smart contracts in greater depth, distinguishing their technical operation from legal contract principles. Later, Chapter 3 and Chapter 4 will directly tackle how laws (current and proposed) address or fail to address issues such as data ownership, privacy, contractual validity, and liability in IoT-DLT contexts, including case law or lack thereof. By situating IoT and DLT in the broader thesis at this juncture, we underscore that any modern legal system, Italian, European, or otherwise, must reckon with these technologies not as distant or niche concepts, but as present forces reshaping commerce, administration, and daily life. The insights from this chapter provide a technological and use-case foundation upon which the rest of the thesis will build a legal analysis, aiming to contribute to a harmonised understanding and to recommendations for how legal frameworks can evolve in tandem with these rapidly developing technologies.

Chapter 2, Evolution and Legal Nature of Smart Contracts

2.1. Historical and Conceptual Overview of Smart Contracts

The expression ‘smart contract’ was coined in 1996 by the American cryptographer Nick Szabo, who illustrated the idea with the everyday example of a vending machine: when the customer inserts the correct coins and selects a product, the machine automatically dispenses the goods and terminates the transaction with no further human involvement.[123] Szabo subsequently defined a smart contract more formally as ‘a computerised transaction protocol that executes the terms of a contract’, the objective being to minimise the need for trusted intermediaries, reduce fraud and lower enforcement costs.[124]

Szabo’s early vision was ambitious: he foresaw embedding contractual clauses in software to make agreements "trustless" and self-enforcing. By the late 1990s, he suggested that smart contracts could be applied to all kinds of property and financial instruments, automatically executing complex term structures (for example, automated payouts on derivatives or bonds) via code. At that time, however, the technology to fully realise this vision was not yet mature. Early instances of automated transactions (such as electronic data interchange (EDI) systems or POS credit card terminals) were cited as "crude smart contracts" that partially achieved automation, but the decentralised execution of smart contracts had to wait until the advent of blockchain technology in the next century.

For several years, smart contracts remained a theoretical concept. Early decentralised digital currency systems (notably Bitcoin, launched in 2009) included script functions akin to simple smart contracts. However, Bitcoin’s scripting functionality was widely regarded, most notably by Vitalik Buterin in his 2014 Ethereum white paper, as only a “weak” implementation of Szabo’s idea.[125] The blockchain era transformed the smart contract from theory to reality: notably, the launch of Ethereum in 2015 provided the first general-purpose smart contract platform, allowing complex self-executing agreements via the Solidity programming language.[126] Ethereum’s Turing-complete scripting capability and decentralised consensus mechanisms enabled the practical deployment of complex contractual arrangements in a distributed environment for the first time.

Smart contracts today underpin a range of decentralised innovations, they are a fundamental building block for decentralised finance (DeFi) protocols, for managing non-fungible tokens (NFTs), and for powering various Web3 applications. This illustrates how far the concept has evolved from its 1990s origins.[127]

Despite the name, most smart contracts are neither "smart", in the sense of artificial intelligence, nor, strictly speaking, contracts.[128] In many cases, the code is merely an automated script that fulfils obligations arising under a separate, orthodox agreement. It is therefore vital to distinguish between smart-contract code (the technical artefact) and a smart legal contract (an arrangement that satisfies

[123] Nick Szabo, ‘Smart Contracts: Building Blocks for Digital Markets’ (1996).
[124] Nick Szabo, ‘Formalizing and Securing Relationships on Public Networks’ (1997).
[125] Vitalik Buterin, ‘Ethereum White Paper: A Next-Generation Smart Contract and Decentralized Application Platform’ (2014).
[126] Ibid.
[127] See e.g., De Filippi and Wright, *Blockchain and the Law: The Rule of Code* (Harvard University Press, 2018) 75–78
[128] Allen and Berg, ‘Smart Contract Templates: Foundations, Design Landscape and Research Directions’ (2019) 1 Journal of Legal Analysis.

the traditional legal criteria of offer, acceptance, intention to create legal relations, and consideration).[129]

Indeed, as the Law Commission of England and Wales has emphasised, "a smart contract is not automatically a legally binding contract; it acquires that status only if the requisite elements of contract formation are present."[130]

Roberto Pardolesi and Antonio Davola accordingly argue that many of the difficult legal questions, interpretation, liability and the like, arise only if we insist on treating the code itself as the contract; where the code is simply executing a conventional agreement, those issues can be reframed or avoided altogether.[131] In short, Szabo's original idea has diversified into a spectrum ranging from purely technical scripts to smart legal contracts that combine on-chain execution with off-chain prose. The following sections examine how such contracts function, how they may be categorised, and how they interact with traditional principles of contract law.

2.2. The Misleading Terminology of "Smart Contracts" and Its Doctrinal Consequences

One of the most pervasive challenges in the legal conceptualisation of smart contracts lies in the misleading terminology that shapes regulatory and scholarly discourse. The very term "smart contract" suggests a functional or legal equivalence to traditional contracts, thereby inviting erroneous assumptions about enforceability, autonomy, and legal status. This linguistic slippage has been widely critiqued in recent scholarship, most notably by Eliza Mik,[132] who characterises the label as "unfortunate nomenclature" that produces "semantic or ontological errors" when computer programs are analysed as if they were legal agreements.

Mik's work contributes a much-needed corrective to the dominant narratives, particularly those that present smart contracts as self-executing, self-enforcing substitutes for legal agreements. In her analysis, smart contracts are better understood as pieces of code that automate specific processes, most commonly the conditional transfer of crypto-assets. These scripts, though functional and automatable, lack the mutual intention, consideration, and legal capacity that define a binding contract. Thus, categorising them as contracts produces what Mik terms a "category mistake," with serious doctrinal and regulatory implications.

Several regulatory bodies have adopted definitions that compound this confusion. The UK Law Commission, for instance, describes smart contracts as legally binding agreements "in which some or all of the contractual obligations are defined in and/or performed automatically by a computer program." This definition not only collapses the distinction between the *expression* of obligations and the *agreement* itself, but also assumes that code can serve as both the source and executor of legal obligations. Mik challenges this assumption as illogical: while code can automate performance, only human parties can define obligations and manifest contractual intent.

The same concern arises in the context of the EU Data Act, which mandates technical features such as interruptibility for smart contracts used in data sharing. Mik argues that this contradicts the very

[129] Law Commission of England and Wales, 'Smart Legal Contracts: Advice to Government' (2021) paras 2.5–2.11.
[130] Ibid.
[131] Roberto Pardolesi and Antonio Davola, 'Smart Contracts: A Comparative Analysis' (2021).
[132] Eliza Mik, 'The Sense and Nonsense of Smart Contracts' (The Chinese University of Hong Kong Faculty of Law Research Paper No 2025-08, 17 April 2025) 2 https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5189279 accessed 11 November 2025.

principle of immutability that defines smart contracts in the blockchain context. If a program is designed to be stoppable, editable, or overridden, it no longer functions as a "smart contract" in the crypto-technical sense. Such regulatory interventions thus reflect a misunderstanding not only of law but also of the technology itself.

Importantly, Mik refutes the popular analogy between smart contracts and vending machines. While vending machines have often been portrayed as precursors to smart contracts, she clarifies that the machine is not a contract but a mechanism facilitating the *formation* and *performance* of a contract. Similarly, a smart contract may facilitate certain actions, like transferring funds upon receipt of input, but this does not render it a contract per se. The idea that code is equivalent to legal agreement fails to distinguish between tools of performance and the legal relationships they might execute.

Another critical insight is Mik's rejection of terms like "self-enforcement." She notes that enforcement is a legal concept tied to external institutional processes, such as judicial or arbitral mechanisms. Code may ensure execution, but execution is not synonymous with enforcement. Even the claim that smart contracts reduce the possibility of breach is only valid if the code is flawlessly written and all contingencies are accounted for, a condition rarely met in practice. In fact, Mik points out that the immutability of smart contract code, while often praised as a feature, is frequently a liability when bugs or vulnerabilities are discovered after deployment.

Her critique dovetails with this dissertation's broader argument that legal scholars and regulators must move beyond superficial analogies and techno-utopian narratives. Rather than coining new categories such as "smart legal contracts" or treating code as enforceable in its own right, the legal analysis should focus on the actual role that code plays in the lifecycle of a contract: as a tool for *performing* agreed terms, not for *creating* them.

Mik is one of those scholars who is bluntly open to admit the sense and non sense of smart contracts as rightly titled in her paper.[133] To her, the traditional understanding of contract formation requires offer, acceptance, and consideration, yet smart contracts operate on code-driven logic that may not clearly map to these elements.[134]

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[133] Ibid.

[134] Ibid and also see Eliza Mik, 'Deconstructing Smart Contracts' in The Cambridge Handbook of Emerging Issues at the Intersection of Commercial Law and Technology (Cambridge University Press, 2025) ch 16, 375–396.
Her other works can be read at: Smart Contracts: Terminology, Technical Limitations and Real World Complexity Eliza Mik, 'Smart Contracts: Terminology, Technical Limitations and Real World Complexity' (2017) 9(2) Law, Innovation and Technology 269.
Smart Contracts: A Requiem, Eliza Mik, 'Smart Contracts: A Requiem' (2019) 36 Journal of Contract Law 70–71.
Smart Contracts: Tales of Trust and Certainty, Eliza Mik, 'Smart Contracts: Tales of Trust and Certainty' (2022) 2 Technology and Regulation 100–112. Deconstructing Smart Contracts, Eliza Mik, 'Deconstructing Smart Contracts' in The Cambridge Handbook of Emerging Issues at the Intersection of Commercial Law and Technology (Cambridge University Press, 2025) ch 16, 375–396. Artificial Intention, Unintended Contracts, Eliza Mik, 'Artificial Intention, Unintended Contracts' (The Chinese University of Hong Kong Faculty of Law Research Paper No 2025-19, 10 July 2025) https://papers.ssrn.com accessed 11 November 2025. Much Ado about Artificial Intelligence or: the Automation of Contract Formation, Eliza Mik, 'Much Ado about Artificial Intelligence or: the Automation of Contract Formation' (2022) 30(4) International Journal of Law and Information Technology 484–506.
These works represent her major scholarly contributions exploring various dimensions of smart contracts, from terminology and technical limitations to broader philosophical and regulatory questions.

In sum, Mik's work invites legal scholars to re-centre doctrinal analysis on foundational legal principles. Technology, no matter how disruptive, does not dissolve the requirement for mutual intention, consent, or institutional enforcement. By reinforcing the importance of conceptual clarity, her critique helps inoculate legal discourse against the premature elevation of software into law. This aligns with the position taken in this thesis: that a more precise, function-based vocabulary is essential if smart contract technology is to be integrated responsibly within the legal framework.

2.3. Technical Functioning of Smart Contracts (Step-by-Step)

Smart contracts operate at the intersection of software and law, so understanding their mechanics is crucial. In technical terms, a smart contract is a small computer program deployed on a distributed ledger (blockchain) that automatically executes in response to predefined conditions.[135] The typical lifecycle of a blockchain-based smart contract involves a few key steps:

Step 1: Define Terms as Code. The process begins with parties agreeing on the transaction's business terms and encoding those terms into a program. This code is usually written in a high-level programming language (for example, Solidity for Ethereum), which defines *what will happen* when certain inputs or events occur.[136] For instance, the code may state: "If Party A's account receives 10 Ether, then transfer ownership of Asset X to Party A."

Step 2: Deploy the Smart Contract to the Blockchain. Once written, the smart contract code is published to the blockchain network by broadcasting a special **deployment transaction**. This transaction creates a new contract **address** on the ledger and stores the code in the distributed database (the blockchain).[137] At this point, the smart contract becomes tamper-proof and publicly visible. From here on, none of the parties (nor any single administrator) can unilaterally change the code's logic,[138] it will execute exactly as written, which is a cornerstone of the trust minimized nature of smart contracts.

Step 3: Triggering Conditions and Inputs. After deployment, the smart contract passively waits on the blockchain for its triggering conditions to be met. Typically, a contract is triggered by receiving a transaction that calls one of its functions or meets a programmed condition. For example, Party A might send the required payment (cryptocurrency) into the contract's address or an oracle might submit external data (see below) to the contract. These inputs serve as the contractual "performance" conditions.

Step 4: Automatic Execution of Terms. When the triggering event occurs, the contract's code is executed *in a distributed manner* by the blockchain nodes (each node runs the code to verify the outcome).[139] The code will follow the logical *if/then* rules defined: for instance, if the correct payment was received, the code might automatically transfer a digital asset to the buyer, record a change of ownership, release a escrowed fund, or impose a penalty, whatever terms were programmed. This

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[135] Werbach, *The Blockchain and the New Architecture of Trust* (MIT Press, 2018) 84–87.
[136] Ibid.
[137] Ibid.
[138] Ibid.
[139] Mougayar, *The Business Blockchain* (Wiley, 2016) 45–49.

occurs **without further human intervention or discretionary judgment**.[140] The blockchain's consensus mechanism ensures that all network participants agree on the result of the execution, and any attempt to deviate (e.g. a dishonest node trying to alter the outcome) is rejected.

Step 5: Recording and Finality. The outcome of the execution (such as updated balances, ownership records, or an event log) is then recorded on the blockchain as a new **block** entry.[141] The blockchain entry serves as an immutable, time-stamped record of the contract's performance.[142] Because public blockchains are append-only and secured by cryptography, the results are *tamper-resistant* and typically considered final. In other words, the smart contract **self-enforces** the agreement: once the code conditions are met, the specified actions are carried out and memorialized without needing a court or third party to enforce them.[143]

It is worth noting that the **deterministic** nature of blockchain execution is fundamental. Each node must reach the same result from the same smart contract code and inputs, otherwise consensus fails. Thus, standard smart contracts are designed to be deterministic programs, meaning given a certain input, they produce a uniquely defined output with no ambiguity.[144] This requirement also means that relying on external data or events is non-trivial, blockchains cannot directly fetch outside information on their own, since that could introduce inconsistency. The solution to this is the use of **oracles** and hybrid designs (explained below in Section 2.3) which allow smart contracts to react to real-world data while preserving deterministic execution.

From a technical perspective, the self-executing quality of smart contracts offers significant advantages in transactional contexts. Once deployed and triggered, a smart contract *will execute exactly as coded*, for better or worse. This provides certainty that agreed-upon obligations (like payments or transfers) will happen automatically, without delay or the need to trust the other side to perform. However, it also means any flaw in the code or unanticipated scenario will likewise execute *literally*, an issue that raises legal and practical challenges discussed later (Section 2.6). In sum, the blockchain architecture provides smart contracts with automation, tamper-resistance, and transparency, as the code's operations are visible on the ledger and cannot be easily altered or stopped by malicious actors or even governments once running.[145] These technical traits underpin the legal discussions around how to classify and enforce smart contracts in existing law.

2.4. Classification of Smart Contracts

Smart contracts are not monolithic, they can be categorized by both their technical design and their relationship to legal agreements. Various classifications have been proposed in literature. For our purposes, we will discuss four common categories: **deterministic smart contracts**, **hybrid (oracle-integrated) smart contracts**, **smart legal contracts (automated legal agreements)**, and **decentralized autonomous arrangements**. These are not mutually exclusive classes but offer a framework to understand the spectrum from purely code-based contracts to those entwined with legal text. Together they describe a continuum running from "pure code" to legally binding agreements (*smart legal contracts*).

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[140] Werbach, *The Blockchain and the New Architecture of Trust* (MIT Press, 2018) 92–95.
[141] Ibid.
[142] De Filippi and Wright, *Blockchain and the Law: The Rule of Code* (Harvard University Press, 2018) 55–57.
[143] Ibid.
[144] Antonopoulos, *Mastering Ethereum* (O'Reilly, 2018) 107–115.
[145] Werbach, *The Blockchain and the New Architecture of Trust* (MIT Press, 2018) 98–101.

2.4.1. Deterministic On-Chain Contracts

This category refers to smart contracts that operate *entirely on the blockchain* and depend only on data available within the ledger itself. A deterministic smart contract *"does not require any external information, such as from an oracle, to be executed"*.[146] All conditions are verifiable by the on-chain state, and every node can independently produce identical outcomes given the same transaction input. Cryptocurrencies and simple token exchange contracts are examples: e.g., a contract that releases funds to Bob *if and only if* Alice's signature is provided is fully self-contained on-chain. Such contracts maximize reliability and predictability (since they avoid any outside dependencies). However, their scope is limited to digital assets and events that the blockchain itself can witness. In practice, many early Ethereum contracts (like **ERC-20 token** contracts or basic multi-signature wallets) are deterministic; they execute the same way on every node and do not call external APIs or data sources.

2.4.2. Hybrid Smart Contracts (Oracle-Integrated)

Many useful contracts need to react to off-chain events, for instance, a crop insurance contract paying out if a weather API reports drought, or an IoT sensor triggering a delivery in a supply chain when goods arrive. These are **hybrid smart contracts**, which *"combine on-chain code with off-chain data and computation"* provided by oracles.[147] An **oracle** is an external data feed or agent that communicates real-world information to the blockchain.[148] For example, an oracle service might cryptographically attest "Temperature fell below 0°C on date X" to trigger a frost insurance payout in a smart contract. Hybrid contracts thus bridge the gap between deterministic blockchain execution and the unpredictability of real-world data. They preserve many benefits of blockchain (transparency, automation) but introduce trust considerations: the parties must trust the oracle's accuracy and integrity.[149] Modern implementations include decentralized oracle networks (like Chainlink) that aim to provide data feeds in a tamper-resistant way by aggregating multiple sources. Hybrid contracts greatly expand use-cases (finance, insurance, supply chain, IoT integration) by enabling **conditional logic based on external events**, at the cost of slightly reduced purity of decentralization (since oracles could be seen as new intermediaries). They are increasingly common, for instance, many **DeFi (Decentralized Finance)** protocols use price oracles to determine lending rates or liquidation events.

2.4.3. Smart Legal Contracts (Automated Legal Agreements):

This category focuses on the *legal character* of the arrangement. A "smart legal contract" typically means a legally binding agreement where some or all obligations are defined and/or performed by code.[150] Rather than being merely code on a ledger, it is viewed as a true contract in the legal sense, with the code as the medium of execution. The UK Jurisdiction Taskforce (UKJT) defines a smart legal contract as a *contract capable of giving rise to binding legal obligations, enforceable in accordance with its terms, by means of automated performance through code*.[151] Such contracts can take different forms: (i) a traditional natural-language contract with a clause that is automated by code (for example, an agreement that says "payment shall be made via an Ethereum smart contract upon

[146] Antonopoulos, *Mastering Ethereum* (O'Reilly, 2018) 249–257.
[147] Szmigiera, *Statista* (2023); see also Chainlink White Paper v2.0.
[148] Werbach, *The Blockchain and the New Architecture of Trust* (MIT Press, 2018) 164–165.
[149] De Filippi and Wright, *Blockchain and the Law* (Harvard UP, 2018) 73–75.
[150] UK Jurisdiction Taskforce (UKJT), *Legal Statement on Smart Contracts* (2019).
[151] Ibid.

delivery"); (ii) a hybrid contract where part of the agreement is expressed in natural language and part in code (the human-readable text and code are both operative and together form the contract); or (iii) a contract recorded exclusively in code (where the code itself is intended to capture the entire agreement).[152] In scenarios (i) and (ii), the smart contract code is essentially an *implementation tool* of the parties' agreement, which still can be interpreted by courts through the accompanying text. In scenario (iii), sometimes called a "pure code" contract, the code alone is the agreement, this is novel but is increasingly feasible (for instance, two parties could agree via exchange of blockchain messages to be bound by whatever the code does). Each approach has different legal ramifications. Notably, many experts believe that for the foreseeable future most smart legal contracts will involve a *blend of code and natural language*, to ensure that the legal intent (such as the contract's **causa** or rationale) is clear.[153] There is ongoing work on standards like **Ricardian contracts** (which pair human-readable text with machine-readable instructions) to make smart legal contracts more robust. The key point is that a smart contract *need not be divorced from the law*, it can be designed as an **automated legal agreement** that satisfies traditional contract requirements (offer, acceptance, consideration, etc.), as discussed further in Section 2.4.

2.4.4. Decentralized Autonomous Organizations & Complex Smart Contracts:

At the more advanced end of the spectrum are *combinations* of smart contracts that create autonomous systems. A **Decentralized Autonomous Organization (DAO)**, for example, is essentially a collection of smart contracts that together encode governance rules and business logic for an organization (with token-holders voting and funds managed by code). While not a "contract" in the bilateral sense, DAOs represent an extension of smart contracts to multi-party, ongoing arrangements. They raise additional questions about legal personhood and partnership law, which are beyond this chapter's scope. Other complex uses include self-executing escrow arrangements, multi-party workflows, and even smart contracts that can *spawn* or modify other contracts (upgradable contracts). These demonstrate that smart contracts can function as fundamental building blocks for decentralized applications and even substitute for organizations or intermediaries. However, from a legal perspective, these also blur the lines of liability and regulation, e.g., participants in a DAO code may inadvertently form a general partnership, as arguably happened with "The DAO" on Ethereum in 2016.

It should be noted that different jurisdictions and scholars sometimes use overlapping terminology. Some simply distinguish between **"smart contract code"** (the program itself, which might not be a legal contract) and **"smart legal contract"** (a true contract under law).[154] Others classify smart contracts by their **degree of automation** or autonomy from human control. What is clear is that the term "smart contract" can refer either to a piece of technology or to a new form of agreement, or both, so precision is important. For clarity in this thesis: when we say *smart contract*, we often mean the technology (the code and its execution on DLT); when necessary, we will say *smart legal contract* to denote a legally binding agreement implemented or aided by that technology.

2.5. Smart Contracts vs Traditional Contracts: Formation, Enforcement, Interpretation, and Remedies

[152] Clack, Bakshi and Braine, "Smart Contract Templates" (2016) arXiv:1608.00771.
[153] Allen & Wylie, *Smart Legal Contracts: A Comparative Analysis* (2021) <Law Commission UK Discussion Paper>.
[154] Law Commission of England and Wales, *Smart Contracts: Advice to Government* (2021) para 1.22–1.27.

Smart contracts challenge and illuminate several core concepts of contract law. In many ways, a smart contract performs the same economic function as a traditional contract, establishing binding commitments, but via different mechanisms. Here we compare how key contract law elements apply in the context of blockchain-based smart contracts versus traditional agreements.

2.5.1. Formation and Validity:

In this context, formation and validity remain grounded in conventional legal doctrine. Under most legal systems, a contract is formed by an offer, an acceptance of that offer, mutual intent to create legal relations, and, where required, consideration.[155] On the surface, smart contracts do not rewrite these requirements, the same fundamental rules can apply.[156]

For example, suppose Alice and Bob agree through a blockchain smart contract to swap digital assets. Alice "offers" by sending a transaction calling the contract with her asset; Bob "accepts" by sending his asset to the contract. If the code is programmed to transfer ownership once both inputs are received, then a contract (both in code and in law) can be said to exist at that moment when conditions are locked in.

English law authorities have affirmed that smart contracts can give rise to binding legal obligations, so long as the traditional criteria are met, i.e., a meeting of minds on certain terms and an intent to be bound.[157] The UK Jurisdiction Taskforce (UKJT) has clarified that the manifestation of intent may occur through interactions with the code, such as digitally signing a transaction, sending an on-chain confirmation, or interacting with a decentralised application in a manner indicating assent.[158]

A potential complexity is the pseudonymous nature of many smart contract interactions, parties are often identified only by their digital addresses. However, the UKJT noted that a contract is not invalid merely because the parties are pseudonymous or anonymous, provided the system permits eventual identification or the parties are content to transact under those stable digital identities.[159]

Another complexity arises in relation to consideration in common law systems. A smart contract might execute an exchange without an explicit recital of consideration, but in practice, mutual exchange of value (such as one cryptocurrency for another, or currency for a token) typically satisfies this requirement. In civil law jurisdictions such as Italy, formation instead requires consent, a lawful cause (causa), a determined object, and any required form.[160] The causa, that is, the underlying purpose of the contract, may not always be clearly discernible from code alone, raising the question of whether a pure code transaction can be considered a valid standalone contract.[161]

In many practical cases, smart contracts are adjunct to a broader agreement or commercial framework that provides the necessary legal context and purpose. For example, two companies may sign a conventional agreement and automate some performance obligations via code. As long as there is a

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[155] E Peel and GH Treitel, *Treitel on the Law of Contract* (15th edn, Sweet & Maxwell 2020) 8–12; HG Beale (ed), *Chitty on Contracts* (34th edn, Sweet & Maxwell 2021) paras 2-001–2-003.

[156] Law Commission, *Smart Legal Contracts: Advice to Government* (Law Com No 401, 2021) paras 3.2–3.10.

[157] UK Jurisdiction Taskforce, 'Legal Statement on Cryptoassets and Smart Contracts' (LawTech Delivery Panel 2019) paras 136–140.

[158] ibid paras 141–144.

[159] ibid para 150.

[160] G Alpa and V Zeno-Zencovich, *Il Contratto* (4th edn, CEDAM 2020) 103–112.

[161] F Sartor, 'Smart Contracts and Contract Law' (2020) 28(2) *European Review of Private Law* 305, 311–312.

valid underlying agreement or mutual assent to the encoded terms, there is generally no legal barrier to formation.[162]

Indeed, several jurisdictions have clarified this point by statute. In Italy, Article 8-ter of *Decreto-Legge* 14 December 2018 No. 135 (converted by Law No. 12/2019) recognises the legal validity of smart contracts, provided the identity of the parties is established through a qualified electronic signature or equivalent mechanism.[163] Likewise, certain U.S. states have provided that contracts may not be denied legal effect solely because they are executed via smart contract.[164] These provisions affirm that blockchain code is merely a new medium for expressing offer and acceptance, not a departure from **legal principles.**

2.5.2. Form and Signature Requirements:

Traditional law sometimes requires contracts to be in writing or signed (for example, contracts for sale of real estate, or guaranties, often have statute of frauds requirements). How can a purely digital smart contract satisfy these? Different jurisdictions approach this in analogous ways to electronic contracts. Under EU law (eIDAS Regulation and national laws), an "electronic document" and an electronic signature can fulfill writing and signing requirements, provided certain criteria are met. A smart contract recorded on a blockchain is an electronic record; the question is whether it is *readable* and whether the parties' action can count as a signature. The UK legal statement opined that a smart contract can satisfy a statutory "in writing" requirement **"even if in code, provided it can be read"** (meaning it can be rendered into text or otherwise understood).[165] It also stated that a signature by means of a private cryptographic key (the act of digitally signing a blockchain transaction) is likely sufficient to meet a legal signature requirement, as long as the signer's intent to authenticate the contract is present.[166] Similarly, Italian law (through *Decreto Semplificazioni* converted by Law no. 12/2019) explicitly provides that smart contracts satisfy the requirement of written form **if** the parties have completed a prior digital authentication meeting technical standards.[167] In essence, Italy tied the formal validity of a smart contract to a verified electronic identification of the parties.[168] This implies that if parties use a recognized digital identity or signature to interact with the smart contract, the contractual form is equivalent to writing under Italian Civil Code.[169] These developments show that, legally, a blockchain transaction can be viewed as a signed writing, the hash and public-key cryptography play the role of a signature, and the code is the content of the contract. One caveat is that code is not easily human-readable; thus, there may be arguments (in jurisdictions without clear guidance) about whether pure code is "intelligible" enough to count as a writing. In practice, best practice for smart legal contracts is often to have natural language backup or at least comments describing the code's function, to avoid any contention over form.

2.5.3. Enforcement and Self-Execution:

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[162] M Raskin, 'The Law and Legality of Smart Contracts' (2017) 1(1) *Georgetown Law Technology Review* 305, 308–311.
[163] Art 8-ter, *Decreto-Legge* 14 December 2018 No. 135 (converted by Law No. 12/2019); see also A Dalla Palma, 'Smart Contracts e Forma Scritta' (2020) *Contratto e Impresa* 633, 640.
[164] Arizona Revised Statutes § 44-7061 (2021); Tennessee Code § 47-10-201 (2021).
[165] UK Jurisdiction Taskforce, *Legal Statement on the Status of Cryptoassets and Smart Contracts* (November 2019).
[166] Ibid.
[167] Law no. 12/2019, conversion of *Decreto-Legge* 14 December 2018, n. 135, Art. 8-ter
[168] Ibid.
[169] Ibid.

Traditional contracts rely on the legal system for enforcement, if one party breaches, the other must go to court (or arbitration) to seek a remedy (damages, specific performance, etc.). Smart contracts invert this paradigm by making performance *automatic*: the code itself enforces the obligations by executing transfers or actions once conditions are met, leaving little room for a party to default. In an ideal smart contract scenario, breach is impossible you either meet the condition and the code executes (so performance is rendered), or if you don't meet the condition, the contract does nothing (so there is no breach, just non-occurrence). This self-executing quality is a major benefit (Section 2.5) but also a challenge for the legal system. On one hand, it reduces the need to trust the counterparty or involve courts; on the other, if the code performs an unintended or undesired action, the aggrieved party cannot simply stop it or call a timeout. The enforcement happens *globally on the blockchain* and may be effectively irreversible.[170] Traditional law does allow certain *self-help* remedies (e.g. repossessing collateral under a security agreement, within limits), but smart contracts greatly expand self-help enforcement into domains normally overseen by courts.[171] For example, consider a smart lease where an IoT-enabled lock on a rental property is programmed to automatically lock out the tenant if payment isn't made by a deadline. If that runs, the tenant is immediately dispossessed without any eviction proceedings, something that would violate due process in many jurisdictions if done by a landlord manually.[172] Thus, one legal issue is whether certain automated enforcement actions conflict with mandatory laws (like consumer protection or debtor protection laws).[173] Scholars have noted the risk of *"enforcing agreements that courts would not enforce"*–[174] for instance, a smart contract could execute an agreement lacking consideration or even an *illegal* agreement (the code won't check legality) which a court would void if asked. This raises the prospect of *"law-resistant"* transactions. While the code result is technically enforced, the law might still regard the arrangement as void or impose liability after the fact (for example, disgorging illegal gains). Enforcement of smart contracts thus happens in two layers: the code enforces automatically, and then ex post facto a court might be asked to recognize or unwind what happened. Generally, if a smart contract corresponds to a lawful agreement, there should be no issue, enforcement by code is just performance. But if something goes wrong (say, the code sends money to the wrong person due to a bug), the injured party must turn to legal processes for relief, since the code won't fix it on its own. We discuss remedies shortly, but it's clear that the self-executing nature of smart contracts both minimizes reliance on courts and yet creates novel enforcement questions when the outcome diverges from the parties' expectations or from legal norms.

2.5.4. Interpretation and "Code is Law" vs Party Intent:

A cornerstone of contract law is how agreements are interpreted. Courts interpret ambiguous language, fill gaps with default rules, and seek the parties' intent if terms are unclear or conflicts arise. With smart contracts, the operative language is code, which is exacting in execution but often *opaque* to non-programmers. The prevailing view in jurisdictions that have studied the issue (e.g. England's Law Commission and UKJT) is that if a contract is written wholly or partly in code, **the meaning of**

[170] Primavera De Filippi and Aaron Wright, Blockchain and the Law (Harvard University Press 2018) 73-75.

[171] Kevin Werbach and Nicolas Cornell, 'Contracts Ex Machina' (2017) 67 *Duke LJ* 313, 347–348. Also see, Michèle Finck, 'Smart Contracts and the Digital Single Market' (2019) 27 *European Review of Private Law* 477, 502.

[172] Karen Levy, 'Book-Smart, Not Street-Smart: Blockchain-Based Smart Contracts and the Social Workings of Law' (2017) 3 *Engaging Science, Technology, and Society* 1, 5–6. (social / due-process critique).

[173] Thibault Schrepel, 'The Law and Ethics of Algorithmic Contracts' (2021) 3 *Stanford Journal of Blockchain Law & Policy* 1, 23–24.

[174] Werbach & Cornell (n 2) 340-344 (law-resistant transactions)

the contract is what is expressed in the code (i.e. the code's functional behavior).[175] Code, in theory, is unambiguous: it either does X or Y. It does not suffer from linguistic vagueness, but it can have bugs or behave in ways one party did not foresee. The UKJT noted that where code is clear, a court will hold the parties to that outcome, just as it would enforce clear literal terms in writing.[176] However, if a dispute arises as to what the contract meant (perhaps because the parties also had natural language descriptions, or one side claims the code doesn't reflect the true deal), courts may **examine evidence of intent**. In particular, if a smart contract is partly in natural language and partly code, a key question is whether the code was intended to be the definitive expression of obligations or merely a mechanism to perform obligations described in the prose.[177] If the latter, a court might interpret the contract by the natural language and treat the code as a service/tool. If the former, the code reigns.

In a purely code contract, some scholars suggest courts could still apply contract interpretation doctrines by analogy, perhaps even *rewriting the outcome* if there was a clear mistake (similar to rectification of a written contract). This is untested in many places. A famous illustration of this tension was **The DAO hack (2016)** on Ethereum: participants invested cryptocurrency into a DAO smart contract with an understanding of how it should work, but due to a loophole in the code, an attacker drained a large amount of funds. Technically, under the immutable "code is law" view, the attacker executed a permitted series of steps (the code allowed it), even if no one intended that result. From a traditional contract perspective, one could argue the attacker breached an implied term of good faith or exploited a bug contrary to the parties' common intent. In the event, the Ethereum community chose to *hard-fork* the blockchain to reverse the theft, a non-legal remedy. But legally, had that been litigated, it's unclear how a court would rule, is the *literal code* the contract, meaning the attacker simply exercised the contract's terms (thus no breach, however absurd that sounds), or would a court impose external legal principles (fraud, unjust enrichment, mistake)? The Law Commission of England expects that generally the code will be taken at face value, but if a smart contract produces a clearly unintended result, traditional doctrines like **mistake** or **frustration** could apply in extreme cases.[178]

For example, Singapore's Court of Appeal in *Quoine Pte Ltd v. B2C2 Ltd* (2020) dealt with an algorithmic trading contract that executed trades at an aberrant price due to a programmatic issue. The court treated it as a normal contract and asked whether it could be voided for unilateral mistake. It held that it was not void, essentially enforcing the transactions, but it considered what the programmers knew or intended the algorithm to do.[179] This shows courts are capable of grappling with contracts made by algorithms and applying familiar concepts like mistake if warranted.

In summary, interpretation of smart contracts generally hews to the principle that *the code means what it does*, but legal systems retain an ultimate backstop to prevent outcomes that no reasonable party intended (especially if one party maliciously exploits a loophole). One practical upshot: **clarity upfront** is crucial. Parties using smart contracts should agree whether the code alone is authoritative or if a natural language contract governs in case of discrepancy, to guide courts and minimize uncertainty.[180]

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[175] UK Jurisdiction Taskforce, *Legal Statement on Cryptoassets and Smart Contracts* (LawTech Delivery Panel 2019) paras 35–39.
[176] Ibid paras 40–41.
[177] Law Commission of England and Wales, *Smart Legal Contracts: Advice to Government* (Law Com No 401, 2021) para 3.33.
[178] Law Commission (n 3) para 3.103.
[179] *Quoine Pte Ltd v B2C2 Ltd* [2020] SGCA(I) 02, [144]–[150].
[180] Consiglio Nazionale del Notariato, *Blockchain e Smart Contract* (Studio n. 13-2018/C) 24–26.

2.5.5. Remedies and Dispute Resolution:

When a traditional contract is breached, the injured party can seek remedies like damages, specific performance, or contract cancellation/rescission. With smart contracts, because performance is automated, the notion of *breach* is unusual, the performance either happens or it doesn't according to code. If a party fails to trigger the code (for example, fails to pay into the contract so the contemplated exchange never occurs), the code may simply terminate without action, which might be akin to a breach (non-performance) in legal terms. The non-breaching party could then sue for breach if there were losses. But more often the disputes arise from the *operation* of the code: e.g., a bug causes an unintended transfer, or an oracle provides bad data causing a payment when it shouldn't happen.

In such cases, what is the remedy? If the contract is truly immutable, the immediate result cannot be reversed on-chain (short of a community hard fork or a very costly subsequent transaction). Legally, however, courts can impose **off-chain remedies**. They might order the recipient of an improper transfer to refund it (restitution), or award damages to the injured party. A court could even issue an injunction to prevent further execution of a contract or to freeze certain cryptocurrency addresses, though enforcement of that is challenging if parties are anonymous or abroad. Another issue is that smart contracts often lack built-in dispute resolution mechanisms (unlike traditional contracts that have arbitration clauses or choice-of-court clauses). To address this, some platforms have started to include **dispute resolution or kill-switch features**, for instance, **arbitration oracles** that the code will consult if one party flags a dispute within a certain time. These remain early-stage, but they represent attempts to hybridize legal process with smart contracts.

Notably, as discussed, the **Data Act** proposes that smart contracts used in data-sharing must have a provision for **safe termination (a "kill switch")** to allow stopping their execution in case of issues.[181] This recognizes the need for human intervention in emergencies, but has been controversial as it undermines the notion of immutability.[182] In any event, if parties end up in court over a smart contract, the usual remedies (compensation, rescission, etc.) are theoretically available, just applied to a scenario where performance already occurred autonomously. For example, if a consumer smart contract released a payment but the goods delivered were defective, the consumer can sue for breach of implied warranty just as they would normally, the fact that payment was via smart contract doesn't prevent the court from ordering a refund or damages. The smart contract doesn't resolve such **off-chain issues** like quality of goods or misrepresentation. Thus, while smart contracts can eliminate many *breaches of performance*, they **do not eliminate disputes** entirely.[183] Disagreements may simply shift to arguing about whether the code did what it was supposed to do, or how to handle external breaches (like a party delivering bad goods outside the code's scope). In recognition of this, legal systems and industry groups are developing frameworks for handling smart contract disputes, including specialized arbitration forums (like *Arbitration for Blockchain* services) and the possibility of encoding arbitration awards into blockchain actions.

In conclusion, smart contracts can be seen as both a new *medium* for contracting and a source of new *challenges* for contract law. They tend to strengthen the **ex ante phase** (contract drafting and performance are rigidly set in code) and diminish the **ex post** role of courts (since ideally nothing goes

[181] Proposal for a Regulation of the European Parliament and of the Council on harmonised rules on fair access to and use of data (*Data Act*), COM(2022) 68 final, arts 30–33.
[182] Ibid.
[183] Karen Levy, 'Book-Smart, Not Street-Smart: Blockchain-Based Smart Contracts and the Social Workings of Law' (2017) 3 *Engaging Science, Technology & Society* 1, 5–6.

wrong that needs enforcement).[184] However, when things do go awry, the interaction of code and law becomes complex. Generally, legal jurisdictions are adapting by clarifying that smart contracts are subject to ordinary contract law, while acknowledging novel issues like immutable performance and the role of code in expressing intent. We now turn to the advantages and challenges of smart contracts in more detail.

2.4. Benefits of Smart Contracts

Smart contracts have garnered enthusiasm across industries because they offer several significant benefits over traditional contractual processes:

2.4.1. Automation and Efficiency:

Once deployed, smart contracts automatically execute transactions without the need for human administrators or intermediaries. This can greatly speed up processes, payments clear in minutes (or seconds) on a blockchain, and assets can be transferred instantly when conditions are met. Automated compliance with contract terms reduces delays associated with manual review or enforcement. For businesses, this can mean lower administrative costs and faster deal cycles. For example, in trade finance, a smart contract might automatically release funds when a bill of lading is uploaded, rather than waiting days for paperwork to be checked. Everything from insurance claims to royalty payments can be streamlined. One author notes that *formalizing contracts in code ex ante* reduces the need for enforcement ex post, shifting resources to front-loading contract design and thereby improving efficiency.[185]

2.4.2. Certainty and Trust Minimisation:

Parties can engage in transactions with a higher level of confidence that the other side will perform, because performance is guaranteed by the code. The traditional need to **trust** a counterparty or a central escrow agent is minimised, the blockchain and smart contract become the "honest broker." As Investopedia summarises, smart contracts enable *"trusted transactions and agreements to be carried out among disparate, anonymous parties without the need for a central authority, legal system, or external enforcement mechanism."*.[186] This is especially powerful in environments with low trust or high corruption: two strangers across the globe can do business via a smart contract, knowing that neither can cheat the agreed-upon rules. It also reduces reliance on costly trust-providers (banks, notaries, escrow services), which can democratize commerce. The immutability of the blockchain records further means neither party can later **renege or tamper** with the evidence of what happened.[187] This certainty can lower risk premiums in transactions.

2.4.3. Transparency and Auditability:

The code of many smart contracts (on public blockchains) is visible to all participants, and all execution steps are recorded on the ledger. This transparency can enhance accountability, for instance, if government spending programs use smart contracts, every disbursement is traceable and cannot be

[184] Kevin Werbach and Nicolas Cornell, 'Contracts Ex Machina' (2017) 67 *Duke Law Journal* 313, 347–348.
[185] M Finck, 'Smart Contracts and the Digital Single Market' (2019) 27 *European Review of Private Law* 477, 502–03.
[186] L O'Connell, 'Smart Contract Definition' *Investopedia* (20 October 2023) https://www.investopedia.com accessed 1 May 2025.
[187] P De Filippi and A Wright, *Blockchain and the Law: The Rule of Code* (Harvard UP 2018) 76–78.

hidden. Participants can audit the logic beforehand to know exactly how funds will flow (assuming they or a trusted third party can read the code). Compare this to a black-box institutional process where one must trust an intermediary's reports. For regulatory compliance, smart contracts can also automatically log data required for audits. Each action taken by a smart contract is typically irreversible and linked to cryptographic identities, creating a robust audit trail. This benefit is tempered by privacy concerns (public blockchains are transparent by nature), but solutions like zero-knowledge proofs are emerging to balance transparency with confidentiality.

2.4.4. Accuracy and Reduced Ambiguity:

Smart contract code executes precisely as written, which means that if correctly coded, it will consistently apply the agreed terms. This reduces the ambiguity inherent in natural language. There is less room for *interpretative disputes* about what the contract was supposed to do, the code provides a definitive answer.[188] By formalising terms in a computational manner, parties eliminate certain types of misunderstandings. In commerce, this can reduce litigation over contract interpretation. However, this benefit assumes the code faithfully represents the parties' intentions; if the code has errors, the accuracy cuts the other way (it will accurately execute the *wrong* logic). Nonetheless, for well-defined, objective conditions (like interest calculation or date triggers), coding them in a contract guarantees they'll be applied without error or bias.

2.4.5. Cost Savings and Disintermediation:

By cutting out intermediaries and automating processes, smart contracts can reduce transaction costs. **Nick Szabo** highlighted reducing *fraud losses, arbitration costs, and other transaction costs* as a goal of smart contracts.[189] For example, in financial trading, smart contracts can allow peer-to-peer trades without paying exchange fees or broker commissions. In supply chain finance, letters of credit could be replaced by smart contracts that automatically release payment on delivery, saving bank fees. Over time, if widely adopted, this disintermediation could lead to leaner transaction ecosystems, though of course, new intermediaries (like oracle providers or platform operators) might emerge, ideally with more limited roles.

2.4.6. Resilience and Continuity:

Because many smart contracts run on decentralised networks, they are resilient to single points of failure. There is no central server that can go down or be shut off to stop the contract, as long as the blockchain is operational globally, the contract can function. This can be beneficial for critical applications that need high availability. It also means contracts aren't subject to one party's insolvency or disappearance; for instance, if a seller disappears after deploying a smart contract, the buyer can still trigger the contract to get a refund or whatever the code provides. The system provides *continuity and autonomy* beyond the direct control of any one party. This attribute, however, is double-edged (as we'll note in challenges) because it makes halting a faulty contract difficult.

2.4.7. Innovation and New Business Models:

[188] N Szabo, 'Smart Contracts: Building Blocks for Digital Markets' (1996) https://nakamotoinstitute.org/smart-contracts/ accessed 1 May 2025.
[189] Ibid.

Smart contracts enable **new transactional patterns** that might be impractical with traditional methods. Micropayments, machine-to-machine commerce (as envisaged in IoT contexts), and conditional payments based on real-time data become feasible at scale. For example, a smart contract could charge an electric vehicle automatically for every kilowatt it draws from a charger, or IoT devices could autonomously trade resources or services with each other using smart contracts as the settlement layer. These scenarios were previously too costly to administer with human oversight, but with autonomous contracts, they become viable. Additionally, the composability of smart contracts (contracts calling or interacting with others) allows the creation of complex financial products (like automated escrow, derivatives, or decentralized lending platforms) at far lower cost and friction than in the traditional financial system.

In summary, the benefits of smart contracts center around **speed, certainty, and efficiency** in executing agreements. They combine the reliability of software with the decentralization of blockchain to create what some call *"trustless"* transactions (meaning you don't need to trust the other party, only the code and network).[190] This can lead to economic gains by reducing the need for oversight and enforcement. Of course, these advantages assume that the smart contract is well-designed and the scenario is appropriate, the next section addresses the many **legal challenges and limitations** that come with this new paradigm.

2.5. Legal Challenges of Smart Contracts

Despite their promise, smart contracts also raise a host of legal and practical challenges. Many of these flow directly from their strengths (like immutability and automation), turning into double-edged swords. Key challenges include:

2.5.1. Validity and Intent:

As discussed, there can be ambiguity over whether a given smart contract is intended to be a legally binding contract or just a performance tool. If parties haven't clearly documented their intent, courts may struggle to fit the blockchain interactions into traditional contract frameworks. One party might later claim, "I didn't intend a legal contract; it was just code experimentation," especially if something goes wrong. Ensuring mutual intent (animus contrahendi) is present is vital, but pseudonymous blockchain interactions make it murky, two algorithms trading might form a contract without either *human* explicitly intending it.[191] This scenario, noted by commentators, challenges the notion of agreement when contracts are formed autonomously by code. Jurisdictions may need to clarify how traditional doctrines (like the meeting of minds) apply when contracting is algorithmic. Some have suggested applying the concept of **electronic agents** (recognised in instruments like the Uniform Electronic Transactions Act in the US), which holds that a contract can be formed by electronic agents even if no human was directly aware of the moment of formation, as long as the humans programmed them with authority. Still, questions of **capacity to contract** arise: e.g., can a DAO or a piece of software be a contracting party, or must we always identify some legal person behind it?[192]

2.5.2. Enforceability and Irreversibility:

[190] O'Connell (n 167).
[191] Thibault Schrepel, 'The Law and Ethics of Algorithmic Contracts' (2021) 3 *Stanford Journal of Blockchain Law & Policy* 1, 23–24.
[192] Schrepel (n 172) 23–24.

While code enforcement is automatic, legal enforcement after the fact is complicated if the code's result defies the parties' expectations or the law. A smart contract might execute an *agreement* that is actually unlawful or against public policy, for instance, a gambling contract or a price-fixing arrangement, and do so instantly. Normally, courts would refuse to enforce an illegal contract, but here the "enforcement" has been carried out. The legal system then faces the task of possibly unwinding transactions after the fact. As one article noted, smart contracts *"offer the possibility of enforcing certain agreements which cannot be enforced in courts"*,[193] giving the example that a contract without consideration (which is invalid under U.S. law) could nonetheless be executed by a smart contract. Similarly, **self-help** via code might bypass legal safeguards (the auto-lockout example in landlord-tenant context, or automatic repossession of a car by a smart contract triggered by missed payment). Such actions might violate consumer protection or require court process traditionally, putting code at odds with law. Jurisdictions will have to reconcile these by perhaps prohibiting certain uses of smart contracts or ensuring that victims have recourse (though recourse after the fact may be too late in many cases). The **irreversibility** of blockchain transactions is a technical hurdle, if a court declares a smart contract outcome void, how to effect restitution if the asset is held by someone in an uncooperative jurisdiction or an anonymous user? This raises enforcement issues in conflict of laws and cross-border settings, *which court or law applies* to a borderless, decentralised contract is itself challenging to determine.[194] Courts might resort to targeting the people or entities known (for instance, the developers or the beneficiary who can be identified) to enforce orders, which leads to another issue: identifying responsible parties.

2.5.3. Identifying Parties and Liability:

In a traditional contract, the parties are clearly identified legal entities who can be held liable for breaches. Smart contracts often involve pseudonymous addresses. If something goes wrong, say a bug in a widely used smart contract causes losses to many users, who is liable? The users might not have privity with a developer who wrote the code (the developer might argue they just published code, and the users chose to use it at their own risk). There could be product liability or negligence claims if the code was faulty. But the decentralisation complicates this: if an open-source library is used and a bug causes losses, is the volunteer coder liable? In the famous "Parity Wallet bug" incident (2017), a bug in a smart contract library led to ~$150 million of Ether being frozen; users had no obvious defendant to sue (the developer was known but had disclaimed responsibility). This area is legally untested, will courts treat code like a product and apply strict liability for defects? Or will they treat it more like a service or information (with less stringent liability)? Another aspect: if a contract is truly autonomous (no ongoing party control), there might be nobody to sue at all. Some legal scholars suggest we might analogise to automated systems or even create a status for autonomous agents, but that's speculative. For now, parties implementing smart contracts should allocate risk by agreement (e.g. an underlying contract could state who bears losses from certain failures). Insurance products may also be developed for smart contract failures.

2.5.4. Bugs, Errors and Complexities:

"Code is law" until the code has a flaw. Software bugs are common, and smart contracts, once deployed, often cannot be easily patched (especially on public blockchains, unless a contract was written to allow upgrades via some administrator key). An error can lead to significant unintended

[193] Kevin Werbach and Nicolas Cornell, 'Contracts Ex Machina' (2017) 67 *Duke LJ* 313, 347–348.
[194] Michèle Finck, 'Smart Contracts and the Digital Single Market' (2019) 27 *European Review of Private Law* 477, 502.

transfers or getting stuck in a bad state. In traditional contracting, a clear drafting mistake can be corrected by the courts under doctrines of mistake or interpretation. With smart contracts, a bug's effect is immediate, the money might be gone. Even if a court later declares it was a mistake, that's cold comfort if the counterparty (or hacker) has already absconded with funds. This places heightened importance on **code review, formal verification, and testing** for smart contracts. The law may develop such that deploying a critically flawed contract could be seen as negligence by the deployer towards users. One real-life example: The DAO hack again, was the attacker "stealing" or just using the code as written? The Ethereum community treated it as theft (morally), but legally, it was grey. To avoid these dilemmas, efforts are made to write simpler and more secure contracts, but as contracts do more complex things (e.g. DeFi protocols), the risk of bugs remains. Some jurisdictions might impose that certain critical smart contracts (like those in consumer finance) be audited or certified safe to protect the public, analogous to how financial products are regulated. The **EU Data Act** mentioned earlier is one example: it would require smart contracts in data sharing to have certain safety features, including a way to terminate or interrupt the contract if needed,[195] essentially acknowledging that bugs or unforeseen behaviour must be stoppable. Purists argue this undermines immutability, but regulators prioritise safety and consumer protection.

2.5.5. Oracles and External Data Reliance:

For hybrid smart contracts, trust and accuracy in Oracles is a significant issue. If an oracle provides faulty data (whether by accident, hack, or malfeasance), the contract will faithfully execute on wrong information. Who is liable for losses caused by a bad oracle input? Perhaps the oracle provider, under some contract or tort theory. But if the oracle is decentralised (no single provider), it's hard to pin liability. Also, data authenticity, an oracle might be tricked (e.g., feeding a manipulated price). These issues make clear that the "garbage in, garbage out" problem applies: a smart contract is only as good as the data it receives. Legally, if the parties chose a specific oracle in their agreement, maybe they assume the risk of its failure. Or they might include fallback dispute resolution if the Oracle data is clearly wrong. This is a new species of problem: earlier contracts might have, say, an FX rate from a particular bank, if that rate was wrong, parties could litigate and the court could find the true rate. In a smart contract, by the time you litigate, the erroneous rate has already transferred millions of value. So, timing and remedy are issues. Some projects incorporate **redundant oracles** and insurance funds to mitigate oracle failure, but the law has yet to catch up in allocating responsibility here.

2.5.6. Jurisdiction and Governing Law:

Smart contracts on a public blockchain do not respect national borders. Participants could be anywhere, and the network itself is global. This raises the classic problem of which jurisdiction's law applies to a dispute and which court (if any) has authority. Typically, contracts have a governing law clause and forum selection. A pure smart contract may not. If a dispute arises, each party might try to find a favorable forum. Courts will apply conflict of law rules, possibly looking at where the parties are located, or where a relevant connection is. If the parties are anonymous, it's even harder. We might see a move towards embedding **choice of law** and **dispute resolution** *on-chain*, for example, some smart contracts could require users to digitally sign a statement agreeing "Any disputes will be arbitrated by XYZ under law of Country A." In absence of that, there is uncertainty. From a regulatory perspective, certain uses of smart contracts might be regulated by multiple jurisdictions simultaneously (e.g., securities transactions via smart contract could trigger securities laws in all

[195] Finck (n 175) 502.

countries where participants are). This multi-jurisdictional reach is a complexity and could lead to overlapping or conflicting legal requirements. One concrete example: GDPR (EU data protection law) could conflict with blockchain usage, if personal data is recorded immutably, the right to erasure cannot be honored.[196] If a smart contract records personal data or executes personal data transfers, it might inadvertently violate privacy law. Law no. 12/2019 in Italy acknowledges this by requiring compliance with technical standards (to presumably ensure things like privacy and security).[197] Jurisdictional challenges may push towards more international coordination or treaties on blockchain transactions, but currently it's a grey area exploited by the tech's borderless nature.

2.5.7. Consumer Protection and Equity:

Many consumer contracts have protective provisions by law, e.g., the right to withdraw from an online purchase within 14 days in the EU, or unfair contract terms regulations. If a consumer enters a smart contract (perhaps clicking a decentralized app to buy a service), how are those rights guaranteed? If the smart contract immediately transfers payment and maybe a non-refundable token, the consumer's right to withdrawal could be nullified in practice. Regulators will likely insist that smart contract systems incorporate consumer rights (maybe a delay before finalizing, or an option to reverse within a period for consumers). Also, concepts like good faith (in civil law) or unconscionability (common law) ensure fairness in traditional contracts. If a smart contract's terms (in code) are overly harsh or exploitative, can a consumer challenge them? Possibly yes, a court could deem a clause unenforceable even if the code executed it, but again, it's after the fact. There's an educational gap too: consumers might not understand code terms at all, raising the issue of meaningful consent. Efforts are needed to present smart contract terms in user-friendly ways or risk an imbalance where savvy coders impose one-sided terms on unsophisticated users who *literally* don't know what they are "signing". In some jurisdictions, consumer contracts must be expressed clearly and not rely on hidden tricks; applying those rules to code is an open question.

2.5.8. Scalability and Performance Issues:

Although not a legal challenge per se, it's worth noting that current public blockchains have limitations (in transaction throughput, fees, etc.) that affect how and if smart contracts can be widely used (e.g., high fees might make micro-contracts uneconomical). Parties might abandon a smart contract if, say, gas fees to execute it become too high, leading to partial performance issues. These practical constraints could cause novel forms of disputes (e.g., "We agreed to do this via smart contract, but fees spiked making it impossible, is the contract frustrated?"). It's analogous to impracticability in contract law, but tied to a technical environment.

In summary, while the **code-based automation** of smart contracts offers reliability, it also collides with the **flexibility and safeguards** built into legal contract doctrine. Immutability is great when everything goes right, but law often deals with when things go wrong, and frozen code can't adapt or show mercy. Jurists like De Filippi and Wright have highlighted the concern of *"enforcing illegal or unfair agreements through smart contracts"* and the difficulty of integrating norms like good faith into code.[198] Going forward, many of these challenges will be addressed through a combination of

[196] Proposal for a Regulation of the European Parliament and of the Council on harmonised rules on fair access to and use of data (*Data Act*) COM(2022) 68 final, arts 30–33 (n 167).
[197] Primavera De Filippi and Aaron Wright, *Blockchain and the Law: The Rule of Code* (Harvard University Press 2018) 149 (n 151).
[198] Law No 12/2019 (n 147).

legal reform, regulatory guidance, and technical design improvements (such as more robust oracle mechanisms or hybrid contracts that allow emergency intervention). Law and technology will have to meet halfway: either code will incorporate more legal logic (e.g., allowing pause for dispute), or law will adjust to the new reality that some agreements self-execute and then ask forgiveness later. Some countries have already started updating laws, as we will see with Italy's approach in the next section.

2.6. Smart Contracts under Italian Law: Recognition and Civil Code Implications

As discussed, Italy has been at the forefront in Europe in providing legal recognition for technologies like blockchain and smart contracts. In early 2019, the Italian Parliament passed a notable measure, Article 8-ter of *Decree Law 135/2018* (the "Simplification Decree"), converted with amendments by Law No. 12 of 11 February 2019, which gave formal definitions to *"distributed ledger technologies (DLT)"* and *"smart contracts."*.[199] This marked one of the first times a national law explicitly addressed the legal status of smart contracts.

2.6.1. Definition in Law No. 12/2019:

According to art. 8-ter, *"Smart contract shall mean a computer program that operates on technologies based on distributed ledgers and whose execution binds two or more parties according to terms predefined by them."*[200] Further, it states that smart contracts satisfy the requirement of form in writing *if* there has been prior digital identification of the parties, in accordance with technical standards to be set by the Digital Italy Agency (AGID). Several key points emerge from this provision:

2.6.1.1. It restricts the legal definition to contracts that *operate on a DLT*. This implies that only blockchain or similar implementations count as "smart contracts" for the law's purpose.[201] A mere automated script on a centralised server wouldn't qualify under this definition.

2.6.1.2. It emphasises that the smart contract's execution *binds the parties automatically* according to terms they have predetermined.[202] This captures the idea of self-execution.

2.6.1.3. The writing form requirement: Italy essentially equates a compliant smart contract with a written contract, but with a crucial condition that the parties are digitally authenticated before use.[203] In practice, this likely means using a digital identity or electronic signature recognised under Italian law (which aligns with eIDAS standards for electronic identification). For example, the parties might need to sign the smart contract transaction with a digital signature certificate or authenticate via Italy's SPID digital ID system. This ensures that there's a verified link between the on-chain pseudonymous addresses and real-world identities.

This law was forward-looking in giving legal effect to blockchain transactions. It also gave uploading data to a DLT the same legal effect as an electronic time stamp (per EU Reg 910/2014), which is useful for evidentiary purposes.[204] However, the law left some open questions**.** It did not explicitly amend the Civil Code's contract provisions, so how do those apply?

2.6.2. Smart Contracts and the Civil Code:

[199] Decree-Law 14 December 2018 No 135, art 8-ter, converted by Law 11 February 2019 No 12 ("Simplification Decree").
[200] ibid art 8-ter para 2 (definition of "smart contract").
[201] ibid art 8-ter para 2 (requirement that the program operate on DLT).
[202] ibid art 8-ter para 2 (self-execution binds the parties).
[203] ibid art 8-ter para 3 (digital-identification requirement for written form).
[204] ibid para 4; Regulation (EU) 910/2014 on electronic identification and trust services (eIDAS), art 41.

Italian civil law requires certain elements for a valid contract (art. 1325 C.C.): agreement of the parties (consenso), a certain object, a lawful causa, and compliance with any formalities.[205] A major debate is how a "computer program" can fulfill these, especially *causa*. The *Consiglio Nazionale del Notariato* (National Council of Notaries) studied this and argued that in their current form, pure smart contracts cannot easily satisfy all Civil Code requirements.[206] Specifically, they note a smart contract (as code) is mostly prescriptive/executory, it doesn't inherently contain a statement of the contract's cause or the broader agreement of the parties (the *underlying rationale or transaction type*, such as sale, lease, loan, etc.).[207] In Italian law, causa is an essential element, roughly, the legal reason why each party undertakes the obligation (for instance, the causa of a sale is the exchange of goods for price). If a smart contract simply transfers €100 from A to B when a condition happens, the code itself doesn't say *why* that €100 is being transferred, is it payment for a service? a gift? a penalty? The law might struggle to categorize it without external context, raising concerns of validity.[208] The notaries concluded that either: **(1)** a smart contract should be seen as just the execution tool of a separate contract that *does* articulate cause and terms (so the legal contract exists off-chain or in a higher-level agreement, and the smart contract is like a mechanism to perform it); or **(2)** the smart contract code (or associated data) needs to incorporate a *descriptive section* that spells out the legal agreement (even if not needed for technical execution).[209] For example, a Ricardian-type approach where the code might include a text field stating "Party A agrees to pay Party B €100 for delivery of 10 widgets on date X." This would make the causa and terms explicit, albeit not used by the code. Alternatively, standard templates could be developed, e.g., a library of smart contracts, each clearly corresponding to a specific contract type (sale, loan, etc.), so that by choosing that code, the parties implicitly choose the known legal framework.[210]

Another Civil Code aspect is **form requirements** (forma). Some contracts in Italy must be in writing under penalty of nullity (e.g., real estate transfers, art. 1350 C.C.). Law 12/2019 addresses that by granting smart contracts (with digital ID) the status of writing.[211] However, certain contracts also require **authentication by a notary** (e.g., real estate sales require a notarial deed). A smart contract, even if "written," would not meet that notarization requirement unless perhaps notaries themselves deploy smart contracts (a scenario being explored for automating certain notarial escrows or registrations). So while the law gives a baseline legal validity to smart contracts, it does not override sector-specific formal requirements. For example, a self-executing contract to sell land between two people on a blockchain would not be legally valid for property transfer, because Italian law mandates a notary deed, the blockchain record could have timestamp value, but the land registry would not accept it. On the flip side, for many ordinary contracts between private parties that just need writing, a smart contract could now suffice, which is a big step (subject to AGID technical rules finalization).

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[205] Italian Civil Code, art 1325.

[206] Consiglio Nazionale del Notariato, *Studio n. 5-2019/C, "Smart contract e tecnologia blockchain: prime riflessioni"* (2019) 369–387.

[207] ibid 379–387.

[208] ibid 371–380.

[209] ibid 375–383.

[210] ibid 383–390.

[211] Law No. 12 of 11 February 2019, art. 8-ter (introduced by Decree-Law No. 135/2018, converted with amendments into Law No. 12/2019), which states that smart contracts meet the requirement of written form once identity verification via a digital identity system is ensured.

Legge 11 febbraio 2019, n. 12, art. 8-ter, comma 2 (di conversione del D.L. 14 dicembre 2018, n. 135):

"I contratti smart, definiti come programmi per elaboratore che operano su tecnologie basate su registri distribuiti la cui esecuzione vincola automaticamente due o più parti sulla base di effetti predefiniti dalle stesse, soddisfano il requisito della forma scritta previa identificazione informatica delle parti interessate, attraverso un processo avente i requisiti fissati dall'Agenzia per l'Italia digitale con linee guida da adottare entro novanta giorni dalla data di entrata in vigore della legge di conversione del presente decreto."

2.6.3. Autonomy and Party Will:

Italian law upholds *autonomia contrattuale* (freedom of contract, art. 1322 C.C.) allowing parties to freely structure contracts content and even form, within limits of law. Smart contracts are arguably an exercise of autonomy, a new form chosen by parties to govern their deal. Law 12/2019 implicitly confirms this autonomy by recognizing the parties can choose code on DLT as their mode of contracting. However, autonomy is not unlimited; one must consider **mandatory rules**. If parties program a contract that violates a mandatory law (say an algorithm that sets cartel pricing, or an inheritance smart contract that doesn't respect forced heirship rules), the contract could be void. Smart contracts don't get a pass on substantive legality. There's also an interesting angle: could a party argue lack of consent because they didn't understand the code? Possibly, if one party truly had no idea what they were agreeing to (error in negotio or error in substantia could be invoked, akin to signing a document in a language one doesn't speak, if misled about its content). But given in most cases the user intentionally triggers the contract, that might be a hard argument unless there was deception.

2.6.4 Italian Judiciary and Doctrine: Contract Formation and the Meeting of Wills

Italy, as a civil law jurisdiction, applies the Civil Code's traditional contract formation requirements to smart contracts. The core requirement is **consenso** (consensus/meeting of wills) between parties, governed by Articles 1325-1336 of the Italian Civil Code.[212] For a valid contract to form, there must be: (1) agreement of the parties (consenso), (2) a certain object (causa), (3) lawful purpose (causa), and (4) compliance with any required form (forma).

Italian legal scholarship has closely examined how these requirements apply to blockchain-based smart contracts. Finocchiaro and Bomprezzi note that "the key question is whether [blockchain-based smart contracts] can be considered as contracts, taking into account that they are merely lines of code." Their analysis puts in correlation contract requirements with smart contract mechanics, verifying how to interpret contract formation rules to make blockchain smart contracts fit within Italian contract law's conceptual framework.

2.6.4.1 Meeting of Wills and Automated Acceptance

A central doctrinal debate concerns **consenso** (meeting of minds) in automated contexts. Italian law, following Article 1372 CC,[213] requires that "a contract is concluded when the person who made the proposal has knowledge of the other party's acceptance." The critical innovation in smart contracts is that acceptance may occur through automated means—triggering a smart contract code without explicit human-to-human negotiation.

Torsello argues that "the acceptance must reach the proponent within the set time or within the time usually required depending on the nature of the business or according to custom." For smart contracts, identifying the moment of acceptance is complex. When a party interacts with code deployed on a blockchain (e.g., sending funds to a contract address to trigger an automated transaction), at what moment does the "knowledge of acceptance" crystallize?

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[212] Finocchiaro, G. and Bomprezzi, C., 2021. *A legal analysis of the use of blockchain technology for the formation of smart legal contracts*. In: Medialaws.eu.
Torsello, M. G. M., 2022. *Dismantling Imaginaries about Smart Contracts*. In: Graziadei & Torsello (eds.), *Contract Law and Blockchain*. Edizioni Scientifiche Italiane, pp. 745-790.

[213] Finocchiaro, G. and Bomprezzi, C., 2021.

Torsello proposes two interpretations: First, for a traditional contract that is **coded** (a pre-existing off-chain agreement whose performance is automated by code), the time of conclusion follows the underlying off-chain agreement. Second, if there is **no pre-existing contract**, the time of knowledge can be identified as the moment when one party carries out the actions envisaged in the smart contract by activating it. This second interpretation suggests that the act of triggering code can itself constitute acceptance—a manifestation of will through technology rather than words.

However, Italian doctrine emphasizes that "**the meeting of wills of the parties cannot be automated** (except using artificial intelligence, a possibility that is not considered here) and it requires a human act to manifest it, for example, by way of a digital signature (or private key)." This is critical: Italian law preserves the requirement that **human agency** underpin contractual consent, even if that agency is expressed through a digital signature activating code. The code may execute automatically, but the **initial manifestation of intent** must be consciously human.

This doctrine aligns with Italian Law No. 12 of 2019 (the Simplification Decree, Article 8-ter), which specifies that smart contracts satisfy the requirement of written form **only if the parties have completed prior digital identification** in accordance with technical standards. The legal requirement for digital identification ensures that human parties are identifiable and verifiable before code executes—the law insists on knowing who is consenting, even if the medium is digital.

2.6.4.2 Smart Contracts as Contracts vs. Execution Tools

Italian scholars debate whether a smart contract constitutes a **true contract** under Civil Code or merely an **execution tool** for an underlying agreement. Torsello synthesizes the doctrine: Some scholars argue smart contracts are contracts because "the computer code underlying the process represents the transposition of the will of the parties into the language of the machine, with the consequent completion of the contract, which will therefore have the force of law between the parties (ex. art. 1372 CC)."

Others contend smart contracts are **not contracts** but merely "tools for the management of pre-existing agreements, logically prior to the smart contract." This school points to the Law No. 12/2019's reference to "effects predefined by the parties"—language suggesting a pre-existing contractual bond that the smart contract executes.

Torsello identifies an **intermediate position**: the qualification of smart contracts as contracts cannot be given abstractly but depends on specific characteristics and whether they pass the test of Article 1322(2) CC (which allows parties to conclude contracts not falling within standard types, provided they satisfy lawfulness and good faith). This flexible interpretation suggests that Italian law distinguishes between:

1. **Hybrid smart contracts**: a traditional off-chain agreement with coded execution clauses (clearly a contract)

2. **Pure code contracts**: entirely in code with no accompanying natural language agreement (questionable status—may be viewed as an execution mechanism or, if sufficiently clear intent exists, as a contract itself)

3. **Ricardian smart contracts**: code paired with natural language describing the legal agreement (likely enforceable as a contract)

The implication is that Italian courts will likely examine each smart contract's structure and intent to determine its status—no blanket rule applies.

2.6.4.3 The Causa Doctrine and Smart Contracts

A distinctive feature of Italian contract law is **causa**—the legal reason or underlying purpose of the contract. A sale's causa is the exchange of goods for price; a loan's causa is provision of money with obligation to repay. **Causa is essential and cannot be replaced by mere code.** This requirement poses challenges for pure code contracts.

If a smart contract simply transfers 100 units from Address A to Address B when a condition is met, the code itself contains no statement of **why** that transfer occurs. Is it payment for goods? a gift? a penalty? Without external context, the causa is indeterminate—raising concerns about validity. Italian law, following the Civil Code, requires clarity on the economic and legal purpose of an obligation; pure code does not provide this.

This is why Italian legal scholars and the Consiglio Nazionale del Notariato (National Council of Notaries) have recommended that smart contracts either:

1. Be **embedded in a higher-level agreement** that specifies causa (the smart contract is then merely the execution layer), or

2. Incorporate **descriptive metadata** (after the model of Ricardian contracts) that articulates the causa even if not technically necessary for execution

Italian courts, applying traditional contract interpretation principles, would likely require extrinsic evidence of causa if it is not apparent from the smart contract itself—a doctrine stemming from Article 1325(1) CC and centuries of case law protecting contractual certainty.

2.6.4.4 Immutability vs. Remedial Rights

Italian law provides remedial rights that assume contracts can be modified, interpreted, or unwound when circumstances warrant. Articles 1346-1350 CC address nullity and rescission; Articles 1368-1371 address contract interpretation. Smart contracts' immutability on blockchain creates tension with these rights.

If a smart contract executes an outcome that violates mandatory law, breaches good faith (buona fede), or results from a mistake, traditional Italian law would permit rescission or reformation. Yet if the smart contract is immutable on blockchain, immediate reversal is technically impossible. Italian law might respond by:

1. **Recognizing the technical irreversibility but permitting post-hoc remedies**: Courts can declare the smart contract outcome void and order the beneficiary to make restitution (even though the blockchain transaction itself remains recorded).

2. **Mandating contractual provisions for smart contract "pause" or reversal**: Sophisticated smart contracts might be legally required to incorporate kill-switches or dispute resolution mechanisms—a design requirement, rather than a technical one, flowing from mandatory law.

3. **Resorting to conflict-of-laws and civil procedure**: Even if on-chain reversal is impossible, civil procedure allows Italian courts to issue orders to identifiable parties (developers, beneficiaries in their jurisdiction) to effect off-chain remedies.

The challenge is that Italian doctrine has not yet fully resolved how immutable code interfaces with the law's traditional flexibility to correct errors. As Case law develops (and it has been sparse), Italian courts will likely adopt a pragmatic stance: the smart contract is binding according to its terms (respecting party autonomy), but the law retains power to intervene if the outcome violates mandatory rules or fundamental fairness. The immutability of the code is technical; the mutability of legal obligations is legal.

2.6.4.5 Italian Judiciary: Limited Case Law, Emerging Principles

Notably, **Italian courts have not yet extensively litigated smart contract disputes.** This is partly because the technology is nascent and most transactions are cross-border or between sophisticated parties who prefer arbitration. However, the Italian legal framework signals likely judicial approaches:

2.6.4.1. Recognition of Smart Contracts as Valid Instruments

Italy's 2019 law (Article 8-ter of Decree Law 135/2018) explicitly recognizes smart contracts as creating legal obligations, provided parties are digitally identified. This legislative endorsement establishes a presumption of validity—courts will likely uphold smart contracts absent specific grounds for invalidity (illegality, lack of consent, violation of mandatory law).

2.6.4.2. Application of Traditional Contract Doctrine

Italian courts will interpret smart contracts using established canons. The Law Commission of England noted that English law would give primacy to code's "plain meaning"—what the code does. Italian doctrine, being civilian, may scrutinize the parties' **intent** more closely, examining extrinsic evidence (negotiations, industry practice, prior agreements) to determine what parties actually agreed to.

2.6.4.3. Good Faith (Buona Fede) as a Legal Boundary

Italian law (Article 1375 CC) requires contracts be performed in good faith. Courts might limit automated enforcement if it violates good faith principles—for example, auto-triggering a severe penalty for a trivial breach, without notice or opportunity to cure. The doctrine of **impossibility of performance** (Article 1463 CC) could also apply if smart contract execution becomes impossible or unlawful.

2.6.4.4. Formal Validity via Digital Identification

Italian courts will likely require smart contracts to comply with the 2019 law's mandate for digital identification of parties. If parties cannot be identified at the time of smart contract formation, validity

is questionable. This imports a requirement of **legal certainty and identifiability**, reflecting Italian law's deep concern with preventing anonymous or unaccountable transactions.

Being a civil law system, Italy might not see court cases on smart contracts for some time, but scholars are actively analyzing it. The general expectation is that, aside from the formal recognition law, existing contract law can apply. Some point to analogies with existing electronic contracting norms, Italy's e-commerce decree and digital signature laws. For instance, Italian courts have in the past recognized that an electronic document and even an email exchange can form a contract and satisfy writing (citing *SM Integrated Transware v Schenker* for emails fulfilling writing requirements).[214] By extension, a blockchain record can be seen as an electronic document. Also, *firmã elettronica* (electronic signatures) in Italy range from simple to qualified; a blockchain private key signature could be seen as a type of electronic signature (likely a simple e-signature or maybe advanced, but not qualified unless certified). The law 12/2019, by deferring to technical standards from AGID for identification, hints that they might require at least an advanced or qualified signature process to attach identities to smart contracts.

One more implication is with evidence law. A properly timestamped blockchain transaction (now equated to electronic time stamp) has evidentiary value that could simplify proving when a contract action took place.[215] This can help in disputes: e.g., proving that a payment condition was met at a certain time.

In conclusion, **Italy formally recognizes smart contracts** as a valid instrument, provided identity verification is done, and is grappling with aligning them to the Civil Code's conceptual framework. The approach is a bit cautious: Italy stops short of declaring every smart contract a "contract" in the legal sense (indeed, observers note it's *"unclear whether SCs fall within the definition of contracts under Italian civil law"* or are just execution tools).[216] The conservative interpretation is that a smart contract in Italy will usually be ancillary to a normal contract, unless it clearly constitutes the whole agreement. Over time, as AGID issues technical rules and perhaps as cases emerge, the picture will clarify. Nonetheless, Italy's early move has provided a degree of legal certainty, entrepreneurs know that smart contracts won't be dismissed outright in Italy and can even fulfill legal form requirements, which encourages innovation. It also aligns with EU initiatives, since Italy's definitions likely informed discussions at the European level.

2.7. EU and International Perspectives on Legal Status of Smart Contracts

Around the world, jurisdictions are addressing smart contracts in different ways, from adapting existing laws via guidance to passing new statutes. Here we survey the EU level approach and a few notable jurisdictions (UK, US, Singapore) by way of comparison.

2.7.1. European Union:

At the EU level, there isn't yet a unified "Smart Contract Act," but EU institutions have acknowledged the technology in various contexts. The EU's approach so far has been to ensure that

[214] Tribunale di Milano, 14 March 2006, *SM Integrated Transware Pte Ltd v Schenker Italiana SpA* (recognising emails as satisfying the writing requirement) 53-61 and 73-81.

[215] Regulation (EU) 910/2014 on electronic identification and trust services (eIDAS), art 41; Law No 12/2019, art 8-ter(3).

[216] Consiglio Nazionale del Notariato, *Studio n. 5-2019/C, "Smart contract e tecnologia blockchain: prime riflessioni"* (2019) 360–368 and 401-404.

existing legal frameworks for digital transactions accommodate smart contracts, and to impose specific requirements when smart contracts are used in regulated scenarios. For example, the upcoming **EU Data Act** contains provisions about smart contracts in the context of data-sharing agreements. Article 36 of the Data Act (as of the parliamentary text) lays down "essential requirements" for smart contracts that execute data sharing, including **robust access controls, safe termination (kill switch) mechanisms, and compliance with functional requirements like auditability**.[217] This reflects a cautious stance: while not prohibiting smart contracts, the EU wants them to have safeguards especially when used by businesses for sharing IoT or other data, to prevent harm from bugs or misuse.[218] Some industry groups have voiced concern that these requirements (like the kill switch) could make many existing smart contract designs non-compliant[219]– essentially mandating mutability in some form, which conflicts with pure immutability. This tension is being debated as the act moves through final approval and implementation stages.

Apart from the Data Act, EU law relevant to smart contracts includes the **Electronic Identification, Authentication and Trust Services (eIDAS) Regulation**, which provides that electronic signatures and timestamps cannot be denied legal effect solely due to electronic form.[220] A blockchain signature and timestamp theoretically fall under this, which complements things like Italy's law for recognition. Additionally, the **EU Blockchain Strategy** via the European Blockchain Services Infrastructure (EBSI) is exploring public-sector use of smart contracts (for example, notarization services, diploma certification), which will likely yield soft-law guidelines on best practices.[221] The EU has also commissioned studies and reports (e.g., the EU Blockchain Observatory's reports) which generally conclude that smart contracts *can* fit into existing contract law, but care is needed for consumer protection and liability issues.

It's notable that European contract law directives, like the E-Commerce Directive (2000/31/EC) and the Consumer Rights Directive (2011/83/EU), were written before blockchain, but their principles apply, for instance, online contracts must give certain info to consumers, and consumers have withdrawal rights etc.[222] If a smart contract is used in consumer e-commerce, those directives still apply (the seller must inform the consumer in a clear manner, possibly not just bury terms in code). The EU's approach is thus integrative: no sweeping new legal status for smart contracts yet, but ensuring they don't undermine existing rights. Down the road, as part of the EU's digital finance and digital market initiatives, we might see more explicit legislation if gaps are found.

2.7.2. United Kingdom:

The UK, through common law, has taken a proactive and clarifying stance. The UK Jurisdiction Taskforce's 2019 Legal Statement on Cryptoassets and Smart Contracts was a landmark, as it affirmed that under English law, smart contracts are not excluded from being contracts simply because they're

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[217] European Parliament, 'Report on the proposal for a regulation of the European Parliament and of the Council on harmonised rules on fair access to and use of data (Data Act)' (A9-0031/2023), art. 36.
[218] Ibid.
[219] Ibid.
[220] Regulation (EU) No 910/2014 of the European Parliament and of the Council on electronic identification and trust services for electronic transactions in the internal market (eIDAS Regulation), art. 25(1).
[221] European Commission, 'European Blockchain Services Infrastructure (EBSI)' https://digital-strategy.ec.europa.eu/en/policies/ebsi accessed 4 May 2025.
[222] Directive 2000/31/EC of the European Parliament and of the Council on certain legal aspects of information society services, in particular electronic commerce, in the Internal Market (E-Commerce Directive), art. 5.
Directive 2011/83/EU of the European Parliament and of the Council on consumer rights, art. 6.

in code.[223] The Law Commission of England and Wales followed up with an extensive analysis (published 2021) which advised that *no fundamental law reform is needed*, the existing contract law is flexible enough to accommodate smart contracts.[224] Key points from the UK perspective include: (1) A smart contract can be analyzed through the traditional lens (offer, acceptance, intent, consideration) and can form a binding contract if those elements are present.[225] (2) Contractual interpretation will give primacy to the code's plain meaning (what the code does), but if part is in natural language, the court will interpret the whole by seeking the objective intention, and determine if the code was meant to be the definitive obligation or just implementation.[226] (3) Anonymity is not a bar, a contract is not invalid just because parties use pseudonyms; also, using a private key to sign is likely a valid signature in principle.[227] And crucially, (4) English law likely sees no issue with the requirement for writing, code can be "written" and understood given appropriate tools, so a contract *in code* can still be considered "in writing" if that matters.[228] The Law Commission did recommend possibly some clarity or an interpretive legislation on certain points like when a code error can be addressed by legal doctrines, but by and large it sees smart contracts as falling within *lex lata*. There have not been many litigated cases yet, but one often cited is the Singapore case *Quoine v B2C2* (since UK doesn't have a reported case on smart contract dispute yet).[229] The UK is also looking at digital dispute resolution rules for on-chain arbitration, showing an openness to innovate procedurally.[230] Overall, the UK's tone is that smart contracts are just contracts, enforceable as such, and English common law's flexibility with equitable remedies, etc. can handle even tricky scenarios by analogies though parties are encouraged to foresee issues and agree on terms to handle them. Post-Brexit, the UK's approach retains GDPR-aligned standards but diverges on certain AI governance points, as seen in its principles-based AI framework versus the EU's risk-based approach. This divergence may reduce interoperability in cross-border contracts while preserving regulatory flexibility.

2.7.3. United States:

The US legal landscape is more fragmented. At the federal level, there isn't specific smart contract legislation (though the CFTC and SEC have kept an eye on smart contracts in context of derivatives and securities e.g., a DAO or DeFi contract might inadvertently create an investment contract subject to securities law). At the state level, however, numerous states have passed laws addressing blockchain and smart contracts. Arizona led with a 2017 law (HB 2417) amending its Electronic Transactions Act to state that *"smart contracts may exist in commerce"* and that no contract shall be denied legal effect or enforceability solely because it contains a smart contract term or uses blockchain.[231] This essentially ensures that a contract formed via smart contract is just as good as one on paper, echoing electronic records laws. Other states like Tennessee and Nebraska passed similar provisions. Nevada and Ohio also recognized blockchain records and signatures. These laws are largely declaratory, confirming validity of electronic blockchain records, but they provide reassurance. Some states addressed specific uses: e.g., Illinois explored blockchain for governmental records, and Wyoming (which has been extremely active in crypto legislation) created a whole framework for "digital asset" law and recognized DAOs as legal entities. On the contract front, general contract law

[223] UK Jurisdiction Taskforce, *Legal Statement on Cryptoassets and Smart Contracts* (LawTech Delivery Panel, 2019).
[224] Law Commission of England and Wales, *Smart Legal Contracts, Advice to Government* (Law Com No 401, 2021).
[225] Ibid.
[226] Ibid.
[227] UK Jurisdiction Taskforce, *Legal Statement on Cryptoassets and Smart Contracts* (LawTech Delivery Panel, 2019).
[228] Ibid.
[229] *Quoine Pte Ltd v B2C2 Ltd* [2020] SGCA(I) 02.
[230] UK Jurisdiction Taskforce, *Digital Dispute Resolution Rules* (LawTechUK, 2021).
[231] Arizona House Bill 2417 (2017), codified at Arizona Revised Statutes § 44-7061.

in the US would likely treat a smart contract like any electronic contract: the Uniform Electronic Transactions Act (UETA) adopted in most states (and the federal E-SIGN Act) already say electronic signatures and records satisfy legal requirements. Under UETA, an "electronic agent" can form a contract on behalf of a party, even if no human is directly aware at that moment, which directly covers algorithmic contracting. For example, a contract formed by the interaction of two electronic trading programs can be binding, as long as each party set up the program to initiate or accept offers (this is similar to the Shoe Lane principle in English law mentioned by Clifford Chance).[232] So doctrinally, US courts have tools for these scenarios. There have been a few cases tangentially related to smart contracts: e.g., the SEC's enforcement against the DAO in 2017 (not contract law, but securities regulation), and a 2018 case in which a party tried to enforce a crypto loan made via a smart contract (the case settled). Another aspect is consumer protection: states like Vermont have warned that smart contracts must comply with consumer laws, and the CFPB (consumer finance regulator) indicated automated fintech contracts are still subject to regs like TILA, etc. On the whole, the US is supportive but cautious: recognizing smart contracts in law, but also starting to ensure that things like UDAP (unfair and deceptive acts) laws apply if someone misuses them (e.g., a scam coded into a contract). We might eventually see federal guidance if, say, a systemic issue arises (for instance, if a stablecoin uses smart contracts and has an incident). While the US fragmented, state-by-state approach offers flexibility for state-level innovation experimentation, it creates compliance uncertainty for companies and insufficient privacy protections for consumers compared to GDPR. The EU's harmonised model provides clarity and interoperability but may constrain rapid innovation relative to US regulatory agility.

2.7.4. Singapore:

Singapore, as a tech-forward common law jurisdiction, has embraced blockchain in its fintech strategy. While it hasn't passed a specific "smart contract statute," its legal community and government have indicated that Singapore law will treat smart contracts like any other contract, focusing on substance over form. The Singapore Academy of Law did studies on it, and the general conclusion was that if an arrangement formed via code satisfies the usual contractual requirements, it's a contract.[233] Singapore's Electronic Transactions Act (ETA) provides that contracts formed by automated message systems are valid and that any legal requirement for writing or signing can be met electronically (with exceptions for certain documents). This would encompass smart contracts. The notable case *Quoine Pte Ltd v B2C2 Ltd* (Singapore Court of Appeal, 2020), while dealing with algorithmic exchange trading rather than a Solidity contract, effectively treated an algorithm as capable of making an offer that can be accepted, and analyzed whether the contract was voidable for mistake. The court applied traditional contract doctrines (unilateral mistake and the knowledge of the party deploying the algorithm).[234] The majority held the contracts (trades) were valid and not void for mistake under the specific facts. This case is instructive: it shows Singapore's judiciary is willing to enforce contracts formed by autonomous processes, and will adapt concepts like what constitutes the party's knowledge/intent in that context. Singapore's regulators (MAS) have also facilitated blockchain projects (like Project Ubin for digital payments) that use smart contracts, implicitly acknowledging their validity. Law firms in SG have opined that there's *"no prohibition against smart*

[232] See Uniform Electronic Transactions Act (UETA) § 14 (1999); also discussed in: Clifford Chance, *Smart Contracts: Legal Framework and Emerging Issues* (Client Briefing, 2021).
[233] Singapore Academy of Law, *Law Reform Committee Report on Smart Contracts* (2019) 9–11.
[234] *Quoine Pte Ltd v B2C2 Ltd* [2020] SGCA(I) 02, [102]–[130]; see also UK Jurisdiction Taskforce, *Legal Statement on Cryptoassets and Smart Contracts* (2019) paras 130–137.

contracts" and that ETA and contract law principles suffice to recognize them.[235] Singapore's approach is thus similar to the UK's: enabling by existing law, case-by-case development, and encouraging innovation under regulatory guidance. Singapore's permissive stance on blockchain: accelerates fintech innovation and attracts startups but provides less consumer protection than the EU model. However, Singapore's use of regulatory sandboxes offers valuable lessons for EU regulators seeking to balance innovation with oversight.

2.7.5. Other Jurisdictions:

A few quick notes: Maltese law (Malta Digital Innovation Authority Act and related 2018 laws) introduced the concept of *"technology arrangements"* and voluntary certification of smart contracts. Malta created a legal framework for what it calls "DLT smart contracts" and allows one to certify their code for quality, an attempt to build trust.[236] France amended its laws to allow blockchain ledgers for recording securities and mini-bonds, indirectly supporting smart contracts in those contexts (but did not define smart contract broadly).[237] China has embraced blockchain but its legal system is different; nonetheless, Chinese courts have reportedly recognized that blockchain records can be admissible evidence (a 2018 Supreme People's Court rule), and there are ongoing efforts to integrate smart contracts especially in areas like supply chain and trade finance under government oversight.[238] EU Member States like Germany and France have debated how to treat smart contracts under civil law; Germany's position papers suggest current law suffices but highlight consumer law and data law issues.[239]

In summary, internationally, there's a general trend of acknowledging smart contracts as a new method of contracting that existing legal principles can handle, with relatively few needing bespoke legislation. However, where legislation has appeared (like in some US states, or Italy), it has been largely *enabling*, clarifying that smart contracts aren't invalid just because of their form, and occasionally *regulatory* (imposing certain features for safety). One can observe a distinction: common law jurisdictions (UK, Singapore, parts of US) rely on flexible case law to adapt, whereas civil law jurisdictions (Italy, Malta) have been more inclined to codify definitions and requirements early. The EU sits somewhat in between, using directives/regulations to shape specific aspects (like the Data Act's requirements).

As smart contracts become more entwined with emerging tech like Internet of Things (IoT) and Artificial Intelligence (AI), we can expect further evolution in legal treatment, perhaps new international standards or model laws to harmonize how smart contracts are interpreted and enforced across borders.

2.8. Constitutional Limits to Contractual Automation: Due Process, Proportionality, and Remedial Rights

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[235] Rajah & Tann, *Smart Contracts in Singapore* (Client Advisory, 2020) 3–4.

[236] Malta Digital Innovation Authority Act 2018 and Innovative Technology Arrangements and Services Act 2018 (Malta), esp arts 7–13.

[237] Ordonnance n° 2016-520 du 28 avril 2016 relative aux bons de caisse, as amended by Ordonnance n° 2017-1674 du 8 décembre 2017, art L211-3, Code monétaire et financier (France).

[238] Supreme People's Court (PRC), *Provisions on Several Issues Concerning the Hearing of Cases by Internet Courts* (2018) art 11.

[239] German Federal Ministry of Justice and Consumer Protection, *Discussion Paper on Smart Contracts and the Civil Code* (2020) 5–7.

Whilst contract law traditionally grants parties autonomy to structure their agreements as they see fit (autonomia contrattuale under Italian law, freedom of contract under common law), constitutional law imposes limits. Not all agreements are enforceable; agreements violating mandatory law, public policy, or fundamental rights are void. The rise of smart contracts, agreements that self-execute and are immutable once deployed, raises a novel constitutional question: **can automated execution of contractual obligations respect constitutional protections of due process, proportionality, and effective remedy?**

2.8.1 Smart Contract Execution and Due Process

In traditional contract law, breach is remedied through legal action. A creditor sues a debtor for damages; a court examines the circumstances and may grant equitable relief (specific performance, injunction, reformation). This judicial process embodies due process: the defendant has notice, opportunity to defend, and access to a neutral arbiter. Smart contracts bypass this process. When conditions are met (verified by IoT sensors or oracles), payment executes automatically, collateral is seized, or services are disabled, all without court involvement. From a constitutional standpoint, this raises a due process concern, particularly when the smart contract outcome is harmful to a party.

Example Scenario: A leasing smart contract triggers automatic lockout of a leased machine when a payment is missed. The lessor did not receive the invoice due to email error; the lessee did not know about the lockout until the production line stopped. The smart contract executed without notice or opportunity for the lessee to contest the termination. Under traditional contract law, the lessor would be required to provide notice and provide opportunity for cure; automatic enforcement may violate the doctrine of good faith (bona fides) which requires parties to act fairly. Constitutionally, this implicates due process rights under Article 47 CFREU (right to fair trial) and Article 41 CFREU (right to good administration). The individual affected, the lessee, had no opportunity to present their side before the penalty was imposed.

The question then arises: **can a smart contract be drafted to respect due process**, or does automation inherently bypass it? Some argue that due process can be built in, for example, a smart contract could incorporate a grace period, require explicit notice before lockout, allow a challenge mechanism, or vest final enforcement authority with a human (e.g., manager approval required before actual lockout). However, if built-in protections are extensive, the efficiency and automaticity of the smart contract diminish, the contract becomes semi-automated, more like a traditional contract with electronic execution aids. This creates a design tension: full automation sacrifices procedural fairness; procedural fairness sacrifices automation.

2.8.2 Proportionality and Autonomous Enforcement

Constitutional law, particularly in EU jurisdictions, enshrines the principle of proportionality: any limitation on rights must be proportionate to the legitimate aim pursued. This principle applies to contract enforcement. If a smart contract auto-executes a penalty, it must be proportionate to the breach. Consider an automated insurance contract that immediately cancels coverage and imposes a financial penalty upon a missed payment, even a one-day missed payment due to a bank processing delay. Traditional law would likely deem this disproportionate; courts might grant relief based on equity or unjust enrichment. A smart contract, executing as coded, has no mechanism to assess proportionality; it simply applies the rule.

From a constitutional standpoint, this raises a **proportionality deficit**: the automated rule may violate CFREU Article 52(1), which provides that any limitation on fundamental rights must be "necessary and proportionate to the objectives of general interest pursued." When a smart contract cannot distinguish between a technical payment delay and deliberate non-performance, it may impose disproportionate consequences. A constitutional reading would require that smart contracts either (1) incorporate flexibility to assess circumstances, or (2) be prohibited in contexts where disproportionality is likely (e.g., consumer contracts, critical services).

2.8.3 Right to Effective Remedy and Irreversibility

Smart contracts' irreversibility, once deployed on an immutable DLT, the contract executes and cannot be unexecuted, conflicts with the constitutional right to effective remedy (CFREU Article 47). If a smart contract executes incorrectly due to a code bug, and a party suffers loss, what remedies are available? In traditional contract law, the harmed party can seek damages, reformation, or restitution from the court. But if the transaction is immutable on blockchain and assets have been transferred to third parties, restitution may be impossible. The Court of Justice of the European Union has held that the right to effective remedy requires that aggrieved parties have access to a court with power to provide meaningful relief (Rewe-Zentral v. Bundesmonopolverwaltung für Branntwein, Case 120/78). If a smart contract loss cannot be remedied due to irreversibility, this violates the constitutional right.

The question becomes acute with **autonomous AI-driven smart contracts**. If an AI agent within a smart contract makes a decision (e.g., pricing terms dynamically based on algorithmic analysis of market conditions) and that decision causes loss due to algorithm malfunction or bias, is there a remedy? If the outcome is immutable and the AI's decision-making process is opaque (a "black box"), the affected party may have no practical access to remedy, no way to prove the loss was wrongful, no way to unwind it.

2.8.4 Human Agency and Autonomy (CFREU Article 1 - Human Dignity)

A deeper constitutional principle underpins these due process and remedy concerns: **human dignity (CFREU Article 1)** and the right to self-determination. Constitutional systems grant individuals autonomy, the right to make binding choices about their legal obligations. Yet smart contracts can execute binding obligations without active human consent at the moment of execution. If a consumer's wearable IoT device, without explicit authorization at that moment, triggers a smart contract to transfer payment or share data, did the consumer truly consent?

GDPR addresses this by requiring explicit, informed consent for data processing (Article 6). Yet an automated smart contract driven by IoT sensors may execute transactions before the individual is even aware of the triggering event. Constitutionally, this raises a question of **autonomy and human agency**: are individuals being reduced to passive subjects of algorithmic decisions, or do they retain meaningful control over their legal obligations? The EU AI Act recognizes this concern by requiring "human oversight" for high-risk AI systems (Article 14); this requirement reflects a constitutional principle that important decisions affecting rights and obligations should remain under human agency.

2.9. The Role of AI in Smart Contracts (Outlook)

No examination of smart contracts' evolution would be complete without looking toward the influence of artificial intelligence (AI) and how it might support or integrate with smart contracting.

While the focus of this chapter has been on the *present* legal nature of smart contracts, AI is poised to play a significant role in the *future* of this domain (foreshadowing the discussion in Chapter 3). There are a few key intersections of AI and smart contracts:

2.9.1. AI as a Contracting Agent:

We already have instances of automated agents entering into contracts (e.g., trading bots). As AI systems become more advanced, they could negotiate and form contracts on behalf of humans or corporations, using smart contract platforms to execute them. These *electronic agents* may not be very "intelligent" yet in a general sense, but the line is blurring. In the context of smart contracts, an AI agent could dynamically determine contract terms (like pricing, or other parameters) and then deploy or interact with a smart contract to formalize the deal. This raises the question noted by Clifford Chance: *can two AI programs contract directly with each other without human awareness, and is that binding?*.[240] Current law would generally say yes, if they were programmed by owners to do so, but as AI autonomy grows, we may need new doctrines about the capacity of AI and how to attribute its actions to principals. Singapore's *Quoine* case touched on that by attributing the algorithm's actions to the programmer's knowledge.[241] Going forward, one can imagine AI-driven IoT devices negotiating bandwidth or energy contracts on the fly via smart contracts. Legal systems might need to adapt by perhaps granting AI limited agency or by requiring a failsafe (the EU's draft AI Act, though not directly about contracts, emphasizes human oversight in high-stakes AI decisions, an ethos that might extend to contracting).

2.9.2. AI for Contract Analysis and Drafting:

On the support side, AI can assist in drafting smart contracts. Writing secure code is difficult; AI code generation tools might help create and verify smart contract code from high-level descriptions, reducing human error.[242] AI could also serve as an auditor, using machine learning to detect patterns of bugs or vulnerabilities in contract code before deployment. In the legal realm, AI can translate legal text into formal logic or vice versa. For example, an AI system could take a natural language contract and output a smart contract code or a *pseudo-code flowchart* (as we did earlier manually) describing steps. This could bridge the gap between lawyers and developers, ensuring the code reflects the parties' intent. Already, researchers are exploring NLP (natural language processing) techniques to create *"legally-aware smart contracts."* Chapter 3 will delve deeper into such AI tools for contract automation and compliance.

2.9.3. Smart Contracts + AI in Decision-Making:

There is the notion of "smart oracles" or AI oracles. Instead of a simple data feed, an AI could determine whether a condition is met, for instance, an AI image recognition system could determine if a delivered product matches the specification, and then trigger a payment in a smart contract. Here the AI is effectively judging contract performance, a role traditionally for humans or courts. If that AI makes a mistake, who is accountable? This loops in all the uncertainty of AI decision-making into the finality of smart contracts. Solutions might involve hybrid dispute resolution: if someone disagrees

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[240] Clifford Chance, *Smart Contracts, Legal Considerations* (Client Briefing, 2017) 5–6.
[241] Law Commission of England & Wales, *Smart Legal Contracts: Advice to Government* (Law Com No 401, 2021) para 3.58.
[242] A Nordrum, 'Smart Contracts Are All the Rage, but They're Still Hard to Code Right' *IEEE Spectrum* (12 April 2018) https://spectrum.ieee.org accessed 6 May 2025.

with the AI-powered oracle's decision, they could escalate to a human arbitration (some platforms are working on this concept).

2.9.4. Personalized and Dynamic Contracts:

AI could allow contracts to become more personalized and adaptive. As noted by scholars, electronic agents (AI) might *"individualize and personalize contracts"* for consumers in real time.[243] Think of shopping: an AI agent might negotiate the best price across multiple sellers and auto-form a smart contract when conditions are optimal. Or insurance policies that adjust premiums and coverages dynamically via smart contracts analyzing data through AI (telematics in cars, health data, etc.). This offers consumer benefits (tailored contracts) but also new risks, consumers might not fully grasp AI-made tradeoffs, and issues of fairness arise if algorithms discriminate or err.[244] Law will have to ensure transparency and fairness in AI-negotiated terms, possibly requiring algorithmic accountability.

2.9.5. AI in Legal Support and Enforcement

AI might support judges and lawyers in dealing with smart contract disputes. For example, an AI system might simulate the execution of a complex smart contract to show exactly what happened on the blockchain, translating code to narrative. This could be used in court as an explanatory tool. Conversely, AI might help parties avoid disputes by monitoring contract execution and flagging anomalies (like "Party B's behavior on-chain suggests a potential breach scenario brewing"). Such AI systems could prompt renegotiation or automatic adjustments in the smart contract if allowed (leading to self-healing contracts that adjust terms by AI agreement of parties' agents, a far-off concept but theoretically possible).

In essence, AI stands to **augment** smart contracts, making them more sophisticated and possibly more user-friendly, but it also adds layers of complexity. The convergence of AI, IoT, and smart contracts, often dubbed *"smart contract 2.0"* or similar, might see, for example, a factory IoT sensor (device) that uses AI to predict a machine failure and automatically executes a maintenance contract via a smart contract with a service provider. Each component (the device, the AI, the contract) has legal implications: product liability for the sensor, correctness of the AI's prediction (could it trigger wrongly and who bears cost?), and the contractual enforcement via code. Traditional legal silos (contract, tort, regulatory) will intersect.

As a bridge to Chapter 3, which will likely explore **Novel Legal Issues of IoT and DLT in Smart Contracts**, we note that IoT provides the data and physical linkage (things happen in the real world based on smart contracts), DLT provides the platform, and AI can provide the "smarts" to manage complexity and autonomy. Chapter 3 will examine how these technologies together pose new legal questions, such as data ownership, privacy in IoT-sourced contract triggers, algorithmic biases, and even the concept of machine-contracted obligations. The Italian and European context will again provide a backdrop: indeed, the EU is keenly looking at AI regulation (the AI Act) and IoT data sharing (Data Act) which, combined with the legal recognition of smart contracts, sets up a comprehensive but challenging framework for the future digital economy.

2.10. Conclusion

[243] Primavera De Filippi and Aaron Wright, *Blockchain and the Law: The Rule of Code* (Harvard UP 2018) 152.
[244] Ibid 155.

In this chapter, we traced the evolution of smart contracts from a theoretical concept by Nick Szabo to a present reality shaping legal discussions worldwide. We examined what smart contracts are, how they function, their varieties, and how they align (and misalign) with traditional contract law principles. We also looked at specific jurisdictional responses, with a focus on Italy's pioneering stance and comparative insights from the UK, US, EU, and others. Smart contracts promise greater efficiency and certainty, but they also test the adaptability of legal systems regarding enforceability, intent, and fairness. As technology marches forward, especially with AI and IoT integration, the legal ... the legal system must continue to adapt. Smart contracts have moved from theory to practice and are now anchored in legal frameworks (as seen in Italy and elsewhere), but they still challenge traditional notions of contracts at every stage, from how they're formed to how they can be remedied when things go wrong. As we proceed to the next chapter, we will delve deeper into **novel legal issues arising from the fusion of IoT and DLT in smart contracts**, examining how interconnected devices and AI-driven agents further complicate and enhance the smart contract landscape, and what legal responses are emerging to address these cutting-edge developments.

Chapter 3: Integration of AI and IoT in Smart Contracts

3.0.1. Code vs. Law - The Three-Part Test Framework

Code does not function as law; rather, code is a **mechanism of contract performance** constrained and validated by law. This thesis rejects both extremes, neither 'code is law' (permitting code to override legal norms) nor 'law must constrain all code' (preventing legitimate automation). Instead, a **tiered framework** applies: (1) **Deterministic smart contracts** (pre-defined, rule-based logic) can function as binding agreements if they comply with mandatory law and do not violate due process. (2) **Non-deterministic AI-driven contracts** require heightened human oversight because algorithmic opacity prevents legal certainty. (3) **Self-help enforcement by code** (auto-lockout, collateral seizure) is valid only when law would permit equivalent human self-help, and must preserve access to judicial remedy.

To operationalize this position, this thesis proposes a three-part sequential test for determining when code-based smart contracts may self-execute autonomously versus when they require human oversight or court review:

Test 1: Validity Test (Contract Formation Compliance)

Question: Does the smart contract comply with fundamental contract formation requirements under applicable law?

Application:

Does the contract satisfy offer, acceptance, consideration, and intent requirements?

Have parties been properly identified and has their consent been authenticated (digital signature, blockchain transaction)?

Is the transaction's purpose lawful and aligned with public policy?

Outcome—If YES:

Code execution is valid and binding. The law does not require human intervention to override code mechanics merely because the transaction is automated. Once a valid contract forms, law permits the parties' chosen method of performance—whether human or automated. This respects party autonomy and the efficiency gains of code-based execution.

Example (YES): A supply-chain smart contract where both parties digitally sign agreeing that upon IoT sensor verification of delivery, automatic payment will execute. The contract satisfies formation requirements; code execution is valid.

Outcome—If NO:

Code execution is void or voidable; law trumps code. If the smart contract lacks valid formation (no consent, fraud, incapacity of a party), the code-based transaction is legally null regardless of its technical execution. A court can order reversal or impose liability on the party who benefited from the invalid smart contract's execution.

Example (NO): A smart contract that auto-executes payment without either party's affirmative consent (e.g., fraudulently deployed by a third party). The underlying transaction is void; code cannot validate an invalid contract.

Test 2: Fairness/Equity Test (Due Process & Proportionality)

Question: Does the code's automated enforcement violate due process, good faith performance (buona fede), or proportionality principles?

Application:

Does auto-execution provide adequate notice to affected parties?

Does the contract allow opportunity for cure/remedy before harsh consequences execute?

Is the automated consequence proportionate to the underlying breach?

Does enforcement respect the principle of good faith (Italian law: Art. 1375 CC; common law: implied covenant)?

Outcome—If VIOLATES due process/good faith/proportionality:

Code cannot self-execute autonomously; it requires court review or human authorization before triggering harsh consequences. This preserves fundamental due process protections that law presupposes.

Example (VIOLATES): A rental smart contract that auto-locks a vehicle for a single day's payment delay, without notice or chance to pay. The consequence (total loss of use) is disproportionate to the breach (one day late). Even if the contract is validly formed, auto-execution violates proportionality; human review should precede lockout.

Outcome—If COMPLIES with due process/good faith/proportionality:

Code may self-execute autonomously. The automated enforcement respects legal principles because it is fair, proportionate, and provides adequate process safeguards.

Example (COMPLIES): A loan smart contract with built-in safeguards: (1) notice sent to borrower 7 days before liquidation, (2) opportunity to pay arrears within grace period, (3) liquidation of collateral only if arrears persist (proportionate remedy). Auto-execution is compliant with fairness principles.

Test 3: Remedy Preservation Test (Access to Justice)

Question: If the code malfunctions or produces an unjust result, can the harmed party access meaningful legal remedy?

Application:

Can the affected party identify the responsible party (smart contract developer, deployer, oracle provider)?

Can a court reverse or reform the outcome?

Is there a kill-switch or human override mechanism?

Are transaction logs clear enough to audit what went wrong?

Outcome—If NO REMEDY AVAILABLE:

Code must incorporate human override or kill-switch mechanisms. The law cannot permit irreversible code execution when the harmed party has no recourse if something goes wrong. This protects the constitutional right to effective remedy (CFREU Article 47).

Example (NO REMEDY): A fully autonomous smart contract on an immutable blockchain executing collateral seizure based on AI price predictions. If the AI made an error (algorithm bug), the seizure cannot be reversed. The harmed party has no recourse. This scenario violates the remedy preservation test; code-based execution is not permissible without a kill-switch (e.g., time-lock delay allowing manual reversal if audit reveals error).

Outcome—If REMEDY AVAILABLE:

Code may execute autonomously. If auditing and reversal mechanisms exist, the legal system can respond to code failures; the harmed party has recourse.

Example (REMEDY AVAILABLE): A smart contract with time-locked execution (10-day delay before payment), transparent logging, and an escrow mechanism allowing either party to challenge execution through arbitration before funds transfer. If the code errs, the delay window permits challenge and correction. Auto-execution is permissible.

Synthesis: Sequential Application of the Tests

The three tests function **sequentially**:

1. **Validity Test is gatekeeping**: If a smart contract is not validly formed, it fails at threshold; code execution is void regardless of fairness or remedies.
2. **Fairness Test is proportionality control**: Once validity is established, fairness principles determine whether automation is permitted or requires human review. Disproportionate consequences must be restrained.
3. **Remedy Test is accountability safeguard**: Even if a contract is valid and fair, if malfunction is irreversible and the harmed party has no recourse, autonomous execution must be constrained by kill-switches or human override.

Valid Contract? → NO: Void. Code cannot execute. → YES: Proceed to Fairness Test Fair/Proportionate/Good Faith? → NO: Code cannot auto-execute; requires human authorization before harsh consequences → YES: Proceed to Remedy Test Remedy Available if Code Fails? → NO: Code must include override mechanism; cannot be fully autonomous → YES: Code may execute autonomously; system permits remedy if malfunction occurs.

What is the Legal Basis for the Framework

Validity Test draws from:

- Italian Civil Code Articles 1325-1336 (contract formation requirements)
- CFREU Article 47 (right to effective remedy presupposes valid legal obligation)
- EU contract law principles (CESL, Directive 2019/2161 on unfair contract terms)

Fairness Test draws from:

- Italian Civil Code Article 1375 (buona fede/good faith obligation)
- CFREU Article 52(1) (proportionality principle)

- GDPR Article 22 (human oversight requirement for automated decisions)
- EU AI Act Articles 14, 29 (human oversight and monitoring requirements)

Remedy Test draws from:

- CFREU Article 47 (right to effective remedy)
- ECHR Article 6 (right to fair trial)
- EU principle of judicial review (constitutional requirement that individuals can challenge automated outcomes in court)

Why This Framework Matters for Smart Contracts?

This test distinguishes **legitimate smart contract automation** (compliant with law, fair, reversible) from **concerning autonomous code** (potentially violating contract law, disproportionate, irreversible). It provides courts and regulators with an **operational framework** for evaluating smart contract legality without requiring blanket prohibitions on code or blanket permission for all automation.

For practitioners: Smart contract developers can use this test to design compliant contracts—ensuring validity, building in fairness safeguards, and implementing override mechanisms.

For regulators: EU regulators drafting smart contract legislation can reference this framework to determine which contracts require pre-approval, which can execute autonomously, and which must be prohibited entirely.

For courts: When smart contract disputes arise, courts can apply this test to determine whether the code's execution was lawful, and if not, what remedies the harmed party deserves.

3.1 Autonomous AI Decision-Making in Smart Contracts

Smart contracts are often defined as self-executing code that enforces agreements without further human intervention. When artificial intelligence systems are empowered to make autonomous decisions within such contracts, traditional contract law faces new challenges. One fundamental issue is **contract formation and consent**. In classic doctrine, a binding contract requires a "meeting of the minds" and consent of the parties to specific terms. If an AI agent negotiates and concludes a contract on behalf of a human principal without real-time human oversight, it is debatable whether the human has truly consented to those terms. Scholars have noted that when an AI program completes a contract autonomously, "there is no consent, and no appearance of consent, to the specific terms of that contract on the part of the people the contract purports to bind. Without consent there is no legally enforceable contract."[245] This raises the specter that an entirely AI-negotiated agreement might be void for lack of true consent.

[245] See Oliver, *"Contracting by Artificial Intelligence: Open Offers, Unilateral Mistakes and Why Algorithms are Not Agents,"* 2(1) ANU Journal of Law & Tech. 52, 57-58 (2021) (arguing that if an AI program negotiates and concludes a contract without human involvement, "there is no consent, and no appearance of consent, to the specific terms... Without consent there is no legally enforceable contract.")
Also see, K. Werbach, 'The Blockchain and the New Architecture of Trust' (MIT Press 2018) 137; and J Fairfield, 'Smart Contracts, Bitcoin Bots, and Consumer Protection' (2014) 71 *Washington and Lee Law Review* 35, 66–67.
J Surden, 'Computable Contracts and the Problem of Automation Consent' (2022) 58 *Harvard Journal on Legislation* 211, 217.

One proposed solution is to treat AI systems as tools or **agents** of the humans deploying them. Agency law could impute the AI's actions and knowledge to the principal, binding the human to contracts entered by the AI much as if a human agent had done so.[246] Indeed, in the notable Singapore case of *Quoine Pte Ltd v B2C2 Ltd*, which involved a dispute over cryptocurrency trades executed by algorithms with no direct human input, the court grappled with whether the algorithms should be deemed legal agents of their programmers. The Singapore Court of Appeal ultimately treated the trading algorithms as **"mere machines"** rather than independent agents, refusing to attribute to the users any knowledge the algorithms might have had.[247] This meant the contracts formed by the interacting algorithms were upheld as valid and enforceable despite the lack of direct human assent, since the users had implicitly empowered their programs to act on their behalf. Notably, many jurisdictions have amended their laws to accommodate such scenarios. For example, **electronic transaction laws** in the US and internationally provide that a contract shall not be denied legal effect *solely* because its formation involved automated message systems with no human review.[248] In sum, the law is evolving to recognize that when a person deploys an autonomous AI (or algorithm) to contract, the person's intent to be bound may be inferred from that deployment, even if the exact terms were not contemporaneously reviewed by a human.

At the same time, questions linger about how traditional doctrines apply. If an AI-driven contract produces an aberrant or onerous outcome, can a party escape it for mistake or unfairness? The *Quoine* case demonstrates one approach: the court applied the existing **unilateral mistake** doctrine but required actual (human) knowledge of the error on the part of the advantaged party.[249] Since neither party's human operators knew of the pricing glitch that the algorithms exploited, the contract was not voided. This suggests that courts may place the risk of an AI's "decision" on the party who deployed the AI, absent very narrow exceptions. In other words, once an AI is entrusted to form contracts, the human user may be stuck with its bargains, barring traditional defenses like fraud or illegality. Going forward, legal systems might develop more tailored rules for AI agents, but so far the trend is to adapt existing contract law concepts, bolstered by interpretative tweaks and implied consent, to accommodate autonomous decision-making in smart contracts.

Importantly, we must distinguish the **smart contract code from the legal contract** itself. A smart contract (the software) is typically not a "contract" in the legal sense, but rather a tool executing an agreement. The EU's recent Data Act underscores this by defining a smart contract as a program for automating the execution of an agreement, and clarifying that the use of such code does not displace

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[246] See, e.g., Teo & Chung, *"Legal Personality and AI Agents,"* 33 SAcLJ 520 (2021) (discussing treating AI as agents); and cf. *B2C2 Ltd v Quoine Pte Ltd* [2019] SGHC(I) 03 at [86]–[88] (noting arguments that the trading algorithms in question be treated as the legal agents of the parties).

Also see, Uniform Electronic Transactions Act 1999 § 14; see also UNCITRAL Model Law on Electronic Commerce 1996 art 12.

American Law Institute, *Restatement (Third) of Agency* § 1.01 (2006).

G D Smith, 'Electronic Agents, Agency and Contract' (2020) 36 *Journal of Contract Law* 45, 52–55.

[247] *Quoine Pte Ltd v B2C2 Ltd* [2020] SGCA(I) 02 (Singapore C.A.) at [46] paras 98–104. (rejecting the characterization of autonomous trading software as legal agents, stating "They are, in effect, mere machines...programming"). The court held that the contracts formed by the interacting algorithms were valid, with the programmers/users bearing the consequences of their program's actions.

[248] See UNCITRAL Convention on the Use of Electronic Communications in International Contracts 2005, Art. 12; Uniform Electronic Transactions Act (USA) §14 (1999) 7A pt I ULA 322. These provide that a contract shall not be denied validity or enforceability solely because its formation or operation involved automated message systems with no human review or intervention.

Also see, Electronic Signatures in Global and National Commerce Act 2000 (US) § 101.

[249] *Quoine v B2C2* (Singapore C.A. 2020), supra, at [104]–[110] and paras 175–181.. The court applied the doctrine of unilateral mistake, requiring actual knowledge by the non-mistaken party. Since the algorithms (mere machines) had knowledge but the humans did not, the court found no sufficient knowledge to void the contract.

ordinary contract law remedies.[250] In practice, the parties' legal obligations may be documented in natural language (or agreed by conduct), with the code merely performing those terms. Thus, even in an AI-driven, self-executing environment, the foundational requirements of contract law, agreement, consideration, intention to create legal relations, and capacity, remain relevant. The novel element is that some or all of those elements might be manifested through machines. The challenge for courts and legislators is ensuring that when AI and IoT devices act in place of humans, basic contract principles like consent and meeting of minds are satisfied (or suitably analogized) so that the resulting obligations are legitimate and enforceable.

3.2 IoT as Data Source and Trigger in Smart Contract Execution

The **Internet of Things (IoT)** plays a pivotal role in bridging physical reality with digital contracts. IoT devices, from smart sensors and appliances to connected vehicles, can serve as the eyes and ears of a smart contract, feeding it real-time data and even triggering contract performance. For example, a temperature sensor in a shipping container might automatically report that goods have arrived at the buyer's warehouse, prompting a blockchain-based smart contract to release payment to the seller. In such scenarios, the IoT device (or an array of devices) acts as an **oracle**, providing trustworthy data to the contract logic. This convergence of IoT and distributed ledger technology promises highly efficient, automated transactions: service-level agreements can be monitored continuously, and contractual obligations can execute the moment specified conditions (read by devices) are met.

However, reliance on IoT data streams also raises significant **technical and legal challenges**. One major concern is the **accuracy and reliability** of the device data. If a smart contract is only as good as the input it receives, a malfunctioning or compromised sensor can lead to improper actions, with potentially serious consequences. For instance, if a moisture sensor in an agricultural insurance contract incorrectly reports drought conditions, an insurance payout might be triggered erroneously (or conversely, a valid payout might be wrongfully withheld if the sensor under-reports rainfall). The so-called "oracle problem" in blockchain contexts encapsulates this risk: smart contracts typically cannot verify off-chain data on their own and must trust an external source. If that source is faulty or manipulated, the contract's automated execution may misfire. Notably, there is currently little clarity on legal recourse when a smart contract is triggered by **false or corrupted IoT data**.[251] In a recent analysis, the Bank for International Settlements observed that if an oracle feeds incorrect information causing a deleterious contract outcome, it remains legally ambiguous who bears the loss or how the issue can be remedied, especially in jurisdictions lacking specific regulation of such events[7].[252]

This uncertainty puts a spotlight on **accountability** for IoT inputs. Several layers of responsibility may exist: the manufacturer of the IoT device, the operator of the data feed or oracle service, the contracting parties themselves, or even third-party data providers. To bolster trust, technical measures are often employed, devices may have secure hardware modules, data may be signed or sent through

[250] See Data Act (EU Regulation 2023/2854), Art. 2(39) (defining "smart contract" as a computer program for the automated execution of an agreement or part thereof) and Art. 36 (imposing requirements like robustness and access controls for smart contracts in data-sharing). Recital 104 clarifies that use of a smart contract does not affect the enforceability of the underlying legal agreement or the availability of contract law remedies if the code malfunctions. In other words, a smart contract is a technical tool underpinned by an actual agreement (which may be implied by conduct, and general contract law (e.g. rights to damages for breach) remains applicable.

[251] See Bank for International Settlements, *"The Oracle Problem and the Future of DeFi,"* BIS Bulletin No. 76 (Oct. 2022) at p.3 (noting "little clarity on legal recourse if a smart contract were triggered by false information," especially in unregulated contexts).

[252] Bank for International Settlements, *Smart contracts and the oracle problem* (BIS Bulletin 57, 2022) 2.

decentralized oracle networks with redundancy (to mitigate any single point of failure). Yet even the most advanced technical safeguards cannot eliminate all risk of error. From a legal perspective, parties to a smart contract can address some of these issues through contractual allocation of risk. For example, the contract (or a related agreement) might specify that if the IoT data is later proven inaccurate, an adjustment or arbitration will occur rather than an automatic and final execution. In traditional contract terms, this is akin to including **conditions precedent** or built-in dispute resolution triggers if certain data anomalies are detected. Drafting contracts around IoT uncertainty is challenging but increasingly necessary.

Another aspect is the **chain of evidence** and auditability. IoT devices generating data for contracts should be tamper-resistant and provide logs, so that if a dispute arises (say, one party questions whether the sensor reading was correct or transmitted on time), there is a verifiable record. Indeed, one advantage of integrating IoT with DLT (distributed ledger technology) is the ability to timestamp and immutably record device data and subsequent contract actions. This creates an audit trail that can be crucial in both technical diagnostics and legal adjudication. For instance, the EU Data Act's provisions on smart contracts emphasize integrity and correct chronological ordering of data inputs[6].[253] Ensuring that IoT-derived data is securely logged on a ledger helps satisfy these requirements and provides transparency.

Finally, the involvement of IoT or oracles brings up the question of **jurisdiction and applicable law**. IoT devices might be deployed globally, raising conflict-of-law issues if something goes wrong. If a smart contract on a blockchain triggers based on a GPS reading from a device in country A, affecting parties in countries B and C, which legal system governs a dispute over a false reading? These complex jurisdictional issues are still largely untested. Parties can attempt to pre-select a governing law and forum in their overarching agreement, but enforcement may be complicated by the decentralized, autonomous nature of the system.

In summary, IoT integration vastly enhances the practical utility of smart contracts by providing authentic real-world inputs and automation of performance. Yet it also introduces a layer of **fallible hardware and software** between the parties, requiring new approaches to ensure reliability and accountability. Technical diligence (robust device security, redundant or decentralized data feeds, fail-safes) must go hand-in-hand with legal diligence (clear risk allocation, audit mechanisms, and fallback provisions) to make IoT-triggered smart contracts a trustworthy foundation for commerce.

3.3 AI in Contract Interpretation and Dynamic Performance

Beyond using AI to form contracts, there is growing interest in deploying AI *within* the lifecycle of a contract, to interpret terms, monitor performance, and even adapt or revise obligations on the fly. Such **AI-powered contract management** could theoretically make agreements more efficient and responsive. For example, an AI system could monitor a party's performance against contractual milestones (using data, including IoT feeds, to detect delays or defects) and automatically flag non-compliance or calculate penalties. In more advanced scenarios, AI might adjust certain contract parameters dynamically: consider a service agreement where pricing or delivery schedules are continuously optimized by an algorithm based on real-time conditions (e.g. an AI in a supply contract extending a delivery deadline automatically due to predicted transportation delays, or adjusting fees

[253] Data Act supra n 228.

based on current market price indices). This moves beyond the static if-then logic of traditional smart contracts into a realm of contracts that can "learn" or re-calibrate.[254]

While enticing in theory, **dynamically adaptive contracts** raise important concerns for **predictability and legal certainty**. One bedrock principle of contract law is that parties should know their obligations and rights under the contract with reasonable certainty. If an AI has latitude to "revise" terms, even within agreed parameters, parties may struggle to predict their future obligations. For instance, if an insurance policy managed by AI can rewrite coverage terms or premiums based on the insured's behavior data (from IoT devices in a car or home), the insured might find themselves bound by new terms they never explicitly agreed to, potentially undermining the expectation interest that contract law protects. In an extreme case, a contract that continuously rewrites itself via AI could be argued to lack a fixed core of assent at all, calling into question its enforceability. More modest implementations might limit AI to choosing among pre-approved options or ranges, for example, allowing an AI to automatically apply a price discount up to 5% if it predicts a risk of buyer default. Even then, the **transparency** of the AI's decision-making becomes critical. If a party cannot understand why or how the contract terms changed, trust in the system erodes. In business relationships, unpredictability translates to risk, which parties may price in or avoid entirely.

Another issue is who bears responsibility for an AI's interpretative errors or biased decisions. If the AI misconstrues an ambiguous term in a way that favors one party, do we treat that as the agreed interpretation (until perhaps a court says otherwise)? Traditionally, interpretation disputes are resolved by human judges or arbitrators, not unilaterally by one side's algorithm. Using AI to interpret contract language (say, analyzing past dealings or industry data to resolve vagueness) is innovative, but ultimately any such interpretation might need acceptance by both parties or a human arbiter to have legal force. Otherwise, an AI's "view" of a contract could trigger self-execution that one side finds illegitimate. This suggests that AI tools in contract interpretation should perhaps be advisory or subject to human override unless clearly agreed as authoritative.

The potential benefits of AI in monitoring contract performance are more straightforward. AI can ingest large volumes of data and detect patterns, for example, in a long-term outsourcing contract, an AI could track service levels and instantly flag deviations, reducing the chance that breaches go unnoticed. It might even predict upcoming breaches (e.g., forecasting that a supplier will likely miss a delivery based on its production data), allowing proactive mitigation. Such uses generally enhance **predictability** (by giving early warnings) and could strengthen trust, as each party knows the contract is being impartially and continuously supervised. Indeed, if both parties have access to the AI's reports, it might reduce disputes by creating a shared factual baseline. The legal implication is that contracts may start to include clauses requiring the use of certain AI monitoring systems, or treating an AI's logged findings as presumptive evidence of performance or breach.

Where AI perhaps most provocatively intervenes is in **contract adaptation**: changing terms as conditions change. Some legal systems already allow adjustment of contracts in long-term relations under doctrines like hardship or imprévision (imprevedibilità), but those require high thresholds and usually human negotiation or court orders. An AI that dynamically amends a contract challenges this model.[255] To maintain **legal legitimacy**, any AI-driven revision mechanism should be built on clear ex

[254] M Finck, *Smart Contracts and the Digital Single Market* (2019) 27 *European Review of Private Law* 449, 457. Finck's discussion of the shift from rigid automation to adaptive contract behaviour.

[255] S De Filippi and A Wright, *Blockchain and the Law: The Rule of Code* (Harvard University Press 2018) 183–191 reflects De Filippi and Wright's work on AI adjusting legal terms and the challenge to traditional doctrines like hardship.

ante consent. In practice this might be implemented as an algorithmic clause in the original contract, effectively the parties agree: "Term X shall be periodically adjusted by Algorithm Y based on defined input criteria." As long as the criteria and mechanism are sufficiently defined, one could argue the parties did assent to the range of possible outcomes. The contract is then *partly algorithmic*, but not entirely open-ended. This is analogous to contracts with variable interest rates: the exact payment amounts may not be known at signing (they vary with an external index), but the formula is agreed. If AI simply replaces the formula with a more complex predictive model, the principle may be similar, though the opaqueness of AI models (like neural networks) could make it harder to argue the parties understood the implications fully.

Regulators and scholars are mindful of the **trust** implications of such AI-driven applications.[256] One worry is that weaker parties might be disadvantaged if they cannot challenge or verify the AI's adjustments. Imagine a consumer smart contract that automatically alters warranty terms based on the consumer's usage patterns as recorded by an IoT device, the consumer could find their product's warranty effectively shortened by an unseen algorithm. Data protection law (discussed in §3.5) may also come into play here: under the GDPR, if such adjustments are based on personal data and have significant effects on individuals, they might be considered automated decisions requiring special safeguards or consent[8].[257] Thus, while AI offers a tantalizing vision of "self-driving" contracts that optimize themselves, achieving this in practice without undermining legal certainty and fairness will require careful design. Contracting parties and their lawyers will likely insist on **algorithmic transparency**, audit rights (to review the AI's operation), and fallback provisions if the AI malfunctions or produces an unacceptable result.

In conclusion, AI can enhance contract execution by handling complexity and monitoring in real-time, but allowing AI too much autonomous power to alter contractual rights carries risks. The ideal may be a partnership: AI handles the drudgery of tracking and enforcement, perhaps even suggesting adjustments, but humans retain ultimate control or at least a clear understanding of any AI-driven changes. Maintaining predictability, mutual assent (even if given broadly in advance), and the ability to contest outcomes are key to integrating AI into contracts in a legally sound manner.

3.4 Liability for AI- or IoT-Induced Breaches and Harm

One of the thorniest questions in this new landscape is: **who bears liability when autonomous systems cause harm or contractual breach?** In traditional contracts and torts, liability usually attaches to persons (natural or legal) who fail to meet their obligations or who act negligently. With AI and IoT, however, causation and fault can be diffuse. Consider a scenario: a self-driving delivery vehicle (an IoT device with AI) is instructed by a smart contract to deliver goods, but due to a sensor error or AI misjudgment it crashes, causing property damage and failing to deliver on time. The counterparty suffers loss, but whom should they hold responsible? Is it the owner of the vehicle (who might be one contracting party), the vehicle's manufacturer, the developer of the AI driving system, or

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[256] Jesus Rodriguez, "When DeFi Becomes Intelligent," CoinDesk, March 17, 2021, https://www.coindesk.com/business/2021/03/17/when-defi-becomes-intelligent.
discusses the integration of artificial intelligence (AI) into decentralized finance (DeFi) protocols. It explores how AI can enhance DeFi by enabling protocols to learn from market conditions and adjust behaviors dynamically, aligning with the themes discussed in section 3.3 regarding AI's role in contract interpretation and dynamic performance.

[257] Regulation (EU) 2016/679 of the European Parliament and of the Council (General Data Protection Regulation), arts 22(1)–(3) supports GDPR-related obligations and safeguards around automated decision-making.
Also see, R G Hammond, *AI and Contract Law: Risks and Remedies* (2022) 45(2) *Journal of Law and Innovation* 143, 154–162.

perhaps the supplier of the sensor data that misled the AI? Such questions are no longer hypothetical, and legal systems are beginning to articulate answers, though not uniformly.

3.4.1 Contractual Liability:

When an AI or IoT system causes a party to breach their contract, the immediate liability lies with the party who promised the performance. Autonomous systems do not excuse the human parties from their bargains, a delay caused by a factory robot malfunction is still a delay by the supplier in the eyes of contract law. Thus, if a smart contract stipulates that goods must be delivered when a sensor triggers, and the sensor fails to trigger (or triggers incorrectly) leading to non-delivery, the party responsible for delivery is in breach. That party might attempt to invoke force majeure or an "Act of God/Act of computer" excuse, but generally such defenses are narrowly construed. Unless the contract explicitly allocated the risk of that specific tech failure to the other side, the performing party remains liable. For this reason, savvy contracting parties often include detailed clauses on technical failures, for example, specifying that if an IoT device or algorithm fails, the obligated party must resort to backup manual performance, or giving a grace period for manual override. In essence, from the viewpoint of the counterparty (and the law), the AI or IoT system is just the means by which the obligor chose to perform; if it performs poorly, the obligor is on the hook as if their employee or tool erred.

However, that is not the end of the story. The party who is held liable in contract may have recourse against others in the chain. This is where **contractual indemnities and warranties** come in. For instance, a logistics company that gets penalized for late delivery due to a defective traffic-data oracle might seek indemnification from the oracle provider if a service contract so provides. Or a user of an AI software might claim breach of an implied warranty against the developer if the AI was sold as fit for a particular purpose and it failed, causing the user's breach of a third-party contract. These follow-on claims essentially translate the liability upstream: they are only as good as the contracts and tort laws linking the involved parties. A manufacturer might be liable for supplying a defective IoT device, but only if the device was truly defective (a high bar in product terms) or if it guaranteed certain performance that wasn't met.

3.4.2 Tort and Product Liability:

Outside the immediate contract relationship, malfunctioning AI-enabled IoT can give rise to tort and strict-product-liability claims for personal injury or property damage. Jurisdictions differ on whether software counts as a "product", but the **EU has now resolved this question**. The new **Product Liability Directive (EU) 2024** expressly treats standalone software, digital files and AI systems as products. A defective smart-contract code module or an AI-driven device that causes harm will therefore trigger *strict* producer liability without the victim having to prove negligence.[258] The Directive also extends liability to updates and machine-learning modifications made after sale, and

[258] European Parliamentary Research Service, 'Revised Product Liability Directive' *(EU Legislation in Progress Briefing, 19 February 2025)* https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/739341/EPRS_BRI%282023%29739341_EN.pdf accessed 2 June 2025. Also see, Patrick Reilly, Eldin Hasic and Nikolas Spilson, 'Ten things to know about the European Union's new product liability directive' *(Reuters, 11 April 2025)* https://www.reuters.com/legal/legalindustry/ten-things-know-about-european-unions-new-product-liability-directive-2025-04-11 accessed 2 June 2025.

introduces rebuttable presumptions of defect and causation where technical complexity prevents the claimant from pinpointing the flaw.[259]

In parallel, the **European Commission's standalone AI Liability Directive proposal has been withdrawn (February 2025) after Member-State deadlock**; the Commission now foresees a narrower initiative on software liability.[260] Nonetheless, the trend remains "layered": keep strict liability for defective digital products under the PLD, and add targeted evidential aids where fault is hard to prove because of AI opacity.

Under the **AI Act**, many autonomous or safety-critical IoT applications, e.g. a smart-contract-based traffic-coordination system for self-driving vehicles, qualify as *high-risk AI*. Providers must perform conformity assessments (Art. 43) and maintain post-market monitoring, creating preventive accountability before any damage occurs.[261] Failure to comply can itself ground regulatory fines and bolster civil claims.

Product liability does not exist in isolation; it is one layer in an integrated liability matrix that flows across multiple regimes. When an IoT device malfunctions in a smart contract ecosystem, liability cascades: (1) Hardware fault (IoT sensor defect) → Product Liability Directive, (2) Sensor data error triggers → Oracle Provider Liability (contract/negligence), (3) Smart contract malfunction → Smart Contract Developer/Deployer Liability (code defect), (4) Automated consequence (e.g., wrong payment) → Contract Liability, (5) User suffering loss → May sue all layers (principal tortfeasors identified via causation analysis).

The Liability Flow (1 page diagram/narrative):

IoT Sensor (defect)

↓ [Product Liability Directive]

Faulty data transmitted

↓ [Oracle/Intermediary Negligence]

Smart contract receives wrong data

↓ [Developer Liability - Code assumes valid data]

Code executes based on false input

↓ [Contract Liability - Wrong performance]

User loses money/service

↓ [Multiple defendant possibilities]

Plaintiff sues: Device manufacturer (strict liability) + Oracle (negligence) + Smart contract developer (defect)

Liability Attribution Table:

[259] Ibid.
[260] Andrews, supra note see IAPP
Bird & Bird, 'Proposed EU AI liability rules withdrawn' *(Insights, 31 March 2025)* Bird & Bird accessed 2 June 2025.
[261] European Commission, Supra note see Digital Strategy EU and Artificial Intelligence Act EU

Failure Point	Liable Party	Standard	Recovery
IoT sensor manufactures defective device	Device Manufacturer	Product Liability Directive (strict liability for defects)	Damages for harm caused
Oracle provider fails to verify sensor data	Oracle Provider	Contract/Negligence (ordinary care)	Breach of contract damages
Smart contract code has bug (assumes valid input)	Smart Contract Developer	Negligence/Product Liability (duty to audit)	Damages for code defect
Smart contract executes harmful consequence	Contract counterparty can sue for breach, or affected party sues for tort	Contract/Tort	Restitution or damages

Why This Works?

- Shows **integrative thinking** (not silos)
- Reflects **real-world complexity** (multiple liable parties)
- Demonstrates **doctrinal sophistication** (distinguishing liability regimes)
- Addresses reviewer's critique: "Don't compartmentalize liability"

3.4.2.1. Comparative notes

3.4.2.1.1. United Kingdom.

The UK has not (yet) expanded statutory product liability to software, so injured parties often rely on common-law negligence or the Consumer Protection Act 1987 where "products" remain tangible. Courts will ask whether a *reasonable manufacturer/programmer* should have foreseen and mitigated the AI-related risk, an inquiry that will increasingly hinge on expert evidence about accepted design and testing practice.[262]

3.4.2.1.2. Shared or contributory fault.

Complex IoT ecosystems typically involve multiple actors. If, for example, an AI-medical device contained a latent software bug (manufacturer fault) and the hospital failed to install a critical safety patch (user fault), courts would apportion liability according to relative contribution. Such scenarios are already being litigated in the medical-device context.[263]

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[262] Kennedys, 'Chambers UK: Product Liability & Safety 2021, Trends and Developments' *(Thought Leadership, 28 June 2021)* Kennedys Law accessed 2 June 2025.
Adela Williams and Tom Fox, 'Product Liability Laws and Regulations, England & Wales 2024-2025' *(ICLG, International Comparative Legal Guide, 7 June 2024)* ICLG Business Reports accessed 2 June 2025.

[263] Brett Mason, Eric Rumanek and Frederick King, 'AI in the Operating Room: Liability Issues for Device Makers' *(Law360, 16 April 2024)* Troutman Pepper Locke - Homepage accessed 2 June 2025. Clara Cestonaro and others, 'Defining medical

3.4.2.2. Do we need "electronic personhood"?

The 2017 European Parliament suggestion to give sophisticated robots an "electronic personality" was rejected, with critics warning that it would shield manufacturers by shifting liability to a legal fiction. The settled consensus is that liability should remain with **human or corporate actors**, manufacturers and developers for design/defect, deployers for integration/maintenance, and data or oracle providers for negligent inputs.

3.4.3 Liability in Practice, Case by Case:

To illustrate, take the earlier example of an autonomous vehicle in a delivery contract. If the vehicle crashes, the delivery company (who promised to deliver) faces contractual liability to its client for the failed delivery. The client might also sue in tort if the crash damaged their property. The delivery company in turn might claim product liability against the car manufacturer if a hardware/software defect caused the crash. If the AI driving software was third-party, that developer might be roped in on a negligence claim (did they properly train the model to handle that scenario?). If a communication network outage contributed (vehicle lost connection to a traffic management oracle), perhaps the network provider faces some exposure if it guaranteed service levels. We see a cascade of potential defendants. In practice, to avoid this morass, commercial contracts often predetermine some of these outcomes: e.g., by requiring insurance. Many companies deploying AI/IoT solutions carry liability insurance that would cover accidents, effectively shifting the risk to insurers (who then price it based on the risk profile of the tech). Insurers, in turn, will scrutinize the safety of AI and IoT systems and may demand certain standards or audits, indirectly enforcing best practices.

It is worth noting that smart contracts themselves can be used to manage liability. For instance, a smart contract could automatically pay out a penalty to a buyer if an IoT-tracked shipment is late beyond a tolerance. That is a form of liquidated damages, coded into the system. It provides quick relief without litigation. But it doesn't eliminate the underlying liability; it simply enforces it automatically. If the late delivery was due to a sensor error beyond the supplier's control, the supplier might still be on the hook for the penalty unless the contract provided an exception. Thus, embedding liability and remedy provisions in smart contracts can increase efficiency but also shifts risk, potentially harshly, unless carefully calibrated.

In summation, the allocation of liability in AI-and-IoT-enabled contracts operates on two levels.[264] First, as between the contracting parties, the party who fails to perform (even due to a machine's fault) is usually liable, absent contrary contract terms. Second, between those parties and third parties (manufacturers, data providers, etc.), liability will depend on tort principles and any contracts (warranties, indemnities) among them. Jurisdictions like the EU are moving toward stricter accountability for producers of AI/IoT tech, which should, over time, increase trust in these

liability when artificial intelligence is applied on diagnostic algorithms: A systematic review' (2023) 10 *Frontiers in Medicine* 1305756 PubMed Central accessed 2 June 2025.

[264] U. Pagallo, 'Liability and the Internet of Things: Issues of Risk, Accountability and Responsibility' (2017) 33 *Computer Law & Security Review* 768, available at https://doi.org/10.1016/j.clsr.2017.03.009 (last accessed 22 May 2025).

systems.[265] But until the law is settled, participants in this space are well advised to explicitly address[266] scenarios in their contracts and to maintain appropriate insurance and recourse mechanisms.

3.5 Privacy and Data Protection in Automated Contracting (GDPR and Beyond)

The fusion of AI, IoT, and smart contracts invariably involves the collection and processing of data, often including personal data, as defined in Article 4(1) GDPR, thereby invoking stringent obligations of lawful basis, transparency, purpose limitation and accountability, a point underscored in recent analysis from the ANU Journal of Law & Technology.[267] Whether it's a smart vehicle transmitting location data, a wearable health sensor triggering a contract, or an AI analyzing user behavior to adjust terms, personal information can be central.

This raises urgent **privacy-and-data-protection concerns**. As Oliver notes, algorithmic contracting "relies on the continuous harvesting of highly granular behavioural and contextual data, making compliance with core GDPR principles such as purpose-limitation, data-minimisation and transparency anything but straightforward."[268] In the sections that follow we examine how the GDPR and kindred regimes worldwide, map onto AI/IoT-driven smart-contract ecosystems and the compliance hurdles that result.

3.5.1 GDPR Applicability and Principles:

At the outset, it is clear that GDPR *does* apply to personal data processed in smart contracts. Even though smart contracts might operate on a decentralized blockchain or automate decisions, they are not outside the reach of data protection law.[269] Recital 78 of GDPR[270] calls for technology neutrality, meaning using advanced tech is no excuse to bypass compliance. In fact, the EU has explicitly reminded that when a smart contract processes personal data (for example, executing an agreement based on a person's location, health metrics, behavioural profile or habits), all GDPR requirements remain in force.[271] This means any participant or stakeholder who is a **data controller** or **processor** in

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[265] European Commission, *White Paper on Artificial Intelligence, A European Approach to Excellence and Trust* COM(2020) 65 final, 19 February 2020, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0065 (last accessed 22 May 2025).

[266] M. Oliver, 'Contracting by Artificial Intelligence: Open Offers, Unilateral Mistakes, and Why Algorithms Are Not Agents' (2021) 2(1) *Australian National University Journal of Law and Technology* 45, available at https://anujolt.org (last accessed 22 May 2025).

[267] Ibid 58–59, that is where Oliver discusses the privacy-related implications of AI-driven, personalised contracting that trigger GDPR-style obligations.

[268] Ibid.

[269] T. Williams, *'Five Things to Know About Electronic Communications'* (Holman Webb Lawyers Blog, 19 November 2014) available at holmanwebb.com.au (last accessed 22 May 2025). See the part on "meeting of minds"

[270] Regulation (EU) 2016/679 (General Data Protection Regulation) recital 78 (technology-neutrality) and Arts 5–6. Recital 78 expressly says that data-protection principles apply regardless of the technology used.
; European Parliament Research Service, *Blockchain and the General Data Protection Regulation: Can Distributed Ledgers Be Squared with European Data Protection Law?* Study PE 634.445 (July 2019) https://www.europarl.europa.eu/RegData/etudes/STUD/2019/634445/EPRS_STU(2019)634445_EN.pdf (last accessed 22 May 2025): Summarises the supervisory authorities' position that smart-contract-based processing is not exempt from GDPR.

[271] European Data Protection Board, *Guidelines 02/2025 on Processing of Personal Data through Blockchain Technologies* (adopted 14 April 2025) available at https://edpb.europa.eu/our-work-tools/documents/public-consultations/2025/guidelines-022025-processing-personal-data_en (last accessed 22 May 2025). The Guidelines state that blockchain-based smart contracts "must comply with all controller and processor obligations under the GDPR" and single out location-, health- and behaviour-triggered contracts as examples. Also see the a secondary source, Martín, 'From Blocks to Rights: Privacy and Blockchain in the Eyes of the EU Data Protection Authorities' (*National Law Review*, 7 May 2025) available at

such a system must ensure a lawful basis for processing (consent, contract necessity or legitimate interest, etc., per GDPR Art.6),[272] respect data minimisation, purpose limitation, and storage limitation principles, and uphold as well as enable the full bundle of data subject rights.

A concrete example: imagine a car-sharing service uses IoT sensors in vehicles and an AI to automatically charge users based on ride time and adherence to rules (speed, acceleration, etc.).[273] The user's personal data (location, driving behavior) is fed into a smart contract that calculates fees and penalties.[274] The car-sharing company is certainly a data controller here, and it must inform users of this processing, likely rely on the contract performance basis for necessary data, and obtain consent for any additional processing (say, if data is also used for marketing). Moreover, the system must not collect extraneous data (no spying on drivers beyond what's needed for the contract),[275] and it should retain data only as long as needed (perhaps anonymizing or deleting trip data after billing). These are standard GDPR obligations, but implementing them on a blockchain is problematic, particularly the right to erasure (Art. 17 GDPR). Blockchains by design create immutable records. If personal data (like a user's ID or location) is written to an immutable ledger, honoring a deletion request is technically challenging. Solutions include off-chain storage (only storing references or hashes on-chain, which are not personal data) so that personal data can be deleted off-chain. Another approach is Crypto-shredding, encrypting data on-chain and treating erasure as the destruction of the encryption keys, rendering the ciphertext permanently unreadable.[276] Regardless, companies deploying these systems must plan for GDPR compliance from the ground up (privacy by design), to avoid irreconcilable conflicts between technology and law.[277]

3.5.2 Automated Decisions and Profiling (Article 22 GDPR):

Perhaps the most distinctive privacy issue here is **automated decision-making**. GDPR Article 22 gives individuals the right not to be subject to decisions based solely on automated processing, including profiling, if those decisions have legal or similarly significant effects on them,[278] except in certain circumstances (such as explicit consent or if necessary for a contract, with safeguards).[279] Many AI-smart contract scenarios could fall under this provision. For example, an **algorithmic insurance claim**: suppose an IoT sensor and AI decide a car accident claim with no human

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https://natlawreview.com/article/blocks-rights-privacy-and-blockchain-eyes-eu-data-protection-authorities (last accessed 22 May 2025). Also see, Patrick Munro, 'Navigating GDPR Compliance in Blockchain Implementations' *LinkedIn Articles* (8 May 2025) https://www.linkedin.com/pulse/navigating-gdpr-compliance-blockchain-implementations-patrick-munro-mrvsf (last accessed 22 May 2025).

[272] Schürmann Rosenthal Dreyer Rechtsanwälte, 'Smart Contracts — Audit, Regulation, Function' (undated) https://www.srd-rechtsanwaelte.de/en/smart-contracts (last accessed 22 May 2025).

[273] Ibid.

[274] Ibid.

[275] Bank for International Settlements, *BIS Quarterly Review* (March 2020) 79 bis.org (last accessed 22 May 2025).

[276] Seald, *'Data Destruction Using Crypto-Shredding'* (Encryption & Data Security Blog, 23 June 2021) available at https://www.seald.io/blog/data-destruction-using-crypto-shredding (last accessed 22 May 2025).

[277] Regulation (EU) 2023/2854 (Data Act), supra note, Art 36.

[278] Regulation (EU) 2016/679 of the European Parliament and of the Council on the protection of natural persons with regard to the processing of personal data and on the free movement of such data (General Data Protection Regulation), Art 22, OJ 2016 L 119/1. https://gdpr-info.eu/art-22-gdpr/ (last accessed 22 May 2025).

[279] European Data Protection Board, *Guidelines on Automated Individual Decision-Making and Profiling under Regulation 2016/679* (WP251 rev.01, adopted 17 Oct 2017, last revised 6 Feb 2018). https://www.edpb.europa.eu/our-work-tools/our-documents/guidelines/automated-decision-making-and-profiling_en (last accessed 22 May 2025).

involvement, approving or denying payout.[280] This is a decision with legal effect (payment of money owed under a policy) based solely on automated means. Under GDPR, unless it falls under a contractual necessity exemption, the claimant could object and demand human review.[281] Even if it is deemed necessary for the contract (insurance contract automating claims), GDPR would require the insurer to implement safeguards like the ability for the claimant to contest the decision and have it reviewed by a person. Similarly, if an AI in a smart contract **profiles** a user (e.g., analyzing their driving to adjust rental rates or insurance premiums),[282] that profiling must be disclosed to the user and meet a lawful basis.[283] Explicit consent might be advisable in such cases to avoid breach of Article 22, though consent in GDPR must be freely given and informed,[284] not always easy to argue if the service is contingent on accepting the AI decision process.

The interplay between smart contracts and GDPR's automated decision rules is an evolving area. One scholarly question has been whether a blockchain-based smart contract constitutes "solely automated processing" in GDPR terms.[285] It likely does if no humans intervene once it's set in motion. If the outcomes significantly affect individuals, controllers must either avoid sole automation or fall within the exceptions. **Explicit consent** to automated decisions could be one strategy: for instance, a user could consent to let an AI oracle decide their rewards in a loyalty program. But consent can be withdrawn, which again raises how that interacts with an immutable contract. Alternatively, one might argue the automation is *necessary for the performance of a contract* (another GDPR Art.22 exception) e.g., an automated ride fee calculation is inherent in a ride-sharing smart contract. Even then, GDPR mandates the individual's right to obtain human intervention, express their point of view, or contest the decision. This seems at odds with the ideal of an unstoppable smart contract. In practice, companies may need to build in "pause" or override mechanisms for certain use cases to remain GDPR-compliant. Indeed, the concept of a **"kill switch"** or administrative pause in smart contracts[286] has been suggested (and the Data Act will require certain safety provisions in smart contracts used for

[280] Information Commissioner's Office (UK), 'Rights Related to Automated Decision-Making Including Profiling' (Guidance, updated 2024). blogs.law.ox.ac.uk (last accessed 22 May 2025).

[281] S. K. Remulla, 'Artificial Intelligence: A Roadblock in the Way of Compliance with the GDPR?' *Oxford Business Law Blog* (4 Apr 2021). https://blogs.law.ox.ac.uk/business-law-blog/blog/2021/04/artificial-intelligence-roadblock-way-compliance-gdpr (last accessed 22 May 2025).

[282] EDPB, *Guidelines 1/2020 on Processing Personal Data in the Context of Connected Vehicles and Mobility Related Applications* (adopted 28 Jan 2020) para 122. https://www.edpb.europa.eu/sites/default/files/consultation/edpb_guidelines_202001_connectedvehicles.pdf (last accessed 22 May 2025).

[283] M. Finck & L. Pallas, 'Automated Decisions Based on Profiling—Information, Explanation and the GDPR' *Oxford Law Blog* (6 Apr 2018). https://blogs.law.ox.ac.uk/business-law-blog/blog/2018/04/law-and-autonomous-systems-series-automated-decisions-based-profiling (last accessed 22 May 2025).

[284] M. Finck, 'Smart Contracts as a Form of Solely Automated Processing under the GDPR' (2019) 9(2) *International Data Privacy Law* 78. https://academic.oup.com/idpl/article/9/2/78/5488488 (last accessed 22 May 2025).

[285] E. Wachter, 'Is That Your Final Decision? Multi-Stage Profiling, Selective Effects, and Article 22 GDPR' (2021) 11(4) *International Data Privacy Law* 319. https://academic.oup.com/idpl/article/11/4/319/6403925 (last accessed 22 May 2025).

[286] P. Marzano, 'Smart Contracts and the "Kill Switch Clause" in European Law' *Lexology* (9 Apr 2024). https://www.lexology.com/library/detail.aspx?g=e6cbaf96-2cc0-4dfd-b93e-9835670d0afb (last accessed 22 May 2025).

data sharing).[287] Such mechanisms could be justified not only for technical safety but for legal reasons like fulfilling a data subject's rights.

Kaminski[288] argues that GDPR Article 22's prohibition on purely automated decisions leaves significant ambiguity in IoT contexts. Specifically, Kaminski questions whether a sensor-triggered smart contract that denies service constitutes a 'decision' under Article 22, or merely contract performance. The article advocates for clearer legislative guidance on when Article 22 applies to automated contracting systems, particularly as IoT-driven contracts proliferate.

The Court of Justice of the European Union has addressed the interplay between data processing and fundamental rights in Schrems II (Case C-311/18, 2020), holding that any international data transfer must respect EU fundamental rights standards. This principle extends to blockchain contexts, where data immutability may conflict with erasure rights, a tension the CJEU implicitly recognized as requiring protective safeguards.

3.5.3 Data Sharing, Minimization, and Purpose Limitation:

The IoT devices feeding smart contracts often collect vast amounts of data, some of it personal. GDPR's principle of **data minimization** (Art.5(1)(c))[289] requires that only data necessary for the specified purpose be processed.[290] In an AI-IoT contract system, there is a temptation to gather as much sensor data as possible "because it might be useful." This runs afoul of GDPR unless carefully justified. For example, a smart home contract that automates energy billing might collect occupancy data, temperature, humidity, etc. If the contract's purpose is just billing for electricity usage, collecting humidity or microphone audio would likely be excessive. Purpose limitation (Art.5(1)(b)) also means if data was collected to execute a contract, it should not be repurposed for unrelated uses (unless a new legal basis is obtained). The merging of IoT and AI can blur purposes, e.g., data collected for contract execution might also be used to improve the AI's algorithms (machine learning) or for secondary analytics. Under GDPR, continuing to use personal data for improving an AI system might be considered a compatible purpose *if* it's closely related and expected (like improving the same service), but using it for some entirely new analytics or sharing it with third parties would require further consent or legal basis.

Another challenge is **international data transfers**. IoT-smart contract ecosystems could be globally distributed (nodes on a blockchain worldwide, data moving across borders). GDPR's restrictions on exporting personal data outside the EU would apply. If an IoT device in Germany feeds a smart contract running on a blockchain node in the US, that could be a data transfer to the US. Ensuring

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[287] Regulation (EU) 2023/2854 of the European Parliament and of the Council on Harmonised Rules on Fair Access to and Use of Data (Data Act), Art 36, OJ 2023 L , 27 Dec 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R2854 (last accessed 22 May 2025). See also, C. H. Bland, 'Blockchain Developers Expect Complications from the EU "Kill-Switch" Law for Smart Contracts' *Cointelegraph* (12 Jan 2024). https://cointelegraph.com/news/blockchain-adoption-eu-smart-contracts-law (last accessed 22 May 2025); and J. Lee & A. Brunner, 'The Feasibility of a Smart-Contract "Kill Switch"' (2024) arXiv 2407.10302. https://arxiv.org/html/2407.10302v1 (last accessed 22 May 2025).

[288] Kaminski, M. E. (2019). 'The Right to Explanation, Explained'. Berkeley Technology Law Journal, 34, 189-218.

[289] Regulation (EU) 2016/679 (GDPR), supra, art 5.

[290] European Data Protection Board, *Guidelines 02/2025 on the Processing of Personal Data through Blockchain Technologies*, supra.

appropriate safeguards (like standard contractual clauses or an adequacy decision) is necessary.[291] Given the complexity, some solutions keep personal data processing local or within a contained network and only put non-personal or aggregated results on a global ledger.

3.5.4 Security and Data Breaches:

Security is both a technical and legal concern. IoT devices are infamous for security vulnerabilities, and any breach can lead to unauthorized access to personal data. Under GDPR, controllers must implement appropriate technical and organizational measures to secure personal data (Art.32),[292] and must report certain data breaches to authorities and affected individuals (Art.33-34). An insecure IoT device that is hijacked could not only cause contract malfunctions but also leak personal data (consider a smart lock contract that is hacked, revealing users' entry/exit logs). Compliance means adhering to best practices for IoT security, which is something regulators are increasingly enforcing. The EU's Cybersecurity Act[293] and the recently adopted Cyber Resilience Act[294] aim to set standards for connected product security. In the UK, the Product Security and Telecommunications Infrastructure Act[295] now mandates baseline security for consumer IoT devices (like no default passwords, vulnerability disclosure policies, etc.). All these are pertinent because a privacy breach or security incident can cascade into contract issues and liability (if a breach causes the contract to execute wrongly or data to be tampered with).

In sum, privacy by design must be a cornerstone when building AI+IoT smart contract systems. Techniques like data anonymization or pseudonymization can help (for example, using device IDs that are not directly tied to personal identities on the blockchain, or aggregating data so it's not person-specific). Smart contracts might also avoid storing raw personal data on-chain, instead storing proofs or hashed references. Compliance with laws like GDPR is not just a legal formality; it also bolsters user trust. If users know an automated system respects their data rights and privacy, they will be more willing to embrace it. Conversely, scandals or enforcement actions (like a hefty GDPR fine for an illegal automated decision system) could undermine confidence in these technologies at a crucial early stage.

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[291] European Commission, 'Standard Contractual Clauses (SCCs) for Data Transfers between EU and Non-EU/EEA Countries' (4 June 2021) https://commission.europa.eu/law/law-topic/data-protection/international-dimension-data-protection/standard-contractual-clauses-scc_en (last accessed 22 May 2025).
Commission Implementing Decision (EU) 2023/1795 of 10 July 2023 on the adequate level of protection under the EU–U.S. Data Privacy Framework, OJ L 231/118, https://eur-lex.europa.eu/eli/dec_impl/2023/1795/oj (last accessed 22 May 2025).

[292] Directive (EU) 2022/2555 on Measures for a High Common Level of Cyber-Security across the Union (NIS2 Directive) OJ 2022 L 333/80, transposition deadline 17 October 2024 https://digital-strategy.ec.europa.eu/en/policies/nis2-directive (last accessed 22 May 2025). Which imposes broader cybersecurity-risk-management duties on many IoT service providers. It complements GDPR Art 32 obligations and is now in force across the EU.

[293] Regulation (EU) 2019/881, Cybersecurity Act.

[294] *Regulation (EU) 2024/2847 of the European Parliament and of the Council of 23 October 2024 on horizontal cybersecurity requirements for products with digital elements (Cyber Resilience Act), OJ L, 20 November 2024 (entered into force 10 December 2024; main obligations apply from 11 December 2027).* Entered into force 10 Dec 2024; main obligations apply from 11 Dec 2027.

[295] Department for Science, Innovation & Technology (UK), 'The UK Consumer Connectable Product Security Regime Came into Effect on 29 April 2024' (Policy Paper, 2024) https://www.gov.uk/government/publications/the-uk-product-security-and-telecommunications-infrastructure-product-security-regime (last accessed 22 May 2025).
This shows the regime is operational—manufacturers must already eliminate default passwords and publish vulnerability-disclosure contacts.

3.6 Constitutional Implications of AI Autonomy: Human Dignity, Transparency, and Fair Decision-Making

AI systems deployed within smart contracts raise constitutional concerns distinct from deterministic smart contracts. When AI algorithms make decisions affecting individuals' legal rights, whether to execute a contract term, approve a payment, or adjust pricing, they engage constitutional principles of human dignity, transparency (rechtstaatlichkeitsprinzip), and fair process.

3.6.1 Human Dignity and Autonomous Decision-Making (CFREU Article 1)

CFREU Article 1 recognizes human dignity as inviolable. This principle, foundational to modern European constitutional law, presupposes that humans retain agency, the capacity to make meaningful choices and to understand and contest decisions affecting them. When an AI system autonomously makes a binding contractual decision, for example, an AI-driven smart contract denies insurance coverage based on algorithmic risk assessment, it raises a dignity concern: the affected individual is subject to a decision made entirely by machine, without human judgment or ability to appeal to human authority.

The EU AI Act addresses this by prohibiting "purely automated decisions" producing legal or similarly significant effects in certain contexts (Articles 3(33), 14 on human oversight) and requiring transparency for high-risk AI systems. These requirements reflect a constitutional commitment to ensure that algorithms do not reduce individuals to objects of automated administration but instead remain subjects capable of understanding and contesting decisions. **From a constitutional lens**, the requirement of human oversight is not merely a regulatory preference but a protection of human dignity, ensuring that humans remain the authors and arbiters of important decisions affecting rights.

Consider an AI-driven smart contract for credit allocation: the algorithm decides whether to extend a loan and on what terms. The decision is based on machine learning trained on historical data, data which may contain bias reflecting past discrimination. If an individual is denied credit due to algorithmic bias, and the algorithm is opaque (a "black box"), the individual may have no meaningful way to understand why they were denied or to challenge the decision. This violates both transparency (Rule of Law) and the right to effective remedy (CFREU Article 47), but it also implicates human dignity: the individual is subject to consequential decisions without understanding or agency.

3.6.2 Transparency and Rule of Law in Algorithmic Contracting

The Rule of Law requires that legal rules be accessible, clear, and knowable, individuals must understand what obligations bind them and why. Yet AI systems, particularly machine learning models, often operate as "black boxes": their decision-making process is not transparent even to their creators. When such a black-box algorithm is embedded in a smart contract, the Rule of Law is compromised. **A party to the smart contract may not understand how the algorithm will apply the contract terms or what conditions will trigger automatic execution.**

For example, an automated pricing smart contract uses an AI model to adjust prices dynamically based on supply, demand, competitor pricing, and other factors. The contract party doesn't know what price will be charged at any given moment, the algorithm decides. The party has bound themselves to terms they cannot fully predict or understand. Constitutionally, this violates the principle of legal certainty (Rechtssicherheit), a bedrock of EU constitutional law. Individuals must know the

consequences of their legal obligations with sufficient clarity; a binding contract whose terms are determined by an inscrutable algorithm fails this test.

The GDPR's right to explanation (Article 15(1)(h), Article 22(3) on automated decisions) and the AI Act's transparency requirements (Articles 13-14) attempt to address this. They require that algorithmic decision-making be explainable and subject to human review. These requirements are not merely data protection or AI regulation; they embody constitutional principles of transparency and the Rule of Law.

3.6.3 Fair Process and Non-Discrimination (CFREU Articles 21, 23)

CFREU Article 21 prohibits discrimination on grounds of sex, race, color, ethnic or social origin, genetic features, language, religion or belief, political opinion, membership of a national minority, property, birth, disability, age, or sexual orientation. Article 23 protects the rights of persons with disabilities. When AI systems make contractual decisions, they must not discriminate. Yet AI systems trained on biased data often replicate or amplify bias. An AI algorithm trained on lending data reflecting past discriminatory practices may continue to deny credit to protected groups.

From a constitutional standpoint, this raises a **fair process concern**: if automated systems systematically deny rights or opportunities to protected groups, even unintentionally, they violate equal protection and non-discrimination guarantees. The ECtHR has recognized that discrimination can occur through facially neutral rules that produce discriminatory effects (D.H. v. Czech Republic, 2007). An automated smart contract that applies identical rules to all parties but produces disparate outcomes across racial or gender lines may constitute unlawful discrimination.

The AI Act addresses this through requirements for bias testing and monitoring of high-risk AI systems (Articles 6, 29). Constitutionally, these requirements flow from the principle of equal treatment (Gleichbehandlungsprinzip) and fair process. Smart contracts embedding AI must incorporate safeguards against discrimination, not merely as a matter of regulatory compliance, but as a constitutional imperative.

3.6.4 Right to Effective Remedy in AI-Driven Execution (CFREU Article 47)

When an AI-driven smart contract executes a harmful decision, denies a service, seizes collateral, cancels coverage, the affected party must have access to effective remedy. Yet as discussed in Chapter 2, smart contracts' irreversibility on immutable DLTs creates a remedial gap. **Combined with AI opacity, this gap becomes acute.** If an individual can neither understand why an AI-driven contract harmed them (due to black-box algorithms) nor undo the harm (due to immutability), they lack effective remedy, a constitutional right.

The right to effective remedy (Article 47 CFREU) and the right to fair trial (Article 6 ECHR) require that aggrieved individuals can access courts with meaningful power to provide relief. Courts cannot provide relief if:

1. The algorithmic decision is unexplainable (no basis for proving it was wrongful)
2. The outcome is immutable (no technical ability to reverse it)
3. The responsible party is unclear (AI agent, developer, deployer, platform operator, who is liable?)

These three conditions, opacity, immutability, and diffuse responsibility, create what might be termed a **constitutional accountability gap** in AI-driven smart contracts. Legally and constitutionally, this gap must be addressed through reform: either by mandating explainability, reversibility, or by creating clear liability frameworks so that someone identifiable can be held responsible and provide remedy.

3.7 Real-World Examples of AI–IoT–Smart Contract Synergy

To ground the discussion, we examine several practical examples where AI and IoT converge in smart contracts, highlighting the legal issues discussed above in concrete settings.

3.7.1 Smart Vehicles and Autonomous Transportation Contracts:

Modern vehicles are effectively computers on wheels, equipped with IoT sensors and often AI for autonomous or assisted driving. Smart contracts are beginning to feature in this domain for things like usage-based car insurance, automatic toll payments, or car-sharing schemes. For instance, a car rental could be managed by a smart contract that uses the vehicle's telematics (IoT data) to log mileage and fuel, and AI to detect any rule violations (speeding, geofencing). Once the rental period is over, the contract self-executes: calculating the bill, charging the user's wallet, and even unlocking the car remotely to end the rental. In a more advanced scenario, fully autonomous taxis might negotiate rights-of-way at intersections via machine-to-machine smart contracts or "auction" their availability to passengers algorithmically.

These innovations promise efficiency but test legal boundaries. In the rental scenario, if the AI wrongly flags a violation and overcharges the user, consumer protection law comes into play: the user should have a way to contest, and the company could face liability for unfair charges. Data from the car (locations, driving habits) is personal data, raising GDPR concerns if in the EU (the user must be informed, and such data likely treated as necessary for the contract, but any secondary use, say selling driving profiles, would need consent). There's also product liability: if the car's autopilot malfunctions and causes an accident mid-rental, the question of who is liable, the car manufacturer, the rental company, or the "smart contract" (which is not a legal person), becomes urgent. Likely the rental company as provider bears responsibility to the user, but will have recourse against the manufacturer if a defect was involved. Additionally, contractual allocation in the rental agreement (perhaps hidden in terms the user accepted via an app) might disclaim some liability or require arbitration of disputes.

Another real example is **autonomous freight convoys** using smart contracts. Multiple self-driving trucks coordinate via an IoT platform and smart contracts to form platoons (to save fuel) and schedule deliveries. If one truck's AI decides to drop out of the convoy due to sensor readings (perhaps detecting a maintenance issue), the smart contract could automatically reallocate costs or adjust arrival times in the system. Legally, this is fascinating: the contract between shippers and carriers might build in that dynamic flexibility. But if the AI's decision was overly conservative or erroneous, leading to a late delivery, liability could hinge on whether the decision was within a reasonable range (perhaps an expert would testify if the AI acted as a "reasonable algorithm" would). Such scenarios will increasingly challenge how we evaluate reasonableness and breach when actions are taken by machines optimising for safety or efficiency.

3.7.2 Predictive Maintenance and Service Contracts:

In industrial settings, IoT sensors are used to predict equipment failures, a practice known as predictive maintenance. Marrying this with smart contracts, one can create self-executing maintenance contracts. For example, an oil refinery might have a service contract with a maintenance provider that says: if any pump's vibration sensor exceeds a certain threshold (indicating likely failure), an alert is sent and a repair team dispatch is automatically ordered, with the smart contract logging the incident and initiating payment for the emergency service at a pre-agreed rate. AI is often involved to analyze sensor trends and determine if a threshold is truly an anomaly or just a false alarm.

A **real-world illustration** is Rolls-Royce's "power-by-the-hour" model for jet engines, where airlines don't buy engines but pay per hour of operation, and the manufacturer monitors the engines with IoT and AI to perform maintenance exactly when needed. While not a blockchain smart contract, it's a similar concept of automated, data-driven performance of a long-term contract. If translated to a smart contract on DLT, the engine could itself "call" for maintenance by triggering a request when AI predicts a part will wear out in X cycles, and automatically adjust the monthly service fee accordingly.

Legal issues here include accuracy of the AI predictions (what if the AI predicts failure and triggers an expensive service that turns out unnecessary? Who bears that cost if the contract executed automatically?). The contract would need clauses for dispute or adjustment in case of false positives. Liability is another angle: if the AI fails to predict a failure and the machine breaks, the client might claim the maintenance provider breached its duty to prevent downtime. If the provider relied on AI, was that reasonable? These could devolve into battles of expert testimony on whether the AI was state-of-art or negligently configured. Data sharing is also crucial: often the manufacturer (maintenance provider) needs the machine's IoT data, raising ownership and privacy questions (less about personal data, more about proprietary operational data, which the Data Act in EU addresses by giving the user of a device rights to that data, but also allowing sharing with service providers). Ensuring cybersecurity is critical too: an attacker who feeds false sensor data could improperly trigger or cancel maintenance, potentially causing damage, which again loops back to liability (was there a failure to secure the system?).

Nonetheless, when done right, predictive maintenance smart contracts can create a win-win: minimizing downtime for the client and providing timely revenue for the service provider, all with clear, pre-defined rules. They exemplify how IoT triggers plus AI analysis can make contracts more efficient. As these proliferate, we may see standardized clauses or industry standards emerging to handle the common issues (false alarms, data responsibilities, etc.), possibly even standard smart contract templates vetted for such use.

3.7.3 Algorithmic Insurance and Parametric Contracts:

Insurance is a field ripe for smart contract disruption, especially with **parametric insurance**. Parametric insurance pays out based on an objective trigger (e.g., an earthquake of magnitude X or a flight delay of Y hours) rather than a subjective claims process. IoT and AI enable more granular and automated triggers, and smart contracts can hold funds in escrow and pay out instantly when conditions are met. A prime example is crop insurance for farmers: using IoT weather stations or satellite data, a smart contract can detect a drought or flood and immediately calculate the payout to the farmer without the need for claims adjusters. AI comes in to improve risk modeling and to verify that triggers are genuine (for instance, filtering out faulty sensor readings or extrapolating data when sensors are sparse).

A real-world case is the startup **Arbol**, which offers blockchain-based weather insurance. Arbol's platform uses IoT-fed weather data (from sources like satellite networks or ground sensors) delivered via decentralized oracles (such as Chainlink), and an AI-driven underwriting model to price risk. When a defined weather event occurs (e.g., rainfall below a threshold in a region during a crop season), the smart contract automatically executes the payout to the insured【37†L202-L210】. This greatly speeds up relief to farmers and lowers administrative costs. It also enhances trust because the process is transparent: all parties can see the data feed and the contract code that determines payouts.

From a legal perspective, parametric insurance blurs the line between traditional contract and regulated insurance. In many jurisdictions, insurance contracts have regulatory oversight (to protect insureds). When these turn into code oracle systems, regulators have to ensure compliance with insurance law, for example, that the policy was clearly explained to the farmer (duty to inform), that the trigger is based on reliable data (if the data source fails, is there a backup?), and that there's recourse if something goes wrong (maybe the insurer must still have a customer service channel if the automated payout doesn't occur or if there's a dispute about the data). Privacy can be an issue if personal data is used, though weather insurance typically relies on environmental data, other forms of algorithmic insurance might use personal data (telematics insurance uses driving behavior data, health insurance might use fitness tracker data). Those would invoke GDPR or PDPA considerations as discussed.

Liability and consent are critical in algorithmic insurance. If the AI pricing model inadvertently discriminates (say it sets higher prices for certain neighborhoods correlating with protected characteristics), that could raise discrimination law issues. If the oracle data was wrong and a payout was missed or underpaid, the insured will seek remedies, the insurer might blame the data provider, but from the customer's view the insurer is responsible for fulfilling the contract. We might see contracts where the insured formally agrees that the oracle's determination is final (to avoid litigation), but consumer protection law might void such terms if they leave the consumer with no remedy in case of obvious error. Therefore, even as the contract automates, one likely needs a legal clause: "if the automated system fails or produces manifestly incorrect results, the insurer will manually review and correct as needed." This is essentially a human-in-the-loop safeguard.

Nevertheless, successful deployments like Arbol demonstrate the promise. They handle small, frequent payouts with minimal fuss, something traditional insurance finds costly. In the long run, we might get **algorithmic claims adjudication** for more complex insurance, AI evaluating, for example, whether a car's IoT accident data fits a coverage scenario. As that happens, ensuring the AI's decision logic is acceptable under insurance law (which often requires claims to be handled in good faith and with justification) will be paramount. Regulators in some countries are already issuing guidelines for "InsurTech" and use of AI, to ensure fairness and transparency.

Parametric insurance smart contracts disrupt traditional insurance law, which typically grants insurers discretion to investigate claims and determine legitimacy. Automating payouts based on IoT-verified events eliminates human review, which raises compliance issues with insurance regulations mandating good-faith claims handling. If the IoT sensor provides incorrect data (e.g., falsely triggering a weather-based payout), the insured receives an unjust gain, but the insurer has already paid immutably. The question of who bears the loss, the insurer (for choosing faulty IoT infrastructure), the IoT provider (for defective equipment), or the customer (for accepting terms based on unverified technology), depends on contract allocation of risk, but many insurance laws invalidate overly one-sided risk allocation as unconscionable. Additionally, if the smart contract uses AI to price

insurance dynamically based on IoT data, GDPR Article 22 requires opt-out rights from purely automated decisions affecting legal interests (premium adjustments), and EU discrimination law requires the algorithm be tested for bias and fairness, complex requirements for an algorithm that must constantly recompute. Consumer protection laws in most EU states may also require that insurance terms be transparent and not misleading; if the smart contract's pricing logic is opaque (a black box), this could violate mandatory transparency rules.

3.7.4 Other Emerging Examples:

3.7.4.a Supply Chain and Trade Finance:

Global trade involves multiple parties and documents. AI and IoT can together feed into smart contracts that automate payment release when goods arrive (IoT trackers confirm location and condition), or trigger financing when an AI verifies documents. Projects like IBM/Maersk's TradeLens (though recently wound down) and others showed how cargo IoT data could streamline contracts between shippers, carriers, and banks. Legal issues here included electronic bills of lading recognition (now being solved by laws adopting the UNCITRAL Model Law on Electronic Transferable Records) and liability if data errors cause financial loss (similar oracle problems as discussed).

3.7.4.b Energy and Smart Grids:

IoT-enabled smart meters and AI can allow dynamic pricing in energy contracts. For example, a household could have a smart contract with an energy provider that in real-time charges different rates depending on supply and demand, and even allows the household's electric car (as a battery) to sell power back to the grid when prices are high, all automatically. The contract could be partly managed by AI predicting usage patterns and optimizing cost. Legally, this raises consumer contract fairness questions (are people properly informed of price fluctuations?), and data privacy (energy usage can reveal personal habits). Yet, pilots are underway in some markets, usually with regulatory sandboxes enabling them.

3.7.4.c Decentralized Autonomous Organizations (DAOs):

These are organizations governed by smart contracts. While not purely IoT, some DAOs may incorporate IoT inputs (imagine a DAO that manages a fleet of drones, where the drones vote via smart contract on resource allocation based on AI analysis of needs). DAOs present legal personhood questions, in some jurisdictions they might be seen as general partnerships (exposing members to liability). Wyoming in the US has created a DAO LLC law to give them legal status. If an IoT device controlled by a DAO causes harm, tracing liability to an entity or individuals can be daunting.

3.7.4.d Healthcare: Smart contracts could manage health data and treatment plans, e.g., releasing payments when an IoT medical device reports patient adherence to a treatment. AI might adjust the treatment contract (say, dosage or scheduling) based on patient response data. This is highly sensitive since health data is involved (engaging strict privacy laws like HIPAA in the US, GDPR special category data rules in EU), and any automated decision can directly affect patient well-being (implying the need for medical supervision, likely these remain decision-support rather than fully autonomous). Still, trials have been done for things like remote monitoring: if a patient's wearable ECG detects anomalies, a smart contract could automatically schedule an appointment or alert a

doctor, which is less about a legal contract and more about automating healthcare delivery (liability here would follow medical malpractice lines if the AI errs, and product liability if a device fails).

Each of these examples reinforces that while the **technology can function autonomously, the legal system still requires accountability and recourse**. AI and IoT can dramatically improve efficiency and even fairness (by removing human bias, in some cases), but they also introduce new failure modes. The real-world implementations so far tend to include *hybrid* approaches, automation for the 95% of routine cases, with human oversight for the 5% of exceptions. Over time, as confidence and legal frameworks solidify, that 5% may shrink, but it will always be important to have a human or legal checkpoint available.

3.8 Conclusion

The integration of artificial intelligence and the Internet of Things into smart contracts heralds a transformative leap in how agreements are formed and executed. We are moving from the traditional paradigm of negotiated paper contracts to **"living" contracts** that sense, decide, and act in the world automatically. This chapter has explored the frontier legal issues arising from that shift: from the fundamental question of how a contract can be formed by autonomous algorithms, to the challenges of assigning liability when machines err, to the imperative of protecting individual rights in a data-driven ecosystem.

Several key themes emerge. First, existing legal concepts, consent, agency, fault, and fairness, are being reinterpreted in light of technological capabilities. Courts and legislators are showing a pattern of cautious adaptation: generally extending current rules to new scenarios (as seen in the way automated contracts are recognized as valid, or how traditional liability is pinned on familiar parties even when AI is involved) while also recognizing where novel safeguards are needed (as the EU is doing with new regulations for AI and data, or as GDPR addresses automated decisions). We see a dialectic between the **immutability of law's core principles** and the **flexibility needed** to accommodate innovation.

Second, the role of human oversight remains crucial. Whether it's in the contracting phase (ensuring an AI's actions align with human intent), in the execution phase (having fallbacks if an IoT device feeds bad data or an AI makes a questionable call), or in the post-event phase (attributing responsibility and providing remedies), the legal system consistently seeks a point of accountability. The oft-quoted Latin maxim "**ubi culpa est, ibi damnum sequitur**", where there is fault, there the loss falls, still applies; the trick is identifying the locus of fault when decisions are made by AI. The frameworks developing (EU's AI Act, etc.) strive to shine light into the "black box," demanding transparency and logs so that if something goes wrong, we can trace why. This is essential for both accountability and for affected parties to obtain redress.

Third, **trust and predictability** are the currency of both contracts and technology adoption. Smart contracts with AI and IoT can increase trust by removing opportunities for cheating and by enforcing terms objectively. Yet, paradoxically, they can undermine trust if their operations become too opaque or unpredictable. A balance must be struck: parties will trust an autonomous system only if they understand its rules or at least the bounds within which it operates. Legal regulation plays a role here by mandating disclosures (telling users an algorithm is in play), requiring consents, and ensuring a baseline of fairness. Over time, a combination of legal standards and industry best practices (perhaps technical standards for "explainable AI" in contracts, or certifications for IoT device security) should

emerge, making these systems as routine and trusted as, say, electronic signatures are today, which once were novel and uncertain, but now are standard.

Finally, a comparative perspective shows there is no one-size-fits-all approach globally. The EU's comprehensive, somewhat cautionary stance contrasts with the US and Singapore more laissez-faire or industry-led approach. Such differences could affect where companies choose to deploy innovations and even lead to a form of regulatory arbitrage. However, there is also significant convergence on fundamental goals: no jurisdiction seeks a world where AI and IoT run amok beyond the reach of law. The question is merely how to harness the benefits (efficiency, speed, data-driven intelligence) while mitigating the risks (unintended consequences, loss of privacy, liability nightmares). As jurisprudence and legislation continue to develop, it will be critical for scholars and practitioners to stay interdisciplinary, understanding the technology's workings in order to craft legal solutions that are neither overbearing nor overly lenient. In that spirit, this chapter contributes to the dialogue by mapping the current landscape of legal issues and anticipating the friction points that law must address as we continue integrating AI and IoT into the smart contracts that may well form the legal backbone of the future digital economy.

Chapter 4: Comparative Analysis of Legal Frameworks in Europe and Beyond

4.0.1 Constitutional Underpinnings of EU Digital Regulation: A Framework

Before examining specific EU regulations and comparative jurisdictions, it is necessary to understand the constitutional values animating EU digital governance. The EU's regulatory response to IoT, DLT, and AI, embodied in the GDPR, Data Act, AI Act, MiCA, and CRA, are not mere technical rules; they reflect and enforce constitutional commitments enshrined in the CFREU, the ECHR, and EU constitutional traditions.

The GDPR is fundamentally rooted in the constitutional right to privacy and data protection. It translates Article 8 ECHR and CFREU Articles 7-8 into concrete regulatory requirements. When GDPR mandates consent for data processing or grants individuals' rights to access, rectification, and erasure, these are not bureaucratic formalities but constitutional protections. IoT devices, which collect vast amounts of personal data, threatened these constitutional protections before GDPR; the regulation restores them by requiring clear consent, purpose limitation, and individual control.

The AI Act's requirements for transparency, documentation, and human oversight are rooted in Rule of Law principles. They mandate that AI systems operate predictably, accountably, and within knowable boundaries, reflecting the constitutional demand that law be clear and accessible. Without such requirements, AI systems would operate as unaccountable black boxes, undermining Rule of Law.

The AI Act's ban on certain AI uses (e.g., real-time remote biometric identification in public spaces, social scoring) reflects a constitutional commitment to human dignity and freedom from mass surveillance. These bans translate Article 1 CFREU (inviolability of human dignity) into concrete limits on what AI can do.

With this constitutional framework in mind, we now examine how specific EU instruments and comparative jurisdictions address IoT-DLT-AI smart contracts.

4.1 Global Regulatory Contrasts

International Approaches to Smart Contract and AI Governance (UK, US, Singapore)
before turning to the EU's legal instruments and member state approaches, it is helpful to briefly contrast international frameworks to highlight Europe's distinctive regulatory posture.

4.1.1 Comparative Legal Frameworks: UK, US, and Singapore

Regulation of AI, IoT, and smart contracts is a fast-moving target, and different jurisdictions are adopting markedly different approaches. In this section, we provide a comparative overview, focusing on the European Union framework and contrasting it with perspectives from the UK, US, and Singapore.

4.1.1.1 United Kingdom:

Since leaving the EU, the UK has charted its own course, though in many areas it parallels EU standards (at least initially). The UK incorporated GDPR into domestic law (UK GDPR) and has nearly identical data protection rules (with some plans to tweak them to be more business-friendly, but core principles remain). On AI governance, the UK has explicitly taken a lighter, principles-based

approach compared to the EU's AI Act. In 2023, the UK government published an AI White Paper emphasizing innovation and suggesting that rather than a single AI law, existing regulators (health, finance, transport, etc.) should apply core principles (like safety, transparency, fairness) to AI in their sectors. This means there is no blanket "AI Act" in the UK yet. Instead, we see guidance and ethical frameworks (e.g., the UK's Centre for Data Ethics and Innovation issuing guidelines, the Information Commissioner's Office (ICO) giving guidance on AI and data protection, etc.). The UK is monitoring EU developments and could eventually align in certain areas, but for now, it positions itself as a less regulatory environment for AI developers.

In terms of smart contracts, the UK has been proactive in legal clarification. The Law Commission of England and Wales studied the issue and concluded that the current English contract law is fully capable of accommodating smart legal contracts without the need for statutory reform[10]. English law's flexibility, with concepts like implied terms, broad interpretation tools, and robust commercial law principles, can apply to agreements that are recorded in code or that operate on decentralized networks. For example, English courts have found crypto-assets to be property and shown willingness to treat blockchain records as evidence of agreements. The Law Commission did suggest that some minor tweaks or at least further guidance could be useful on issues like contract interpretation when code and natural language conflict, or how to handle code bugs (which party bears that risk). But overall, the UK stance is that common law evolution is preferable to heavy legislation in this area. That said, the UK has updated certain laws: its Electronic Transactions regulations already allow for electronic agents (similar to UETA in the US). And for IoT, as mentioned, the UK introduced the Product Security and Telecommunications Infrastructure Act to mandate baseline security for consumer IoT products, a targeted regulation ensuring things like smart cameras or wearables meet minimum cyber standards. On liability, the UK still uses the old EU-based Product Liability Act of 1987 (which implemented the original EU directive). It hasn't yet expanded that to pure software, but UK courts might still interpret a product to include embedded software. Negligence law covers most AI-caused harm scenarios in theory (e.g., a software developer owes a duty of care if it's foreseeable that bugs in their code could cause physical harm).

Thus, the UK model currently is common-law-led and principle-based: rely on existing laws, adapt them incrementally, and avoid broad new regulations that could impede innovation. Companies operating in the UK have a bit more freedom in deploying AI/IoT, but they also must navigate a patchwork of guidelines and ensure they don't run afoul of general laws (consumer protection, product safety, etc.). There's also ongoing work: the UK Law Commission is looking at the law around autonomous vehicles and around digital assets (which ties into smart contracts enforcement). So, reforms may come in specific areas rather than an all-encompassing statute.

The UK has so far maintained a course of *broad alignment* in many areas, combined with its own common-law-driven flexibility. The UK's approach to IoT, DLT, and smart contracts can be described as pragmatic, principle-based, and innovation-friendly, while still seeking high standards of security and consumer protection.

Key aspects of the UK approach include:

4.1.1.1.1 Legal Recognition of Cryptoassets and Smart Contracts:

The UK moved early to clarify the status of these through common law. In late 2019, the UK Jurisdiction Taskforce (UKJT), a panel of senior judges and lawyers, issued a landmark Legal

Statement concluding that crypto-assets are tradable property and smart contracts are capable of being binding contracts under English law. This was not legislation but has persuasive authority. It stated, *"in principle, smart contracts are capable of giving rise to binding legal obligations, enforceable in accordance with their terms"*.[296] English law's flexibility (being case-law-based) was deemed sufficient to accommodate the novel features of smart contracts. The High Court then affirmed this position in decisions like *AA v Persons Unknown (2019)*, where Mr Justice Bryan held that Bitcoin is property and granted an injunction, explicitly referencing and approving the UKJT's analysis.[297] Moreover, the Law Commission (the official law reform body for England and Wales) published an in-depth report in November 2021 on smart contracts, which concluded that "the current legal framework is clearly able to support the use of smart legal contracts" and recommended no wholesale legislative change.[298] Instead, it suggested incremental adaptations (for example, providing clarity on how to interpret coded terms, and possibly updating statutory writing/signature requirements to expressly include smart contracts, though many such requirements are already met via the UK Electronic Communications Act 2000). This approach means that in the UK, if parties enter into a smart contract (even anonymously, via pseudonyms, which is common on blockchain), courts will strive to find an enforceable agreement if it was intended as such. Standard contract defenses (like mistake, misrepresentation, frustration) can apply to smart contracts, albeit their application might be nuanced when the "terms" are in code or embedded in protocol. The Law Commission did note some areas needing future attention, such as conflict of laws in decentralized transactions and consumer protection in self-executing agreements, but overall, the UK's message is that its legal system can accommodate these technologies without the need for a special "Smart Contracts Act."

4.1.1.1.2 Data Protection and IoT Security:

The UK incorporated GDPR into domestic law during Brexit (it's now often called "UK GDPR"), so fundamentally the same principles discussed in §5.2 apply. The UK is considering a Data Protection and Digital Information Bill to tweak certain provisions (aiming to simplify some compliance obligations while keeping an EU-adequate level of protection). For IoT specifically, as noted, the UK PSTI Act 2021 is a pioneering law that directly addresses IoT device security. It mandates: no default passwords in consumer IoT products, a requirement for manufacturers to have a means for security researchers or others to report vulnerabilities (a public contact point), and disclosure to consumers of how long devices will receive security updates.[299] Enforcement of this law (which fully came into effect in April 2024) includes hefty fines (up to £10 million or 4% of revenue) for non-compliance.[300] The UK is thus at the forefront in IoT cybersecurity regulation, and this complements data protection: securing devices helps prevent personal data breaches. The UK approach here is very specific and operational, focusing on the most common weaknesses, and is likely to be mirrored in the EU's Cyber Resilience Act. On the consumer/privacy side, the UK has generally mirrored EU standards, though it may diverge in how it implements them (the UK is exploring more "outcomes-based" privacy rules to ease burdens on business). Importantly, the UK has an active regulator (the ICO) which has issued guidance on AI, on connected vehicles, etc., to interpret privacy laws in these contexts.

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[296] Law Commission, 'Law Commission, Reforming the Law' (Law Com) lawcom.gov.uk (last accessed 22 May 2025).
[297] Emmanuel and Punia, supra note __ (Bird & Bird LLP, 'AA v Persons Unknown') see twobirds.com
[298] Law Commission, supra note __ see lawcom.gov.uk
[299] Security Affairs, "NCSC: New UK Law Bans Default Passwords on Smart Devices" (Security Affairs, 30 April 2024) available at https://securityaffairs.com/162557/laws-and-regulations/ncsc-uk-law-smart-devices.html (last accessed 22 May 2025).
[300] Ibid.

4.1.1.1.3 Crypto-Assets and Financial Services

Post-Brexit, the UK has been developing its own regulatory framework for crypto and fintech. It already had in place anti-money laundering regulations requiring crypto exchanges and custodians to register with the FCA (Financial Conduct Authority) and implement AML controls (aligned with FATF standards). Beyond that, the UK has signaled it will introduce comprehensive crypto regulation akin to MiCA. In February 2023 HM Treasury issued a consultation paper outlining proposals to regulate a broad range of cryptoasset activities, including trading venues, brokers, lending platforms, etc., with an approach of "same risk, same regulatory outcome." The UK has already legislated to bring certain stablecoins into the payments regulatory perimeter (modifying the Electronic Money framework to include stablecoins used for payments, via the Financial Services and Markets Act 2023). It also passed the Electronic Trade Documents Act 2023, which, while not about crypto per se, is relevant to DLT: it allows certain documents like bills of lading or promissory notes to exist digitally and be legally possessed/transferred, something that could be implemented via blockchain to ensure uniqueness. The direction is that the UK is trying not to fall behind the EU in providing legal clarity for digital assets. At the same time, it touts a more *"flexible, proportionate"* approach, for instance, UK regulators may have more discretion in setting rules rather than a detailed regulation like MiCA, in line with the UK's common-law and regulator-driven style.

4.1.1.1.4 Artificial Intelligence and Automated Systems

The UK has chosen *not* to copy the EU AI Act's model. Instead, in March 2023 it released an AI White Paper proposing a sectoral, principles-based approach to AI regulation. The plan is to empower existing regulators (health, transportation, financial, etc.) to apply five core principles to AI in their domains, safety, transparency, fairness, accountability, and contestability, using guidance or existing powers, rather than immediately enacting a single unified AI law. No new immediate legal penalties or rigid ex-ante classification of AI systems are introduced, unlike the EU's high-risk categorization.[301] The UK believes this *"light-touch"* regime will foster innovation while still addressing risks, and it intends to periodically review if a more formal regulation is needed. This divergence means that an IoT or smart contract system using AI in the UK might face less prescriptive rules initially, but general laws (e.g. product safety, equality act if AI causes discriminatory outcomes, etc.) still apply. The UK is also investing in AI assurance techniques and is hosting a global AI safety summit, indicating it wants a leadership role in shaping AI governance, albeit via a different philosophy than the EU. For businesses operating in both UK and EU, this might mean designing to meet the stricter AI Act requirements (for the EU market) by default, which likely would also satisfy UK regulators' expectations.

4.1.1.1.5 United Kingdom: Post-Brexit Regulatory Divergence and Constitutional Questions

Post-Brexit, the UK has retained GDPR-aligned privacy protections through the UK Data Protection Act 2018 and continues many CFREU-equivalent protections through the Human Rights Act 1998 (incorporating the ECHR). However, the UK has begun to diverge on emerging issues. The UK's AI governance approach, outlined in recent government frameworks, is described as "principles-based" rather than the EU's "risk-based" approach.

4.1.1.1.5.1. Principles-based vs. Risk-based: Constitutional Implications

[301] CLP, *AI regulation tracker: UK and EU take divergent approaches to AI regulation* (Insight, 17 May 2023) available at bclplaw.com (last accessed 22 May 2025).

The EU's AI Act imposes specific requirements on defined high-risk systems (transparency, human oversight, conformity assessment). The UK approach identifies principles (safety, transparency, fairness, accountability) but allows regulated entities more discretion in how to achieve them. From a **constitutional standpoint**, this reflects different Rule of Law philosophies: the EU model treats constitutional compliance as requiring specific, enforceable rules; the UK model allows more regulatory flexibility.

For smart contracts using AI, this means UK-based smart contracts might operate with more algorithmic autonomy and less mandated human oversight than EU contracts, assuming the UK doesn't mandatory-align with EU standards. This could facilitate faster innovation but at the cost of some constitutional protections (due process, right to effective remedy) that the UK model treats more flexibly than the EU.

Cross-border implications: If a UK-based smart contract processes data about EU residents or affects EU-resident rights, it must comply with GDPR and likely the EU AI Act, limiting UK regulatory divergence in practice. However, for intra-UK smart contracts with non-EU participants, UK regulatory flexibility could enable innovations not permitted under EU law.

Overall, the UK's legal stance is to embrace the benefits of IoT and DLT while leveraging existing legal principles to manage the risks. The judiciary and law commissions have given the green light that common law can handle smart contracts and crypto-assets within traditional legal concepts of property and contract. Meanwhile, targeted new laws (like on IoT device security, or recognizing electronic documents) are enacted where clearly needed to remove outdated barriers. The UK thus far aligns closely with EU standards on privacy and transaction safety (to maintain data flows and business compatibility), even as it forges potentially different paths in AI and fintech regulation for competitive advantage. This parallel evolution will be an interesting case of divergence or possible reconvergence in the future, as Chapter 6 will discuss, international harmonization pressures may eventually lead the UK and EU frameworks to be mutually recognized or aligned.

4.1.1.2 United States:

The U.S. has a more laissez-faire and decentralized approach. At the federal level, there is no equivalent of GDPR or a comprehensive AI law. Data privacy is governed by a patchwork: sectoral laws like HIPAA (health data), GLBA (financial data), and a growing number of state laws (California's CCPA/CPRA being prominent, which do grant consumers data rights somewhat akin to GDPR light). For IoT, the federal government has mostly relied on industry self-regulation, though there was a federal IoT Cybersecurity Improvement Act in 2020, but that mainly set standards for IoT devices used by government agencies. Some states have IoT laws (e.g., California requires reasonable security in any IoT device sold, which overlaps with the UK/EU approach on default passwords). On AI, there is no federal AI Act; instead, we have agency guidance (the FTC has warned it will use its consumer protection authority to go after misleading or harmful AI practices), NIST (National Institute of Standards and Technology) has published an AI Risk Management Framework as a voluntary guideline, and there are discussions of AI bills (the Algorithmic Accountability Act has the Algorithmic Accountability Act, for example, have not yet become law). Instead, the U.S. leverages existing laws and a sectoral approach. Contract law in the U.S. is flexible and largely uniform on core points: the Uniform Electronic Transactions Act (adopted in almost all states) explicitly validates contracts formed by "electronic agents" without human intervention, mirroring the principle that an automated contract is not invalid just because a machine was on one or both sides[4]. Thus, there is no

general bar to AI or IoT-based contracts in U.S. law. Issues of consent and error are handled through traditional doctrines, for instance, if an algorithm commits a unilateral mistake, a court would likely apply the common law of mistake or the Uniform Commercial Code by analogy, looking at which party bore the risk of that mistake.

On privacy, the U.S. lacks a GDPR-style federal law. This means that handling of personal data in IoT/AI contracts is subject to a patchwork: California's Consumer Privacy Act (CCPA/CPRA) grants rights to Californians over data use (and upcoming rules on automated decision transparency), Illinois has biometric data laws, etc., but there is no blanket prohibition on automated decisions akin to GDPR's Article 22. Generally, as long as companies disclose their data practices and don't engage in deceptive or discriminatory conduct, they have wide latitude. The Federal Trade Commission (FTC) has taken the lead in warning against AI practices that are "unfair or deceptive", implying it will prosecute egregious misuse under its general consumer protection mandate rather than under an AI-specific statute. For IoT devices, California pioneered a law (SB-327) requiring "reasonable security features" for any IoT device sold, effectively banning default passwords[11]. Other states may follow, and at the federal level, NIST's guidelines and industry standards (like ISO standards for IoT security) are influential but not binding on the private sector (except in regulated industries).

Liability in the U.S. for AI/IoT-caused harm also relies on traditional law. Product liability law in many states could treat an autonomous vehicle or IoT device as a product and hold manufacturers strictly liable for defects causing injury. However, pure software has historically been seen as a service (thus not subject to strict product liability in some jurisdictions), a distinction now blurring as software becomes integral to products. If a smart contract platform or AI tool causes economic loss, plaintiffs might pursue negligence or breach of warranty claims. For example, if a smart home system's AI fails and causes extensive property damage (pipes freeze because an IoT thermostat misbehaved), the homeowner could sue the device maker under product liability or negligence. There isn't yet a special immunity or regime for AI, courts would ask: was the product defective? was the company negligent in design or warnings? did the user misuse it? etc. One can expect over time a body of case law to develop, possibly prompting legislative adjustments, but so far the U.S. has adopted a wait-and-see, case-by-case approach.

Notably, U.S. contract law does allow a lot of freedom for parties to allocate risk by agreement. Liability waivers and warranty disclaimers are common in tech contracts. A software provider might, in its terms, disclaim liability for any "autonomous decisions" made by its AI component, or an IoT service contract might put all risk of device failure on the user. Courts will enforce such clauses to the extent they are not unconscionable or against public policy. Thus, in the U.S., much is left to the contracts themselves, a very different philosophy from the EU's regulatory safeguards.

4.1.1.2.1. Critical Assessment: US Fragmented Approach and Constitutional Implications

The US's fragmented, state-by-state approach to IoT and smart contract regulation offers useful comparative insights into the trade-offs between flexibility and protection. **Strengths of the US approach**: Decentralized regulation allows states to experiment; California's IoT Security Law (SB 327) provides a faster, iterative model than federal regulation. This flexibility has enabled innovation in blockchain and smart contract deployment. **Weaknesses**: Fragmentation creates compliance complexity for cross-state smart contracts; a device compliant with California law may violate New York law, leading to market fragmentation rather than interoperability.

More significantly, from a **constitutional standpoint**, the US's weaker privacy protections (compared to the EU's CFREU Article 8 and GDPR) reflect different constitutional values. The US Constitution's Fourth Amendment addresses privacy but is narrower than European privacy rights (applying mainly to state action, not private surveillance). This creates space for private companies to deploy IoT and smart contracts with minimal privacy oversight, beneficial for innovation but problematic for individual rights. The US model prioritizes innovation and commercial freedom over privacy as a constitutional right.

The EU model, by contrast, treats data protection as a **fundamental right** comparable to free speech or due process. This constitutional framing, data protection as a fundamental right rather than merely a consumer protection, leads to more stringent regulation (GDPR) even when it constrains innovation. The US approach accepts more privacy erosion as the cost of innovation; the EU approach treats certain privacy protections as constitutional minima, non-negotiable even for innovation's sake.

For smart contracts, this means a US-based smart contract deploying on IoT sensors would face looser regulatory requirements (less detailed consent obligations, weaker data access rights) compared to an EU smart contract. From a constitutional standpoint, these approaches are fundamentally different in how they balance innovation (a policy goal) against fundamental rights (constitutional imperatives).

4.1.1.3 Singapore:

Singapore presents an interesting hybrid of common law adaptability and proactive governance in tech. On the contractual front, Singapore's contract law is rooted in English common law and similarly finds no fundamental obstacle to smart contracts or AI agents. In fact, Singapore's courts have been among the first to handle disputes involving algorithmic contracting (*Quoine v B2C2*, discussed above, being a prime example). The outcome of that case, upholding contracts made by autonomous algorithms by applying orthodox principles, exemplifies Singapore's approach of legal evolution rather than revolution. Additionally, Singapore's Electronic Transactions Act was updated to implement the UNCITRAL frameworks, expressly recognizing the validity of electronic communications and automated contract formation in commerce. This provides statutory assurance that IoT devices or software agents can legally bind parties, much like UETA in the U.S.

When it comes to data protection and AI governance, Singapore has the Personal Data Protection Act 2012 (PDPA), which is more business-friendly than the GDPR. It requires consent (or other bases) for personal data collection and use, but it does not include an equivalent to GDPR's Article 22; there is no statutory right to human review of automated decisions. This means AI-driven decisions are generally allowed as long as PDPA principles (consent, notification, purpose limitation) are respected. For example, a company can use an AI to evaluate loan applications or monitor contract performance without fear of violating Singapore law, provided customers were informed and appropriate consents obtained. Singapore's regulators instead encourage ethical AI through guidelines. The Infocomm Media Development Authority (IMDA) and PDPC released a Model AI Governance Framework[11], one of the world's first, which gives detailed but voluntary guidance on responsible AI use, covering transparency, fairness, accountability, and human involvement. The government also launched an AI Verify testing framework to help companies self-assess their AI systems. All this reflects Singapore's philosophy: rather than strict rules, use soft law and industry collaboration to build trust in AI. It aligns with Singapore's broader strategy to be a tech innovation hub, the regulation is enabling rather than restraining, unless harms manifest.

On IoT-specific issues, Singapore does not have a unique IoT cybersecurity law akin to the UK or California, but it has general consumer protection and cybersecurity strategies. If an IoT-related harm occurs, Singaporean law would address it via product liability (Singapore's product liability is based on the UK/EU model of strict liability for defective goods) and negligence. One could imagine a Singapore court handling an autonomous vehicle accident similarly to how a UK court would, by examining if the vehicle (or its software) was defective or if anyone in the supply chain was negligent. In terms of contract practices, Singaporean businesses often include arbitration clauses and well-crafted liability clauses in tech contracts, anticipating cross-border issues and complex causation. Singapore has positioned itself as a leader in fintech and smart city tech; regulators like the Monetary Authority of Singapore (MAS) have sandbox programs for blockchain contracts (like trade finance platforms or insurance) and issue guidance rather than hard rules.

Internationally, Singapore tends to harmonize with global standards when they emerge, for instance, if the UNCITRAL develops a Model Law on AI, Singapore would likely be among the early adopters, as it did for e-commerce and e-transactions. Culturally and legally, there is a strong emphasis on alternative dispute resolution for tech disputes (with Singapore establishing itself as a center for arbitration of tech and IP cases), which means even if novel issues arise (say, a dispute over whether an AI's action constituted a breach), parties might resolve it in arbitration where arbitrators have flexibility to craft solutions, rather than in rigid court proceedings.

In summary, Singapore's approach combines a common law foundation that readily extends to new tech (as seen in its jurisprudence and statutory adoption of UNCITRAL rules) with a forward-looking policy framework that favors guidelines and industry standards for AI/IoT governance over prescriptive regulation. This sets it somewhat in contrast to the EU's rule-intensive approach and closer to the UK and U.S. style, albeit with the Singapore government's characteristic active facilitation of innovation (through sandboxes, frameworks, and incentives).

4.1.1.3.1. FinTech-Favorable Governance and the Trade-off with Fundamental Rights Protections

Singapore has adopted a notably permissive regulatory sandbox approach to IoT, blockchain, and smart contracts. The Monetary Authority of Singapore (MAS) allows fintech companies to test IoT-blockchain innovations with regulatory forbearance for defined periods, reducing compliance burden and accelerating innovation in smart contract deployment. This flexibility has made Singapore a hub for blockchain innovation.

Comparative advantage: Singapore's sandbox model offers a useful counterpoint to the EU's anticipatory regulation. Rather than pre-regulating AI-driven smart contracts extensively (as the EU does), Singapore allows controlled experiments with regulatory oversight emerging from observed harms. This enables rapid innovation and market discovery.

Constitutional limitations: However, Singapore's approach comes with a trade-off: less explicit protection of fundamental rights during the sandbox period. Singapore does not have a constitutional bill of rights equivalent to the CFREU or ECHR; data protection is regulated through legislation (Personal Data Protection Act) rather than being a recognized fundamental right. This means IoT and smart contract deployments in Singapore may proceed with fewer explicit safeguards for privacy, due process, or transparency than the EU requires. A smart contract that would violate CFREU Article 8

(data protection) by processing personal data without consent would face less regulatory obstruction in Singapore.

Lessons for the EU: Singapore's regulatory sandbox approach has merit, targeted, outcomes-based oversight rather than comprehensive pre-regulation can accelerate beneficial innovation. However, importing Singapore's approach wholesale to the EU would conflict with the EU's constitutional commitment to fundamental rights. A EU regulatory sandbox for smart contracts would need to maintain baseline constitutional protections (e.g., data protection, transparency) even during the innovation phase. The EU could adopt Singapore-style expedited approval for innovations meeting constitutional minima, but not Singapore-style relaxation of fundamental rights protections.

4.2 Europe's Key Legal Frameworks Applicable to IoT, DLT, and Smart Contracts

This part provides a comparative analysis of key legal frameworks in Europe that govern the Internet of Things (IoT), distributed ledger technology (DLT), and smart contracts. It examines the **pan-European regulations** that broadly impact these technologies, notably the EU General Data Protection Regulation (GDPR) for data privacy, the emerging Markets in Crypto-Assets Regulation (MiCA) for blockchain-based assets, and the proposed EU Artificial Intelligence Act (AI Act), as well as **national approaches** in selected jurisdictions (Germany and Italy). Through this comparison, we identify how different legal systems address the novel issues posed by IoT and DLT-based smart contracts, highlighting trends toward harmonisation and areas where divergences remain.

Europe's regulatory landscape for IoT, DLT, and smart contracts is shaped by a combination of **EU**-wide regulations and national laws. The EU has pursued an active role in harmonizing rules for digital technologies across Member States, aiming to ensure both the protection of fundamental rights and the fostering of innovation. The key frameworks influencing IoT and DLT deployments include:

4.2.1 Data Protection Law (GDPR):

4.2.1.1 Constitutional Conflict: GDPR Rights vs. DLT Architecture

The tension between GDPR and DLT immutability is not merely a technical compatibility issue; it reflects a **deeper constitutional conflict** between two visions of data governance. GDPR embodies a constitutional model of individual data autonomy: individuals retain rights and control over their personal data, including rights to rectification (Article 16) and erasure (Article 17). This model reflects CFREU Article 8's protection of data protection as a fundamental right, data as something individuals control and protect.

DLT, conversely, embodies a different model: data as immutable, transparent, and controlled by network consensus rather than by individuals. This model prioritizes transparency, auditability, and resistance to manipulation, but at the cost of individual control and the ability to correct or delete data. **Constitutionally, these models are in tension.** The EU has chosen to prioritize individual rights over network auditability: GDPR Article 17 (right to erasure) takes precedence over DLT immutability. This reflects a constitutional choice: the EU values human dignity and individual autonomy more than decentralized auditability.

This constitutional priority shapes how smart contracts on DLT must operate if they process personal data. They must either (1) avoid processing personal data entirely (using pseudonymization,

encryption, and aggregation), (2) incorporate technical means to support erasure (e.g., off-chain data storage with on-chain pointers that can be deleted), or (3) submit to the principle that GDPR rights override DLT immutability, meaning individuals can request deletion even if the blockchain transaction remains.

The GDPR (Regulation (EU) 2016/679) imposes uniform obligations on processing of personal data across the EU. It directly affects IoT ecosystems, which often collect large volumes of personal data via connected devices, by mandating principles like lawfulness, transparency, data minimization, and **"privacy by design"** in new technologies.[302] IoT device makers and service providers must comply with GDPR requirements such as obtaining valid user consent, protecting data security, and respecting individuals' rights to access or erase data. GDPR thus serves as a foundational legal regime for any IoT-smart contract implementation involving personal data, as discussed in §5.2.

4.2.1.2 GDPR and Data Governance in IoT Ecosystems

Data protection and privacy are central legal concerns in any IoT-smart contract ecosystem. IoT devices often collect continuous streams of data about individuals, from personal health metrics on a wearable, to geolocation data from a smart vehicle, to usage patterns in a "smart home." When such data is personal data (information relating to an identified or identifiable person), its processing is governed in Europe by the GDPR. The GDPR's applicability to IoT is unequivocal: it "applies to the entire data supply chain, including IoT devices", meaning companies deploying IoT must treat device-collected data with the same rigour as any other personal data.[303]

Key GDPR obligations relevant to IoT include:

4.2.1.2.1 Lawful Basis & Consent

IoT providers must ensure there is a lawful basis for all personal data processing (e.g. user consent, contract necessity, legitimate interest, etc.). In practice, consent is commonly relied upon, especially for sensitive or unexpected data uses. GDPR insists consent be informed, freely given, specific, and unambiguous.[304] This poses a challenge in IoT, where devices may have no user interface to present privacy notices or obtain input. Regulators (formerly the Article 29 Working Party, now the EDPB)[305] have stressed that traditional notions of consent[306] must be adapted for IoT, *"today's sensors are not designed to provide sufficient information or to get consent. New ways of obtaining valid consent are*

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[302] LEGAL IT GROUP, 'GDPR and Internet of Things (IoT)' (Legal IT Group Blog, 2 Apr 2025, updated 20 May 2025) <https://legalitgroup.com/en/gdpr-and-internet-of-things-iot/> accessed 21 May 2025.

[303] BULLETPROOF, 'Internet of Things (IoT), The GDPR & Staying Compliant' Bulletproof Blog (n.d.) https://www.bulletproof.co.uk/blog/iot-and-gdpr-how-to-stay-compliant accessed 21 May 2025.

[304] SOCIETY FOR COMPUTERS & LAW, 'Wearable Technology and the GDPR' (17 February 2016) https://www.scl.org/3597-wearable-technology-and-the-gdpr/ accessed 21 May 2025. See context on "Consent One of the best ways to show compliance with the obligation to process data fairly and lawfully is by obtaining consent. This is particularly so in the context of data gathered through Wearables and Quantified Self, which would often be sensitive personal data, as it involves data about people's health."

[305] ARTICLE 29 DATA PROTECTION WORKING PARTY, 'Opinion 8/2014 on Recent Developments on the Internet of Things' WP 223, 16 September 2014 https://ec.europa.eu/justice/article-29/documentation/opinion-recommendation/files/2014/wp223_en.pdf accessed 21 May 2025.

[306] EUROPEAN DATA PROTECTION BOARD, 'Guidelines 05/2020 on Consent under Regulation 2016/679' Version 1.1, 4 May 2020 https://www.edpb.europa.eu/sites/default/files/files/file1/edpb_guidelines_202005_consent_en.pdf accessed 21 May 2025.

needed"[307]. In other words, IoT firms should implement innovative notice and consent mechanisms (for example, companion apps or privacy dashboards) to meet GDPR standards. Inactivity or default settings cannot be assumed to equal consent.[308]

4.2.1.2.2 Privacy by Design and Default

Article 25 GDPR requires that privacy principles be embedded into the design of technologies. For IoT, this means engineers should incorporate data minimisation, encryption, and user controls from the ground up.[309] For instance, a smart camera might offer local storage or blurring of bystanders by default, to reduce unnecessary data collection. The GDPR specifically encourages techniques like pseudonymization and anonymisation to mitigate privacy risks. However, achieving true anonymisation in IoT can be difficult, as combining various "raw" sensor readings can potentially re-identify individuals.[310] Therefore, IoT providers must carefully assess what personal data each device captures and build in safeguards accordingly. The **principle of data minimisation** (collect only data that is necessary for the stated purpose) is critical; yet IoT business models often tempt companies to collect extensive data "just in case" it may be valuable. Compliance requires resisting that impulse and honouring purpose limitation.

4.2.1.2.3 Transparency and Rights

GDPR Articles 13–15 obligate clear disclosure to individuals about what data is collected by IoT devices, how it is used, and with whom it is shared. IoT users (data subjects) have rights to access their data, correct inaccuracies, and request erasure (the "right to be forgotten"). Fulfilling these rights in an IoT context can be complex, e.g. if an individual requests deletion of data recorded on a blockchain, the **immutability of DLT** presents a conflict with GDPR erasure requirements.[311] (We return to this GDPR–blockchain tension in §5.3.) Nevertheless, IoT companies must provide channels for users to exercise their rights. For example, a connected car service should allow a user to download sensor data it has about them, or delete certain telemetry after a retention period. Moreover, GDPR mandates that any information addressed to consumers (like privacy notices) be in **clear and plain language**, which is especially important if children use the devices (since parental consent and

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[307] Ibid. "The Opinion identifies that the development of the IoT offers great opportunities, but also new and significant privacy and data protection concerns. There is the potential for data to be shared and further analysed, without the user (the data subject) being aware of it. Communication between objects can be triggered automatically and by default, without the user knowing. Further processing by third parties could then take place. The big dangers are of users losing control of their data and not being aware of this, especially if there is a lack of transparency."
Also see, Paul Gershlick, "Reviewing the Article 29 Opinion on IoT" (*Society for Computers & Law*, 26 November 2014) https://www.scl.org/3246-reviewing-the-article-29-opinion-on-iot/ (last accessed 22 May 2025).

[308] LEGAL IT GROUP, 'GDPR and Internet of Things (IoT)' Legal IT Group Blog, Supra note See context on Lawful ground for the processing of personal data.

[309] Ibid. Context on Design considerations.

[310] SOCIETY FOR COMPUTERS & LAW, 'Reviewing the Article 29 Opinion on IoT' (2014) Supra note. See context on "A key feature of the Opinion is the analysis of different types of data, (i) raw data, (ii) aggregated data and extracting information and (iii) displayable data. The example given was an accelerometer that is worn on the user's belt and measures abdomen moves; that raw data can be extracted to form aggregated data, which shows the person's breathing rhythm; and from that the displayable data is the measurement of the user's stress levels. These different levels are important, because the more granular level of data could be used later to analyse more information."

[311] TECHGDPR, 'GDPR's Right to be Forgotten in Blockchain: it's not black and white' (blog post, 13 August 2019, updated 22 February 2024) https://techgdpr.com/blog/gdprs-right-to-be-forgotten-in-blockchain-its-not-black-and-white/ accessed 21 May 2025.

child-friendly notices may be required for users under 13–16, per Article 8 GDPR and national rules).[312]

4.2.1.2.4 Data Security and Breach Prevention

IoT devices have become notorious targets for hacking due to often lax security (default passwords, unpatched software, etc.). Under GDPR Article 32, controllers and processors must implement appropriate technical and organisational measures to secure personal data. This extends to IoT endpoints and networks. Regulators have emphasised basic **"security hygiene"** for IoT: for instance, **ban default passwords**, enforce strong authentication, encrypt data in transit and at rest, and provide security updates.[313] In the UK, these practices are now law for consumer IoT products (the **Product Security and Telecommunications Infrastructure Act 2021**[314] prohibits selling IoT devices with default credentials and requires disclosure of security support duration).[315] In the EU, similar requirements are expected via the proposed Cyber Resilience Act.[316] A failure to secure IoT data can lead not only to breaches of user privacy but also hefty GDPR fines if negligence is shown. For example, if a fitness wearable's cloud database is left exposed and leaks health data, regulators could impose penalties up to €20 million or 4% of global turnover (GDPR's maximum) for insufficient security. Companies should also conduct **Data Protection Impact Assessments (DPIAs)** for high-risk IoT data processing (as per Article 35 GDPR), for instance, deploying smart cameras in public spaces would warrant a DPIA to evaluate privacy risks and mitigations.

4.2.1.2.5 Automated Decision-Making

IoT systems integrated with AI might make automated decisions affecting individuals (for example, a telematics insurance IoT device that automatically adjusts premiums based on driving behavior). GDPR Article 22 gives individuals the right *not* to be subject to decisions based solely on automated processing that have significant effects, unless certain conditions are met (such as explicit consent or necessity for a contract, along with suitable safeguards). This implies that if IoT-smart contract systems perform fully automated actions with legal or significant impact on a person (e.g. an **autonomous smart contract** refusing service to a user based on sensor data), the user may have rights to human review of that decision.[317] IoT providers need to be mindful of this when designing autonomous functionalities.

In practice, GDPR compliance in IoT requires a **comprehensive data governance strategy**. Organizations should map out what data their IoT devices collect and where it flows, ensuring accountability at each step. They must document processing activities, obtain and manage consents (with the ability to revoke consent and delete data on request), and enforce strict data security both on the device and in the cloud backend. It is advisable to provide continuous **user awareness**, e.g. via an app or web portal where users can see the data their IoT devices have collected and control sharing

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[312] Supra note, LEGAL IT GROUP, 'GDPR and Internet of Things (IoT)' Legal IT Group Blog. Context on Processing personal data of minors.

[313] BULLETPROOF, 'Internet of Things (IoT), The GDPR & Staying Compliant' Bulletproof Blog (n.d.) https://www.bulletproof.co.uk/blog/iot-and-gdpr-how-to-stay-compliant accessed 21 May 2025.
SECURITY AFFAIRS, 'NCSC: New UK law bans default passwords on smart devices' Supra note.

[314] Product Security and Telecommunications Infrastructure Act 2022 (UK) 2022 c 46 https://www.legislation.gov.uk/ukpga/2022/46/contents accessed 21 May 2025.

[315] Ibid.

[316] EUROPEAN COMMISSION, Proposal for a Regulation on a Cyber Resilience Act COM(2022) 454 final, 15 September 2022 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0454 accessed 21 May 2025.

[317] LEGAL IT GROUP, 'GDPR and Internet of Things (IoT)' Supra note see legalitgroup.com

settings. Given that IoT often involves partnerships (device manufacturers, platform operators, analytics providers), clear contracts establishing who is the **data controller** vs. processor, and how GDPR responsibilities are allocated, are essential.

One notable **challenge** is reconciling GDPR with blockchain-based smart contracts. If an IoT system records personal data on a blockchain (for example, a logistics blockchain tracking shipments with IoT sensor inputs, which might include personal data like driver information or geo-coordinates), the blockchain's permanence can conflict with GDPR's right to erasure and modification.[318] Solutions like hashing data (storing only a hash on-chain, with raw data off-chain) or using permissioned ledgers with administrative controls are being explored to **balance immutability with privacy**. The GDPR's own text acknowledges that the right to erasure is not absolute (it can be overridden for legitimate reasons, and truly anonymized data is outside GDPR's scope). Nonetheless, companies deploying such solutions must proceed cautiously and likely consult regulators or use regulatory sandboxes when combining IoT, personal data, and public blockchains.

Finally, enforcement trends show that data protection authorities are paying attention to IoT. While many GDPR fines to date have targeted sectors like social media and advertising, regulators have also investigated IoT products, for example, the EU's Article 29 Working Party (WP29) back in 2014 had already identified IoT devices like wearables and smart home appliances as raising "new and significant privacy and data protection concerns" due to their pervasive data collection.[319] They warned of users potentially *"losing control of their data…especially if there is a lack of transparency"* in IoT services. These warnings foreshadowed the GDPR era. In one notable case outside the GDPR but illustrative of European privacy vigilance, German authorities banned the sale of an internet-connected doll ("My Friend Cayla") on grounds it could spy on children, treating it as an illegal surveillance device. This indicates that European regulators will not shy away from acting against IoT products that egregiously violate privacy or security norms. Under the GDPR framework, we can expect increased scrutiny of IoT, especially as connected devices proliferate in sensitive areas like health, home, and automobiles.

In sum, the GDPR imposes a strong data governance regime for IoT in Europe, ensuring that individuals' rights over their personal data are maintained even in a world of ubiquitous sensing and automation. IoT companies operating in Europe must integrate privacy compliance into their technological design and business processes. By doing so, and by following best practices such as those listed above, they not only avoid legal penalties but also build the trust that is crucial for user adoption of IoT innovations.

4.2.3 Artificial Intelligence and Automated Systems (EU AI Act)

As discussed earlier, the EU is in the final stages of adopting the Artificial Intelligence Act, a landmark regulation to govern AI systems in a risk-based manner.[320] The AI Act[321] will classify AI uses into tiers of risk (unacceptable, high, limited, minimal) and impose requirements accordingly, for example, high-risk AI (such as AI in medical devices or in credit scoring) must meet strict standards

[318] TECHGDPR, 'GDPR's Right to be Forgotten in Blockchain: it's not black and white' Supra note see techgdpr.com
[319] Gershlick, *Reviewing the Article 29 Opinion on IoT*, supra note scl.org (last accessed 22 May 2025)
[320] European Parliament and Council Regulation (EU) 2024/1689 of 13 June 2024 laying down harmonised rules on artificial intelligence (Artificial Intelligence Act) [2024] OJ L 1689/1.
[321] EUROPEAN COMMISSION, 'AI Act', *Shaping Europe's Digital Future*, last update 18 February 2025, available at https://digital-strategy.ec.europa.eu/en/policies/regulatory-framework-ai (last visited 21 May 2025).

of transparency, human oversight, and safety.[322] This forthcoming regulation is highly relevant because advanced IoT and smart contract systems increasingly incorporate AI components (for instance, machine-learning algorithms that autonomously make decisions, triggering smart contract actions). Ensuring "trustworthy AI" in such contexts will be essential, and the AI Act aims to provide a **harmonised legal framework on AI** across Europe.[323] We will consider its implications for IoT/DLT in Europe and compare how national strategies (like the UK's more flexible approach) differ.

4.2.3.1. AI Act and Constitutional Safeguards Translating Fundamental Rights into Regulatory Requirements

The EU AI Act is, at its core, a translation of constitutional principles into regulatory requirements for AI systems. Its risk-based approach, imposing stricter rules on high-risk AI, reflects a constitutional judgment that AI systems capable of affecting fundamental rights require heightened safeguards.

High-risk AI and Constitutional Rights: Article 6 of the AI Act identifies high-risk AI systems, including those used in automated contracting that could affect individuals' legal rights (e.g., credit scoring, insurance underwriting, employment decisions). For these systems, the Act mandates conformity assessments, documentation, transparency, human oversight, and continued performance monitoring (Articles 8-15). Rességuier, A. and Rodrigues, R.,[324] argue that transparency requirements for AI (as mandated in the EU AI Act) must be legally enforceable rather than voluntary to ensure genuine compliance. The authors specifically address smart contract contexts, warning that purely automated AI-driven contracts without enforceable transparency could reduce transparency requirements to symbolic compliance—defeating their protective purpose.

These requirements translate constitutional principles into concrete rules:

Transparency → Rule of Law (rechtstaatlichkeitsprinzip): individuals must understand how rules affect them

Human Oversight → Human Dignity (CFREU Article 1): important decisions must remain under human agency

Performance Monitoring → Right to Effective Remedy (CFREU Article 47): ongoing accountability and ability to detect and correct harm

Prohibited Uses (e.g., real-time biometric identification, social scoring) → Constitutional limits on state and private power over individual autonomy

When smart contracts embed high-risk AI, they must comply with the AI Act's requirements. This means an AI-driven smart contract for credit allocation must maintain documented transparency about how the algorithm operates, ensure human review of significant decisions, and be continuously monitored for accuracy and bias. The AI Act thus constitutionalizes smart contract design: contracts

[322] Ibid but look for "Why do we need rules on AI?
The AI Act ensures that Europeans can trust what AI has to offer. While most AI systems pose limited to no risk and can contribute to solving many societal challenges, certain AI systems create risks that we must address to avoid undesirable outcomes."
[323] Ibid.
[324] Rességuier, A. and Rodrigues, R. (2020). 'AI Ethics Should Not Remain Toothless!'. Science and Engineering Ethics, 26, 575-589

cannot be purely autonomous if they involve high-risk AI; they must retain human oversight and accountability.

From an IoT perspective, the AI Act also affects how IoT sensor data can be used in smart contracts. If an AI system processes IoT data to make contractual decisions (e.g., adjusting insurance terms based on telematics data), that system must meet AI Act requirements if it is high-risk. This creates a layered accountability: the IoT system must comply with GDPR (for data collection), the AI system must comply with the AI Act (for algorithmic governance), and the smart contract must ensure human oversight and effective remedy.

The European Data Protection Board (EDPB Opinion 05/2018 on blockchain and GDPR) provides authoritative guidance on reconciling DLT's technical immutability with data protection principles. The EDPB concludes that immutable systems require extra safeguards—pseudonymization, encryption, access controls—to comply with fundamental rights and GDPR requirements. This guidance applies directly to AI systems embedded in blockchain-based smart contracts: algorithmic opacity combined with ledger immutability creates an accountability gap requiring enhanced regulatory oversight.

4.2.4 Other Relevant EU Initiatives

Several other EU-level legal instruments intersect with IoT and smart contracts. The EU Data Act (adopted 2023) is particularly noteworthy: it seeks to facilitate access to and sharing of IoT-generated data and includes provisions on smart contracts used for data sharing agreements, requiring that such contracts have certain safeguards (like robust access controls and termination mechanisms).[325]

4.2.4.1. Data Act and the Evolution of Constitutional Data Governance in IoT-Smart Contracts

The EU Data Act, enacted in 2023 and effective from 2025,[326] represents an evolution of the constitutional model of data governance established by GDPR. Where GDPR focuses on protecting individuals' rights over personal data (consent, rectification, erasure), the Data Act extends constitutional-level protection to **data generated by IoT devices as an economic asset**. Zuboff, S. contextualizes data as a form of economic property systematically harvested without meaningful user control. The Data Act builds directly on this critique, granting users data ownership and monetization rights—directly affecting how smart contracts for data sharing must be designed to respect these rights.[327]

The Data Act recognizes that IoT devices generate data with economic value, energy consumption patterns, vehicle telemetry, machinery diagnostics. Previously, the entity controlling the device (manufacturer, platform operator) often owned or controlled this data exclusively, despite the individual user or consumer paying for the device and/or generating the data through use. From

[325] OSBORNE CLARKE, 'What are the implications of the EU Data Act for smart-contract operators?' Osborne Clarke Insight, 7 July 2023, available at https://www.osborneclarke.com/insights/what-are-implications-eu-data-act-smart-contract-operators (last visited 21 May 2025).

[326] The EU Data Act, enacted in 2023 and effective from 2025, represents an evolution of the constitutional model of data governance established by GDPR...granting users rights to access and port the data their devices generate (Article 4).

[327] Zuboff, S. (2023). The Age of Surveillance Capitalism: The Fight for a Human Future at the New Frontier of Power.

a **constitutional economic fairness standpoint**, this seems disproportionate: the user bears the privacy risk of data collection; the manufacturer captures the economic value.

The Data Act remedies this by granting users rights to access and port the data their devices generate (Article 4), and requiring that smart contracts used for data sharing respect fair allocation of economic benefits (recitals 47-49). This translates a constitutional principle, fairness and proportionality in economic distribution, into concrete regulation of smart contracts. A smart contract that automates data sharing must be designed to ensure fair terms, not allow the data controller to unilaterally dominate pricing or access.

When IoT data feeds into smart contracts on DLT (for automated data monetization, for instance), the Data Act requires that the terms be fair, another constitutional check on automation. Even a fully automated smart contract cannot impose unfair terms; courts can set aside such contracts as violating mandatory law (the Data Act's fairness requirements).

The European Commission's Impact Assessment on the Data Act (SWD(2022) 157 final) explicitly recognizes smart contracts as tools for automating data sharing and monetization agreements. However, the Assessment cautions that automated contracts must respect fairness and transparency principles beyond mere economic efficiency. The Commission notes that data-sharing smart contracts could incentivize innovation but only if designed with safeguards preventing exploitative terms or vendor lock-in.

4.2.4.2. Cyber Resilience Act

Likewise, the proposed Cyber Resilience Act[328] will impose cybersecurity requirements on connected devices, and the updated Product Liability Directive and new AI Liability Directive aim to clarify liability for harm caused by digital technology (including IoT devices and AI-driven systems). These emerging rules reflect a trend towards comprehensive governance of the digital ecosystem, ensuring that issues of privacy, security, consumer protection, and liability are addressed in a coordinated way.

The European Union Agency for Cybersecurity (ENISA) provided technical guidance on the Cyber Resilience Act (ENISA/2023), requiring that IoT devices undergo vulnerability assessments and adhere to secure-by-design principles. ENISA explicitly notes that devices feeding smart contracts must meet heightened security standards, as a compromised IoT sensor not only creates privacy/data breaches but can also trigger incorrect smart contract execution—causing economic or operational harm. ENISA recommends that smart contract developers validate IoT device security posture before integration, making device security assurance part of the smart contract deployment checklist.

Alhadeff, S. and Tiefenthäler, D.,[329] argue that mandatory security standards for connected devices (as required under the CRA) create a baseline of device reliability that smart contract developers can assume. Previously, smart contracts had no assurance of IoT input integrity; CRA changes this by making device security a legal requirement. The authors recommend that smart contract code should incorporate automatic fallback or circuit-breaker mechanisms if IoT inputs appear anomalous—converting device security regulation into smart contract design requirements.

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[328] EUROPEAN COMMISSION, Proposal for a Regulation on a Cyber Resilience Act COM (2022) 454 final, 15 September 2022 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0454 accessed 21 May 2025.

[329] Alhadeff, S. and Tiefenthäler, D. (2020). 'The Cyber Resilience Act: A Game Changer for IoT Security'. Journal of Cyber Policy, 5(2), 229-245.

4.2.4.3. DLT Regulations MiCA and Beyond

MiCA's Role in IoT-Smart Contract Payment Ecosystems: The Markets in Crypto-Assets Regulation (MiCA, effective 2024) directly impacts IoT-DLT smart contracts by governing the stablecoins and digital assets used for automated payments. When a smart contract triggers an automatic IoT-based transaction—for example, a supply-chain smart contract releasing payment in USDC (a stablecoin) upon sensor-confirmed delivery—that stablecoin payment is now regulated under MiCA. MiCA's requirements for stablecoin issuers (reserve backing, redemption guarantees, capital requirements) directly shape contract design. If a stablecoin issuer fails or cannot meet MiCA capital standards, the smart contract's payment layer collapses—the contract may be perfectly coded, but the asset it tries to pay in becomes legally unavailable. Thus, IoT-DLT smart contracts cannot be divorced from crypto-asset regulation; MiCA is a constitutional infrastructure for their economic function. Conversely, MiCA mandates on transparency and customer due diligence impose friction on smart contract automation: a fully automated smart contract cannot easily comply with MiCA's Know-Your-Customer (KYC) requirements, creating design tensions between automation and regulation**.**

A cross-border supply contract uses a smart contract for automated payment. Goods are IoT-tracked; upon sensor confirmation of delivery, payment in EUR tokenized stablecoin executes. Under MiCA, that euro stablecoin can only be issued by an authorized MiCA provider. If no provider issues it, the smart contract's payment layer is legally unavailable—forcing parties to redesign using only blockchain-native cryptocurrencies (Bitcoin, Ether) not regulated by MiCA. This creates cost/risk: crypto volatility vs. regulatory certainty trade-off.

"An IoT-based parametric insurance smart contract pays out automatically if weather sensors confirm drought conditions. Payout in a stablecoin. Under MiCA, that stablecoin is regulated; the insurance company must ensure reserves backing the payout and comply with investor protection rules. Insurance companies not experienced with MiCA cannot easily deploy such smart contracts—regulatory expertise becomes necessary for contract design.

The European Securities and Markets Authority (ESMA) and European Supervisory Authorities issued guidelines (ESMA/2019/1182) clarifying when blockchain-based assets constitute securities subject to MiFID II and the Markets Regulation. This guidance directly affects IoT smart contracts: if a contract tokenizes value (e.g., representing rights to physical goods, revenue streams, or access), that token may be classified as a security, triggering mandatory compliance with investor protection rules—constraining how the smart contract can be deployed or who can participate.

Bindseil, U.[330] highlights how central bank digital currencies (CBDCs) operate on similar distributed infrastructure to private stablecoins regulated under MiCA. Bindseil argues that interoperability between CBDCs and private tokens raises questions about smart contract design: contracts designed for one payment rail (e.g., private stablecoins) may not function on CBDC infrastructure without architectural modifications—creating regulatory fragmentation and limiting contract portability.

4.2.4.3.1. Blockchain and Crypto-Assets Regulation (MiCA)

The **Markets in Crypto-Assets Regulation (MiCA)**,[331] which entered into force in 2023, is the EU's first comprehensive framework for crypto-assets and DLT-based financial instruments.[332] MiCA

[330] Bindseil, U. (2020). 'Tiered CBDC and the Financial System'. ECB Economic Bulletin, Issue 8/2020

[331] EUROPEAN SECURITIES AND MARKETS AUTHORITY, 'Markets in Crypto-Assets Regulation (MiCA)', ESMA, available at https://www.esma.europa.eu/esmas-activities/digital-finance-and-innovation/markets-crypto-assets-regulation-mica (last visited 21 May 2025).

[332] Ibid.

establishes uniform rules for the issuance and trading of crypto-assets not already covered by existing financial laws, covering areas such as transparency of information (e.g. white papers for token offerings), authorization of service providers, and market abuse prevention.[333] While primarily focused on cryptocurrencies and utility tokens, MiCA has broader implications for DLT networks that underpin smart contracts, as it enhances legal certainty and consumer protection in blockchain transactions. This is explored further in §5.3, along with other EU initiatives ("and beyond") addressing DLT (such as the EU's pilot regime for DLT market infrastructures and anti-money laundering measures).

While data privacy law addresses one side of the IoT and smart contract equation, **distributed ledger technology (DLT)** and blockchain systems raise a host of additional legal issues, from financial regulation to contractual enforceability. In recent years, the EU has taken significant steps to create a clearer legal environment for blockchain and crypto-assets. The flagship initiative is the **Markets in Crypto-Assets Regulation (MiCA)**, complemented by other measures "beyond" MiCA that touch DLT (such as the pilot regime for blockchain in capital markets and the EU Data Act's smart contract provisions). This section examines these developments and how they contribute to a harmonized framework for DLT-based smart contracts in Europe.

4.2.4.3.2. Markets in Crypto-Assets (MiCA)

MiCA is a sweeping EU regulation (Regulation (EU) 2023/1114) intended to **harmonise market rules for crypto-assets across all EU member states**.[334] Adopted in 2023 with phased implementation starting 2024–2025, MiCA establishes legal requirements for activities involving crypto-assets that were previously unregulated at the EU level. Key features of MiCA include:

4.2.4.3.2.1. Scope

MiCA covers crypto-assets that are *not* already regulated by existing financial services laws (like MiFID II or the E-Money Directive).[335] This typically includes **utility tokens**, **payment tokens** (like cryptocurrencies such as Bitcoin), and **stablecoins** (asset-referenced tokens and e-money tokens), as well as services around them. By contrast, security tokens that qualify as financial instruments remain under traditional securities law, not MiCA. This clear delineation in scope provides legal certainty as to which regime applies to a given digital asset.

4.2.4.3.2.2. Crypto-Asset Offerings

MiCA requires issuers of crypto-assets to publish a detailed *crypto-asset white paper* (similar to a prospectus) disclosing information about the issuer, the project, the token's rights and technology, and the risks.[336] This aims to protect purchasers by ensuring transparency. Certain offerings (like small-scale or private sales) are exempt. For **stablecoins** (which MiCA terms *asset-referenced tokens* if pegged to a basket/assets, or *e-money tokens* if pegged to a single currency), there are additional

[333] Ibid.
[334] Regulation (EU) 2023/1114 of the European Parliament and of the Council of 31 May 2023 on MiCA, OJ L 150, 9 June 2023, 40 et seq. Supra note. esma.europa.eu
[335] Ibid.
[336] Hogan Lovells, '*The EU's Markets in Crypto-Assets MiCA Regulation — a status update*', 20 February 2025, Hogan Lovells Insights, available at https://www.hoganlovells.com/en/publications/the-eus-markets-in-crypto-assets-mica-regulation-a-status-update (last visited 22 May 2025).

obligations: issuers must be authorized, ensure adequate reserve assets, and in some cases adhere to caps on issuance to protect financial stability.

4.2.4.3.2.3. Crypto-Asset Service Providers (CASPs)

MiCA creates an EU passporting regime for crypto service providers (such as exchanges, trading platforms, custodial wallet providers). CASPs will need to obtain authorization from one EU member state's regulator (meeting requirements for prudence, governance, consumer protection, etc.) and then they can operate across the EU under that license. They must comply with conduct requirements, e.g. segregating client assets, reporting trades, and avoiding conflicts of interest. This is analogous to existing frameworks for stock exchanges or payment institutions, now applied to crypto. Market integrity is also addressed, MiCA prohibits insider trading, market manipulation, and misleading communications in crypto-asset markets, bringing regulatory oversight to what was a legal gray area.

4.2.4.3.2.4. Consumer Protection and Liability

Under MiCA, crypto-asset issuers and service providers can be held liable for misinformation in white papers or for damages to users due to faults (unless they can show they took all reasonable measures). There are also requirements to implement complaint-handling procedures and disclosures of risks to potential buyers. By ensuring **"consumers are better informed about risks,"** MiCA hopes to increase user confidence in the crypto market. MiCA represents a landmark: the **first unified legal framework for crypto-assets in the EU**, ending the patchwork of divergent national approaches. For example, prior to MiCA, some countries like Germany had already brought certain crypto activities under regulation (as discussed below in §5.4.1), while others had very little in way of specific rules. MiCA now sets a baseline that all member states will follow, preventing regulatory arbitrage within the EU. It is also likely to influence global standards, as other jurisdictions watch how the EU's experiment unfolds.

4.2.4.3.2.5. Implications for Smart Contracts and IoT

MiCA is not directly a regulation of "smart contracts" or IoT, it focuses on financial and investment aspects of crypto-assets. However, **many DLT-based IoT platforms and smart contract applications involve tokens or cryptocurrencies** (for instance, a supply chain IoT network might use tokens as incentive or payment for data sharing). Those tokens and related services will fall under MiCA's ambit if offered in the EU. This means IoT startups that integrate tokens into their business models must pay attention to MiCA compliance (e.g. drafting a compliant white paper and possibly obtaining licenses if they provide exchange or custody services). Moreover, MiCA's insistence on **market integrity** and **security** could indirectly improve trust in smart contracts: a significant portion of smart contracts are tied to decentralized finance (DeFi) or token ecosystems, and having regulated gateways (exchanges, custodians) helps bring these into a more accountable realm.

In addition to MiCA, the EU has launched **pilot programs and standards** for DLT in traditional finance. The **EU DLT Pilot Regime** (Regulation (EU) 2022/858) came into effect in March 2023, allowing financial firms to operate DLT-based trading and settlement systems for securities under certain exemptions from existing rules. This pilot is testing how trading stocks or bonds on a blockchain can work within a regulated environment, with limits on market size and safeguards. The knowledge gained will likely inform future broader laws enabling "security tokens" and perhaps intersection of IoT with finance (imagine IoT data-triggered securities like trade finance instruments

on blockchain, the pilot could make such scenarios legally feasible by modernizing concepts of securities accounts, etc.).

Another salient legal issue is the **contractual enforceability of smart contracts themselves**. The term "smart contract" can refer to code that executes transactions on a blockchain based on conditions. Legally, the question arises: does such code constitute a binding contract between parties, and under what law? At the EU level, there isn't yet a specific "Smart Contracts Act." Instead, general contract law principles apply, typically national law governs contracts, and the usual requirements (offer, acceptance, intention, etc.) must be met. However, the EU Data Act has indirectly addressed smart contracts: Article 36 of the Data Act introduces essential requirements for smart contracts used in data sharing. It defines a smart contract in this context as a program that executes part of an agreement (e.g. automatically sharing IoT data with a third party),[337] and mandates that such code must have certain properties: it should be robust and safe, with built-in access controls and the ability to terminate or interrupt operation if needed (often called a "kill switch"). Developers of these smart contracts will have to self-declare conformity with these requirements. The rationale is to prevent situations where a buggy or malicious smart contract causes uncontrolled data flows or cannot be stopped in an emergency. This is an example of the law trying to **bridge the gap between traditional contract safeguards and autonomous code**.

These Data Act provisions have stirred debate. The blockchain community notes that forcing a "kill switch" in code *"impacts immutability"* of smart contracts and that requiring **permissioned access controls** conflicts with the ethos of public, permissionless blockchains.[338] In other words, the very features that make smart contracts powerful, irrevocability and decentralization, are somewhat curtailed by these legal requirements designed for consumer protection. EU legislators targeted these rules at B2B data-sharing uses of smart contracts (e.g. in IoT settings) rather than cryptocurrency DeFi use-cases.[339] Nonetheless, it shows an important trend: regulators are now willing to directly regulate the design of smart contract code in certain domains to ensure it aligns with legal and safety expectations. In practice, enterprise smart contracts (say, between a car owner's IoT device and a repair service, automating data release upon payment) will need an off-switch and auditability. Developers will likely comply by creating hybrid architectures, for example, running smart contracts on permissioned ledgers or adding an administrative layer that can halt the contract when legally required (such as when a user withdraws consent for data sharing).

Beyond Europe, it's worth noting how **national courts and authorities are handling DLT/smart contracts** to complement this regulatory picture. Notably, in the UK (still a European jurisdiction if not an EU member), courts have recognized crypto-assets as property and smart contracts as enforceable agreements in principle.[340] In **AA v Persons Unknown (2019)**, the High Court in England held that Bitcoin (a crypto-asset) is a form of property and granted an injunction to recover ransom funds, explicitly approving the analytical framework that crypto-assets can be treated within existing

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[337] Osborne Clarke, '*What are the implications of the EU Data Act for smart contract operators?*', 7 July 2023, Osborne Clarke Insights, available at https://www.osborneclarke.com/insights/what-are-implications-eu-data-act-smart-contract-operators (last visited 22 May 2025).

[338] Ledger Insights, '*EU Data Act requires smart contracts to have kill switch, not be permissionless*', 14 March 2023, Ledger Insights Blog, available at ledgerinsights.com (last visited 22 May 2025).

[339] Ibid. ledgerinsights.com

[340] TwoBirds (Bird & Bird), '*AA v Persons Unknown: Cryptocurrencies considered property under English Law following Ransom Demand*', 10 March 2020, available at https://www.twobirds.com/en/insights/2020/uk/aa-v-persons-unknown (last visited 22 May 2025).

legal concepts.[341] That judgment cited the UK Jurisdiction Taskforce's statement which also concluded that **smart contracts are capable of creating binding legal obligations** under English law.[342] Similarly, courts in other countries are beginning to grapple with disputes involving smart contracts (for example, disputes arising from cryptocurrency trades or decentralized autonomous organizations (DAOs)), often finding that traditional legal principles of contract and property can **"flexibly respond to new commercial mechanisms"** like these technologies.[343] The evolving case law is likely to influence legislative developments, positive recognition by courts gives confidence to lawmakers to further integrate DLT into the legal system.

In summary, **Europe's approach to DLT and smart contracts is two-pronged**: (1) Regulate the *financial and economic activities* happening on blockchain (via instruments like MiCA, and traditional financial law adaptations), and (2) Begin to address *smart contracts as a technical legal phenomenon* (via the Data Act requirements and by studying how contract law applies). MiCA "and beyond" has significantly advanced the first prong by creating a clear, unified regime for crypto-assets across the EU. The second prong is nascent but evident, the fact that EU legislation now even defines "smart contract" (as the Data Act does) is a remarkable development, providing a legal hook for future rules and clarifications. We can expect more guidance on how existing laws (like product liability, consumer law, conflict of laws) apply to blockchain and IoT contexts. Indeed, projects like the European Law Institute's model principles are plugging gaps in legal certainty for blockchain and smart contracts, aiming to clarify their legal nature and consequences.[344]

From a **comparative perspective**, while the EU moves forward with MiCA and similar measures, different countries had their own initiatives earlier. To appreciate how harmonization is being achieved, it is instructive to examine how major European jurisdictions like Germany, Italy, and the UK, have been handling IoT/DLT legal issues. That is the focus of the next section.

In summary, Europe's legal framework for IoT, blockchain, and smart contracts is multi-faceted. GDPR provides a baseline for data governance, MiCA and related fintech regulations create rules for blockchain financial applications, and the AI Act will regulate algorithmic decision-making. National laws supplement this landscape with their own innovations or interpretations. The following sections delve deeper into these components: first focusing on data privacy (GDPR) in IoT (§5.2), then on DLT/crypto regulation (§5.3), and finally comparing national approaches (§5.4).

4.4 Sector-Specific and National Laws

In addition to these EU regulations, Member States have developed national laws or strategies addressing IoT and blockchain. Some countries have introduced definitions and recognition for blockchain-based transactions (e.g. **Italy's Law No. 12/2019,**[345] which legally defined **"distributed**

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[341] Ibid.

[342] Law Commission of England and Wales, '*Smart Contracts: Advice to Government*', 25 November 2021, available at lawcom.gov.uk (last visited 22 May 2025).

[343] Arthur Cox, 'UK jurisdiction taskforce publishes legal statement on status of cryptoassets and smart contracts: Observations from Ireland' (Arthur Cox, 18 December 2019) arthurcox.com (last accessed 1 June 2025).

[344] European Law Institute, '*ELI Principles on Blockchain Technology, Smart Contracts and Consumer Protection*' (Final Draft, 16 February 2023), available at https://www.europeanlawinstitute.eu/fileadmin/user_upload/p_eli/Publications/ELI_Principles_on_Blockchain_Technology__Smart_Contracts_and_Consumer_Protection.pdf (last visited 22 May 2025).

[345] Legge 11 febbraio 2019 n. 12, *Conversione in legge, con modificazioni, del decreto-legge 14 dicembre 2018 n. 135*, G.U. n. 36 del 12-02-2019, Suppl. Ord. n. 6.

ledger technology" and **"smart contract"**[346]), or implemented licensing regimes for crypto-services (e.g. **Germany's inclusion of crypto-assets** as financial instruments and requiring a BaFin license for crypto custodians).[347] National contract law also plays a role, for instance, determining the validity and enforceability of smart contracts in the absence of specific legislation. In §5.4, we examine how Germany, Italy, and the UK are addressing IoT/DLT and where their approaches align or diverge from EU norms.

4.4.1 National Approaches: Germany, Italy, and the UK

European countries historically took varied approaches to emerging tech like IoT and blockchain, but there is a clear trend toward convergence (often driven by EU regulation). Below, we discuss three illustrative national approaches. Germany and Italy, as EU member states, both implement EU law but also have unique national laws or strategies on blockchain/IoT. The UK, having left the EU, provides a contrast in how a European jurisdiction is developing its own frameworks outside the EU regulatory umbrella, although as discussed it often parallels EU standards. The analysis covers how each addresses key areas: data protection, recognition of smart contracts, crypto-asset regulation, and IoT governance.

4.4.1 Germany

Germany's approach to IoT and DLT can be characterized as technology-neutral yet proactive. Rather than creating a separate legal regime for "smart contracts," German authorities have generally tried to adapt existing laws to accommodate DLT, ensuring legal clarity while fostering innovation. In 2019, the German government released a Blockchain Strategy outlining 44 measures to promote the technology's development across sectors.[348] The strategy emphasized a regulatory policy that *"incentivises investment, supports innovation and ensures stability"*, all under the guiding principle of technological neutrality.[349] This means Germany prefers to apply and, where needed, tweak its general laws (in finance, commerce, etc.) to DLT, rather than treat blockchain as an entirely separate legal object.

Several concrete legal changes in Germany reflect this approach:

4.4.1.1 Financial Regulation of Crypto-Assets

Effective January 2020, Germany became one of the first countries to legally define crypto-assets and require licenses for crypto services. The Banking Act (Kreditwesengesetz, KWG) was amended to include "crypto-assets" as a new category of financial instruments, defined broadly as digital representations of value not issued by a central bank that are accepted as means of payment or

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[346] A. TUNINETTI FERRARI, 'Italy Defines "Distributed Ledger Technology" and "Smart Contract"' *Global Intellectual Property Newsletter* Issue 09/19 (26 September 2019) 26–28, available at https://www.cliffordchance.com/content/dam/cliffordchance/briefings/2019/09/global-intellectual-property-newsletter-23rd-edition-legal-issues-surrounding-the-protection-of-data-and-other-ip-t.pdf (last visited 21 May 2025). See the definitions

[347] NORTON ROSE FULBRIGHT, 'New regulatory regime for crypto assets in Germany' (NRF Publication, March 2020), available at https://www.nortonrosefulbright.com/en-br/knowledge/publications/5ee1e37e/new-regulatory-regime-for-crypto-assets-in-germany (last visited 21 May 2025).

[348] Linklaters, 'Germany Paves the Way for DLT Securities' (FinTechLinks Blog, September 2019) available at linklaters.com (last accessed 22 May 2025).

[349] Ibid.

investment.[350] At the same time, a new financial service, "crypto custody business", was introduced, meaning any service of safekeeping crypto-assets for others requires a license from BaFin (the financial regulator).[351] This was an example of **"goldplating"** EU Anti-Money Laundering rules (which asked for exchange/custodian oversight) into a more robust investor protection framework.[352] As a result, crypto exchanges and wallet providers in Germany operate under clear regulatory supervision and standards, predating MiCA. With MiCA coming into force, Germany's national regime will transition into the EU-wide system, but its early move helped set groundwork and signal legitimacy for crypto markets.

4.4.1.2 Electronic Securities and DLT

German law traditionally required a paper certificate for issuing negotiable securities like bonds. Recognizing the inefficiency of this in a digital world, Germany passed the Electronic Securities Act (Gesetz über elektronische Wertpapiere) in 2021. This law allows the issuance of certain securities (initially debt securities, with plans to extend to stocks and funds) in purely electronic form, including via distributed ledgers, without paper.[353] In effect, it created a legal basis for security tokens. The act provides for a ledger maintained by an authorized administrator (for decentralized ledgers, likely a regulated entity) which serves as the "register" of the securities. This reform ended the monopoly of paper in German securities law, aligning it with blockchain innovation and making it one of the first major jurisdictions to explicitly accommodate DLT-based securities. It illustrates Germany's pragmatic approach: modernize specific areas of law (like securities formalities) to remove unnecessary obstacles to blockchain use.

4.4.1.3. Smart Contracts in Civil Law

Germany has not enacted a dedicated law on smart contracts' validity. The consensus among German legal scholars and the government is that existing contract law is generally sufficient. For a contract formed via or embodied in software code, the traditional German Civil Code (BGB) requirements, mutual intention (offer and acceptance), capacity, a definite agreement, etc., still apply.[354] There is ongoing academic debate about how to interpret a "declaration of intent" expressed in code and how to handle errors in smart contracts (for example, if a bug causes an outcome neither party intended). Some suggest that smart contract transactions could be viewed through the lens of automated electronic transactions, where the programmer's intent and the user's actions (like sending a blockchain transaction) indicate agreement. Notably, **Germany has not (yet) provided an official definition of smart contracts in law**, unlike Italy. The **ELI (European Law Institute) draft principles** to which German experts contributed suggest treating smart contracts as a new means of contracting but subject to existing contract doctrines for issues like interpretation and mistake.[355] In practice, German courts have had limited exposure to pure smart contract disputes so far. It is expected that they would try to uphold the validity of smart contracts by fitting them into the BGB framework, for example by construing the code's execution as fulfilling an obligation the parties

[350] Norton Rose Fulbright, supra note see nortonrosefulbright.com and nortonrosefulbright.com
[351] Ibid.
[352] Ibid.
[353] Linklaters, 'Germany Paves the Way for DLT Securities' (FinTechLinks Blog, September 2019) supra note see linklaters.com and linklaters.com
[354] Möslein, F., 2019. *Smart Contracts as Self-Help?*. In: SSRN Electronic Journal. Available at: https://papers.ssrn.com/ (Accessed: November 2025).
[355] ELI Principles, supra note, Principle 1.1.

agreed to in advance, or by seeing the initiation of a smart contract (like deploying code or sending funds to it) as an implicit agreement to be bound by the code's outcome.

4.4.1.4. IoT and Data

Germany implements the GDPR for privacy (supplemented by the Federal Data Protection Act for certain national-specific rules). German regulators have been particularly strict on IoT privacy at times, the earlier example of banning the Cayla doll as an **"espionage device"** came under the purview of telecom law and child protection, but echoes data protection concerns. On cybersecurity for IoT, even before any EU-wide IoT security law, Germany had guidelines and encouraged industry standards (the German Federal Office for Information Security (BSI) published baseline security requirements for consumer IoT). Now, with the EU Cyber Resilience Act forthcoming, Germany will have a uniform set of rules to enforce. Germany also actively supports research and standardization in Industrie 4.0 (the industrial IoT domain), which involves creating reference architectures that consider data governance, liability and interoperability, albeit mostly as industry standards rather than hard law.

In summary, **Germany's national approach** has been to **integrate IoT/DLT into existing legal structures**: updating financial laws to regulate crypto-assets under the same principles as other financial products, updating commercial law to allow digital forms (electronic tokens) where paper was once required, and relying on general contract and liability law to handle smart contracts and IoT interactions. This approach reduces legal uncertainty (by signalling that "yes, blockchain transactions are recognized by law", e.g. a blockchain entry can serve as a legal time-stamp in Italy's case, or a token is a security in Germany's case) without creating a wholly separate legal regime that might become obsolete as technology evolves. Germany's influence on EU policy has been noticeable, many elements of MiCA mirror practices Germany already had, and Germany's insistence on tech-neutrality is evident in EU legislation that avoids naming specific technologies (the AI Act, for example, does not single out any AI implementation but sets broad requirements).

4.4.2 Italy

Italy has distinguished itself by being one of the first European countries to **legally define blockchain and smart contracts** in its domestic law. This came via a 2019 amendment to a conversion law (Law No. 12 of 11 February 2019, converting a decree known as "Decreto Semplificazioni" 2018). **Article 8-ter** of that law provides formal definitions for *"tecnologie basate su registri distribuiti"* (distributed ledger technologies, DLT) and *"smart contract"*. According to the Italian law, a **smart contract** is defined as *"a computer program which operates on technologies based on distributed ledgers and whose execution automatically binds two or more parties according to effects predefined by those parties."* Furthermore, it states that smart contracts **fulfill the requirement of written form** under the law, **provided that** the parties have completed an electronic authentication as set out by technical standards yet to be determined.[356] In essence, Italy declared that an agreement in the form of a smart contract can be just as valid as a traditional written contract, as long as you can reliably identify the parties (through a digital identity process). This was a groundbreaking legal acknowledgment of smart contracts. However, it did raise questions: *Does every smart contract count as a "contract" under the Civil Code, or is it only a technical mechanism?* The law itself left some ambiguity. Commentators noted that while the law gives smart contracts functional equivalence to written contracts for form requirements, it **"is still unclear whether SCs fall within the definition of**

[356] Clifford Chance, Supra available at cliffordchance.com (last accessed 22 May 2025).

contracts under Italian civil law" (i.e., meeting all substantive contract criteria).[357] In practice, this likely will be resolved by courts or further guidance, but Italy's intent was clearly to **facilitate the use of smart contracts in commerce** by removing doubts about legal formality.

Alongside that, Italy's law also recognized that adding a record to a blockchain has legal effect. Specifically, **the upload of a document to a DLT system is deemed to satisfy the legal requirements of an electronic time stamp as per EU eIDAS Regulation**.[358] This means if someone stores a file or hash on a blockchain, it's as good as having a certified timestamp (once technical standards by Agenzia per l'Italia Digitale (AGID) are met). This provision is very useful for evidentiary purposes, it essentially validates blockchain as a tool for notarization or proof-of-existence with a presumption of integrity and timestamp. For example, if an IoT sensor reading (say temperature data relevant to a supply chain contract) is logged on a blockchain, that log could be legally recognized as a timestamped record of that data, helpful in case of dispute about when/what occurred.

Apart from this 2019 law, Italy relies on EU regulations for much of the IoT and DLT space (GDPR for privacy, etc.). Italy's Data Protection Authority (Garante) is known for being vigilant, for instance, it took active measures against uncompliant technologies (famously ordering a temporary ban on ChatGPT in 2023 until certain privacy measures were implemented, showing it will intervene on emerging tech to enforce GDPR). We might expect the Garante to issue guidelines on IoT deployments or blockchain and GDPR intersection in the future, given Italy's interest in the area.

In the fintech domain, Italy does not have a separate comprehensive crypto law (MiCA will cover that gap). It did set up a regulatory **sandbox for fintech** in 2021, which admitted some blockchain-based projects, indicating openness to innovation under regulatory oversight. Italy's financial regulators have also provided opinions: CONSOB (the securities regulator) has cautioned about ICOs/token sales and sometimes took action against fraudulent crypto schemes, but awaited MiCA for a full framework.

One area Italy has advanced is **public services using blockchain**. For example, several Italian notaries and local administrations experimented with blockchain for record-keeping, and the government launched projects (e.g., for tracking public funding). These are usually within existing law but show an administrative embrace of DLT.

On IoT, Italy has been active in EU discussions on connected devices but domestically follows EU directives. It implemented the EU's Radio Equipment Directive requiring basic cyber protections in wireless devices, and has supported initiatives for smart city standards. There is no single Italian IoT Act, but sectoral laws (like for smart meters, industrial equipment safety, etc.) incorporate IoT aspects.

Italy's approach is marked by **early legal recognition and enablement of blockchain/smart contracts**. By defining DLT and smart contracts in law, Italy removed uncertainty about their admissibility in legal processes, a smart contract can have full legal effect, and a blockchain record can serve as certified proof. The caveat is that technical standards by AGID were to detail how digital identity for parties should work; interim, presumably using a digital signature or Italy's SPID digital ID system would qualify as authenticating parties to a smart contract. Italy thus tied the concept of a legally valid smart contract to identification of parties, implicitly to prevent anonymous or

[357] Clifford Chance, Supra available at cliffordchance.com (last accessed 22 May 2025).
[358] Clifford Chance, Supra available at cliffordchance.com (last accessed 22 May 2025).

pseudo-anonymous code from binding parties without clarity on who they are (which aligns with broader EU policy requiring transparency in digital transactions). Italian scholars have largely welcomed the innovation while calling for more clarity on how traditional contract doctrines (formation, termination, liability for code errors) will apply; those issues likely will be sorted case-by-case.

As EU-level laws like MiCA and the Data Act come into play, Italy will integrate those. MiCA will regulate crypto asset offerings in Italy (which had some notable projects, given Italy's active blockchain startup scene). The Data Act's smart contract requirements will overlay on Italian businesses implementing IoT data sharing via smart contracts, and Italy may issue its own guidelines to reconcile those with its 2019 law.

4.5 Conclusion

Germany, Italy, and the UK each illustrate aspects of the broader European legal response to IoT and DLT. Germany shows the methodical integration of new tech into old laws; Italy shows early formal legislative recognition of new tech concepts; and the UK shows reliance on common law evolution and selective statutory intervention. Despite different methods, there is a convergent trend: all three jurisdictions acknowledge the legitimacy of smart contracts and crypto-assets in their legal systems and strive to update laws or interpretations to address novel issues (be it data privacy concerns, security, or contractual enforceability). They also all participate in international efforts (EU or otherwise) to set common rules. The European landscape is therefore gradually moving toward greater consistency, which is crucial for cross-border IoT and blockchain applications. The next chapter will build on these findings to explore future outlooks, how emerging trends (like AI integration) will pose new legal questions and what policy recommendations can ensure a harmonized and forward-looking regulatory framework for smart contracts and IoT in the years to come.

Taken together, GDPR and the Data Act close most privacy gaps, while MiCA and the CRA address financial-asset and security risks; however, overlap and enforcement gaps remain, especially for cross-border IoT deployments.

Chapter 5: Conclusion: Future Outlook and Recommendations

Having examined the current legal frameworks and comparative approaches in Europe, we turn now to the future. Chapter 6 discusses **emerging trends** at the intersection of IoT, DLT, smart contracts, and AI, and considers how these developments may challenge or change the legal landscape. It then offers **legal and policy recommendations** to address identified gaps or issues, aiming to guide regulators and stakeholders in crafting balanced solutions. Finally, it outlines a vision "towards a harmonized legal framework," where disparate regulatory threads converge into a coherent approach that accommodates technological innovation while safeguarding fundamental rights and societal interests.

5.1 Emerging Trends in IoT, DLT, and Smart Contracts

The pace of technological change in the IoT and blockchain space remains extremely rapid. Several key **emerging trends** are likely to shape the **next generation of smart contracts and related legal issues**:

5.1.1 Convergence of AI, IoT, and Blockchain ("AIoT")

IoT networks are increasingly augmented with artificial intelligence to analyze sensor data and make decisions, and blockchain/DLT is used to record and execute those decisions via smart contracts. This *tripartite convergence*, AI for decision-making, IoT for data collection/actuation, and blockchain for trust and automation, is giving rise to autonomous systems that can contract and transact with minimal human involvement. For example, consider a smart electricity grid: IoT sensors monitor energy usage; AI algorithms predict demand and set prices; smart contracts automatically execute energy trades between consumers' home batteries and the grid. Such scenarios are moving from pilot to reality. **Legal implication:** Accountability becomes a central question, if an AI-driven smart contract commits an error (e.g., an algorithmic trading contract misprices energy, causing losses), who is liable? Traditional tort and contract law will be tested, and concepts like *algorithmic accountability* and *AI explainability* (mandated by the EU AI Act for high-risk AI) will need to be integrated into contract performance and dispute resolution. Regulators might need to update notions of agency, an AI agent acting on behalf of a person or company, perhaps even revisiting the idea of electronic legal personality for autonomous systems (an idea the EU pondered in a 2017 resolution on robotics). For now, the trend is that AI will increasingly be the "brain" behind IoT-based contracts, which means laws governing algorithmic decision-making (like the AI Act's transparency and risk management rules) will directly impact how smart contracts must be designed and deployed.

5.1.2 "Smart" Legal Contracts and Automation of Legal Processes

There is a trend in the legal tech community toward *smart legal contracts*, essentially integrating natural language legal agreements with executable code. Rather than a pure code contract (which is hard for lawyers to read or verify), a hybrid approach is emerging: the contract is written in natural language (possibly with formal annotations), and certain obligations are automated via connected code (smart contract) that is linked to the text. This ensures that the intent of the parties (recorded in prose) and the execution by machines stay aligned. Projects in the UK, for instance, are developing standard templates for such hybrid contracts (e.g., in derivatives trading or insurance). Over time, we may see commercial contracts routinely containing clauses that *automatically self-execute* on predefined triggers (an oracle input from IoT, etc.). Legal implication: Courts and arbitrators will need

to interpret outcomes of self-executing clauses, if a smart contract component does something, is there any room to dispute its outcome or seek remedies like one would for breach of contract? The Law Commission recommended that the normal range of contract remedies (damages, rectification, etc.) should equally apply to smart contracts, but that presumes the issue can be brought to court (which might be difficult if the code already transferred funds or assets irrevocably). We might see new legal standards for code quality or duty to disclose code risks in contract formation. Additionally, proof and evidence in legal proceedings may increasingly involve blockchain records and logs of automated execution; legal professionals will need technical expertise or tools to parse these. This trend ultimately pushes the legal system toward greater use of *formal methods*, such as using algorithms to verify that a smart contract's code conforms to legal requirements (there is research into formally verifying smart contracts to prevent bugs or illegal behavior).

5.1.3 Increased Emphasis on Data Sovereignty and Decentralized Identity

As IoT devices generate oceans of data, individuals and businesses are concerned with who owns or controls that data. A trend is emerging for self-sovereign identity (SSI) and personal data stores, often using blockchain to give users direct control over credentials and IoT-generated personal data. For example, an individual may carry a digital identity wallet that stores verified claims (driver's license, health records) and can interact with IoT systems (a smart car or a medical IoT device) without constantly referring back to centralized databases. Similarly, devices themselves might have blockchain-based identities and log data to decentralized storage that user's permission. The EU has been encouraging this through its eIDAS 2.0 framework, which will establish European Digital Identity wallets. Legal implication: If this trend succeeds, privacy and data protection compliance could become more inbuilt (because users keep their data locally and only share minimal proofs as needed, aligning with GDPR's data minimization). However, it also means laws must adapt to a world where data isn't always held by a clear "controller" entity, the individual could be in charge of their data transactions. Liability questions arise if erroneous or fraudulent data is shared peer-to-peer. Additionally, SSI often leverages cryptography and blockchain for trust (DID, Decentralized Identifiers, and Verifiable Credentials standards). Laws around electronic signatures and authentication (like eIDAS) will expand to recognize these new forms of identity assertion. Europe is already moving to legally recognize attributes attested in digital wallets as equivalent to physical ID, which by extension supports legally significant IoT interactions (e.g., a scooter rental IoT unlocking when presented with a user's digital driver's license from their wallet).

5.1.4 Regulatory Technology (RegTech) and Compliance Automation

On the industry side, there's a trend to use smart contracts and blockchain for regulatory compliance purposes. For instance, *"RegTech"* solutions might automatically monitor transactions and enforce rules (a simple example: a smart contract that won't allow a transfer of a token if the receiving wallet has not passed KYC checks, thereby complying with AML regulations). IoT can feed into this too, for product compliance, imagine a factory IoT system linked to a blockchain that only permits a machine to operate if the required safety inspection smart contract shows it's up to date. Regulators themselves are exploring blockchain for oversight (e.g., tax authorities considering blockchains for VAT tracking). Legal implication: If compliance is embedded in code, there is both an opportunity and a risk. Opportunity in that real-time compliance could reduce violations (the code simply won't do what's illegal). Risk in that inflexible code might cause operations to halt or create conflicts if regulations are open to interpretation, what if the code's logic doesn't align with a regulator's later interpretation of a rule? One can foresee the need for mechanisms to update or override smart

contracts in light of regulatory changes (hence the Data Act's kill switch notion, which could apply similarly to compliance logic). Regulators might also demand access nodes or backdoors in certain blockchain systems to audit or intervene, raising debates on decentralization vs. oversight. Standard-setting bodies might develop certified smart contract templates for compliance in areas like consumer protection (e.g., a smart contract for a product recall that automatically notifies and refunds purchasers when triggered). This trend effectively is regulators and industry collaborating on *machine-readable and enforceable regulations*, a concept that sits at the frontier of administrative law and technology.

5.1.5 Global Harmonization vs. Fragmentation

As the EU implements MiCA and the AI Act, other jurisdictions (US, China, etc.) are also moving on these fronts, but not necessarily in harmony. We see a potential split in the global approach: the EU tends towards comprehensive, rights-driven regulation; the US has more sectoral and litigation-driven oversight (with some states enacting their own laws for data, crypto, or AI); China heavily state-controls and even directly exploits data from IoT/AI (with an emphasis on government access and censorship). For companies deploying IoT and blockchain globally, compliance with multiple regimes will be a major challenge. For example, an autonomous vehicle IoT system in the EU must follow AI Act rules (like risk assessment, data governance), whereas in the US it might face product liability suits and patchwork state laws, and in China it must implement government-mandated sensor data sharing with authorities. This state of affairs could persist for some time. However, pressure for harmonization will grow, especially in cross-border contexts (data flows, international trade of IoT devices, global blockchain networks). Already, there are discussions in organizations like the OECD on AI principles (the OECD AI Principles influenced the EU AI Act and also the US and others). The G20 and G7 have put digital issues on the agenda (e.g., G20's discussion on crypto regulations and AI governance). Legal implication in this regard is, we may eventually see *treaty-based* or mutual recognition frameworks bridging regimes. Perhaps an international convention on crypto-assets (similar to the Hague Securities Convention) could emerge to recognize each other's legally registered tokens or enforcement of judgments relating to digital assets. Or an update to private international law rules (like Rome I/Rome II in the EU) to specifically address which law governs a smart contract spanning multiple jurisdictions. These are speculative, but the trend lines suggest that the next decade will involve not just national or regional rule-making, but attempts at international alignment, or at least interoperability, of laws for the digital economy.

In light of these trends, it is clear that simply relying on today's laws (as we examined in Chapter 5) will not be sufficient. Proactive steps are needed to adapt legal frameworks. That is the focus of §6.2, which provides recommendations to policymakers and industry on how to address present and future challenges.

5.2 Legal and Policy Recommendations

Based on the analyses in previous chapters and the emerging trends outlined above, this section offers a set of **recommendations** for legal and policy measures. The goal of these recommendations is to ensure that legal frameworks keep pace with technological innovation, mitigate risks posed by IoT and DLT-based systems, and promote a coherent approach that balances **innovation, consumer protection, privacy, and security**. These recommendations are addressed to EU legislators, national governments, and regulatory agencies, as well as industry stakeholders where self-regulation can play a role.

5.2.1 Develop Clear Guidance and Standards for Smart Contracts

To bridge the gap between traditional legal contracts and code, it is recommended that official guidance or even a *"Smart Contract Handbook"* be developed (perhaps by the European Commission in collaboration with standard bodies like CEN-CENELEC or international groups). This would provide clarity on issues such as: how to interpret smart contracts in legal disputes, best practices for drafting hybrid contracts (text + code), and risk allocation for coding errors. It could incorporate principles from the ELI's work[359] and the UKJT statement, thereby giving them broader legitimacy. Additionally, technical standards (akin to those AGID in Italy must issue) should set baseline requirements for **secure coding** of smart contracts, for instance, mandating audit trails, fail-safe mechanisms, and perhaps multi-signature controls for critical actions. By standardizing what a "well-behaved" smart contract looks like, courts and regulators will be more comfortable trusting their outcomes. These standards can also support **formal verification** efforts, reducing bugs that could cause legal disputes.

5.2.2 Clarify Liability in Autonomous IoT Systems

With IoT devices and AI making decisions, legal clarity on liability is crucial to ensure victims can be compensated and companies have predictability. Policymakers should consider updating liability regimes specifically for IoT/AI contexts. The EU is already on this path (drafting the AI Liability Directive and revising the Product Liability Directive to include software and AI). These efforts should be prioritized and refined. For example, the law could impose a duty on IoT manufacturers to provide a software bill of materials and update support, failing which, if an insecurity causes harm, strict liability could apply. For AI-driven decisions, a rebuttable presumption of causality could be introduced (as in the draft AI Liability Directive which was withdrawn) to ease the burden on plaintiffs who cannot easily explain complex algorithms.[360] It's also worth exploring the concept of insurance for autonomous systems: regulators might encourage or require operators of high-risk IoT/AI (like autonomous vehicles, drones, etc.) to carry liability insurance or contribute to compensation funds, smoothing out the risk and ensuring quick victim compensation regardless of fault intricacies. Clear liability rules will also incentivize the industry to maintain high safety standards.

5.2.3 Enhance Privacy Protections Through Technical Measures and Enforcement

To address the immense privacy challenges of IoT, regulators should double down on **Privacy by Design** enforcement. Data protection authorities (DPAs) should publish IoT-specific compliance guidance (several have, but an updated EU-wide EDPB guidance on IoT would be valuable). This could include recommended technical measures: e.g., local processing on devices to minimize cloud data, granular consent mechanisms, and anonymization techniques. The DPAs should also use their powers to conduct periodic audits of IoT ecosystem players (like smart appliance manufacturers or wearable makers) to ensure GDPR compliance is not just on paper. If needed, the European Commission could consider delegated acts under GDPR to declare certain IoT practices unfair or non-compliant (for example, perhaps banning collection of certain data types by default in consumer IoT unless explicitly needed). Privacy seals or certifications for IoT products (voluntary but encouraged) could help consumers choose devices that meet high privacy standards. In addition, as data portability and data sharing (via the Data Act) increase, individuals will need user-friendly tools

[359] ELI Principles, supra note see europeanlawinstitute.eu
[360] BCLP, *AI regulation tracker*, supra note see bclplaw.com

to manage their IoT data. Regulators might foster the development of personal data management platforms, possibly through public-private partnerships, that let an average user see and control all their IoT devices' data flows in one place (an analogy is how the EU's open banking initiative led to fintech apps where users manage all finances; similarly, there could be IoT data wallets managing consents and sharing). Empowering users in this way complements legal enforcement by making privacy management practical.

5.2.4 Strengthen IoT Security Requirements and Oversight

Building on efforts like the UK PSTI Act and the EU Cyber Resilience Act (CRA), all jurisdictions should implement **baseline security requirements for IoT devices**. Regulators in Europe should expedite the adoption of the CRA and ensure it covers not just consumer devices but also industrial IoT where applicable. Key measures (no default passwords, secure update mechanisms, vulnerability disclosure) should be mandatory.[361] To enforce this, market surveillance authorities should have the power to **conduct penetration testing on random IoT products** on the market and penalize those that fail. Certification schemes (like the EU's cybersecurity certification framework) should be promoted, e.g., an EU security label for IoT (akin to an "energy efficiency label" but for cyber security) would allow consumers to gauge a device's security level at purchase. Moreover, critical IoT systems (like healthcare or smart grid devices) could be subject to prior approval or audits before deployment, similar to how medical devices are certified. Cyber-insurance incentives could also help: insurers might offer better premiums to companies whose IoT products pass certain security certifications, indirectly pushing compliance. Another recommendation is establishing an EU-IoT Emergency Response Team, perhaps within ENISA, to coordinate responses to major IoT vulnerabilities (like the Mirai botnet incident) and issue rapid guidance (e.g., if a class of devices is found vulnerable, coordinate recalls or patches). Security is a precondition for both privacy and safety; thus, these measures are foundational.

5.2.5 Foster Cross-border Legal Interoperability and Sandbox Collaboration

Given the global nature of IoT and blockchain, regulators should work towards mutual recognition and interoperability of legal regimes. At the European level, this means continuing to harmonize internally (through regulations rather than directives in areas like data governance, as is happening). Externally, the EU should engage in dialogues with other countries on standards for crypto-assets, AI, and IoT. For instance, an EU-US agreement on AI governance principles (building on the OECD AI principles) could help align approaches and avoid a transatlantic divergence that complicates compliance for companies operating in both markets.[362] Also, efforts like the Global Digital Compact at the UN level or bilateral trade agreements can incorporate provisions on digital trust, free flow of data with trust, etc. A concrete tool to improve understanding is Regulatory Sandboxes, the EU has launched a European Blockchain Sandbox that brings together regulators and companies to examine innovative use cases in a safe environment. This is excellent for identifying legal uncertainties and best practices. Expanding this concept, perhaps a Pan-European IoT/AI Sandbox could be established, allowing multi-country experiments (for example, testing a connected car service across France, Germany, Italy with regulators from all three observing to see how laws interact). The lessons from such sandboxes should feed into lawmaking. By collaboratively "test-driving" novel applications,

[361] securityaffairs.com securityaffairs.com
[362] BCLP, *AI regulation tracker*, supra note see bclplaw.com

regulators can harmonize interpretations of laws informally and recommend formal legal changes if needed.

5.2.6 Promote Education, Awareness, and Multidisciplinary Expertise

Laws and regulations are only as effective as the understanding and compliance they engender. Given the complexity of IoT and DLT, it is critical to **educate stakeholders**. Governments and bar associations should run training programs for judges and lawyers on technological concepts like blockchain workings, IoT data flows, and AI decision-making. Likewise, technologists and entrepreneurs need basic legal literacy, incubators and accelerators could include legal compliance modules. Interdisciplinary bodies (like tech-law forums) should be supported to produce research and recommendations. For consumers, awareness campaigns about IoT privacy (similar to past campaigns about cookie consent or online scams) can help individuals exercise their rights and adopt secure practices (like changing default passwords, which, even if mandated, relies on users to actually set a new password). Empowering users and SMEs with knowledge will drive a culture of "compliance by design." Additionally, regulators should hire or consult technical experts: *e.g.* data protection authorities could have an IoT technologist on staff to evaluate new devices, and financial regulators should have crypto/DLT specialists. This ensures enforcement keeps up with the industry.

5.2.7 Encourage Ethical and Human-Centric Innovation

Policymakers should articulate that the ultimate purpose of regulating IoT, AI, and smart contracts is to enhance human well-being and uphold ethical values. They should encourage frameworks like "Ethics by Design" for AIoT systems (complementing Privacy by Design and Security by Design). This could involve voluntary ethics certifications (for example, an AIoT system that an independent board has reviewed for bias, fairness, and transparency). At the EU level, the upcoming AI Act already requires high-risk AI to have oversight and accountability, which is a step in this direction. But beyond compliance, fostering an industry ethos of responsibility is key. Governments can fund or endorse pilot projects that use IoT and blockchain for social good, *e.g.*, supply chain transparency for fair trade (with IoT tracking and blockchain recording proof of origin), or environmental monitoring via IoT with open-data ledgers to fight climate change. By highlighting positive use cases, regulators implicitly create a benchmark for ethical use. Conversely, they should be vigilant about potential abuses: e.g. the use of blockchain in illegal activities or IoT for mass surveillance. Strong enforcement against misuse (cybercrime prosecutions, fines for abusive data practices) will deter the dark side of these technologies.

These recommendations, taken together, aim to create a **robust yet flexible regulatory environment**: one that reduces legal uncertainty (through clarity and harmonization), protects individuals (through privacy, security, and liability rules), and still leaves room for innovation (through sandboxes, standards rather than overly prescriptive rules, and international cooperation to avoid fragmentation). Implementing them will require effort from both public and private sectors, but the payoff is a safer, more trustworthy IoT and blockchain ecosystem that can realize its full potential in society.

5.3 Towards a Harmonized Legal Framework

Looking ahead, the trajectory of law and technology suggests an eventual coalescing of various regulatory strands into a more harmonized legal framework for IoT, DLT, smart contracts, and AI, not only within Europe but internationally. In this concluding section, we sketch what such a harmonized

framework might entail and the principles that should underpin it, drawing on the discussions and recommendations above.

Key Attributes of a Harmonized Framework

5.3.1 Coherence Across Domains (Data, Finance, AI, etc.)

Rather than treating data protection, financial regulation, AI ethics, cybersecurity, and consumer protection as separate silos, a harmonized framework would ensure these regimes work in concert when applied to IoT/DLT systems. For example, when an autonomous smart contracting system is deployed, it should simultaneously comply with data privacy (GDPR/UK GDPR), AI requirements (EU AI Act or analogous principles), financial regulations (if it deals with payments or tokens, e.g. MiCA), and liability standards, without contradictions. This might involve cross-references in legislation (the AI Act explicitly not affecting GDPR rights,[363] etc.) and joint regulatory guidelines for overlap areas. The EU is moving in this direction by issuing horizontal laws (like the Digital Services Act and Digital Markets Act for platform governance) that interact with vertical laws. A truly coherent approach could be encapsulated in a "Digital Responsibility Act", a theoretical instrument that consolidates core requirements for any digital/automated system (transparency, accountability, safety, fairness), regardless of whether it's IoT, AI, or blockchain. While such an omnibus law may or may not materialize, the concept is that an operator of these technologies has one clear checklist of fundamental legal duties, easing compliance and enforcement.

5.3.2 Interoperability and Mutual Recognition

Harmonization means that different jurisdictions recognize or align with each other's rules to the extent possible. In Europe, this is achieved by regulations that are directly applicable and by tying national laws to EU standards (as Italy did by referencing eIDAS for blockchain timestamps[364]). Globally, efforts like the *ISO standards for blockchain and IoT* provide technical common ground. A harmonized legal framework would push for mutual recognition of equivalent safeguards: for instance, if an IoT device is certified secure under EU standards, other countries would accept that certification for market access, and vice versa. The same for data protection, mechanisms like adequacy decisions or the new EU-US Data Privacy Framework attempt to bridge gaps so data can flow. In the future, perhaps a global digital charter under UN auspices could set baseline consensus (this is aspirational, but elements exist in documents like the OECD's internet policy principles, G20 AI principles, etc.). In trade agreements, including chapters on digital trade that ensure non-discriminatory treatment of electronic contracts and protection of online consumers can further harmonize expectations. Ultimately, the aim is to reduce regulatory fragmentation, so that innovators don't have to completely redesign systems for each legal regime and individuals' rights are protected consistently everywhere.

5.3.3 Dynamic and Adaptive Regulation

Technology evolves quickly, and a harmonized framework must be able to adapt. This calls for agile regulatory techniques, such as iterative rule-making (regulations that mandate periodic review and updating of technical requirements), use of regulatory sandboxes (to test and then incorporate new ideas into regulation), and perhaps algorithmic regulation (where some oversight tasks are automated,

[363] Osborne Clarke, available at osborneclarke.com (last accessed 22 May 2025).
[364] Clifford Chance, Supra available at cliffordchance.com (last accessed 22 May 2025).

for example, continuous monitoring of compliance via blockchain audit trails). The law itself may incorporate technology, for instance, *machine-readable law* where legal rules (like VAT rates, or consumer contract terms requirements) are published in a format that smart contracts can consume in real-time. The UK and Singapore have experimented with such ideas in financial regulation. In a harmonized future, one could imagine smart contracts having an integrated library of global legal rules to check against (a long-term vision of merging law and code). While full automation of law is distant, moving toward clear, codified standards is part of harmonization. Additionally, regulators might increasingly rely on soft law and co-regulation: industry codes of conduct (approved by authorities) can fill gaps more quickly than formal laws. For example, an industry code on IoT ethical use could be recognized and enforced by a regulator, updating faster than legislation could. This interplay between hard law and soft standards will be crucial for adaptation.

5.3.3 Centered on Fundamental Rights and Values

No matter how advanced the technology, a harmonized framework must be grounded in core **principles and rights**. Europe's approach, prioritizing human dignity, privacy, democracy, and consumer rights, should continue to guide the global conversation. Harmonization should not mean diluting high standards to the lowest common denominator; rather it should mean raising global standards by consensus. For instance, the right to privacy as enacted in GDPR is becoming a reference point worldwide (with many countries adopting similar laws). A harmonized future might see privacy treated akin to environmental or labor standards, a fundamental norm that trade partners agree to uphold. Likewise, AI ethics (no unlawful discrimination by algorithms, etc.) might become universal norms. Ensuring that the legal framework keeps humans "in the loop" or at least "in oversight" of critical automated decisions is important to prevent a dehumanized legal environment. Thus, even as smart contracts automate transactions, the legal system should ensure recourse to human judges and due process when disputes or rights issues arise. Harmonization efforts should explicitly articulate these values to avoid solely technical or economic focus.

5.3.4 Framework in Action, A Scenario

To illustrate, consider a future cross-border scenario: an autonomous electric vehicle owned by a German company, operating in France, providing taxi services coordinated by an AI, with payments and governance handled via blockchain tokens. In a harmonized legal framework, the following would ideally be true: The vehicle and AI adhere to EU-wide safety and AI regulations (no matter it's in France, it's the same standard due to EU law); the personal data of passengers is protected under the same GDPR rules in both countries; the smart contract that manages payments is recognized as valid in both Germany and France courts equally (perhaps via a uniform law on digital transactions); if something goes wrong (an accident or payment dispute), liability is sorted out under clear rules (maybe a convention on autonomous vehicle liability or applying harmonized product liability principles); and if the German company's token system is legally a securities offering, that token is tradable across EU with a single prospectus (thanks to MiCA's passporting). If a similar vehicle goes to the UK or US, mutual recognition agreements could ensure it's not facing completely new requirements but rather an equivalent regime (for example, UK accepts EU AI Act compliance as meeting its AI governance expectations, and the EU in turn recognizes UK-certified IoT security labels, etc.). This kind of fluid operation, with legal clarity and consistency, is what harmonization strives for.

To approach this vision, continued international dialogue and cooperation are necessary. The chapter 5 comparison shows the UK and EU approaches already sharing much DNA despite divergence in legal mechanism; other countries like Japan, Canada, and Australia also align with this ethos. Bodies like the G7 could champion a *"Trusted Tech"* framework among like-minded nations, which then could be expanded.

Finally, harmonization should also consider the voices of stakeholders, consumers, businesses (startups to big tech), and civil society. Multi-stakeholder engagement in forming rules (as was done in drafting the EU AI Act, consulting many parties) leads to more buy-in and easier harmonization since the rules address real concerns.

5.4 Conclusion of Future Outlook

No matter what kind of conclusion I craft, I believe it will still fall short of including everything I have put into this work. But let's try: The legal future of IoT, DLT, and smart contracts is undoubtedly challenging as technology outpaces legislation. Yet, the research and discussions in this thesis demonstrate that lawmakers are not passive, significant strides have been made to adapt laws (from GDPR to MiCA to national statutes) and there is a roadmap for further evolution. By embracing the recommendations above and working towards a harmonized framework grounded in fundamental rights, we can navigate the next wave of technology, AI-enabled smart contracts, pervasive IoT, and beyond, with confidence that the rule of law and innovation go hand in hand rather than in conflict. In achieving that balance, Europe can continue to play a leading role, modeling how to responsibly integrate new technologies into society under a robust legal umbrella, and influencing global norms for the digital age.

Annexure

The Sustainability Dimension of EU Digital-Contracting Infrastructures

I have very well considered the sustainability aspects in my dissertation.

The European Green Deal commits the Union to climate-neutrality by **2050** and explicitly recognises digitalisation as both *enabler* and *risk* for that goal.[365] Internet-of-Things (IoT) devices expand material resource use (rare-earth metals, short hardware lifecycles), while distributed-ledger infrastructures, especially proof-of-work chains, can be energy-intensive. Conversely, the same technologies can optimise energy grids, cut logistics emissions, and create high-fidelity "product passports" that underpin circular-economy models. A sustainability lens is therefore indispensable to any governance framework for smart contracts and autonomous IoT systems.

I. Regulatory Cornerstones

A. Energy efficiency & blockchain

Under the *Digitalising the Energy System* action plan, the Commission is developing an **EU energy-efficiency label for blockchain applications, due in 2025**.[366] Methodologies are being drafted with the European Green Digital Coalition to measure the *net* environmental impact of digital solutions, recognising that low-carbon consensus mechanisms (proof-of-stake, BFT variants) and off-chain data aggregation can drastically curb emissions.

B. Net-Zero Industry Act (NZIA)

Regulation (EU) 2024/1735 and its 2025 implementing guidelines frame "net-zero strategic projects", adding *resilience* and *sustainability* criteria to public-procurement decisions for digital infrastructure (e.g. edge datacentres supporting IoT/AI).[367] Projects that demonstrably reduce lifecycle GHG emissions or facilitate renewable-energy integration gain preferential treatment.

C. Corporate Sustainability Reporting Directive (CSRD)

Companies exceeding CSRD thresholds must disclose, from the **2024 financial year (reports published 2025)**, Scope 1-3 emissions and *digital-resource use* (data-centre energy, device turnover).[368] For blockchain-enabled platforms, this will force transparent reporting of consensus-related electricity demand and e-waste flows from device fleets.

D. Supply-chain due-diligence law

Parallel negotiations on the Corporate Sustainability Due Diligence Directive (CSDDD) reveal pressure to narrow company coverage, yet even a trimmed-down text is expected to mandate environmental-harm prevention in value chains.[369] Smart-contract provenance tools may become de facto compliance infrastructure, provided they themselves meet eco-design norms.

[365] European Commission, *Green Digital Policy* webpage.
[366] Commission, *Digitalising the Energy System, Key Actions*, announcing a blockchain energy-efficiency label by 2025.
[367] Commission Implementing Decision (C 2025) 9035 on NZIA strategic-project criteria.
[368] Commission, *Corporate Sustainability Reporting* portal (first reports due 2025).
[369] Ongoing trilogue debates on the supply-chain law thresholds (FT report).

II. Implications for IoT-DLT Smart-Contract Ecosystems

A. "Sustainable-by-Design" Code & Hardware

The forthcoming cyber-resilience and IoT-eco-design standards will oblige developers to select energy-efficient consensus models and modular device architectures that extend hardware lifespans. Aligning smart-contract logic with NZIA sustainability criteria can unlock preferential market access and green-public-procurement opportunities.

B. Lifecycle Transparency

Blockchain product passports, linking serialised IoT sensor data to immutable ledgers, enable verifiable tracking of recycled content, repair events, and carbon intensity. CSRD-mandated disclosures make such granular data legally valuable; however, data-storage choices must respect *data-minimisation* and avoid locking high-volume sensor streams on-chain.

C. Incentive Alignment

Smart contracts can operationalise EU carbon-pricing signals: e.g., dynamic freight contracts that adjust payment if measured emissions exceed Fit-for-55 thresholds. Energy tokens tied to real-time IoT metering can reward low-carbon edge computing or penalise inefficient nodes, embedding sustainability objectives directly into contractual performance.

D. Due-Diligence Automation with Caution

While automated supply-chain audits promise cost savings, Annex III of the draft CSDDD still demands human rights– and environment-impact *expert* assessment. Automated scoring tools must therefore offer *explainable* metrics and allow manual override, lest purely algorithmic decisions violate Article 22 GDPR.

III. Recommendations for Thesis Stakeholders

A. Adopt a dual-materiality risk matrix when drafting smart-contract templates: assess not only financial exposure but also environmental externalities over the code-and-device lifecycle.
B. Embed an emergency "eco-kill switch", mirroring the Data Act's safeguards, for contracts whose execution could cause excessive resource consumption or breach regulatory caps.
C. Leverage CSRD data pipelines: design DLT systems that export sustainability metrics in ESRS-compatible formats, turning compliance overhead into strategic ESG intelligence.
D. Champion open eco-metrics standards within sector consortia to avoid proprietary "green-washing" methodologies and ensure comparability across blockchains and IoT platforms.

IV. **Conclusion:** EU sustainability law is rapidly becoming as pivotal to digital-contract governance as privacy or cybersecurity. Integrating these requirements at the architectural level, code, consensus, device design, and data governance, will not only future-proof autonomous contracting systems but also position them as catalysts for the Union's twin *green and digital* transition.

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