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Analytical insights into the global digital ecosystem (DGTES)

Overview and analysis

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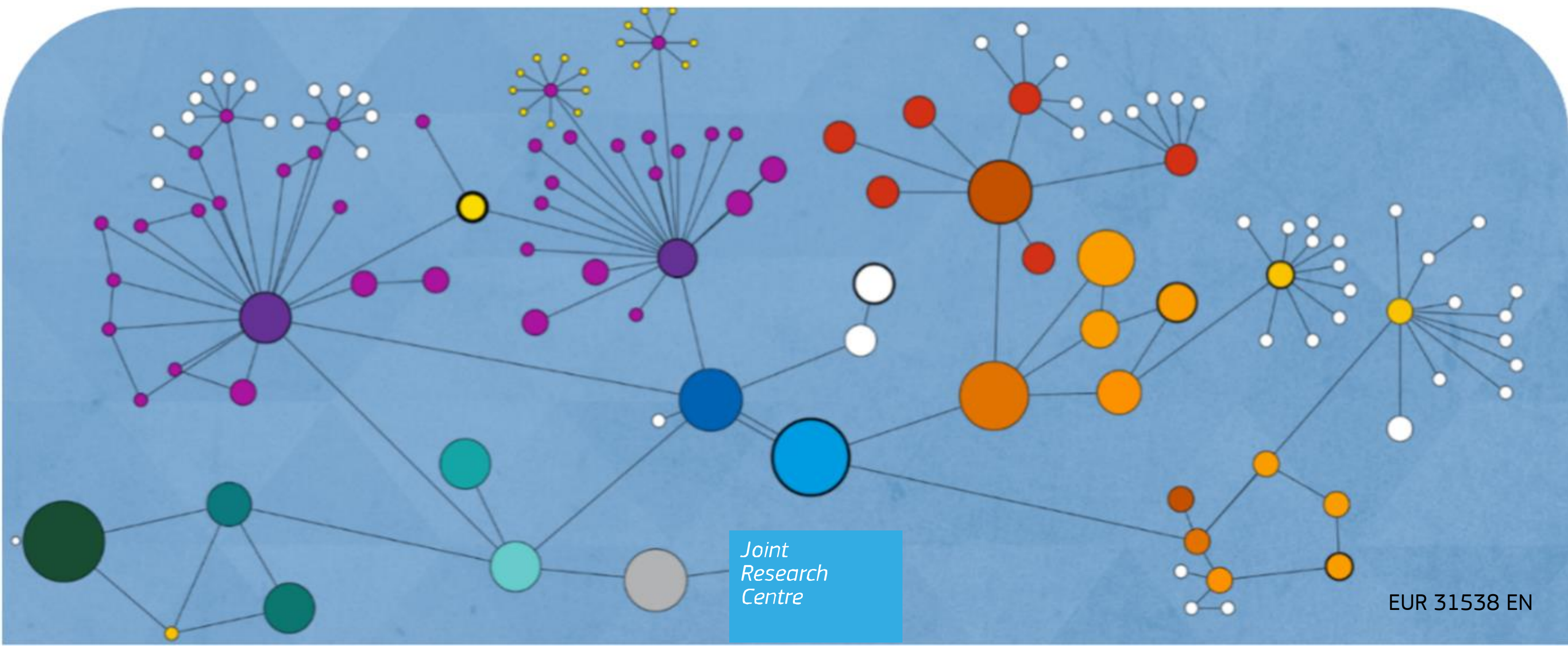

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Contents

Abstract

This report presents and discusses the results of the application of the Techno-Economic ecoSystem (TES) methodological approach to the analysis of the digital ecosystem (DGTES). At the same time, the report reflects on the advantages of using DGTES as a tool to investigate the European Union (EU)'s role in the global digital landscape and to inform related policies.

Relying on a selection of indicators and metrics obtained from the DGTES database, this report offers a general overview of the global digital ecosystem over the time period 2009-2022. Besides describing its main features and structure, it provides a first mapping of the digital ecosystem through two main dimensions, geographical and technological. Keeping the policy perspective in mind, the report also presents examples of how the network structure of the DGTES database can be exploited to provide analytical insights on policy-relevant questions. In particular, it offers an original analytical look at digital leadership from the angle of strategic autonomy, dependencies and capabilities, giving examples for the critical digital subdomains of cybersecurity, autonomous systems, and raw materials. It also underlines the role of EU funding programs in shaping the capabilities needed for a vibrant and globally competitive European digital ecosystem.

Feeding into a broader discussion on EU's competitiveness and digital sovereignty, the presented DGTES-based analysis of the digital ecosystem contributes to supporting policy making and policy initiatives aiming at steering the digital transformation and fostering the development of a flourishing digital ecosystem in Europe.

This report builds on the JRC Technical Report "An analytical approach to map the digital ecosystem (DGTES)", which describes in detail the application of the TES methodology to the analysis of the digital ecosystem, explains the steps leading to the generation of the DGTES graph database, and introduces related metrics and indicators.

Foreword

Digital transformation is reshaping the boundaries of technological, social and economic development. In the current phase of accelerated technological change, digital leadership is an essential condition to secure the European Union's competitiveness and a leading role in the global technological and industrial landscapes.

Europe's ability to lead the twin transition and its present and future prosperity depends on this.

In times of uncertainty and changing global scenarios, digital leadership cannot remain an aspirational slogan. On the contrary, it needs to be the North Star for Europe's economic and industrial ambitions, and the core of a policy agenda grounded on anticipating, monitoring and steering the digital transformation. Attaining EU's digital leadership would ultimately depend on finding the right balance between the need to assess our strategic vulnerabilities and reduce our dependencies. The EU needs to leverage on its strategic partnerships to prepare for, face and overcome the challenges of the twin transition.

This report contributes to the debate on EU's digital leadership from the perspective of the digital ecosystem, which is the heart and engine of digital transformation. The digital ecosystem lies at the intersection of EU's digital and industrial policy and at the centre of the European policy stage, marked by far-sighted policy initiatives like the Digital Decade. This requires us to look at the digital ecosystem from multiple analytical perspectives, integrating its technological and industrial nature.

Now more than ever, understanding the digital ecosystem has become an urgent and policy relevant exercise. The analysis presented in this report opens up new perspectives to look at the twin transition and monitor its course, with several policy implications to foster the digital transformation and make Europe a more sustainable, digital, resilient and globally competitive economy. At the same time, it feeds the discussion on strategic autonomy and capabilities, contributing to the definition of a policy roadmap for EU's digital leadership.

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Preface

This report has been prepared within the framework of the project IDITES (The Impact of Digital Transformation on the Economy and Society) implemented by the Joint Research Centre (JRC)'s Digital Economy Unit. It is a key contribution to the JRC's portfolio on Monitoring and Shaping the Digital Transition.

The project seeks to meet its objectives by providing appropriate metrics to measure and monitor critical aspects of the digital transformation and of emerging digital technologies within their economic and technological ecosystems, and by investigating technology-driven innovation and change in a global perspective. More specifically, the work presented in this report builds on the experience of the 'Prospective Insights on ICT R&D' (PREDICT) project, which aimed at providing new methodologies and indicators to measure and analyse the digital transformation and the evolution of emerging technological domains that are likely to impact future economic trajectories.

This work continues the thread of research on the Techno-Economic ecoSystems (TES) methodological approach conducted within the framework of the PREDICT project.

TES is an analytical approach originally developed to target technology-based dynamic segments that play an important role in the digital transformation but tend to elude official statistics or standard classifications. The lack of indicators adequate to capture the pervasiveness and evolution of emerging technologies raises a call for new analytical instruments and metrics to better inform policies for a more sustainable, digital, resilient and globally competitive European economy. TES offers a suitable tools to describe and analyse emerging digital technologies, whose pervasiveness and evolution are better assessed using metrics and indicators capable to account for their holistic nature and complex structure.

This report builds on the JRC Technical Report "An analytical approach to map the digital ecosystem (DGTES)" (Calza el al., 2022), which describes in detail the application of JRC's TES methodology to the digital ecosystem, explaining the steps leading to the construction of the DGTES graph database and introducing metrics and indicators.

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Executive summary

Policy context

Digital technologies have been reshaping the way our societies and economies operate, produce and deliver value. Their rapid evolution is driving the digital transformation, which is leading to a deep shift of market and non-market activities and processes by means of digital technologies, implying fundamental changes in the horizon of technological, social and economic development. Achieving a successful, efficient and fair digital transformation is key for Europe to be able to lead and enhance the twin transition – thus, to ensure Europe's present and future prosperity.

Digital transformation occupies a central place in the European Union (EU)'s policy landscape. It represents one of the six European Commission's priorities for the period 2019-2024 and lies at the intersection of major EU policy initiatives and programmes - such as the Digital Compass and the Digital Decade Policy Program, the European Green Deal, the New Industrial Strategy, the New Innovation Agenda. In line with the vision of a safe and competitive European digital future, the Digital Services Act (DSA) and Digital Markets Act (DMA) have recently been added to EU digital regulation.

While recognizing the pervasiveness of digital technologies, all these policy initiatives reflect a growing support for a policy roadmap to enhance Europe's digital leadership. In a global scenario of accelerated technological changes and growing scientific, technological and productive interconnections, digital transformation and competitiveness have, indeed, become increasingly related. Digital leadership has become essential for the EU's current and future competitiveness. In fact, only mastering the emerging digital technologies would grant the EU's competitiveness and a leading role in the technological and industrial landscape, allowing to achieve the EU's industrial and technological ambitions. This holds especially for what concerns technological domains and sectors that are critical for EU's strategic autonomy, thus of crucial importance for the twin transition.

The digital ecosystem as powerhouse of the digital transformation

Enhancing digital leadership and leveraging a successful twin transition calls for a better understanding of all forces driving the digital transformation. In this regard, the digital ecosystem lies at the heart of the digital transformation. The digital ecosystem can be defined as a techno-economic space where digitally-relevant activities take place in an interconnected way and with the participation of heterogeneous actors pursuing different goals. Here digital technologies emerge though processes of creation, production and exchange, triggered and moulded by interactive relations and interlinkages across heterogeneous actors. The digital ecosystem represents the engine of the evolution and uptake of digital technologies: exploring the digital ecosystem and monitoring its evolution is, therefore, key to understand and leverage the digital transformation in all industrial ecosystems and to understand the overall path of technological evolution. Thus, analysing the digital ecosystem has become a necessary, urgent and policy-relevant exercise.

About the report: objectives and audience

The inadequacy of traditional indicators and metrics in capturing the pervasiveness and the rapid evolution of emerging digital technologies from an "ecosystem perspective" raises a call for novel analytical instruments to explore and better understand the digital ecosystem in its whole complexity. The Digital Techno-Economic ecoSystem (DGTES) is the application of the Techno-Economic Segment (TES) analytical framework to the analysis of the digital ecosystem. This approach responds to this call for an appropriate scientifically-based and policy relevant analytical tool to characterize, explore and better understand the digital ecosystem within the scope of the digital transformation.

DGTES is designed to generate a graph database that serves to identify players engaging in different types of activities related to the production and exchange of knowledge, goods or services in the digital realm. The DGTES database allows mapping the digital ecosystem and analysing its elements, structure, interconnections and features from a holistic, multidimensional and policy-relevant perspective.

This report discusses the application of DGTES to map the global digital ecosystem and explore it from multiple analytical angles, while keeping the policy perspective in mind. More specifically, this report pursues three main goals:

- presenting a first overview of the digital ecosystem over the time period 2009-2022;

- mapping the global digital ecosystem through its geographical and technological dimensions, to offer an increasingly refined analysis of the features and structure of the global digital ecosystem;
- discussing how a DGTES-based analysis of the digital ecosystem can provide novel and original analytical insights on policy–relevant issues related to the digital transformation.

This report targets a broad audience, which includes that part of the scientific community engaging in policy-relevant research as well as decision- and policy-makers. The style and the content of the report try to be consistent with the aim of favouring its reading and understanding also by a non-technical audience, without sacrificing the complex nature and the scientific rigour that characterise the DGTES analytical approach.

Main findings

An overview of the digital ecosystem

This report presents an overview of the global digital ecosystem over the time period between 2009 and 2022. To do so, it addresses three fundamental questions, relying on a series of indicators and metrics obtained from the DGTES graph database:

- Which are the players involved in research and innovation (R&I) activities, as well as in different types of activities related to the production and exchange of knowledge, goods or services in the digital realm?
- How are these players geographically distributed? Which digital technologies have they got engaged with?
- How are these players connected to each other? How is the network resulting from their interactions and interlinkages shaped and what does this imply from a policy point of view?

Answering the first two questions, DGTES identifies about 670,000 relevant activities performed by more than 330,000 players worldwide involved in the global digital ecosystem, as defined by DGTES. The global digital ecosystem is geographically concentrated: despite their different characteristics and features, three geographical areas - China, the US and the EU - host around 70% of all worldwide players and activities. The information on the digital areas allows focusing on the technological composition of the digital ecosystem: although none of the 15 digital areas clearly dominates in terms of number of activities, five digital areas - “Data, data dynamics”, “Artificial intelligence”, “Cloud computing, digital platform, IaaS, SaaS, PaaS”, “Autonomous systems, robotics”, and “Semiconductors, power electronics” - take a more prominent share. Looking at the composition of digital areas of the three main leading geographical areas, the EU and the US are both mainly engaged in the digital areas of “Cloud computing, digital platform, IaaS, SaaS, PaaS”, “Artificial intelligence” and “Data, data dynamics”.

Looking at the EU, Germany, France, Spain, Italy and the Netherlands are the leading countries in terms of number of activities and players. The size and the composition of the EU digital landscape changes remarkably when activities related to EU funded projects are included: these correspond to 17% of all activities in the EU digital ecosystem and represent more than 50% in some Member States (MS). The number of players in the European digital ecosystem increases by more than 60% when EU funded projects are taken into account.

An analysis of digital leadership from an “ecosystemic perspective”

To answer the questions about the ecosystem’s linkages, another set of indicators can reveal the forms and features of the connections and collaborations across players in the digital ecosystem. In this regard, the structure of the DGTES database allows representing and exploring the digital ecosystem from a network perspective**.** Depending on the focus of analysis, this can be specified in different ways and offer a view of the digital ecosystem from different thematic angles. An example is the DGTES representation of the digital ecosystem as a network of players and collaborative activities, where nodes are groups of players aggregated at the level of geographical area and edges represent the shared R&I activities (e.g. co-patenting, co-authorship in scientific publications) across players located in different geographical areas. Corresponding to the web of collaborative R&I activities across geographical areas, these explicit and formal interconnections describe the digital ecosystem as a network of interdependent entities.

DGTES is, therefore, a valid instrument to address different policy-relevant issues related to the digital transformation. In this report DGTES is employed to grasp a better and timely understanding of the opportunities and challenges for EU’s digital leadership through the analysis of strategic dependencies in the digital realm. As first example of how DGTES can contribute to informing and shaping a European policy roadmap for digital leadership, this report proposes and discusses a first set of indicators based on a network representation of the digital ecosystem, offering novel insights on the EU’s strategic autonomy in the context of the global digital ecosystem. Then, the report looks deeper into some technological segments and subdomains in the digital ecosystem that are critical for Europe's digital leadership and twin transition, and in which Europe needs to minimize the risks of overdependence on third parties, such as cybersecurity, autonomous systems, and raw materials. Finally, the report also looks at EU funded projects and how these contribute to shaping the capabilities needed for a vibrant and globally competitive European digital ecosystem.

Key conclusions

According to the findings presented in this report, the global digital ecosystem is geographically concentrated around the three main geographical areas of China, the US and the EU, and does not have a specific technological "flavour", in the sense that it is not dominated by a single prominent digital domain. The EU digital ecosystem is rather heterogeneous, with five MS - Germany, France, Spain, Italy, and the Netherlands - accounting for more than half of players and activities. Moreover, the presented DGTES-based analysis of collaborations in EU-funded projects (including FP7, Horizon 2020, Horizon Europe) underlines the role played by these funding instruments in balancing the geographical distribution of digitally-relevant activities within the EU. Finally, the analysis of the global digital ecosystem with a network approach suggests that the EU may hold a strategic position thanks to the shape of its collaborations in R&I activities, with the potential to influence the functioning of the network by acting as connecting bridge or as bottleneck. At the same time, a deeper look at the networks of cybersecurity, autonomous systems and raw materials of the digital ecosystem informs about the risks of overdependence, as the EU turns out to play a rather marginal role in these critical subdomains.

Next steps and future work

This report presents just some examples of the analytical angles through which DGTES can look at the digital ecosystem from the point of view of the digital transformation. The granularity and flexibility of DGTES allow to bend it to more analytical purposes, directing the focus of the analysis towards specific policy-relevant issues. In this respect, taking into consideration diverse and multiple layers and dimensions, future works will target and explore different types of interconnections and attributes of the players in the digital ecosystem, such as foreign ownership relations or venture capital investments. Moreover, as the digital ecosystem is not simply intersecting but also transforming the other industrial ecosystems from inside, the analysis of the intersection of the industrial ecosystems with the digital one will be informative about the interlacing of digital and industrial transformation in the EU.

1 Introduction

Digital technologies have been leading to major changes in our economies and societies. They are deeply transforming the way we consume, learn, work and enjoy life, and revolutionizing production processes with important innovations in business operations, industrial activities and value chains. These technologies are horizontal by nature: the extreme permeability of all activities to digital technologies implies that they are characterising and transforming any aspect of economies and societies. Besides their broad and far-reaching implications, digital technologies are distinguished by dynamic technological change and complex interconnections. These features are particularly evident in the processes leading to their creation, adoption and diffusion.

The digital transformation occupies a central place in the EU's policy space. The rapid evolution of digital technologies is catalysing the digital transformation. This is intended as the deep transformation of market and non-market activities and processes by means of digital technologies, leading to fundamental changes in the way to operate, produce and deliver value. The digital transformation represents one of the six European Commission's priorities for the period 2019-2024[1] and lies at the core of several policy initiatives — such as the Digital Compass and the Digital Decade Policy Program[2], the European Green Deal[3], the Recovery and Resilience Facility[4], the EU Industrial Strategy[5]— that set unprecedented opportunities to boost the digital transformation across the EU. Achieving a successful, efficient and fair digital transformation is, indeed, key for Europe to be able to lead and enhance the twin transition – thus, to ensure Europe's present and future prosperity.

Leveraging a successful twin transition calls for a better understanding of the digital transformation. To be policy-relevant, the analysis of this multifaceted transformation requires *monitoring* the digital landscape, *anticipating* trends related to digital technologies, and *shaping* the development, implementation and evaluation of policies and initiatives aiming at reaping the benefits from the application of digital technologies and related opportunities. This analysis is based on identifying which are the relevant players driving the digital transformation, how they interact and engage, where their activities take place, and around which digital domains and technologies. This is what we name as the *digital ecosystem*.

The digital ecosystem lies at the heart of the digital transformation. The digital ecosystem can be defined as a techno-economic space where digitally-relevant activities take place in an interconnected way and with the participation of heterogeneous actors pursuing different goals. Being "the *locus* of digital transformation" (Calza et al. 2022, p.10), the digital ecosystem is characterized by accelerated technological change and is horizontal by nature. This means that the digital ecosystem is not simply intersecting, but also transforming the other industrial ecosystems from inside, setting the technological scope within which they operate. Understanding the digital ecosystem and monitoring its evolution is, therefore, key to leverage the digital transformation in all industrial ecosystems and to understand the overall path of technological evolution of EU's economy and society.

Analysing the digital ecosystem is an urgent and policy-relevant exercise, which can open up new angles to look at the digital transition and monitor its course. From the perspective of the digital ecosystem, *anticipating* trends requires identifying *emerging digital technologies; monitoring* the digital landscape requires *mapping* the global digital ecosystem; and *shaping* policies to reap the potentials of digital technologies requires novel *analytical insights* on how these technologies can actually ensure and increase EU's competitiveness.

([1]) See the webpage of 'A Europe fit for the digital age' (https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age_en) and the Commission's communication 'Shaping Europe's digital future' (COM (2020)67 final).

([2]) See the Commission's communication '2030 Digital Compass: the European way for the Digital Decade' (COM (2021) 118 final) and the Decision (EU) 2022/2481 of the European Parliament and of the Council of 14 December 2022 establishing the Digital Decade Policy Program 2030.

([3]) See the Commission's communication 'The European Green Deal' (COM(2019) 640 final).

([4]) The Recovery and Resilience Facility is the key instrument at the heart of NextGenerationEU to mitigate the impact of the COVID-19 pandemic crisis and help the EU emerge stronger and more resilient. For more information, see Commission's communication 'Europe's moment: Repair and Prepare for the Next Generation' (COM (2020) 456 final).

([5]) See the Commission's communications 'A new Industrial Strategy for Europe' (COM(2020) 102 final) and 'Updating the 2020 New Industrial Strategy: Building a stronger Single Market for Europe's recovery' (COM(2021) 350 final).

Digital leadership has become an essential driver for EU's current and future competitiveness. In a context of accelerated technological changes and characterized by increasing scientific, technological and productive interconnections, digital transformation and competitiveness have become increasingly related. Increasing EU's competitiveness in digital and green technologies is indeed crucial to better prepare for the challenges and opportunities of the twin transition. As they are reshaping the horizon of technological development, only the mastering of digital technologies can grant the EU a leading role in the global technological and industrial landscape, and ensure a successful twin transition.

In a period of uncertainty and fast-changing global scenarios, EU's digital leadership is challenged. The exposure of disruptions and bottlenecks in supply chains, markets, and technology transfer has revealed the vulnerabilities of the European digital space as well as its dependencies on non-European technologies and actors. Keeping the pace with the emergence and evolution of digital technologies plays a fundamental role in shaping EU's current and future social and economic trajectories, but the EU needs also to leverage its global position and achieve a digitally autonomous Europe. This requires the EU to strengthen its strategic autonomy as well as to assess and mitigate dependencies, especially in critical areas and digital technologies that are strategically important for EU's industrial competitiveness and twin transition[6]. Being the engine of the evolution and uptake of digital technologies, the digital ecosystem represents a useful perspective from where to look at, analyse and monitor EU's digital leadership.

The digital ecosystem is the framework of analysis of the digital transformation. Given its complex and transversal nature, it is necessary to explore the digital ecosystem with appropriate tools and analytical approaches. This poses some challenges. First of all, as digital technologies are multi-purpose and horizontal by nature, their understanding requires going beyond traditional classifications, which have become less able to describe and explore production phenomena shaped by multisector processes and by a high technological content. Then, conventional indicators also fail to detect the web of interconnections and relationships that characterizes the generation, diffusion and application of digital technologies, and cannot properly account for the multiple layers and intersections of the digital ecosystem. The inadequacy of traditional indicators and metrics in capturing the pervasiveness and the rapid evolution of emerging digital technologies from an "ecosystem perspective" raises a call for novel analytical instruments to explore and better understand the digital ecosystem in its whole complexity.

The Digital Techno-Economic ecoSystem (DGTES) responds to this call for a scientifically-based and policy oriented analytical tool to map and analyse the digital ecosystem. DGTES is the application of the Techno-Economic Segment (TES) analytical framework to the analysis of the digital ecosystem. TES is a replicable methodological approach developed by the Joint Research Centre (JRC)'s Digital Economy Unit to describe and analyse dynamic and complex segments of rapidly evolving and emerging technologies, which are expected to drive innovation and technological development and to sustain growth and employment but are hardly captured by traditional metrics, nor correspond to industrial or a product classifications (Righi et al., 2020). TES allows collating heterogeneous data sources into a graph database, making it possible to map, monitor and benchmark dynamic technological segments. Continuing a thread of research on the application of DGTES to the global digital ecosystem, this report builds on a previous JRC Technical Report (Calza el al. 2022) that describes in detail the JRC's TES methodology and its application to the digital ecosystem, explaining the steps leading to the generation of the DGTES graph database.

This report presents the application of TES to the analysis of the global digital ecosystem. This report aims at offering an overview of the digital ecosystem over the time period 2009-2022 and at exploring it from multiple analytical angles, while keeping the policy perspective in mind. Relying on a series of indicators and metrics obtained from the DGTES graph database, the report maps the global digital ecosystem and provides a refined analysis of the features and structure of the global digital ecosystem through its geographical and technological dimensions. It also discusses how a DGTES-based analysis of the digital ecosystem can provide novel and original analytical insights on policy–relevant issues related to the digital transformation, such as digital leadership and related capabilities.

([6]) Among other documents, see the Commission's communications 'A new Industrial Strategy for Europe' (COM(2020) 102 final), 'Updating the 2020 New Industrial Strategy: Building a stronger Single Market for Europe's recovery' (COM(2021) 350 final), 'Strategic dependencies and capacities' (SWD(2021) 352 final), 'Action Plan on synergies between civil, defence and space industries' (COM(2021) 70 final).

DGTES is a policy-relevant analytical tool. The analysis presented in this report offers an idea of the potential of DGTES and of how it can provide analytical insights to inform and shape a European policy roadmap for EU's competitiveness and digital leadership. This report analyses a network representation of the digital ecosystem, as a whole and focusing on some critical subdomains such as cybersecurity, autonomous systems and raw materials. Results represent a first contribution to the debate on digital leadership through the lens of strategic autonomy, looking at the relative strategic positions of main players in the digital ecosystem – China, the US and the EU – and on their involvement in mutual collaborations in research and innovation (R&I) activities in the digital realm. The report also underlines the role of EU funding programs in shaping the capabilities needed for a vibrant and globally competitive European digital ecosystem. This type of analysis aims at feeding into the discussion on EU's competitiveness in the global digital landscape, informing policy making and policies aiming at fostering and steering the digital transformation.

This report presents just few examples on the analytical possibilities of DGTES. **DGTES offers more flexibility in exploring the digital ecosystem**, fitting multiple perspectives and scopes depending on the focus of the analysis. It can provide a more compelling characterization of the digital ecosystem by taking into consideration its multiple and interconnected layers and dimensions. In this regard, future works should exploit this and target different types of interconnections and attributes, such as foreign ownership relations or venture capital investments. Still, the granularity of the microdata used to generate the DGTES graph database remains one of the most powerful features of DGTES: it allows identifying specific groups of players or individual entities and relate these with their role and position in the digital ecosystem. This would make it possible to detect the presence of European champions in emerging digital technologies or to qualify "gatekeeper" companies that have a strategic position, in the whole digital ecosystem or in a specific subdomain, and that can influence a large number of businesses, within as well as outside the EU.

This report unfolds throughout different sections. Section 2 sets the EU policy background about digital transformation and gives a higher-level description of the Digital Techno-Economic ecoSystem (DGTES) as policy-relevant instrument for the analysis of the digital ecosystem. In this respect, the workflow of DGTES has been described in detail in a previous JRC Technical Report (Calza el al., 2022). Section 3 presents a global overview of the digital ecosystem emerging from the application of DGTES over the period 2009-2022. To do so, it introduces and discusses some indicators and metrics generated using the DGTES database. Section 4 outlines the analytical potential of DGTES by presenting examples of how DGTES can be employed to investigate EU's digital leadership. The last section concludes summarizing the main results of the presented analysis, with a few main take-home considerations stressing the policy relevance of these contributions.

2 Exploring the digital ecosystem from a policy relevant perspective

This section sets the European Union (EU) policy background for digital transformation and introduces the Digital Techno-Economic ecoSystem (DGTES). The first subsection contextualizes digital transformation and the digital ecosystem in the EU's policy landscape, setting the policy background for the discussion of digital leadership as the guiding principle of a policy roadmap for EU's competitiveness. The second subsection describes the main elements and structure of DGTES and presents it as an appropriate tool for a policy-relevant analysis of the digital ecosystem, whose results contribute to anticipating, monitoring and shaping the digital transformation.

2.1 Digital transformation in the European policy landscape

2.1.1 The digital ecosystem as the heart of digital transformation

An integrated technological paradigm of digital technologies

Different waves of technological change have been moving forward the frontier of technological possibilities and pushed economic development. The latest of these waves has been associated with the emergence of *digital technologies*, whose journey started several decades ago with the creation of the first microchip. Since then, digital technologies have been evolving and consolidating into an integrated technological paradigm, leading to deep changes into economic as well as social dynamics: they have been deeply transforming the way we learn, work, enjoy life, consume and produce, revolutionizing industrial processes and bringing important innovations in business operations, production activities and stages of the value chain. More recently, the aftermath of the COVID-19 pandemic triggered an acceleration of the uptake of digital technologies as well as of the debate on their evolution and impact - in particular, on how to reap their expected benefits while mitigating or avoiding their risks and drawbacks.

> ***Digital technologies*** *have been evolving and consolidating into an integrated technological paradigm, leading to deep changes into economic as well as social dynamics.*

Digital technologies are distinguished by accelerated technological change and far-reaching implications on society, economy, and production. This type of technological environments tend also to be characterized by dense relational dimensions, where an actor influences the behaviour of other actors or parts, giving rise to a complex structure of interconnections. In the case of digital technologies, these interlinkages spread also across and within industrial activities, revolutionizing the notion of industrial sector as set of producers of similar and homogeneous products and creating cross-sectorial processes and linkages across interdependent value chains. The horizontal nature of digital technologies further reinforce their dynamism and complexity: as digital technologies represent the substrate of almost any technical solution and have multi-purpose applications, their evolution is redefining the technological scope of all activities – not only economic ones - and reshaping the horizon of technological, social and economic development.

The digital ecosystem as powerhouse of the digital transformation

This same relational and horizontal flavour characterizes the *digital ecosystem*. The digital ecosystem can be defined as a techno-economic space where digitally-relevant activities take place in an interconnected way and with the participation of heterogeneous actors pursing different goals (COM(2020) 102 final)[7] - from the smallest start-ups and the largest companies to service providers and suppliers, from large government institutions to small universities and research centres. Here digital technologies emerge though processes of creation, production and exchange, triggered and moulded by interactive relations and interlinkages across heterogeneous actors. Hence, defining the digital ecosystem requires looking at who the key actors are, which different roles they play, in which technologies they specialise, how they are geographically distributed, how

(7) The 2020 New Industrial Strategy identifies 14 industrial ecosystems based on their economic and technological relevance, and on their expected contribution to the decarbonisation, digitalisation and resilience of the EU economy (COM(2020) 102 final). These ecosystems are: Aerospace & Defence, Agri-food, Construction, Cultural and Creative Industries, Digital, Electronics, Energy Intensive Industries, Energy-Renewables, Health, Mobility-Transport-Automotive, Proximity, Social Economy and Civil Security, Retail, Textiles, and Tourism. They represent approximately 70% of the EU economy and 80% of the business economy (as a share of value added). See Box 2 for a discussion of the different definition of digital ecosystem.

they are connected to each other, how innovation spreads through the networks (Calza et al. 2022). Recognizing the importance of all horizontal and vertical links among economic actors, this “ecosystemic perspective” acknowledges a role also for those activities often considered as ancillary to industry, such as research activities supporting industrial innovation. Given the multi-purpose nature of digital technologies, the digital ecosystem is not simply intersecting but also transforming the other industrial ecosystems from inside, setting the technological scope in which they operate. The digital ecosystem is, thus, forward-looking, as it already incubates the technological trajectories that will shape the economy in the future.

The digital ecosystem is the centre of *digital transformation*, intended as the evolution of digital technologies leading to fundamental and deep changes in market and non-market activities and processes by means of digital technologies (Calza et al. 2022). As digital technologies are reshaping the horizon of technological development, exploring and understanding the digital ecosystem is an urgent policy-relevant exercise. It is urgent because only *anticipating, monitoring and steering the digital transformation* can grant the EU a leading role in the technological and industrial landscape as well as enabling the green transition. Hence, the analysis of the dimensions, elements and features of the digital ecosystem can open up new angles to look at the digital transformation and forecast its course.

> ***Digital transformation*** *refers to the evolution of digital technologies leading to fundamental and deep transformations of market and non-market activities and processes by means of digital technologies, changing the way to operate, produce and deliver value.*

Digital transformation in the EU’s policy spotlight

Digital transformation occupies a central place in the EU’s policy landscape. ‘*A Europe fit for the digital age*’ (COM (2020)67 final) - one of the six European Commission’s priorities for the period 2019-2024 - represents the EU’s Digital Strategy and envisions Europe as a strong and sovereign digital player. This was followed by the introduction of the Digital Compass (COM (2021) 118 final) and the Policy Programme ‘Path to the Digital Decade’ (Decision (EU) 2022/248) which translate EU’s digital ambitions into concrete targets to realize the goals of ‘*the digital decade’*. The Recovery and Resilience Facility (COM (2020) 456 final) promotes reforms and investments dedicated to digital technologies as a way to improve EU’s resilience and competitiveness at the aftermath of the COVID19 pandemic crisis. In line with the same goal of shaping Europe’s digital future, the EU digital regulation has been recently completed with the Digital Services Act (DSA) and Digital Markets Act (DMA), which aim at creating a safer digital space and establishing a level playing field for businesses to foster innovation, growth, and competitiveness, both in the European Single Market and globally.

While recognizing the pervasiveness of digital technologies and how their mastering is necessary for a successful twin transition, these initiatives also reflect a growing support for a policy roadmap to enhance Europe's digital leadership (Tambiama Madiega, 2020). Along this same line, the EU Industrial Strategy (COM(2020) 102 final; COM(2021) 350 final) also emphasises how achieving Europe’s industrial and technological ambitions is conditional on reinforcing EU’s digital leadership in an open and interconnected world. In a global scenario of accelerated technological change, digital leadership has become a fundamental driver for EU’s competitiveness and twin transition - and, consequently, for EU’s present and future prosperity.

2.1.2 Towards a policy roadmap for EU’s digital leadership

Digital leadership and strategic autonomy for Europe’s prosperity

A phase of uncertainty and fast-changing global scenarios, coupled with a period of rising geopolitical tensions and trade frictions, has revealed the existence of disruptions and bottlenecks in supply chains, markets, and technology transfer, exposing the vulnerabilities of the European digital space such as its dependencies on non-European players. Enhancing digital leadership has thus become increasingly challenging. As this may threaten Europe’s path towards the twin transition and future prosperity, the discussion of a policy roadmap for EU’s digital leadership has become more urgent than ever.

> ***Digital leadership*** *refers to Europe’s ability to act independently and autonomously in the global digital landscape.*

The term *digital leadership* is here used to refer to Europe’s ability to act independently and autonomously in the global digital landscape; therefore, it cannot be discussed separately from the notion of *strategic autonomy*. The documents related to the EU Industrial Strategy emphasise how attaining EU’s digital ambitions requires to address strategic vulnerabilities and dependencies in key areas where Europe relies on its global competitors and in critical inputs necessary for the green transition (COM(2020) 102 final; COM(2021) 350 final). More precisely, the New Industrial strategy defines strategic autonomy as "reducing dependence on things we need the most: critical materials and technologies, food, infrastructure, security and other strategic areas" (COM(2020) 102 final). This position is shared by other policy documents[8], which underline the need to strengthen EU's strategic autonomy and mitigate strategic dependencies. The European Council[9] stressed that achieving strategic autonomy while preserving an open economy is a key objective of the EU. Enhancing digital leadership is thus subject to assessing and understanding where Europe's strategic dependencies lie, which segments and technologies are strategically important, how they may develop in the future, and to which extent their evolution could turn into a vulnerability for the EU (COM(2021) 350 final).

Strategic autonomy *refers to reducing dependence on things the EU needs the most: critical materials and technologies, food, infrastructure, security and other strategic areas.*

At the same time, although attaining its ambitions of digital sovereignty requires Europe not to be naïve in front of unfair competition nor ignore strategic dependencies, the EU's position on the global technological and industrial stages should resist the "temptation of protectionism" (COM(2020) 102 final) and remain based on competition, open markets, exchanges in research and technologies. The upcoming industrial era will witness the physical, digital and biological worlds coming together: this convergence between digital technologies and scientific fields - such as in *deep tech* innovation (COM(2022) 332 final) - and the increased technological complexity would make it more challenging to keep the pace with the evolution of these dynamic technology-based segments and to remain globally competitive without global synergies and collaborations. EU's industrial competitiveness will ultimately depend on the balance between the need to address strategic vulnerabilities and reduce dependencies, while leveraging on strategic partnerships to prepare for, face and overcome the challenges of the twin transition.

Capabilities for EU's industrial transformation and innovation

Keeping the pace in the global technological and industrial race requires the EU to build and further strengthen the capabilities and competences to produce strategic goods and services, as well as the infrastructures, industrial know-how and emerging technologies (SWD(2021) 351 final). In this way, strategic autonomy represents an opportunity for Europe's to develop its own markets, products and services in critical and strategically important technologies and sectors, boosting industrial transformation and competitiveness. Efforts and resources can be directed to maintain and gain positions in domains where no global incumbents have yet emerged (Calza et al. 2022). This can provide the basis for targeted policy measures to foster industrial transformation while grasping the benefits of the digital transformation and granting the open, competitive, trade-based EU economy.

The discussion on capabilities also concerns the need to catch the wave of *deep tech* innovation by supporting innovation-based competitiveness and the EU's innovation performance, as stated by the New European Innovation Agenda (COM(2022) 332 final) and by the European Research Area (ERA) (SWD(2020) 214 final). Besides strengthening supply chain resilience through trade opportunities and collaborations, European actors need to upgrade their capabilities to deal with the increasingly international nature and technological content of innovation (COM(2022) 332 final). For this to happen, the EU needs to make better use of its research capacities and infrastructures, in order to increase the performance of the European R&I system (especially for green and digital transitions) and to better link R&I results with the EU's economic and industrial performance, effectively turning its research efforts into innovation-based competitiveness. This would benefit from dedicated Horizon Europe measures and complementarities with smart specialisation strategies under Cohesion Policy (SWD(2020) 214 final), but also from mobilizing more resources form individual Member States (MS). Moreover, investigating the features of partnerships and collaborations in EU funded programmes can contribute to a better understanding of their role in driving innovation across Europe.

([8]) See the Commission's communications 'Action Plan on synergies between civil, defence and space industries' (COM(2021) 70 final) and the document 'Strategic dependencies and capacities' (SWD(2021) 352 final).

([9]) European Council Conclusions, EUCO 13/20 of 2 October 2020.

Understanding digital transformation to enhance digital leadership

Digital leadership is crucial to guarantee EU's present and future prosperity. Its enhancement requires a deeper understanding of all forces driving the digital transformation. For this reason, a policy roadmap for EU's digital leadership needs to be grounded on the intersection of major EU's policy initiatives - such as the Digital Decade, the New Industrial Strategy, the New European Innovation Agenda, the Green Deal -, which are consistent in their goal of fostering digital transformation and in line with the priorities and visions for a peaceful, secure and prosperous Europe.

Table 1 summarizes the main challenges of a policy roadmap for digital leadership. These are grouped into three broad policy areas. As discussed, a first policy area looks at strategic autonomy (1); here challenges are related to detecting and assessing the relevance of strategic dependencies, and identifying which actors occupy a strategic position. However, a policy roadmap for digital leadership that successfully fosters EU's competitiveness and the twin transition has to avoid getting locked-in into a narrow narrative around strategic autonomy and dependencies. For this reason, a second policy area regards EU's capabilities and capacities (2), especially (but not exclusively) in critical and strategic technologies and subdomains, calling for novel ways of measuring capabilities and of accounting for the role of collaborations in shaping innovation outcomes. A last policy area points towards industrial transformation (3); its main challenges regard the emergence of new digital technologies, the intersection across the digital and other industrial ecosystems, and the outcomes in terms of industrial performance.

Table 1. Towards a policy roadmap for digital leadership

Policy areas	Policy-relevant challenges	Policy initiatives
(1) Strategic autonomy and dependencies	• Assess and mitigate strategic dependencies in key and critical digital technologies, subdomains and inputs • Identify stakeholders with a strategic role or occupying a strategic position in the digital ecosystem in critical subdomains (e.g. gatekeepers, bottlenecks)	Industrial Strategy European Chips Act Observatory of Critical Technologies
(2) Capabilities and capacities	• Map, localize and reinforce the presence of a 'critical mass' of capabilities in the digital ecosystem • Explore the effect of collaborative links between academia, government and industry (in particular for deep tech innovation) • Localize capabilities in critical digital technologies and subdomains (in particular for strategic autonomy) • Explore proximities across digital subdomains and anticipate synergies for innovation • Investigate and address the intra-EU (regional) divide in innovation	Digital Decade New European Innovation Agenda New ERA for R&I (roadmaps) Cohesion Policy/ Smart Specialization
(3) Industrial transformation	• Identify and foster emerging and next-generation digital technologies (in particular for the green transition) • Investigate and support the scaling up of leading players in the digital ecosystem (e.g. technologically advanced firms, leading firms, start-ups) • Relate industrial performance with engagement in the digital ecosystem • Explore the intersections of the digital ecosystem with other industrial ecosystems • Promote more resilient and less vulnerable supply chains (beyond a sectoral approach)	Industrial Strategy Digital Decade New European Innovation Agenda New ERA for R&I (roadmaps) Digital Innovation Hubs Green Deal

Dealing with the challenges highlighted in Table 1 would help better understand the digital transformation, allowing to *anticipate, monitor and steer* this major transformative process. Being the engine of digital transformation, the analysis of the digital ecosystem would represent a first step towards addressing these challenges. The rest of this report discusses how DGTES is an appropriate analytical tool to look at the digital ecosystem in a non-conventional way, from a more relational and "ecosystemic" perspective, and how the derived analytical insights can contribute to informing a policy roadmap for EU's digital leadership.

2.2 A policy-oriented analytical approach to map the digital ecosystem: DGTES

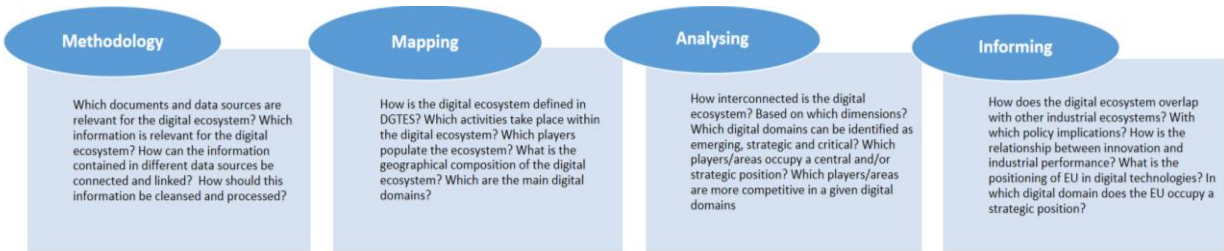
2.2.1 DGTES in a nutshell

DGTES is the application of the Techno-Economic Segment (TES) analytical approach to the digital ecosystem. The TES methodology has been developed by JRC's Digital Economy Unit to map and explore dynamic and complex segments of rapidly evolving and emerging technologies, which are hardly captured by traditional metrics or classifications (Righi et al., 2020). A recent JRC Technical Report by Calza et al. (2022) describes in detail the application of the JRC's TES methodology to the digital ecosystem, explaining the steps leading to the generation of the DGTES graph database and introducing its main metrics and indicators.

> ***The Digital Techno-Economic ecoSystem (DGTES)*** *is the application of the Techno-Economic Segment (TES) analytical approach to the digital ecosystem.*

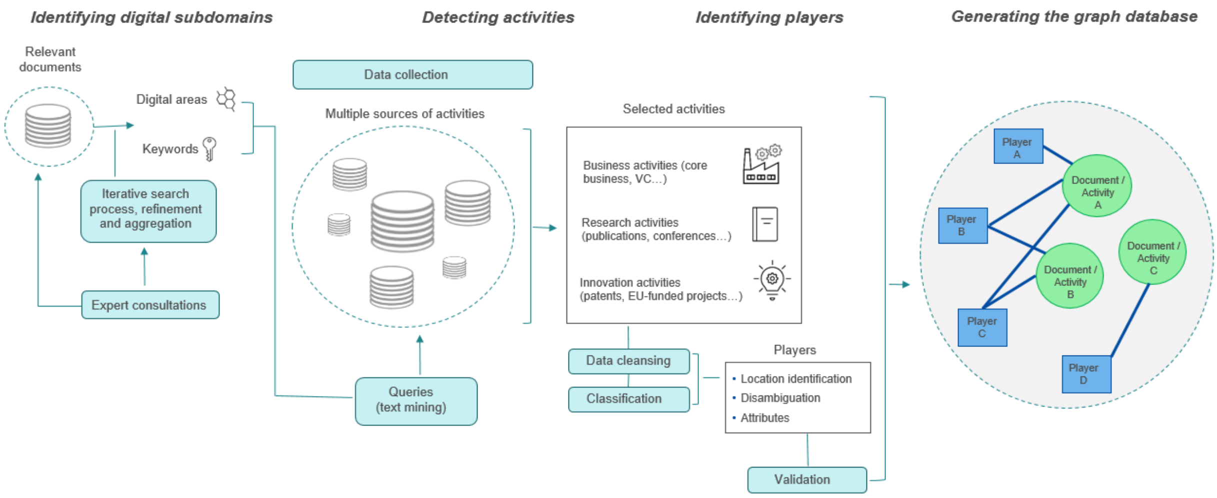
Figure 1 summarizes the main steps of DGTES. DGTES relies on the TES methodology to collect, connect and converge multiple sources of microdata into a harmonized database, enriching and amplifying the information contained in individual datasets. DGTES is indeed designed to generate a graph database that allows identifying players engaging in different types of activities related to the production and exchange of knowledge, goods or services in the digital realm. This DGTES database can be employed to map the digital ecosystem and to analyse its elements, structure and features from a holistic, multidimensional and policy-relevant perspective. By giving access to a comprehensive set of relevant elements of the digital ecosystem, the DGTES database enables the generation of a series of indicators and metrics to describe, investigate and better understand the digital ecosystem, providing a compelling characterization of its main elements (i.e. actors, activities, interlinkages) and features, structure and complexity. Finally, DGTES serves as policy-relevant analytical instrument to inform, assess and ultimately improve policies aiming at fostering digital transformation and leveraging a successful twin transition.

Figure 1. DGTES: main steps



Source: Calza et al. (2022).

Figure 2. DGTES workflow and methodology



Source: Calza et al. (2022).

Figure 2 provides an overview of the DGTES workflow, which can be described as follows:

(i) Identification of the digital domains (digital areas) that define the technological perimeter of the digital ecosystem: these domains consist of 15 digital areas, corresponding to informal, internally-coherent, techno-economic categories used to cluster digital technologies that relate to the same technological domain (e.g. "Artificial Intelligence") or to the same type of application or final use (e.g. eHealth solutions). The 15 digital areas in DGTES are compliant with the two criteria of being forward-looking and policy-relevant. Each digital area is associated to a unique list of keywords (see Box 1).

Digital areas *are informal, internally-coherent, techno-economic categories used to cluster digital technologies that relate to the same technological domain or to the same type of application or final use.*

(ii) Detection of the activities in the digital ecosystem: in DGTES, an activity is associated to a document that carries textual information about the activity itself and its attributes. In order to detect which activities are relevant to the digital ecosystem, the keywords related to each digital area are used to build queries that are launched on the database made up by various repositories of textual documents[10] (Calza et al. 2022). In DGTES, activities are grouped as follows:

- *business activities*, derived from textual documents containing information on companies' core business and on the production, supply or exchange of goods or services, or on investments and funds financing industrial and business initiatives (e.g, venture capital deals);
- *innovation activities*, corresponding to outputs of research and development (R&D) activities in the form of patenting initiatives (i.e. filing of priority patents) or participation in innovative research projects (i.e. EU-funded projects such as FP7, Horizon 2020 (H2020) and Horizon Europe);
- *research activities*, reflecting academic contributions of frontier research, such as publications in selected journals[11].

(iii) Identification of players: the players engaging in the digital ecosystem are identified through the analysis of the textual information contained in the document associated to a relevant activity. This requires a multi-step process of data cleansing that includes (among others) disambiguation[12], classification, and validation. Based on the available information, players are associated to three organizational types:

- *companies and firms;*
- *academic institutions and research centres;*
- *governmental authorities and bodies*.

(iv) Generation of the final DGTES graph database: the final DGTES graph database reflects a complex system made of players, activities, their respective attributes and the connections between them. The analysis of the textual information in the relevant documents allows connecting activities and players, thus identifying how players relate to each other and are interlinked through their shared activities. The DGTES database also includes information on features and attributes of activities and players, such as organizational type, digital areas, geographical location, foreign ownership, etc. The connection of all these elements and information defines the structure of the DGTES graph database, which ultimately allows mapping and analysing the digital ecosystem.

([10]) See Appendix A for the list of repositories used to generate the DGTES database presented in this report.
([11]) See Appendix B for the list of selected journals used to generate the DGTES database presented in this report.
([12]) Disambiguation is a crucial step of the workflow leading to the generation of the final DGTES graph database. The process of disambiguation allows identifying if the same player is involved in multiple activities and correcting for eventual duplications. This process is based on: (i) the geographical location of players (eliminating players with the same name that share the same location at city level); (ii) algorithms measuring similarity of names that identifies misspelled names and variations of the same name; (iii) algorithm working on network of similarities that identifies groups of potential duplicated agents. This implies that the information on each player can result from the combination of what collected from different sources. If the same economic institution is detected in multiple locations, these are considered as different, individual players, belonging, when applicable, to the same multi-site organisation (i.e. firms with headquarters and several subsidiaries).

Box 1: Digital areas: setting the technological perimeter of the digital ecosystem

In DGTES, digital areas correspond to informal, internally-coherent, techno-economic categories used to cluster digital technologies that relate to the same technological domain (e.g. "Artificial Intelligence" can be defined as a digital area, entailing various technological solutions based on the principles of artificial intelligence, such as Natural Language Processing (NLP), machine learning, etc.) or to the same type of application or final use (e.g. eHealth solutions).

The notion of digital area primarily responds to the need to set clear boundaries to the digital ecosystem. In practice, digital areas have been introduced to systematise the application of criteria to tighten the scope of the digital ecosystem. Digital areas are by construction mutually exclusive, in line with the aim of reducing as much as possible the rise of possible ambiguities and of minimising the return of false positive results (even within the same global technological domain).

In addition, digital areas comply with the two criteria of being forward looking and policy relevant. This means that these domains do not include devices and tools that are associated with more conventional and mature digital solutions now seen more as commodities (i.e. terms as personal computer, printer, scanner and the like), but only those related to digital transformation, defined as the integration of digital technology into different market and non-market activities and processes, fundamentally changing the way to operate, produce and deliver value.

A final set of 15 digital areas was identified through a series of sequential and iterative phases and steps, with the goal of progressively refining results towards a final number of internally coherent and techno-economically relevant digital areas:

"3D Printing, Additive manufacturing"

"Artificial Intelligence"

"Internet of Things, AIDC"

"Autonomous Systems, Robotics"

"Extended Reality, Virtual Reality, Augmented reality"

"Cybersecurity, Safety & Security, Digital Identity"

"5G and beyond, Autonomous Networks, Communications, Telecommunications and connectivity"

"Infrastructure, Cloud Computing, Digital Platform, IaaS, SaaS, PaaS, on-line platforms, Social "Networks, Internet"

"Data, Dynamic Data"

"eBusiness, e-Commerce"

"Blockchain, Distributed Ledger"

"Quantum Technologies"

*"Verticals" **

"Electronics, Semiconductors, Power Electronics"

"Advanced Computing, High Performance Computing (HPC), edge computing"

In DGTES, each digital area encompasses a set of related technologies that are associated to a unique dictionary of keywords that constitutes the 'semantic space' characterizing the digital ecosystem. This list of keywords is then used to identify from the database of textual documents (patents, journals, business activities, EU projects, etc.) the activities (business, research, innovation) that generate the DGTES digital ecosystem[13].

* The "Verticals" area has been added in order to include keywords that refer to final applications rather than to technologies, and keywords that conceptually seem to belong more appropriately to other industrial ecosystems (e.g. Transportations, Healthcare, etc.), although still maintaining a link to the digital one. One example is the keyword *health data sharing*: despite belonging to the healthcare ecosystem, it anyway maintains a strong link to the digital ecosystem (besides looking more like a class of final applications rather than a technology).

Source: JRC Technical Report by Calza et al. 2022.

2.2.2 Potential and current limitations of DGTES

The advantages of employing DGTES over more conventional methodologies and indicators stem from different sources. First, DGTES allows generating novel metrics and indicators for the analysis of digital technologies. Since these technologies are multi-purpose and horizontal by nature, their understanding requires going beyond traditional industrial classifications that have become less able to describe and explore

([13]) The complete list of keywords is publicly available and accessible from the European Data Portal and from the JRC PREDICT website (https://joint-research-centre.ec.europa.eu/predict/digital-ecosystem-analysis-dgtes-2022).

production phenomena increasingly shaped by multisector processes and by more technological content. Some of these indicators are presented and discussed in section 3. In this respect, the DGTES interpretation of the digital ecosystem differs from the definition of the industrial digital ecosystem presented by the EU New Industrial Strategy (COM(2020) 102 final) (see Box 2).

Second, differently from conventional statistics and indicators, DGTES is an “ecosystem by design” (Calza et al. 2022, p. 13). DGTES allows exploring the digital ecosystem from a relational and systemic perspective, revealing its complex structure made of interlinkages and interconnections. This feature makes this approach particularly suitable for technological segments where knowledge creation and diffusion take a network structure, and where weak signals of emerging technological domains are likely to shape the future trajectory of knowledge flows such as in the case of digital technologies. This feature of DGTES is discussed in more detail in section 4.1.

Third, data are collected at micro-level, so the final DGTES database contains detailed information about how individual actors participate in and how they contribute to the digital ecosystem, as well as about their features and attributes. The granularity of microdata enriches the scope of analytical possibilities, at the same time allowing for more flexibility – for instance, adding or removing layers of analysis (i.e. considering different geographical levels such as cities, countries, regions, or zooming-in on specific types of players). Thanks to this granularity and flexibility, DGTES fits a wide range of analytical purposes. Sections 4.2 and 4.3 offer examples of possible analytical angles of DGTES.

Finally, DGTES helps address several policy-relevant questions related to the digital transformation. For instance, DGTES can offer a timely understanding of the opportunities and challenges for EU’s digital leadership through the analysis of strategic autonomy, dependencies and capabilities. The results of such a DGTES-based analysis provide original and novel insights to policies aiming at fostering the EU’s position and role in the global digital landscape. Some examples are reported in section 4.

Despite these advantages, DGTES is not free from limitations[14]. First, DGTES defines the digital ecosystem from a supply-side perspective. As discussed, DGTES is designed to generate a graph database that allows identifying players engaging in industrial, research or innovation activities in the digital realm, but it cannot explore the demand-side on the market and the micro-level mechanisms underlying the adoption and adaptation of digital technologies at firm level.

Box 2: One digital ecosystem, different levels of granularity

The digital ecosystem emerging from the DGTES database is characterized by specific features: it is obtained with the replicable TES methodology (Righi et al., 2020); its perimeter is identified by a set of 15 digital areas, corresponding to internally-coherent, techno-economic categories used to define digital domains (see Box 1); it is an 'ecosystem by design'; it is forward-looking and policy-relevant; its granularity allows for great flexibility in the scope of analysis; it is horizontal.

In the 2020 New Industrial Strategy (COM(2020) 102 final), the digital ecosystem is one of the 14 considered industrial ecosystems. The boundaries of the New Industrial Strategy’s digital ecosystem (as well as those of the other 13 industrial ecosystems) are based on its economic and technological relevance, and on the expected contribution to the decarbonisation, digitalisation and resilience of the EU economy, in aggregated terms. In the New Industrial Strategy the digital ecosystem is defined by the aggregation of the following NACE* sectors: ICT manufacturing, ICT services (excluding telecommunications), telecommunications, and publishing activities. The New Industrial Strategy acknowledges that there is no precise matching between the sectors as per NACE classification and the concept of digital ecosystem, and that some approximation is required. The DGTES approach allows to consider the digital ecosystem as horizontal by nature, and to overcome the constraints of the industrial classifications, potentially embracing all industrial sectors, and reflecting a techno-economic definition of digital domains.

* NACE: Nomenclature statistique des Activités economiques dans la Communaute Europeenne - Statistical Classification of Economic Activities in the European Community.

(14) For a broader discussion of the limitations of the application of the TES methodology, see section 2.2. in Calza et al. (2022).

Second, as already observed, the generation of the DGTES graph database relies on various repositories of textual documents (e.g. patents, publications, funded projects, descriptions of business activities). These correspond to codified knowledge, containing both proprietary and public information that is formalised and accessible DGTES does not take into account information that is not explicitly observed and transferred, as it is the case, for instance, of industrial secrets or transactions not reflected in accessible and codified data. This information is invisible to DGTES.

Third, at this stage DGTES still has a limited overview of industrial production linkages distributed along an entire value chain. DGTES does not use information about the position of players within existing value chains, nor does it include information on products and their features (e.g., primary input, intermediate, final) or market structure. DGTES is, thus, not suitable to directly capture market dynamics or assess market shares.

Finally, although DGTES covers publicly funded research at EU level (e.g. EU-funded projects such as FP7, H2020 and Horizon Europe), it disregards public funding initiatives at national level. DGTES identifies only a part of financing and investments that take place within the digital ecosystem. This requires to be careful when drawing comparisons across geographical areas, as other important sources of financial inputs and resources may be missing. DGTES is however in the phase of increasing its coverage of financial aspects of the digital ecosystem by improving the quality and scope of the considered information on funding deals and investments (e.g. information on venture capital funds).

3 A DGTES-based overview of the global digital ecosystem

This section presents a global overview of the digital ecosystem over the period 2009-2022, as it emerges from the application of the TES analytical approach. The presented indicators and metrics were produced from the DGTES database. Several of these indicators can be calculated for each year, adding a longitudinal perspective to the analysis of the digital ecosystem. These - and more - indicators can also be explored through the dedicated DGTES dashboard (see Box 3).

The first subsection offers a general overview of the DGTES digital ecosystem, describing its main elements from a worldwide perspective and providing a broad outlook of its main features, structure and evolution. The second subsection maps and analyses the digital ecosystem in more detail, presenting a comparative analysis across geographical areas and at different geographical levels. It also discusses the technological composition of the digital ecosystem, as defined by the digital areas that set the technological boundaries of the ecosystem. This subsection dedicates a special attention to the situation of the EU and its MS.

Box 3: Navigating through the digital ecosystem: the DGTES dashboard

DGTES maps the global digital landscape by considering the industrial, innovation and research activities performed worldwide in the digital ecosystem and the economic players engaging in them. Based on a unique data collection of multiple micro-based data sources and supported by a methodological framework for the analysis of techno-economic ecosystems (TES), DGTES takes into account information about location and technological aspects, in order to generate a series of indicators and metrics that can return a detailed and dynamic picture of the state of the digital ecosystem between 2009 and 2022. Differently from traditional indicators, which can hardly capture dynamic and complex segments of rapidly evolving technologies, DGTES can produce a timely as well as holistic and integrated view of the global digital landscape, contributing to informing policies aiming at steering and fostering the digital transformation.

Part of the information contained in the DGTES database can be explored through the DGTES interactive dashboard. The DGTES dashboard is a dedicated webpage to navigate indicators and metrics in an intuitive and informative way, with the possibility of focusing on a selection of elements and features at time, and of applying different filters and levels of aggregation. In this way, this flexible tool provides a detailed picture of the digital ecosystem —for instance, the number and composition of activities, current and emerging patterns of technological specialisation in digital domains—, while allowing for comparability, across countries or geographical areas, in terms of players, activities, technological specialisation, and interlinkages. The DGTES dashboard is currently available to selected users, but at a later stage it will be open to the public and access granted to its main functions.

3.1 Introducing the digital ecosystem

What happens in the digital ecosystem? Which activities are conducted? How has the ecosystem evolved over time?

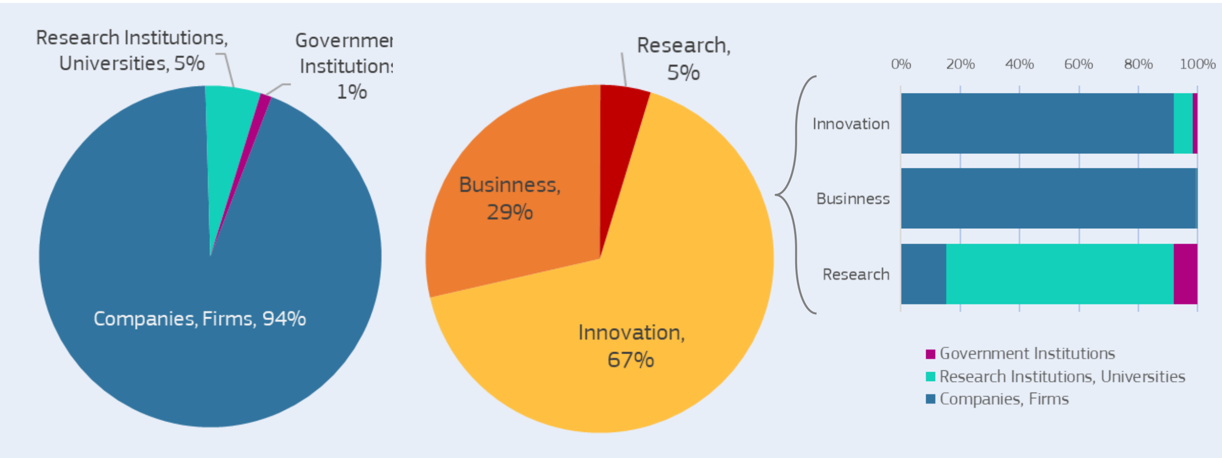
Who populates the digital ecosystem? Which players participate in the supply, creation and evolution of digital technologies?

DGTES captures the worldwide state of the digital ecosystem, offering a holistic view of the global digital landscape between 2009 and 2022. The description of the global digital ecosystem starts with the identification of its main elements: activities and players[15].

Figure 3 considers the total number of activities and corresponding players that populated the global digital ecosystem between 2009 and 2022[16]. The DGTES digital ecosystem database counts of more than 330,000 players identified through about 670,000 activities. Panel a. presents the composition of players operating in research, industry or government in the digital ecosystem. This reveals that the digital ecosystem is mostly composed by firms and companies (94%), followed by research institutions and universities (5%), and government institutions (1%). Panel b. shows that 2 out of 3 activities are patent applications (innovation activities); the remaining third are business activities (29%), while publications (research activities) represent a smaller share (about 5% of total activities). Panel c. displays the number of players that perform each type of activity as well as their organisational types. Each type of activity differs in terms of player composition: business activities are almost entirely conducted by firms and companies (99% of players); innovation activities are also mostly performed by firms (92% of players), with a minor role for research institutions (6%) and an even smaller one for government institutions (2%); research institutions and universities represent the majority of players in research activities (77%), followed by firms (15%) and government institutions (8%). Thus, government institutions play a certain role only in research activities. This can be explained by the higher level of uncertainty that typically characterizes frontier research in emerging and dynamic technological domains, which may benefit from the participation of governmental organisations or similar entities that are able to bear the risks of exploratory research.

Figure 3. Composition of players and activities in the global digital ecosystem (2009-2022)

Panel a. Players by organisational type | *Panel b. Activities by type* | *Panel c. Players performing each type of activity, by organisational type*



Note: In Panel c, the same player can engage in more than one of the three types of activity (i.e. the same firm engaging in both business and innovation activities). Thus, the sum of the number of players in each type of activity can exceed the total number of individual players.

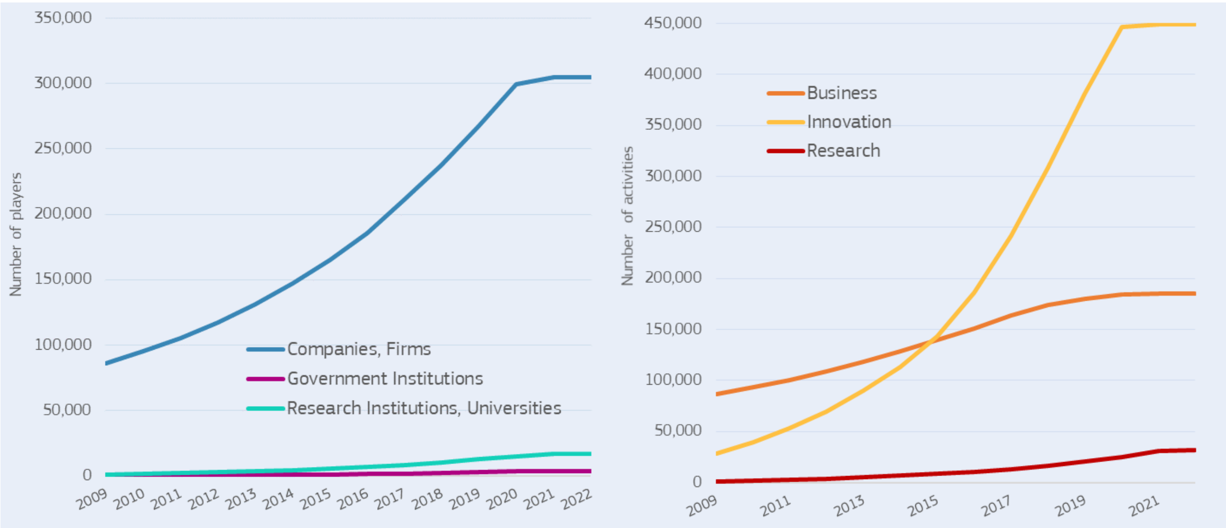
(15) See section 2.2.1 in this report for a description of the main elements of the DGTES graph database.

(16) Unless otherwise stated, for the sake of comparability, activities concerning EU-funded projects (FP7, H2020, Horizon Europe) are not considered when looking at the global digital ecosystem.

Calculating the DGTES indicators and metrics in different years allows adding a longitudinal perspective to the analysis, giving an idea of the evolution of the digital ecosystem over time. Figure 4, Panel a. shows that firms always had a central role in the digital ecosystem, representing the most common type of players since the first year of the considered period (2009). Panel b. reveals how, differently from players, the composition of total activities has instead changed remarkably over time: while research activities have always occupied a smaller share, innovation activities overtook business activities in 2015 and have been growing at a much faster rate than the other types of activities until 2020. This pattern is mostly explained by a marked increase in the number of China's patent applications since 2015, as a result of Chinese government's policies (Righi et al., 2021, 2022).

Figure 4. Evolution of players and activities in the global digital ecosystem by year (2009-2022)

Panel a. Players by organizational type *Panel b. Activities by type*



Note: Figures show the cumulative number of players and activities in each year of the considered period.

3.2 Mapping the digital ecosystem

3.2.1 Drawing a digital landscape

Where are players located? How are they geographically distributed? Which country hosts more players?

Which type of players, geographical areas and countries are more engaged, more active in the global digital ecosystem?

The spatial dimension is a fundamental feature of DGTES. Thanks to the information on their location, players can be grouped together at different geographical levels (i.e. world geographical area, country, region, city), offering a detailed figure of where most players concentrate and how they participate in and contribute to the digital ecosystem.

Worldwide digital ecosystem

We start mapping the ecosystem at the level of geographical areas, grouping together players located in the same country or world region[17]. Figure 5, Panel a. displays the top ten geographical area per absolute number of players. The global digital ecosystem turns out to be highly concentrated: while the ten top regions host more than 92% of all worldwide players, 2 out of 3 players are located in China, the US or the EU. However, there is a remarkable distance across the three leading geographical areas: the EU hosts 11% of all

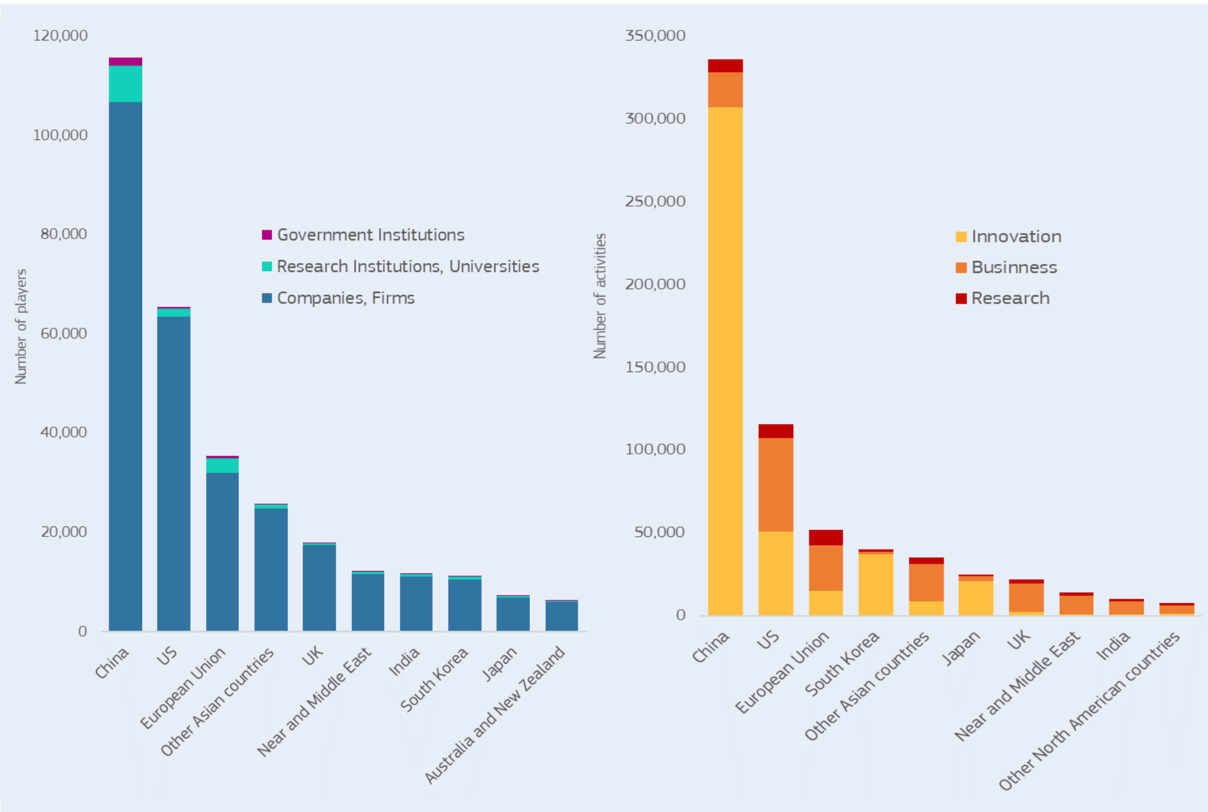
([17]) The definition of the geographical areas is based on Eurostat's recommendations about geographical zones (Eurostat 2020). For descriptive purposes, the group "Other Asian countries" excludes China, Japan, South Korea and India, which are considered as separate geographical areas.

worldwide players, while China and US that account for about 36% and 20% of players, respectively – thus, each of these regions is home to almost double the number of players hosted by the one following in this ranking. Other geographical areas with a relevant presence in the global digital landscape are: the group of other Asian countries (where 3 out of 4 players are located in Singapore or Taiwan), the UK, and Near and Middle Eastern countries (whose high rank is due almost entirely to players located in the United Arab Emirates (UAE) or Israel)[18].

Panel a. also provides information on the composition of players by organisational type. In each of the top ten geographical areas, firms and companies represent the large majority of players (above 90%). To be noted is the relatively larger presence of research institutions and universities in China (6%), in the EU (8%), South Korea (5%) and Japan (5%), with respect to the other top regions (where the share associated to this type of player is below 4%). Hence, the composition of players on the EU's digital landscape turns out to be less concentrated around firms than what observed in the US and the UK. Even if this information does not allow assessing the quantity or the quality of conducted research, a relatively larger engagement of research institutes and universities can be considered as a potentially useful feature of the digital ecosystem, as it may increase the links between research and innovative outcomes (Righi et al., 2022). As already noticed in the global overview of the digital ecosystem (see Figure 3, Panel a.), government institutions occupy a very small share in all considered regions, being slightly above 1% only in the case of China, South Korea and the EU. This is consistent with the typically larger presence of the public sector and its involvement in production and market activities in Asian countries.

Figure 5. Composition of players and activities in top ten geographical areas (2009-2022)

Panel a. Players by organisational type *Panel b. Activities by type*



Note: In Panel b., the number of activities by geographical area was obtained counting as one each activity conducted by a player located in a certain geographical area, even when an activity is performed in collaboration with players located in different areas (i.e. co-publishing, co-patenting). If the collaborative players are located in the same geographical area, then one activity is assigned to that area (see also footnote 19).

(18) When looking at country level, China, the US, the UK, Singapore and India lead the ranking, followed by South Korea, UAE, Japan and Germany. The latter is the only EU MS among the top ten countries per total number of players.

Using the information on the location of players, it is possible to get an idea of the spatial distribution of activities in the global digital ecosystem[19] (Figure 5, Panel b.). The ranking is basically the same as the one based on the number of players (with the only exception of the last geographical area), confirming the leading position of China, the US and the EU in the global digital landscape. It is, however, interesting to notice how two distinct groups seem to emerge: on the one side, China, South Korea and Japan, which have in common a prevalence of innovation activities (more than 85%)[20]; on the other side, the EU, other Asian countries, the UK, India and Near and Middle Eastern countries, which are characterized by a large majority of business activities. The US lies in between these two groups, with about 49% of business and 44% of innovation activities.

Despite providing a good indication of the size and of the degree of dynamism of a certain geographical area, indicators such as the number of players and of activities have some limitations, especially when it comes to cross-country - or cross-area - comparability. The absolute number of players does not take into account the size of the players (e.g., whether it is a SME, a start-up, a large multi-national company, a big rather than small research institution), nor considers the size of the economy of countries or geographical areas. In this regard, the indicator “player intensity” can provide a more balanced perspective of how much a geographical area contributes to the global digital ecosystem respect to its economic weight (De Prato et al. 2019). This indicator is calculated as the ratio of the number of players over the size of a country’s economy (proxied by GDP, measured in billion current USD[21]). It has to be kept in mind, however, that this indicator may reflect also other country-level factors possibly influencing the population of players in the digital ecosystem, such as the amount invested in R&D activities, or the implementation of policies that foster the generation of activities, such as industrial or STI policies, or that support the attraction of players by offering favourable business conditions.

The number of activities provides a useful characterization of ‘how active’ (or ‘productive’, in terms of number of activities) a certain geographical area is, but that does not allow to disentangle whether this is driven by the number of players (that is, more players, more activities) or by ‘how active’ and engaged in the activity of the digital ecosystem individual players are. To be able to compare the intensity of players’ engagement across geographical areas, we can use the indicator “activity intensity” (Righi et al., 2021). This is calculated as the average number of activities per player located in a given geographical area.

Figure 6 displays both indicators of “player intensity” (blue dots, right axis) and “activity intensity” (orange dots, left axis) for the top ten geographical areas. The indicator “player intensity” produces a different ranking than the absolute number of players: although China still leads this ranking (8 players per billion USD of GDP), smaller economies outperform in terms of the ratio of players to GDP. This is the case of South Korea and the UK (6.7 and 6.3, respectively), but also the regions of other Asian countries and of Near and Middle East do relatively well, thanks to the presence of small but technologically dynamic economies with many players such as Taiwan, Singapore and Israel. Thus, there does not seem to be a clear correlation between number of players and “player intensity”. This result may reflect favourable business conditions and supporting policies of attraction of digital and technological businesses implemented in these geographical areas. Looking at “activity intensity”, India (3.9), South Korea (3.9) and Japan (3.7) turn out to be the most activity-intensive geographical areas, followed by China (3.4), the EU (2.3) and the US (1.9). The group of Asian countries

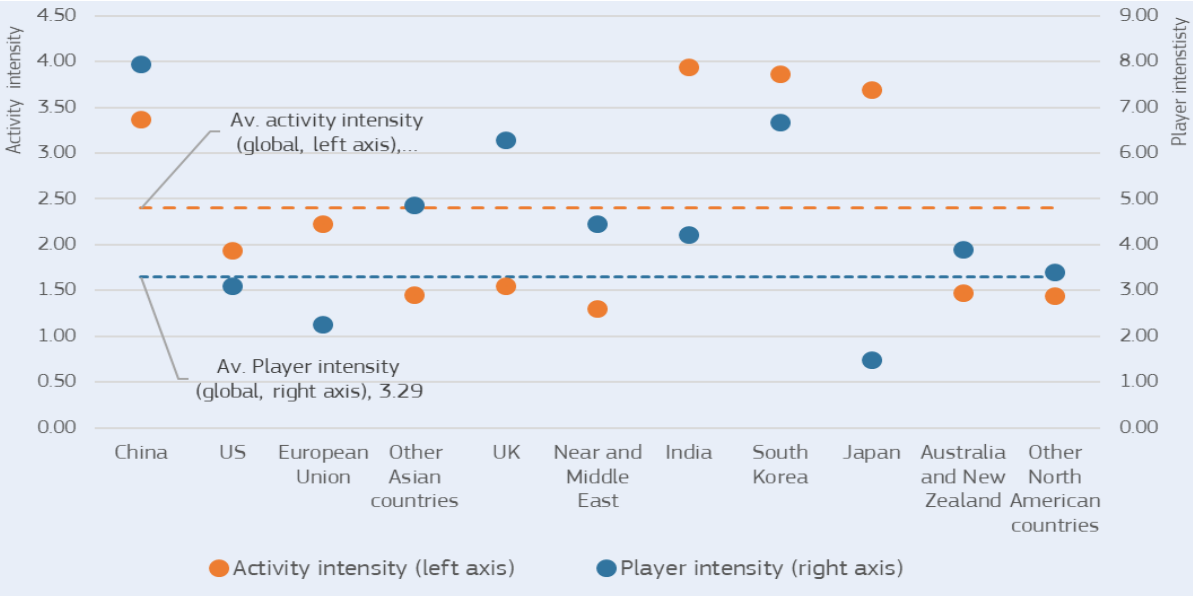
(19) The number of activities per geographical area has to be taken carefully, as relating players’ geographical location with their activities is not straightforward when an activity is collaborative (that is, it is performed by more than one player, such as in co-patenting or co-publishing). If all players that collaborate in a given activity are located in the same geographical area, one activity is assigned to that geographical area. If the collaborative players are located in different geographical areas, one activity is assigned to each geographical area where a collaborative player is located (for instance, if the collaborative players are located one in the UK and one in the EU, one activity is assigned to the EU and one to the UK). This implies that the sum of the number of activities of each individual geographical area can exceed the actual global number of activities. An alternative would be to employ a fractional counting method, when a fraction of the collaborative activity is assigned to each player depending on the number of players involved in that activity (for instance, if two players share a patent, then they would be assigned half an innovation activity each). Unless otherwise stated, in this section we do not employ a fractional counting method for activities shared by players located in different geographical areas, in order not to penalize players that collaborate more outside their geographical area.

(20) The high share of innovation activities in these geographical areas is likely to be due to mainly two factors: i) China’s number of patents increased remarkably since 2015, as result of Chinese government’s policies supporting patent applications (Righi et al. 2020, 2022); ii) the business databases used to generate the presented version of the DGTES database (Orbis, Dow Jones, Crunchbase) have a less accurate coverage of companies in China and in other Asian countries, thus may underestimate the volume of business activities whose player are located there.

(21) We take the last 5-year average (2017-2021 or latest available) of GDP values in current USD, to account for monetary differences across countries and for the impact of the recent COVID-19 pandemic crisis.

formed by China, South Korea and Japan is leading in terms of "activity intensity" of their players, all scoring above the global average value (2.4) for this indicator.

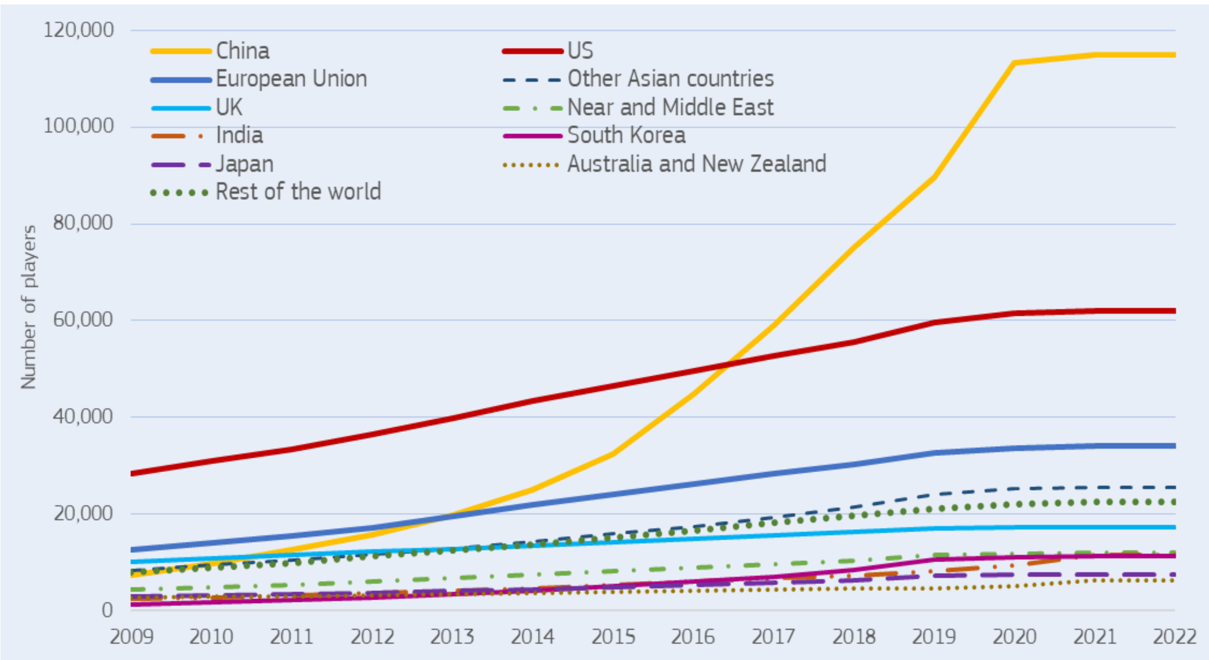
Figure 6. Player intensity and activity intensity in top geographical areas (2009-2022)



Note: For the indicator "player intensity", the data on GDP (current USD) were obtained from World Bank Development Indicators (retrieved 23.01.2023); for Taiwan, from IMF Statistics (retrieved 23.01.2023). The indicator "activity intensity" was obtained counting as one each activity conducted by a player located in a certain geographical area, even when an activity is in collaboration with players located in other regions (i.e. co-publishing, co-patenting) (see also footnote 19). The orange dotted line shows the global average value of "activity intensity". The blue dotted line shows the global average value of "player intensity".

Figure 7 provides a dynamic overview of the geographical composition of the global digital ecosystem over the considered period (2009-2022). It reveals how the relative participation of the different geographical areas has changed in terms of number of players, allowing to highlight which regions' or countries' relative position has changed more remarkably. Although all geographical areas have been experiencing a constant increase in number of players in the digital ecosystem, the growth of China was particularly fast during the first part of the period, slowing down after 2016.

Figure 7. Number of players per year in top ten geographical areas (2010-2022)



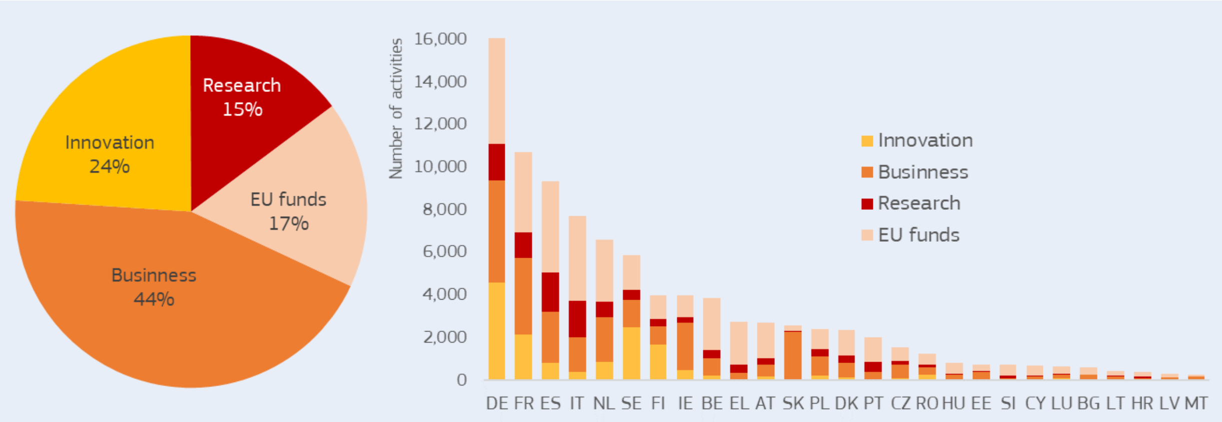
Focus on the EU

DGTES is a flexible analytical approach: by changing the level of geographical aggregation and focussing on EU MS, it allows obtaining a refined picture of the European digital ecosystem. In order to guarantee comparability, until now players and activities related to EU-funded projects (FP7, H2020, Horizon Europe) have been excluded from global and cross-country figures of the digital ecosystem, as similar funding programs from other world regions or countries are not considered in the DGTES database. Still, these EU-funding programs play a big role in supporting R&D in Europe: when included in the DGTES database, FP7, H2020 and Horizon Europe projects (more than 10,500 across the three programs) represent 17% of total activities performed in the digital ecosystem in the EU (about 60,000) (Figure 8, Panel a.). This average value, however, does not fully reflect the great importance of these funding programmes for the digital ecosystem of many MS. This becomes clear when looking at individual countries' activities and players' composition.

In terms of number of activities, Germany, France, Spain, Italy, the Netherlands and Sweden are the six leading countries (Italy and Sweden swap position when EU funds are excluded) (Figure 8, Panel b.)[22]. Still, the composition of activities varies largely across countries: the share of EU-funded projects goes from 72% in Greece to 26% in Ireland, 10% in Slovakia. In more than half of EU MS the number of activities included in the DGTES database doubles when EU-funded projects are considered. Business activities take the largest share in most MS, while Germany, Sweden and Finland are characterized by a relatively larger share of innovation activities (between one third and half of activities).

Figure 8. Activities in the EU digital ecosystem (2009-2022)

Panel a. Activities by type *Panel b. Activities by country and type*



Note: Activities related to EU-funded programmes (FP7, H2020, Horizon Europe) are included. In Panel b., a collaborative activity performed across more than one country (i.e. collaborations on a patent, an article, an EU-funded project) counts as one activity for each of the participating country (see also footnote 22).

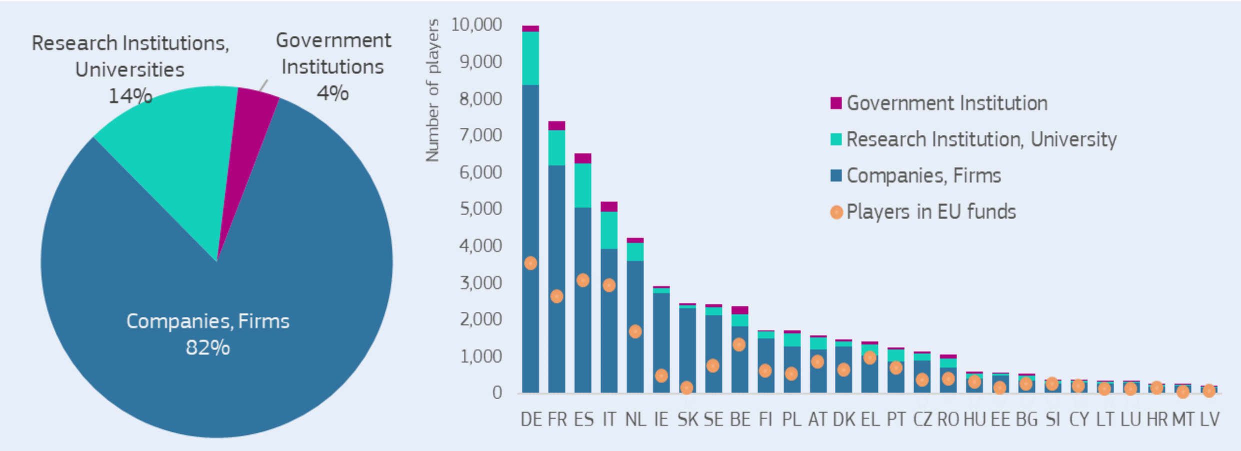
The role of EU-funding programmes in shaping the European digital ecosystem becomes even more prominent when looking at players. Once EU-funded projects are taken into account, the number of European players in the digital ecosystem increases by 66% (from 35,000 to about 55,000). Figure 9, Panel a. shows how this is not just a quantitative, but also a qualitative improvement: it changes the composition of the players, involving more research institutions and universities (14% of all players) and more government institutions (4%), even if firms and companies remain the predominant type of players (82%). This reveals that many European players do not have a core business, nor a patent, nor a publication that is relevant for the definition of the digital ecosystem; still, their participation in EU-funded projects suggests that they do have the capabilities to perform digitally-relevant activities. Hence, EU funds play an important role for the vitality of the European digital ecosystem, as they effectively mobilize and engage players that would otherwise not enter the ecosystem despite their capabilities and potential.

(22) EU-funded projects tend to involve players from different countries. In the case of projects involving players located in more than one country, the EU funded project is counted as one activity for each of the participating countries - for instance, if involved players are located in three different countries, one full EU-funded project activity is assigned to each of the three countries. This implies that the sum of the number of activities associated to each individual country can exceed the actual number of activities performed by European players. We still prefer this over a fractional-counting method in order not to underestimate the importance for individual MS of cross-country collaborative EU funded projects.

Germany, France, Spain, Italy, the Netherlands and Ireland lead the digital landscape in terms of number of players, these six countries hosting more than 60% of all European players (Figure 9, Panel b.). Looking at organisational types, firms and companies dominate in all MS (above 70% in all MS but Bulgaria, Croatia and Romania), followed by research institutions, whose share is particularly high in Croatia (25%), Bulgaria (24%), Hungary (23%) and Romania (23%). Governmental institutions account for only 4% of total players, but their presence is around 10% in Latvia, Slovenia and Belgium, and relatively large also in Romania (9%), Bulgaria (8%), Greece (7%) and Lithuania (7%). The share of players participating in EU-funded projects also varies largely across countries, going from 6.5% for Slovakia and 16% for Ireland, to 56% in Italy and 68% in Greece and Slovenia.

Figure 9. Players in the EU digital ecosystem (2009-2022)

Panel a. Players by organisational type *Panel b. Players by country and organizational type*



Note: Information related to players participating in EU funded programmes (FP7, H2020, Horizon Europe) are included.

3.2.2 Exploring the technological dimension

Which digital areas define and characterize the global digital ecosystem?
How involved are players and geographical areas in the main digital areas? How competitive are players and geographical regions in the main digital area?

The technological dimension is an important aspect of the digital ecosystem. In DGTES, this is associated to the notion of *digital area*[23]. As presented in section 2, digital areas correspond to the techno-economic domains that define the boundaries of the digital ecosystem from a forward-looking and policy relevant perspective. The information on the digital areas enriches the analysis of the digital ecosystem with a technological focus: by associating each activity to one or more digital areas, DGTES gives an overview of what is the weight of the different digital domains in the global digital landscape. Moreover, by looking at this information by year, it can represent the evolution of the technological composition of the digital ecosystem over time, which helps detect weak signals of emerging technological domains in the global digital landscape.

A technological landscape

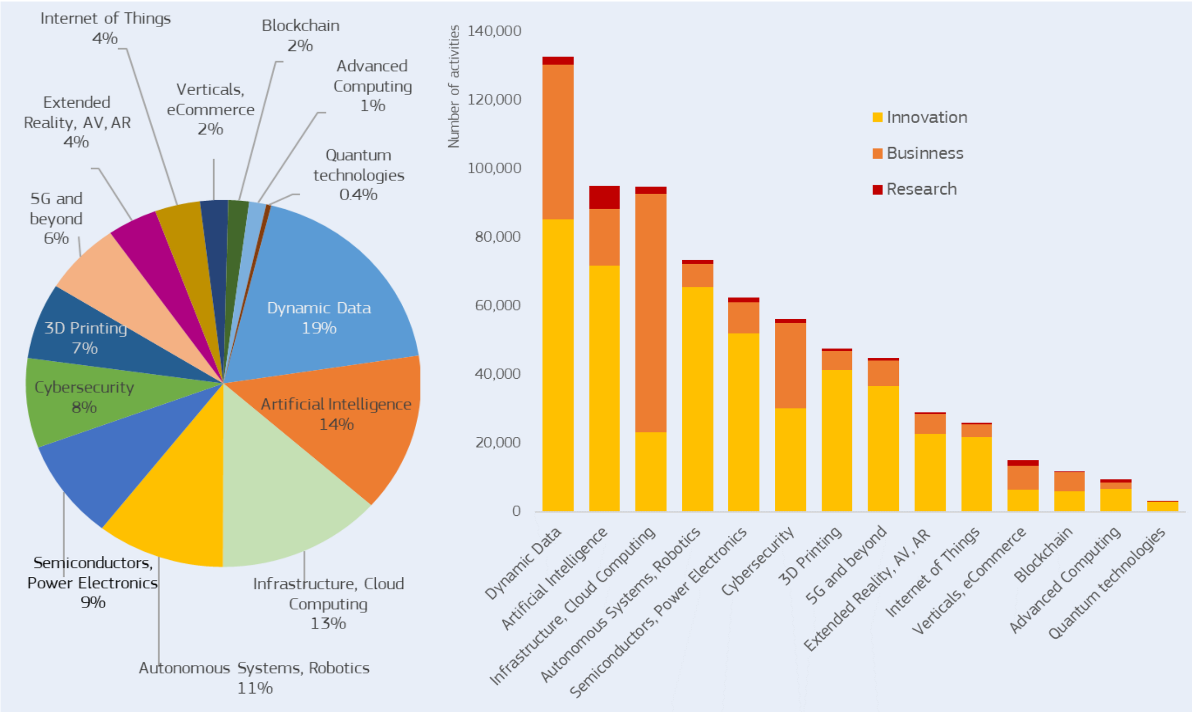
Figure 10, Panel a. displays the composition of the activities by digital area[24]. It can be notices that the DGTES digital ecosystem is not dominated by one or a few digital domains; instead, almost 90% of activities are distributed across nine main digital areas, each covering between 19% and 4% of activities. Top five digital areas are "Data, Dynamic data", "Artificial Intelligence", "Infrastructure, cloud computing, digital platform, IaaS, SaaS, PaaS", "Autonomous systems, robotics" and "Semiconductors, power electronics". Panel b. shows the

(23) About the definition and construction of the digital areas, see Box 1 in section 2.2 of this report.
(24) In this report we present the digital areas of "Verticals" and "eCommerce, eBusiness" as a unique digital area ("Verticals, eCommerce"). This choice is mostly due to the relatively small size (in terms of number of activities) of the "eCommerce" domain, supported by the argument that both digital areas refer to applications rather than to specific technologies.

composition of activities by type in each digital area. Innovation activities represent the majority in all digital areas. Yet, there are exceptions: business activities account for the largest share (73%) in “Infrastructure, cloud computing, digital platform, IaaS, SsaaS, PaaS” and are relatively more common also in “Cybersecurity” (44%), “Verticals, eCommerce” (47%) and “Blockchain” (48%).

Figure 10. Composition of activities by digital area in the digital ecosystem (2009-2022)

Panel a. Activities by digital area *Panel b. Activities by digital area and type*



Note: An activity that is associated with more than one digital area counts as one activity for each of the digital areas (see also footnote 31).

Around 94% of activities in the digital ecosystem are associated to a unique digital area[25] (Table 2). This suggests that activities are rather “technologically homogeneous”, presenting little overlapping of diverse digital domains within the same activity. This confirms that the identified digital area are effective in clustering activities into internally-coherent, techno-economic categories. When looking at type of activities, 14% of research activities have more than one digital area. This is in line with the nature of these activities, which are commonly associated to frontier research, and it is thus possible for more cross-contamination across domains and disciplines to take place in these more explorative activities.

Table 2. Share of activities associated to different digital areas

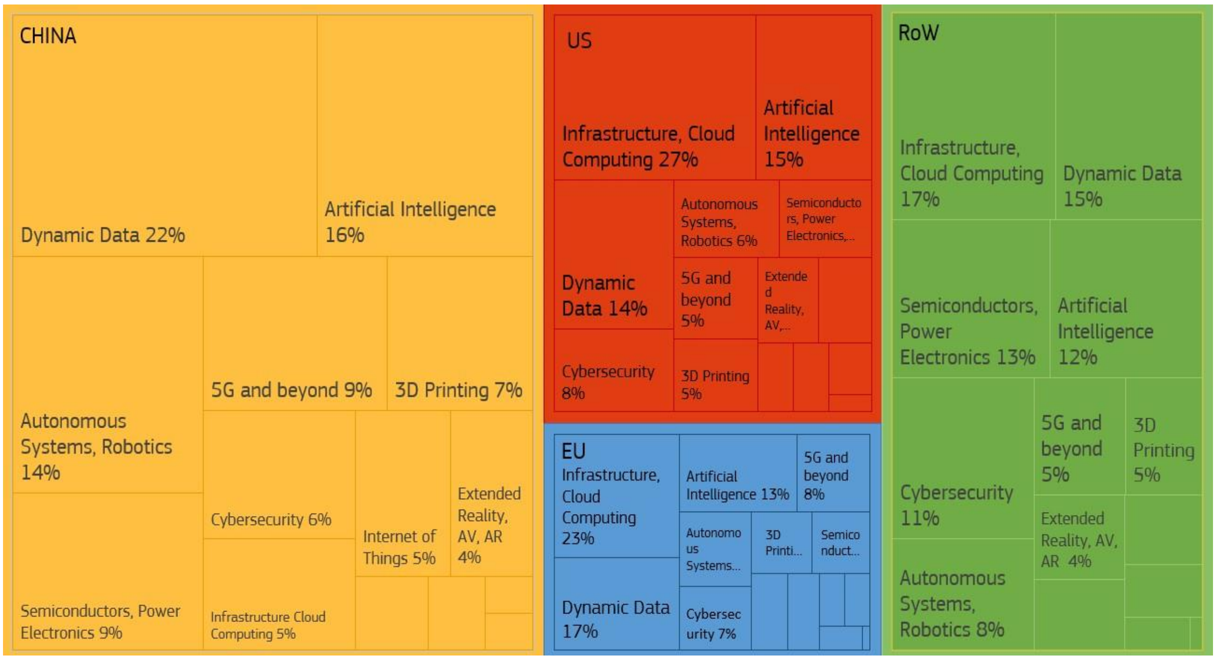
	Innovation	**Business**	**Research**	**Total**
Activities in 1 digital area	95.3 %	92.6 %	85.7 %	94.0 %
Activities in 2 digital areas	4.4 %	6.6 %	12.0 %	5.4 %
Activities in more than 2 digital areas	0.3 %	0.8 %	2.3 %	0.6 %
All activities	100%	100%	100%	100%

(25) When an activity is associated with more than one digital area, it counts as one full activity for each of the involved digital areas. For example, a patent associated to the digital areas of “Cybersecurity” and of “Data, Dynamic data” counts as one activity in “Cybersecurity” and one in “Data, Dynamic data”. The chosen approach does not challenge a straightforward interpretation of the results, as almost all activities are associated one-to-one with a single digital area (6% of activities are associated to two or more digital areas). An alternative would to employ a fractional counting method, where a fraction of the activity is assigned to each digital area involved (in the given example, this implies assigning half activity to each of the two digital areas).

The flexibility of DGTES allows crossing its geographical and the technological dimensions. By relating the information about digital areas with the information on geographical location of players, DGTES provides an overview of the involvement of each geographical areas in the different digital domains. This technological landscape can offer novel insights on the geographical distribution of technological competences and capabilities in the global digital ecosystem.

Figure 11 displays the composition of activities by digital area in the top three geographical areas of China, the US and the EU, and the rest of the world (RoW). The digital profile of the top three world regions can be characterized as non-specialized, due to their participation in most digital areas. Half of China's activities fall under "Data, Dynamic data" (22%), "Artificial Intelligence" (16%) or "Autonomous systems, robotics" (14%). The US and the EU display a different 'technological profile': "Cloud Computing, Digital Platform, IaaS, SaaS, PaaS" (which occupies the eighth position in China) represents the main area (with 27% and 23% of activities, respectively), followed by "Artificial Intelligence" (15% in the US, 13% in the EU) and "Data, Dynamic data" (17% the in EU, 14% in the US). As the digital area "Cloud computing, digital platform, IaaS, SaaS, PaaS" refers to the provision of infrastructure, software and platform services and applications, its large share in the US and the EU may be explained by the strong expansion of platform providing services in these geographical areas (De Prato et al., 2019). The US has also a rather relevant presence in "Cybersecurity" (8%), which is the fourth digital area in the ranking, while in the EU the fourth position is occupied by "5G and beyond" (8%).

Figure 11. Composition of activities by digital area in selected geographical areas (2009-2022)



Note: An activity that is associated with more than one digital area counts as one activity for each of the digital areas (see also footnote 25). Activities that are shared across the geographical areas (i.e. collaborations on a patent, an article) count as one activity for each of the involved geographical areas (see also footnote 24). RoW: rest of the world.

Revealed comparative advantage (RCA)

Figure 11 gives an idea of the relative weights of the digital areas within the three main geographical areas. However, it does not provide additional information on how these weights translate into the relative global positioning of each of these world region. In other words, what does it imply for the US to have almost the same share as China in "Artificial intelligence"? And for the EU to have 17% of activities in "Data, Dynamic data"? These questions are relevant, as the relative strength of a certain geographical area in a given digital area can serve as proxy for its level of technological specialisation.

In this regard, a useful indicator is the revealed comparative advantage (RCA). This measures the relative engagement of a certain geographical area (i.e. world region, country) in a given digital area, in comparison with the world average. RCA is calculated by comparing the geographical area's share of activities in a specific digital area against the global average in that same digital area (Samoili et al., 2020). A value of RCA above 1 means that the geographical has a higher-than-world average proportion of activities in that digital area, therefore revealing a relative advantage in that digital area[26] (see Box 4).

Box 4: The Relative Competitive Advantage (RCA)

The Relative Competitive Advantage (RCA) serves as an indicator of the relative competitiveness of a geographical area (or a country) in a digital area in comparison with the global average (or with the average of a broader geographical area of reference, i.e the EU). This indicator is calculated as the ratio of two shares: *i)* the sum of a geographical area's activities in a digital area over the total number of activities performed by players located in that geographical area, and *ii)* the sum of activities worldwide in that digital area over the total number of activities worldwide.

By construction each activity is associated to one or more digital areas through a set of keywords, which are used to identify the activities (business, research, innovation) that define the digital ecosystem (Calza et al. 2022). Based on players' location, the activities are summed up by geographical area. The RCA is thus calculated as follows:

$$RCA_{C_i,k_z} = \frac{\frac{A_{C_i,k_z}}{\sum_z A_{C_i,k_z}}}{\frac{\sum_C A_{C_i,k_z}}{\sum_{C,Z} A_{C_i,k_z}}} = \frac{\frac{sum\ of\ activities\ of\ country\ C_i\ in\ topic\ k_z}{sum\ of\ activities\ of\ country\ C_i\ in\ all\ topics}}{\frac{sum\ of\ worlwide\ activities\ in\ topic\ k_z}{sum\ of\ worlwide\ activities\ in\ all\ topics}}$$

where $A_{Ci,kz}$ is the number of activities of the geographical area C_i in digital area k_z, defined as the sum for all the country's players (*j*) of activities in a given digital area. Hence, in practice the RCA measures a geographical area's distance from the average share of activities in a given digital area: when the RCA is greater than 1 for a geographical area in a given digital area, that geographical area has a comparative advantage in that digital area.

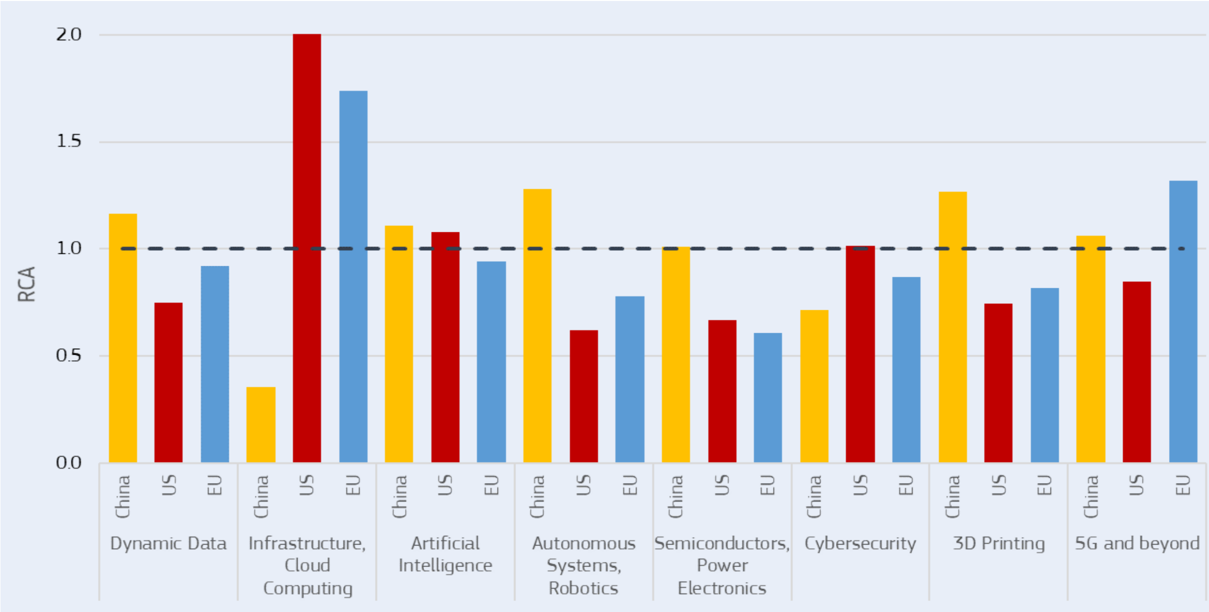
The comparability of RCA scores across different worldwide geographical regions is possible when only innovation, research and business activities are considered – thus, excluding activities related to EU-funded projects. These can be included only for specific analyses of the EU and its MS. In this case, the world average share (that is, the denominator of the RCA) is replaced by the EU average share and the RCA, therefore, measures the relative competitiveness of countries within the EU.

Source: Authors' elaboration based on Samoili et al. 2020.

Figure 12 displays the RCA scores of the three leading geographical areas (China, the US and the EU) in the top seven digital areas. China has RCA scores above 1 and higher than the US and the EU in all considered digital areas but in "Infrastructure, cloud computing, digital platform, IaaS, SaaS, PaaS", "Cybersecurity"; in "5G and beyond" it scores higher than 1 but below the RCA score of the EU (1.32). Thus, in terms of RCA, China is the most competitive geographical area in most digital domains. The digital areas "5G and beyond" and "Infrastructure, cloud computing, digital platform, IaaS, SaaS, PaaS" represent the digital areas of relative strength for the EU (in which this geographical area hosts 10% and 13% of worldwide activities, respectively). In particular, the EU leads in terms of relative specialisation in the digital subdomain of "5G and beyond", with 1.35 times the world average of activity share and scoring higher than China (RCA 1.06) and the US (RCA 0.85). With a RCA score of 1.74, the EU displays a larger-than-world average concentration of activities in "Infrastructure, cloud computing, digital platform, IaaS, SaaS, PaaS", following the US (RCA 2.04) and ahead of China (0.36). Although remaining below the world's average, the EU displays a relative advantage also in "Cybersecurity", with a RCA score of 0.87 (closely following the US with RCA score of 1) and in "Data, Dynamic data", with a RCA score of 0.92 (following China with a RCA score of 1.2).

(26) International comparability is granted when only innovation, research and business activities are considered. Therefore, activities related to EU-funded projects are excluded when calculating the RCA. The information on EU-funded projects can be used for a more in-depth analysis of the situation of EU and its MS.

Figure 12. Revealed comparative advantage (RCA) by digital area in China, the US and the EU (2009-2022)



Note: An activity that is associated with more than one digital area counts as one activity for each of the digital areas (see also footnote 25). Activities that are shared across the geographical areas (i.e. collaborations on a patent, an article) count as one activity for each of the involved geographical areas (see also footnote 24). The dotted line corresponds to the world average (RCA = 1).

Finally, calculating these indicators at different points in time makes it possible to draw some conclusions on the technological dynamism of the digital ecosystem. For instance, changes in the composition by digital areas can disclose weak signals of emerging technological trajectories, highlighting how some clusters of digital technologies have emerged and become relatively more relevant. Similarly, changes in the composition of activities in a certain digital area can reveal different patterns of technological maturity (i.e. if the majority of activities shift from research to innovation or business over time). The results of these analyses can support policymaking with the identification of which digital areas are more likely to shape future digital and technological leadership.

The information on the geographical distribution of digital areas also sheds light on the co-evolution of the geographical and technological dimensions in the global digital ecosystem. This can help better understand the episodes of technological ‘catching up’ experienced by some geographical areas in correspondence to successful reductions of the technology gap (Lee and Malerba, 2017). As the technology gap is one of the root causes of strategic dependencies, this exercise would provide original insights on the evolution of global patterns of digital and industrial leadership.

4 A DGTES-based analysis of digital leadership in a global digital landscape

Besides providing a broad overview of the digital ecosystem (see section 3), DGTES can offer analytical insights on several policy issues related to the digital transformation. In fact, thanks to the granularity of the underlying data and to the flexibility of the TES methodology, DGTES can fit several analytical purposes: it can steer the focus of the analysis towards different aspects, explore specific digital technologies and subdomains, and zoom-in/out at different geographical levels.

This section discusses how a DGTES-based analysis of the digital ecosystem can provide novel and policy-relevant analytical insights on the digital transformation. The first subsection illustrates the analytical potential of the DGTES graph database, presenting two DGTES-based network representations of the digital ecosystem and highlighting possible policy-relevant analyses. The following subsections propose examples of such in depth analysis: the second subsection discusses a first set of network-based indicators that contribute to the discussion of the EU's digital leadership; the third subsection focuses on some subdomains of the digital ecosystem that are critical for Europe's digital leadership, acknowledging the policy-relevance of cybersecurity, autonomous systems, and raw materials, and offering an analytical look from the point of view of strategic autonomy. The last subsection looks at how the web of collaborations in EU-funded projects contribute to shaping the capabilities needed for a vibrant and competitive European digital ecosystem.

4.1 DGTES as ecosystem by design

How can we use the DGTES graph database to explore and analyse the digital ecosystem?

Which type of interconnections can generate a network representation of the digital ecosystem? Which layers and attributes can characterize a certain network representation of the digital ecosystem?

DGTES is designed to generate a graph database that allows identifying players engaging in business, research or innovation activities (see section 2.21). This DGTES graph[27] database is obtained from the integration of several sources of data and reflects the complex system of relations and interlinkages ongoing across the elements of the digital ecosystem, through different layers and attributes. The DGTES graph database is, thus, a suitable instrument for a comprehensive analysis and a better understanding of the digital ecosystem as a dynamic space of interdependencies.

In this report, the term *graph* refers to the whole system of interconnections and attributes underlying and characterizing the relations across entities in a complex system. A graph analysis allows to simultaneously account for these different elements, layers and attributes, eventually leading to the detection of hidden patterns or implicit connections. In this section, we refer more frequently to the term *network*, which we associate to a specific projection of the graph based on the selection of specific nodes and edges. In practice, we employ the graph structure of the DGTES database to visualize and explore the digital ecosystem as a complex network, where different entities (nodes) are connected through forms of relations (edges) that can be based on different dimensions, layers and attributes. Hence, depending on the focus of the analysis, different network representations can be generated, where nodes (i.e. individual players, geographical areas, countries) and edges (i.e. formal and informal collaborations on R&I activities, ownership relations, co-participation in EU-funded projects, venture capital investments, etc.) can be characterized in different ways, depending on the chosen attributes (i.e. the level of geographical aggregation, type of activities, technological domains, etc.). This means that more network representations can be generated from the DGTES graph database, with a different aggregation level for nodes (i.e. by individual players or grouped at region- or city-level) or based on different types of interconnections across nodes (i.e. through ownership relations, venture capital investments, collaborations on EU-funded projects, etc.). Each type of network allows concentrating on some specific aspects at time and offers an overview of the digital ecosystem from a different angle. A certain network representation can also be compared with a different one or over time, adding a dynamic perspective to the analysis.

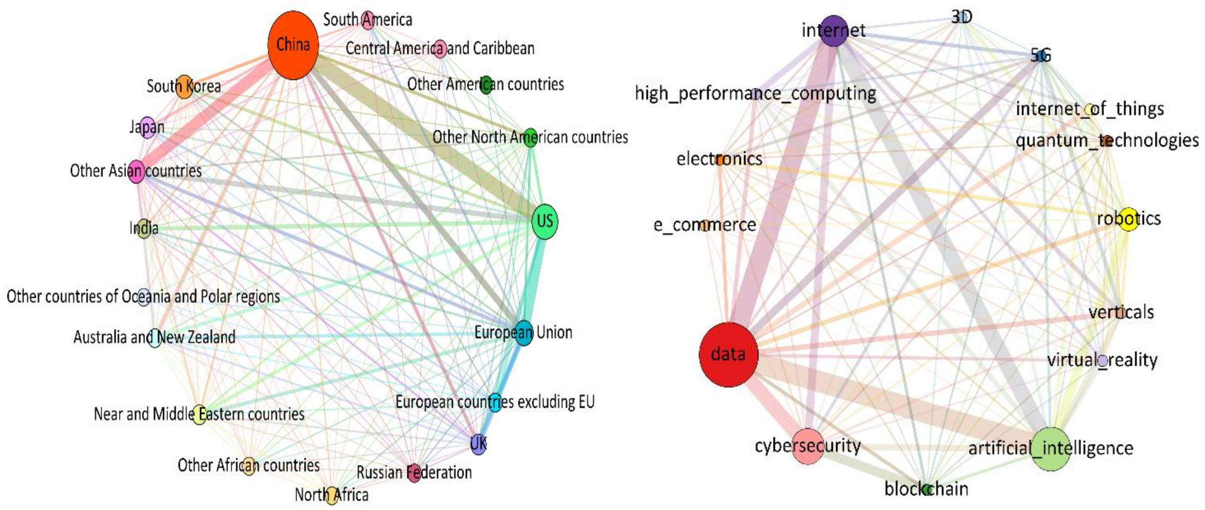
([27]) The term *graph* here refers to the whole system of interconnections and attributes underlying and characterizing the relations across entities in a complex system. In this report we refer more frequently to a *network*, which we associate to a specific projection of the graph based on the selection of specific nodes and edges.

> *A* ***graph*** *refers to the whole system of interconnections and attributes underlying and characterizing the relations across entities in a complex system. A* ***network*** *corresponds to a projection of a graph, as defined by specific nodes and edges.*

Figure 13 presents two examples of network representation of the DGTES digital ecosystem. Panel a. displays a *network of players and collaborative activities*: nodes are groups of players aggregated at the level of geographical area[28] and edges represent the shared R&I activities (e.g. co-patenting, co-authorship in scientific publications)[29] across players located in different geographical areas. Corresponding to the web of collaborative R&I activities across geographical areas, these explicit and formal interconnections describe the digital ecosystem as a network of interdependent entities. Panel b. displays represents the DGTES digital ecosystem as a *network of digital areas and keywords*[30]: here a node corresponds to a set of keywords associated to a specific digital area, while edges represent the co-occurrence of keywords associated to different digital areas within the same activity (that is a textual document). As different keywords can be detected in a single activity (co-occurrence of distinct keywords), this can signal the appearance of different knowledge-contents and suggest a connection across them. The analysis of the co-occurrence of keywords associated to different digital areas can reveal how different knowledge domains are related to each other through the activities in the digital ecosystem, and unveil unknown relationships between them. By revealing the web of interlinked digital subdomains, this type of network describes the digital ecosystem as a space of interdependent knowledge domains.

Figure 13. DGTES-based network representations of the digital ecosystem

Panel a. A network of players and collaborative activities in R&I *Panel b. A network of digital areas and keywords*



Note: In Panel a., the size of a node depends on the total number of collaborative and non-collaborative activities (research, business and innovation) performed by players located in that geographical area; the width of an edge depends on the number of R&I activities shared across two geographical areas. In Panel b., the size of a node depends on that node's score in terms of betweenness centrality; the width of an edge depends on the total number of activities in which a co-occurrence between two digital areas is detected.

Table 3 summarizes how the analysis of DGTES-based network representations - such as the ones in Figure 13 - can contribute to informing policies for anticipating, monitoring and steering the digital transformation.

([28]) The geographical areas are defined in the same way as in section 3 in this report.

([29]) Unless stated otherwise, for comparability reasons, activities related to EU- funded projects (FP7, H2020, Horizon Europe) are not included.

([30]) In this report, *keywords* can be interpreted as the "atomic semantic units" or "modules of embedded knowledge" of a digital area. In DGTES the digital areas are the techno-economic subdomains that define the perimeter of the digital ecosystem (see Box 1 in section 2.2 in this report for a better definition and discussion of the digital areas). The set of keywords associated to a digital area represents the semantic space that defines the knowledge boundaries of that digital area.

Table 3. What can we do with a DGTES-based network representation of the digital ecosystem?

Policy-relevant DGTES-based analyses	Policy areas
Panel a. A network of players and collaborative activities in R&I	
• Investigate the innovation processes in the digital ecosystem by analysing the generation, exchange and acquisition of knowledge across geographical areas through formal R&I activities.	Capabilities and capacities
• Explore the intensity of collaborations within and across geographical areas (even at different level), while comparing the attributes of collaborative players and of non-collaborative ones.	Capabilities and capacities
• Investigate technological maturity in the digital ecosystem and the evolution of digital technologies through the analysis of the changes in the composition of shared R&I activities by digital area and by type of activity (i.e. when the majority of shared activities shift from research to innovation over time).	Capabilities and capacities; Industrial transformation
• Analyse how the structure of the network (i.e. clusters and components) and how its features (i.e. density) influences how knowledge flows through and across its parts, allowing to detect whether certain nodes occupy a particularly relevant and strategic position (i.e. bottlenecks, gatekeepers) and whether this may reveal the existence of important relations and connections from the point of view strategic autonomy.	Strategic autonomy and dependencies
• Apply community detection algorithms to reveal the presence of clusters of players more densely interconnected and analyse their characteristics.	Industrial transformation
• Employ nestedness analysis to detect the frequency of features (e.g. digital areas) within clusters of players, allowing to assess the distribution of capabilities and the quality (i.e. as unique, rare) of their knowledge and competences.	Capabilities and capacities
• Exploit the information about other layers of the DGTES graph database (i.e. foreign ownership, venture capital investments, co-participation in EU-funded projects) to enrich the scope of the analysis and explore the co-existence, co-evolution and interaction of different dimensions in the digital ecosystem.	Capabilities and capacities; Industrial transformation
Panel b. A network of digital areas and keywords	
• Investigate the interlinkages across digital domains to see whether an eventual cross-contamination among different technological realms leads to innovation represented by the emergence of new fields or technologies, or has the potential to create cross-domain innovation (i.e. deep tech innovation), or whether, instead, a certain digital subdomain tends to remain isolated from the rest of the network and to evolve towards an increasing specialization.	Capabilities and capacities; Industrial transformation
• Explore a particularly strong interconnection between digital domains, looking at which type of activities tend to generate these linkages (e.g. whether co-occurrences of keywords are more frequent in research or innovation activities) and which type of players tend to get more involved in cross-domain activities (i.e. individual or groups of players). This may help reveal strategic dependencies and vulnerabilities in critical digital domains.	Strategic autonomy and dependencies
• Apply latent community detection algorithms to reveal groups of more densely interrelated keywords, allowing a more granular analysis of the relationships between digital domains.	Capabilities and capacities
• Employ dynamic analysis to study the evolution of this network of digital domains, in order to predict emergent ties between keywords and the possible appearance of new activities based on these combined fields of knowledge.	Industrial transformation

Note: The categories in the column "Policy areas" are the ones already used in Table 1 in section 2.1 in this report.

4.2 Network indicators for digital leadership

What indicators can be used to measure digital leadership in the global digital ecosystem?

Which roles and positions do players have in the global digital ecosystem? Which players occupy strategic roles or positions, or reveal strategic dependencies? What does this imply in terms of their ability to shape and steer the global digital ecosystem?

What is the situation of the EU as a global player in the digital ecosystem? What does this imply in term of its competitiveness and leadership in the global digital landscape?

As discussed in section 2.1, EU's digital leadership is founded on achieving strategic autonomy in the digital realm. DGTES allows approaching strategic autonomy from a network perspective: drawing on a network representation of the digital ecosystem, it can help reveal strategic strengths or detect vulnerabilities and bottlenecks in specific subdomains or digital technologies. The results of such DGTES-based analysis feed into the discussion about the EU's ability to compete at the frontier of digital technologies relying on its own resources and competences, or whether it depends, instead, on knowledge inflows from extra-EU players. These considerations represent novel analytical insights on the EU's digital leadership.

Here we introduce a first set of indicators and metrics[31] that can serve as proxies for players' engagement, strategic position, dependencies and vulnerabilities (Table 4). To obtain these indicators, we use the DGTES graph database to generate a representation of the global digital ecosystem where nodes correspond to players agglomerated at geographical level and edges to R&I activities shared across players located in different geographical areas. As discussed in section 4.1, this is only one of the possible networks of creation, diffusion and exchange of knowledge, products and services that can be obtained using the DGTES graph database. This specific DGTES-based network representation allows exploring the digital ecosystem from a relational and systemic perspective, contributing to the ongoing debate on the EU's strategic autonomy in the context of knowledge creation and transfer in the global digital landscape. The analysis of the change of these indicators over time may allow detecting patterns of evolution of strategic autonomy as well as predicting emerging strategic positions and future strategic strengths and vulnerabilities.

Table 4. Indicators and metrics for digital leadership

Indicator name	Metric	Purpose
Volume	Weighted degree (collaborative R&I activities)	*Engagement*: proxy for the relevance of a node in terms of its contribution to the generation and exchange of knowledge, products and services in the digital ecosystem
Intermediation	Weighted betweenness centrality	*Strategic position:* proxy for the influence and control a node can exert on the rest of the digital ecosystem
CONcentration	Number of connections of node *i* with node *j* over total connections of node *i*	*Dependency:* proxy for the importance of the connections across two paired nodes with respect to all the connections of one of the nodes
Asymmetry	Absolute value of the difference in the values of CONcentration of two paired nodes	*Vulnerability*: proxy for the asymmetric dependency across two paired nodes

Engagement

A player displays a high *engagement* when it has a large weight in the global digital ecosystem. This is the case when a node engages in a lot of activities and, therefore, gives a relevant contribution to what is produced (knowledge, goods or services) and exchanged in the global digital ecosystem. An indicator of engagement is the number of R&I collaborative activities conducted by a node (that is, a player or the set of players located in a certain geographical area), which represents how involved a node is in the network and how much it contributes to its activity through collaborative R&I. We name this indicator "volume" and measure it at the weighted degree of a node, where edges are weighted according to the number of collaborative activities between a pair of nodes.

Strategic position

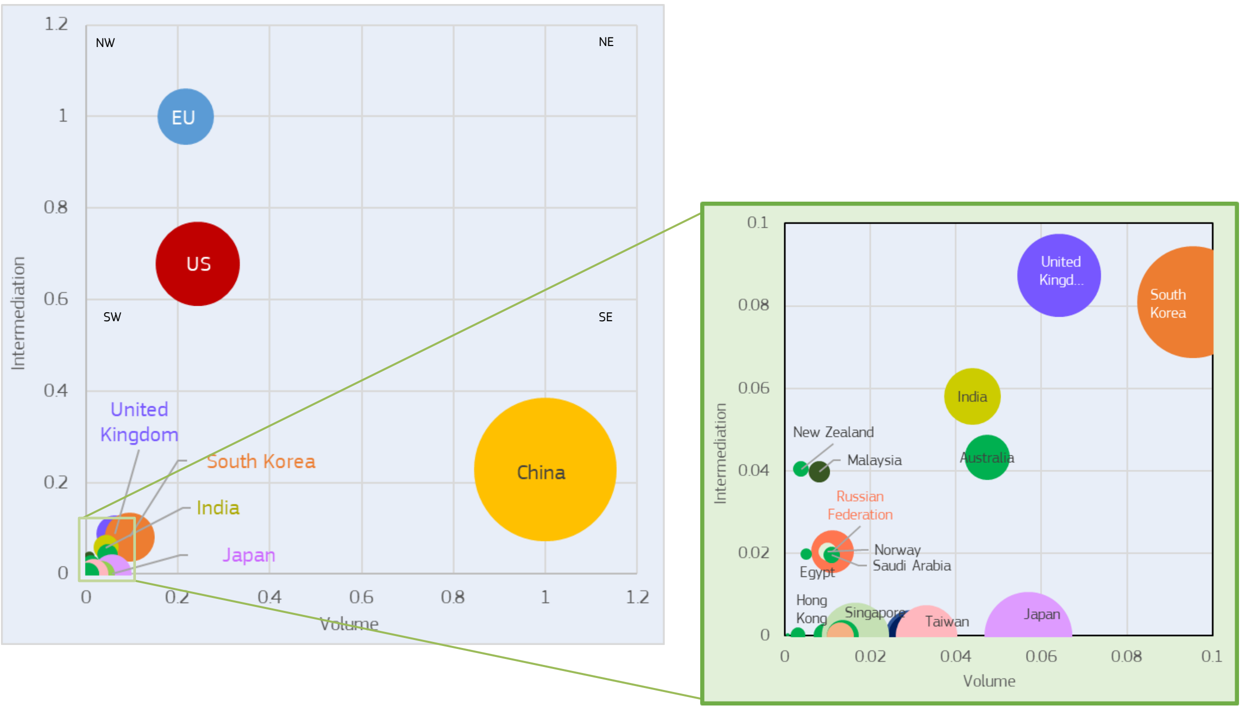
Strategic position is defined as the ability of a node to influence the rest of the network by acting as intermediator. This is the case when a node serves as point of juncture of different parts (components) of the network of R&I collaborations in which it is involved. This is strategic in two ways: on the one hand, this node acts as a bridge, essential for connecting not otherwise connected players in the network, whose structure would be changed and disrupted if the intermediator node is removed; on the other hand, this node acts as bottleneck, as it can exert a relevant influence on the rest of the network and be able to steer, control or even

(31) See Calza et al. (2022) for an overview of the indicators that can be generated from the DGTES database.

interrupt the knowledge flowing to and from other nodes (Samoili et al. 2020; Righi et al. 2021). We name this indicator as "intermediation" and measure it using the Weighted Betweenness Centrality (WBC)[32].

Figure 14Figure 14 displays the values of the indicators for engagement and strategic position. Nodes falling in the SE quadrant are very relevant for defining the magnitude of the network representing the digital ecosystem, but do influence nor control it. In this regard, China is the node with the strongest engagement: it has the highest "volume" score, as it is responsible for the highest number of shared R&I activities; yet, it scores low in "intermediation". Nodes falling in the NW quadrant have, instead, a strong strategic position: they can influence the network by controlling the knowledge flowing through its different parts, but give a smaller contribution in terms of overall level of activity. The EU and the US occupy the NW quadrant. The EU has the highest "intermediation" value: this means that the EU plays a key connecting role in the digital ecosystem, exerting a relevant influence on the network due to the structure of its collaborations and to its ability to act as connecting bridge or as bottleneck between nodes. Moreover, even if they score much lower than China in terms of engagement, the EU and the US still display relatively higher values in "volume" compared to the rest of the world. The SW quadrant is populated by non-strategic nodes. Still, zooming-in allows drawing some considerations: for instance, South Korea and the UK perform relatively better in both dimensions than other countries with a comparable score in "volume", such as Japan; the same holds for India and Australia compared to Taiwan and Singapore. Finally, it has to be noticed that the indicators for engagement and strategic position are not strongly correlated: a node characterized by a high "engagement" in terms of activities is not necessarily associated to a high "strategic position" – thus, despite its relatively large weight, it would not able to influence the network, whose topological features would remain mostly unaffected if the node is removed. It is thus not surprising that the NE quadrant remains empty.

Figure 14. Engagement and strategic position in the global digital ecosystem



Note: For visualization purposes, the values of both indicators have been normalized within a range 1 (max. value) – 0 (min value). The size of the bubbles correspond to the number of total (collaborative and non-collaborative) activities (business, research and innovation) of a node.

([32]) In a network, the Betweenness Centrality (BC) of a node is the number of shortest paths that pass through that node. When the metric is Weighted Betweenness Centrality (WBC), the weight of the links are taken into account for deciding which path is the shortest. In our network, weights refer to the number of shared activities (thus, collaborative activities) between a pair of nodes. Thus, the higher the weight of the link, the shortest the path is (i.e., the more activities are shared between two actors, the shortest the path between those actors is). To calculate the WBC we use as weight of links the inverse of the number of activities shared between two actors: $w(i,j) = 1 / \text{count}(a(ij))$, where $a(ij)$ is the number of shared activities between nodes i and j.

Dependency and vulnerability

We associate the notion of *dependency* with the relative importance of the connections across two nodes: a node *i* has a high level of dependency with respect to the node *j* when the connections with *j* represent a relatively large share of all connections of node *i.* Hence, a straightforward indicator of dependency is the share of connections between nodes *i* and *j* (n_{ij}) over the total number of connections of node *i* (N_i). As dependency is high when a node concentrates most of its connections around another single node, we name this indicator as "CONcentration". In this analysis, we say that a node (here, a geographical area) has a high degree of dependency with respect to another node when it displays a value of "CONcentration" above 25%.

Figure 15 shows the affinity matrix calculated over the network of R&I collaborations across nodes. The cells on the diagonal (green) display the shares of collaborative activities within the same geographical areas (internal collaborations), which do generate connections across nodes. It has to be noticed that for several players these represent the large majority of collaborative activities: more than 80% for China, almost 70% for South Korea, 60% for Japan, more than 50% for Russian Federation. The US and the EU have a similar share of internal collaborations, around 45%. On each row, the cells off-the diagonal display the values of the indicator "CONcentration". Almost all geographical areas reveal a high dependency (that is, a value of "CONcentration" above 25%) with respect to at least one of the three leading areas – China, the US and the EU –, which turn out to be very important R&I partners for the rest of the world. The three global leaders also reveal interesting patterns of dependency among them. The EU displays dependency on the US, with which it performs one out of four European external collaborations in R&I, but not with China. Although internal collaborations represent more than 80% of all Chinese collaborative activities, almost one out of three external collaborations take place with the US - a level of interaction higher than with any other geographical region. The same holds for the US, for which China covers almost 30% of external collaborations.

Figure 15. Dependency: affinity matrix

	China	US	EU	South Korea	Other Asian countries	Japan	UK	Near and Middle Eastern countries	India	Other North American countries	European countries excluding EU	Australia and New Zealand	Russian Federation	South America	Other African countries	Central America and Caribbean	North Africa
China	84.1%	30.2%	12.3%	4.3%	22.9%	3.3%	6.7%	2.7%	1.5%	4.6%	1.5%	7.9%	0.4%	0.5%	0.5%	0.3%	0.7%
US	28.5%	44.9%	20.6%	4.5%	7.9%	2.7%	5.8%	5.3%	6.0%	4.5%	3.7%	4.9%	0.5%	2.4%	0.9%	1.1%	0.5%
EU	13.9%	24.7%	43.1%	2.5%	6.1%	3.5%	13.2%	6.2%	3.1%	4.4%	7.4%	5.2%	1.3%	4.6%	1.2%	0.9%	1.9%
South Korea	21.5%	23.9%	10.9%	69.4%	13.0%	4.2%	4.1%	4.8%	3.9%	2.7%	2.0%	4.0%	1.2%	1.6%	0.4%	0.1%	1.5%
Other Asian countries	39.4%	14.4%	9.2%	4.5%	25.3%	2.8%	4.9%	5.9%	3.7%	2.3%	2.1%	7.3%	0.4%	0.9%	0.7%	0.5%	1.0%
Japan	21.6%	19.2%	20.6%	5.6%	10.6%	62.3%	6.9%	2.0%	2.2%	2.2%	2.1%	4.0%	0.4%	1.1%	0.4%	0.4%	0.6%
UK	16.2%	14.9%	28.4%	2.0%	7.0%	2.5%	20.6%	5.4%	3.3%	3.0%	5.1%	6.6%	0.9%	1.8%	1.2%	0.4%	1.3%
Near and Middle Eastern countries	9.0%	18.4%	18.0%	3.2%	11.3%	1.0%	7.3%	20.1%	6.0%	6.3%	3.9%	8.8%	0.8%	1.7%	0.7%	0.5%	3.2%
India	6.2%	27.2%	11.6%	3.4%	9.1%	1.4%	5.8%	7.8%	36.4%	2.1%	1.5%	18.1%	1.1%	1.6%	1.6%	0.5%	1.2%
Other North American countries	21.0%	22.1%	17.8%	2.5%	6.0%	1.5%	5.7%	8.8%	2.3%	20.4%	3.7%	4.5%	0.4%	1.8%	0.7%	0.4%	0.7%
European countries excluding EU	7.4%	19.4%	32.4%	2.0%	5.9%	1.6%	10.4%	5.9%	1.8%	4.0%	24.1%	4.2%	0.8%	1.5%	1.1%	0.6%	1.0%
Australia and New Zealand	21.7%	14.4%	12.8%	2.2%	11.7%	1.7%	7.5%	7.4%	11.7%	2.7%	2.3%	22.3%	0.3%	1.8%	1.0%	0.1%	0.6%
Russian Federation	8.6%	13.5%	28.6%	5.6%	5.3%	1.6%	8.6%	5.9%	6.2%	2.3%	3.9%	2.3%	51.6%	5.3%	0.7%	0.7%	1.0%
South America	4.1%	21.9%	34.5%	2.7%	4.6%	1.4%	6.5%	4.4%	3.1%	3.4%	2.5%	5.4%	1.9%	30.5%	1.3%	1.4%	1.0%
Other African countries	9.3%	19.3%	20.4%	1.6%	7.4%	1.3%	9.3%	4.0%	7.1%	3.2%	4.5%	7.1%	0.5%	2.9%	17.6%	0.3%	1.9%
Central America and Caribbean	8.9%	32.8%	21.4%	0.7%	8.1%	1.8%	4.8%	4.1%	3.0%	2.6%	3.3%	1.5%	0.7%	4.4%	0.4%	16.6%	1.5%
North Africa	10.4%	7.9%	25.8%	4.6%	8.7%	1.5%	8.1%	15.0%	4.2%	2.5%	3.1%	3.3%	0.6%	1.9%	1.5%	0.8%	19.6%

Note: On each row, the values in the cells sum up to one, subtracting the value in the cell on the diagonal (green).

Although high, the dependency between US and China is rather symmetric. This consideration allows us to introduce a last indicator for *vulnerability*. Here we use the notion of vulnerability to complement the one of dependency, indicating whether dependency is or not symmetrical across two nodes: the larger is the difference between two nodes' values for "CONcentration", the more asymmetrical and unbalanced is their collaboration, which can be taken as a proxy for the vulnerability of a node with respect to the other. We measure the vulnerability for node *i* and *j* as the absolute value of the difference between the values of "CONcentration" for node *i* with *j*, and for node *j* with *i*. We name this indicator as "asymmetry". In this analysis, we associate a high level of vulnerability to a difference of more than 20 percentage points in the reciprocal shares of collaborative R&I activities between two nodes.

Figure 16 displays the values of "asymmetry" for each pair of nodes. Some of the relationships displaying a high dependency in Figure 15 are not asymmetric, thus do not rise an issue of vulnerability - for instance, the already commented collaborations across the three leading geographical areas of China, the US and the EU. Non-EU European countries turn out to be relatively vulnerable with respect to the EU, as the role of the EU as main partner in collaborative R&I activities (32%) is not corresponded (7%), thus showing an "asymmetry" value of 25. Other examples of vulnerabilities are observed between the EU and Russian Federation, South America, and North Africa: for these areas, the EU plays a disproportionately important role in external R&I collaborations.

Figure 16. Vulnerability: asymmetry in dependency

	China	US	EU	South Korea	Other Asian countries	Japan	UK	Near and Middle Eastern countries	India	Other North American countries	European countries excluding EU	Australia and New Zealand	Russian Federation	South America	Other African countries	Central America and Caribbean	North Africa
China																	
US	1.7																
EU	1.6	4.1															
South Korea	17.2	19.4	8.4														
Other Asian countries	16.6	6.5	3.2	8.5													
Japan	18.4	16.5	17.1	1.3	7.8												
UK	9.6	9.1	15.2	2.1	2.0	4.4											
Near and Middle Eastern countries	6.2	13.1	11.8	1.7	5.4	1.0	1.9										
India	4.8	21.1	8.5	0.6	5.4	0.8	2.5	1.8									
Other North American countries	16.4	17.5	13.4	0.2	3.8	0.7	2.7	2.5	0.2								
European countries excluding EU	5.9	15.7	25.0	0.0	3.9	0.5	5.3	2.0	0.3	0.3							
Australia and New Zealand	13.8	9.5	7.5	1.8	4.4	2.4	0.9	1.4	6.4	1.8	1.9						
Russian Federation	8.2	13.0	27.3	4.4	4.9	1.2	7.7	5.1	5.2	1.9	2.0	2.0					
South America	3.6	19.5	29.9	1.1	3.7	0.3	4.6	2.7	1.6	1.6	3.7	3.4	3.4				
Other African countries	8.8	18.4	19.2	1.2	0.9	0.9	8.1	3.3	5.6	2.4	6.1	0.7	1.6	1.6			
Central America and Caribbean	8.5	31.7	20.5	0.6	7.6	1.4	4.4	3.6	2.5	2.1	1.3	0.1	3.0	0.1	0.1		
North Africa	9.7	7.4	23.9	3.1	7.8	0.8	6.8	11.8	3.0	1.8	2.7	0.4	0.8	0.4	0.4	0.6	

Note: Values in the cells correspond to percentage points.

4.3 Zooming in on critical subdomains: cybersecurity, autonomous systems, raw materials

Attaining EU's digital leadership requires to identify, analyse and address strategic dependencies in key sectors and technological subdomains. Strategic dependencies are related to the EU's strategic interests and affect areas at the core of the EU's priorities (SWD(2021) 351 final). Some strategic dependencies fall within the perimeter of the digital ecosystem: this is the case when they have to do with the access to inputs, technologies and services that can affect the EU's ability to achieve the green and digital transitions, or with security issues related to aerospace, defence and cybersecurity. The "*Action Plan on Synergies between civil, defence and space industry"* defines critical sectors and technologies as "relevant across the defence, space and civil related industries and contribute to Europe's technological sovereignty by reducing risks of overdependence on others for things we need the most" (COM(2021) 70 final). Thus, among others, these critical subdomains entail digital technologies related to cybersecurity and autonomous systems, as well as the raw materials needed for the green and digital transitions. Given the horizontal nature of digital technologies, this does not exclude technological dependencies in other ecosystems (SWD(2021) 351 final).

This subsection showcases examples of how DGTES can be employed to investigate strategic strengths or dependencies in strategic subdomains, whose mastering is expected to enhance digital leadership by achieving strategic autonomy: cybersecurity, autonomous systems and raw materials. The granular structure of the DGTES database allows indeed for great flexibility in steering the focus of the analysis towards these specific subdomains in the digital ecosystem. It also shows how DGTES can offer policy-relevant analytical insights to inform policy recommendations targeted at strengthening the EU's participation and position in these critical realms and at fostering the EU's digital as well as industrial leadership.

A critical digital area: cybersecurity

What does the critical digital area of cybersecurity look like as a network of players and activities?
Which geographical area or country occupies a strategic role and position? How is the EU positioned?

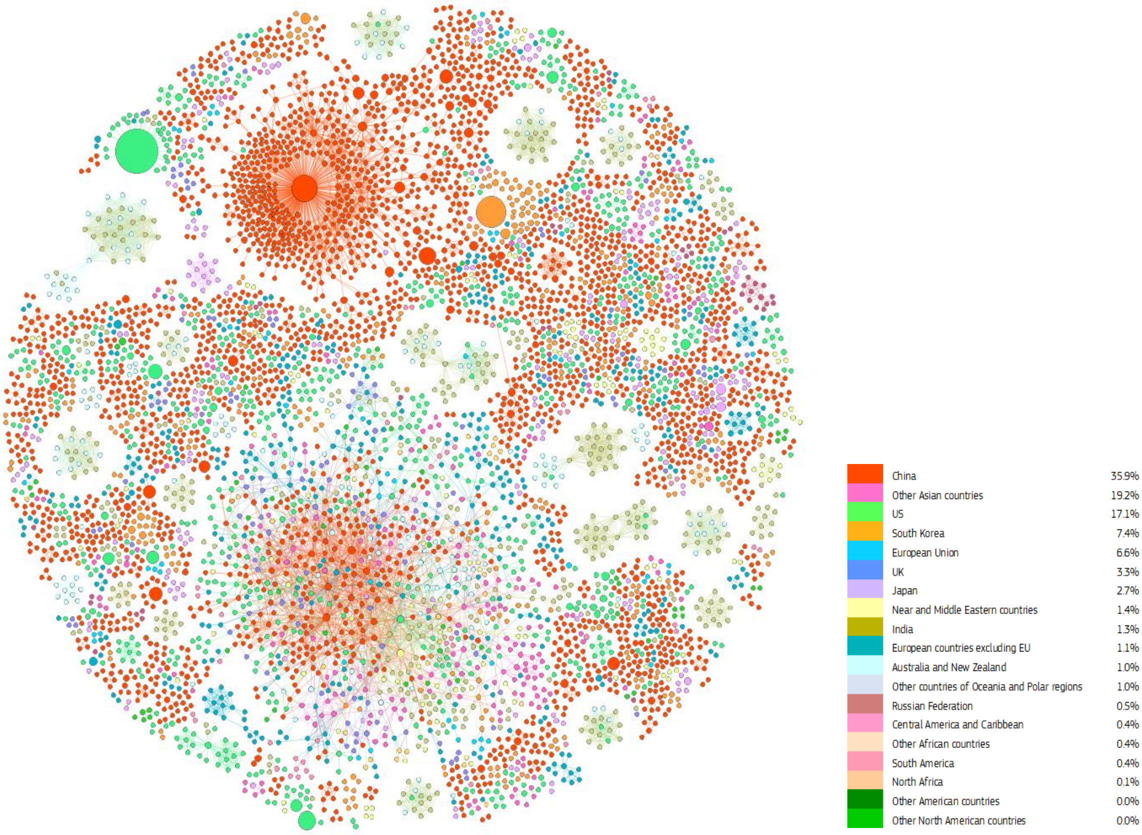
In DGTES, the digital area of cybersecurity entails more than 56,600 activities (around 8% of total activities in the global digital ecosystem) and about 40,000 players (12% of total players). Activities are distributed in a rather balanced way between innovation (53%) and business activities (44%), while research activities cover the remaining 3%. This relatively high share of business activity is a peculiarity of cybersecurity. Looking at the geographical distribution, China performs about 36% of activities in cybersecurity, followed by other Asian countries (20%), the US (17%), South Korea (7.5%) and the EU (6.5%).

We use the DGTES graph database to draw a global network of cybersecurity where nodes correspond to individual players (individual firms, research centres, universities or governmental institutions) and edges to R&I activities jointly performed by players active in cybersecurity (Figure 17). A quick visual inspection of this network reveals some interesting features:

- the three largest (in terms of number of activities) individual players are located in China, the US and South Korea (recognizable as the three largest dots, in the upper part of Figure 17);
- many players (mostly located in China, South Korea and US) perform only one activity and in isolation, thus they do not generate connections with other players in cybersecurity;
- the different geographical areas follow very different collaboration patterns: a) the majority of China's collaborative players are connected to the largest Chinese player, implying that their collaborative activities take place within China, while only a small set of Chinese players display a dense network of relations with players outside China (mostly located in the US, the EU, the UK and other Asian countries); b) the EU displays a more distributed network, with several players characterized by few activities but several connections, mostly with EU-based (and also UK-based) players; c) US players tend not to cluster among them and reveal more "spread out" collaborations with players from different regions; d) finally, several clusters of Indian players can be noticed.

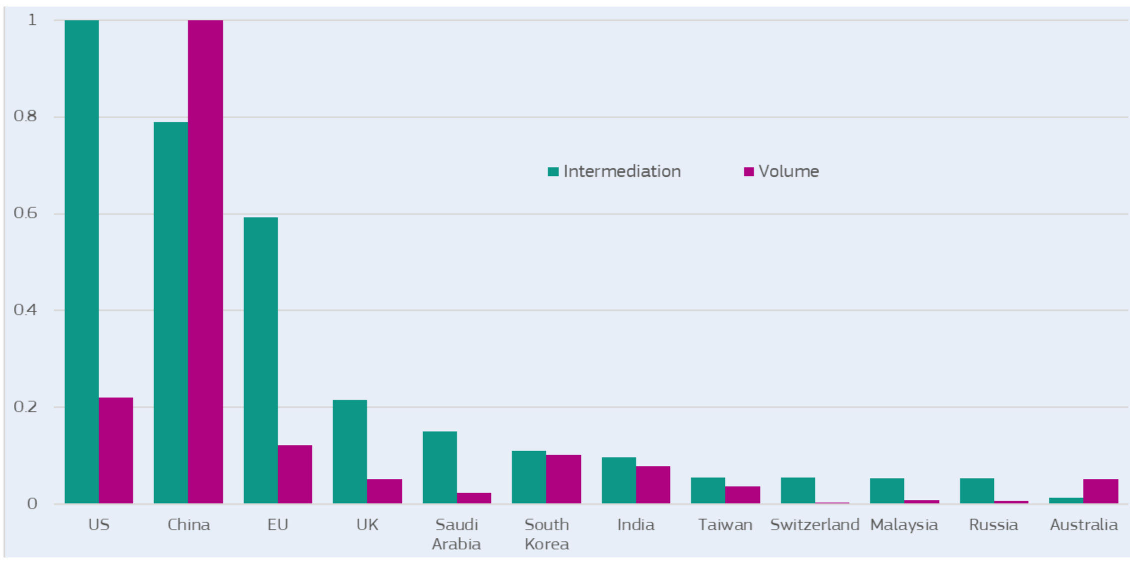
We then calculate the indicators of engagement and strategic position (introduced in section 4.1) for the network of cybersecurity, after grouping players by their location (thus, a node now corresponds to a single country or geographical area). Figure 18 shows the results for top countries and geographical areas. China is by far the node with the highest "volume" value (this, the highest engagement), followed (but with a certain distance) by the US and the EU. The US displays the highest "intermediation" value, which suggests a strategic position in cybersecurity. This is due to the structure of the network by geographical areas: China and the EU tend to act more as closed clusters, where players collaborate mostly within the same area and have few connections outside it. However, the fact that the EU and China follow the US rather closely in terms of their values of "intermediation" may reveal that no nodes occupy a clear strategic position in cybersecurity.

Figure 17. A global network of cybersecurity



Note: The size of a node corresponds to the total number of activities performed by the player associated to that node. The colours correspond to the geographical area where the individual player (node) is located. The shares in the legend correspond to shares over total activities in cybersecurity.

Figure 18. Indicators for engagement and strategic position in cybersecurity



Note: For visualization purposes, the values of both indicators have been normalized within a range 1 (max. value) – 0 (min value).

A group of critical technologies: autonomous systems

> *What does the critical subdomain of autonomous systems technologies look like as a network of players and activities?*
>
> *Which geographical area or country occupies a strategic role and position? How is the EU positioned?*

To enhance digital leadership, the EU needs to support those sectors in which the EU has to maintain and strengthen its technological edge and reduce risks of overdependence on others (COM(2021) 70 final). In this respect, autonomous systems[33] represent a critical subdomain in the digital ecosystem.

The subdomain of autonomous systems entails more than 56,000 activities (around 8% of total activities in the global digital ecosystem) and more than 26,000 players (8% of total players). Almost all of these activities (87%) correspond to innovation activities (patent applications). Activities are very much concentrated in China (70% of activities), followed by the US and South Korea (9% and 5%, respectively). The EU performs 4% of activities in autonomous systems. This is not surprising, considering how spending on R&I in the EU remains far below the level of the US and China, although R&I efforts are decisive for this industry's competitiveness and Europe's autonomy (COM(2021) 70 final).

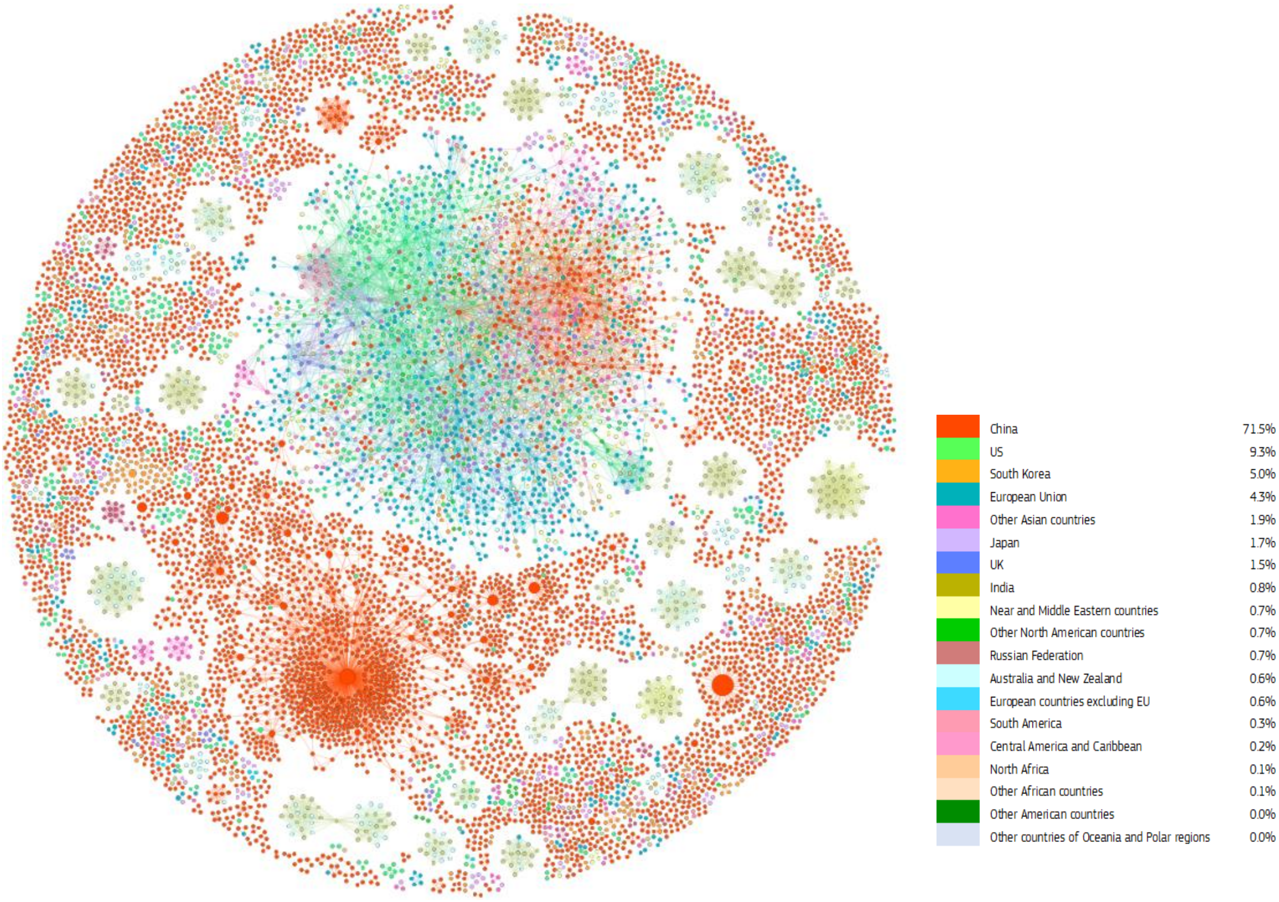
Figure 19 shows a network representation of the subdomain of autonomous systems, where nodes correspond to individual players and edges to collaborative R&I activities. A quick visual inspection reveals some interesting features:

- the majority of individual players (mostly located in China) perform only one activity and in isolation, thus they do not generate connections with other players active in autonomous systems;
- only a few players stand out in terms of number of activities (i.e. the size of the dots) and they are all located in China;
- the majority of China's collaborative players are connected to the largest (in terms of number of activities) Chinese player, implying that most of China's collaborative activities remain within China; still, some small Chinese players are connected with players in the US, the EU and other Asian countries;
- a densely connected section of the network reveals the presence of an intense collaboration across players located in the EU and the US and (even if to a lower extent) in China.

We calculate the indicators of engagement and strategic position (introduced in section 4.1) also for the network of autonomous systems. Figure 20 shows the results for top countries and geographical areas. China dominates this subdomain in terms of level of engagement, being by far the node with the highest value for "volume". The EU displays the highest "intermediation" value, which suggests a strategic position in the network of R&I activities in autonomous systems. This may be due to the fact that EU players display an intense collaboration with players located outside the EU, implying that the EU may be in the position to act as bridge or as bottleneck controlling the flow of knowledge through this specific network representation of the global digital ecosystem.

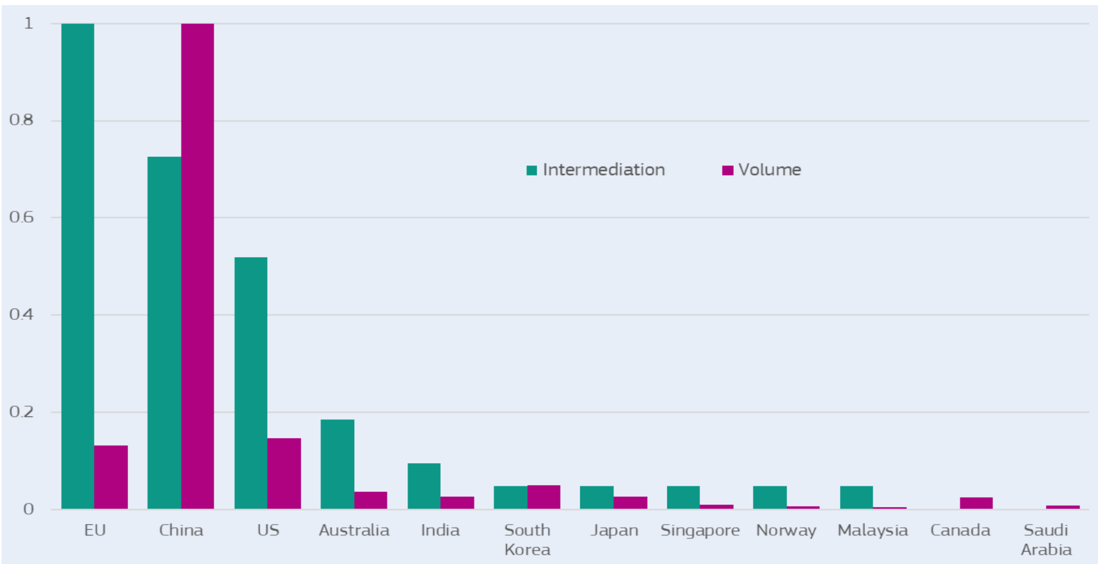
([33]) The application of the DGTES approach and database for the analysis of critical technologies related to autonomous systems is part of an ongoing collaboration between the JRC Digital Economy Unit (T1) and the Observatory of Critical Technologies (OCT).

Figure 19. A global network of autonomous systems



Note: The size of a node corresponds to the total number of activities performed by the player associated to that node. The colours correspond to the geographical area where the individual player (node) is located. The shares in the legend correspond to shares over total activities in autonomous systems.

Figure 20. Indicators for engagement and strategic position in autonomous systems



Note: For visualization purposes, the values of both indicators have been normalized within a range 1 (max. value) – 0 (min value).

Critical inputs: raw materials

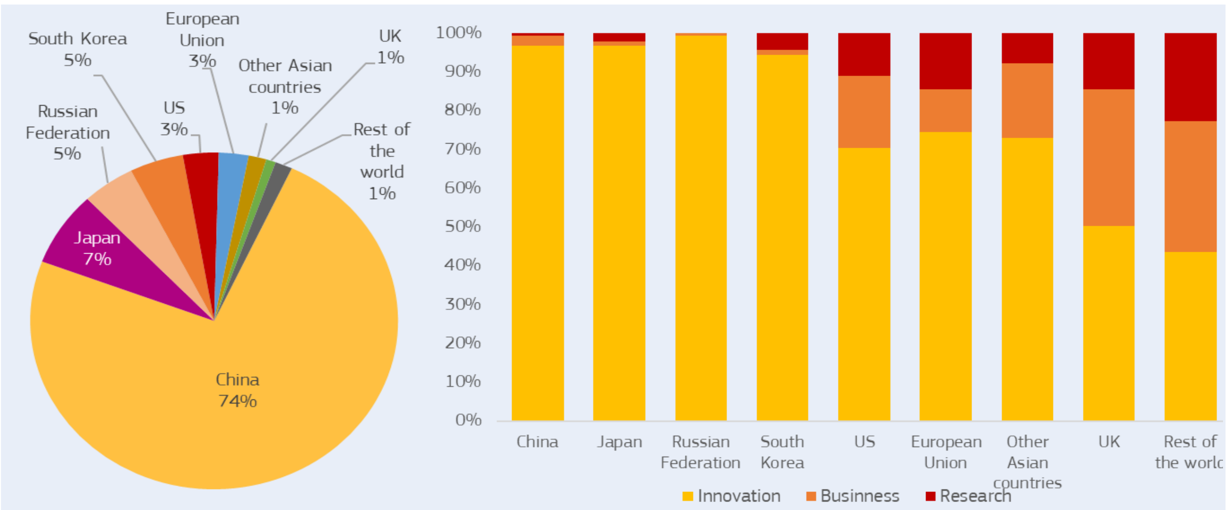
> *How is the subdomain of critical raw materials characterized? Where do most activities take place?*
>
> *What does the subdomain of critical raw materials look like as a network of foreign ownerships? Which features does it display? How is the situation of players in EU MS?*

A secure access to critical raw materials is crucial for the green and digital transitions. Critical raw materials are indeed essential for strategic sectors such as renewable energy, electric mobility, defence and aerospace, and digital technologies (COM(2020) 474 final). With the shift towards renewable energy and e-mobility, the twin transition requires primary inputs for batteries and fuel cells; at the same time, critical raw materials are also crucial for aerospace, defence and digital applications (COM(2020) 102 final). The EU industry is still largely dependent on imports for many raw materials and in some cases is highly exposed to vulnerabilities along the supply chain (European Commission, 2020).

In DGTES, the subdomain of the global digital ecosystem associated to raw materials[34] entails about 18,000 activities and 10,000 players. In terms of geographical distribution (Figure 21, Panel a.), China performs most of the activities (more than 70%), followed by Japan (7%), Russian Federation (5%), South Korea (5%), the US and the EU (both with about 3%). Almost all activities (94%) correspond to innovation activities (patent applications). However, Panel b. reveals how the composition of activities changes remarkably across geographical areas: as in the case of the global digital ecosystem, China, South Korea, Japan and also Russian Federation display a larger share of innovation activities with respect to the other world regions, where a more balanced presence of business and research activities is observed.

Figure 21. Activities in the subdomain of raw materials by geographical area (2009-2022)

Panel a. Activities *Panel b. Activities by type*



The information contained in the DGTES graph database allows representing the subdomain of critical raw materials as a network of ownership relations across companies. In this example, we define nodes as individual players, while edges identify a connection across two individual players based on ownership – in practice, a connection is established when a player in the digital ecosystem (that now we name as "local player") is owned by an entity located in another country or geographical area (that we now name as "foreign owner")[35]. If we associate "local players" and "foreign owners" with the information on their geographical location, the obtained network of ownership can give an idea of the possible influence that a certain

([34]) When generating the DGTES database, activities related to raw materials were identified through a list of keywords specifically referring to critical raw materials (in particular, metals and rare earths) and their application to digital technologies. This list of keywords is based on the classifications proposed in the document *"Critical materials for strategic technologies and sectors in the EU - a foresight study"* (European Commission 2020).

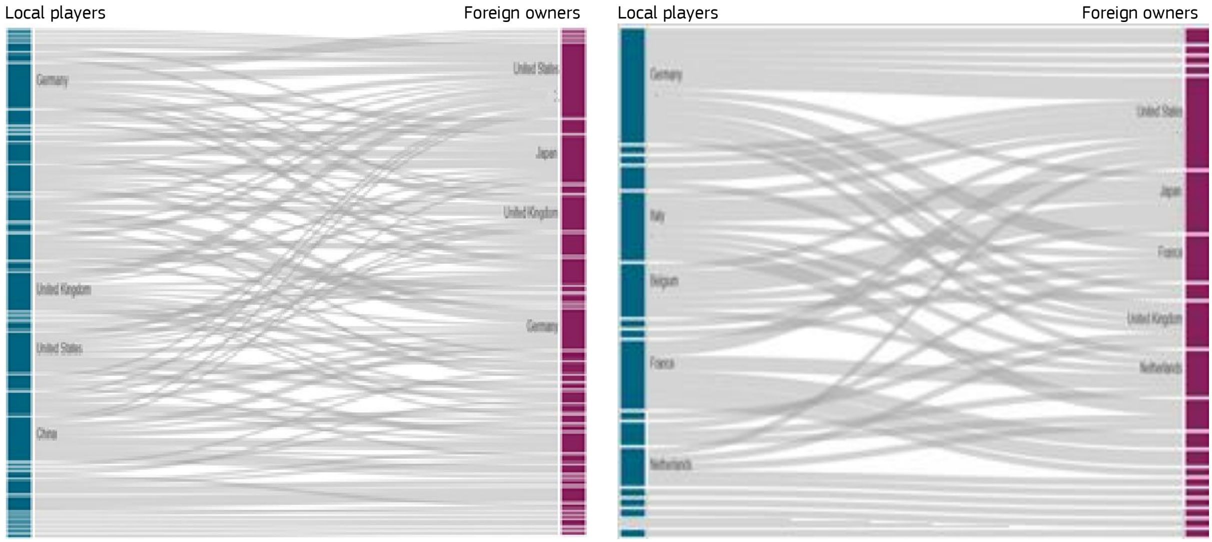
([35]) The foreign owner may or may not be a player in the digital ecosystem. Thou, in order to avoid confusion, we prefer to refer to owners as "foreign entities" or "foreign owners", not as "foreign players".

geographical area could exert on the rest of the network through foreign ownership relations. This can provide novel insights to the detection and assessment of strategic dependencies in critical subdomains, such as raw materials.

Figure 22 shows a representation of the network of foreign ownership in the subdomain of raw materials. Panel a. displays the worldwide network for all "local players", while Panel b. shows only "local players" located in EU. Most of these players are companies and firms. In the case of EU MS, more than 25% are owned by entities located in the US or Japan. The analysis of the evolution over time of the network of foreign ownership can help identify patterns of dependencies. For instance, if a geographical area gets more engaged over time by increasing its number of owned players, it can be expected that it will become more influential over the whole network. In fact, as foreign ownership can be a channel of knowledge transmission, this means that the "foreign owners" located in that geographical area can be able to exert full control and shape the knowledge generated and eventually exchanged by the owned "local players".

Figure 22. Network of foreign ownership in raw materials (2009-2022)

Panel a. All local players *Panel b. EU local players*



N. of local player companies: 8,393

N. of local player companies: 248

4.4 Strengthening capabilities: the role of EU-funded projects

How is the network of activities based on EU-funded projects? Which features does it display?

Have EU-funded programs fostered collaboration across EU players? How does the network of collaborations in EU-funded activities look like compared to the one of collaborations in R&I activities?

EU funding programmes - such FP7, H2020 and Horizon Europe - are designed to promote collaborations of consortia across entities from different countries, in the large majority from EU MS, but eventually also from non-EU countries. The aim of these programs is to promote and activate the generation of frontier knowledge in a collaborative way, fostering the development of networks of excellence that facilitate knowledge development and exchange, and pool resources for advanced research - not only financial, but also in terms of human resources and social capital.

Using the DGTES graph database, we generate a network representation of the digital ecosystem based on the collaboration on EU-funded projects across players located in the EU and in the UK[36]. In this network, nodes correspond to players located in the same country and edges represent the EU-funded projects that are co-performed by players located in different countries (external collaborations). Shedding light on the structure of connections that develop and build on these shared activities, the analysis of such a network can

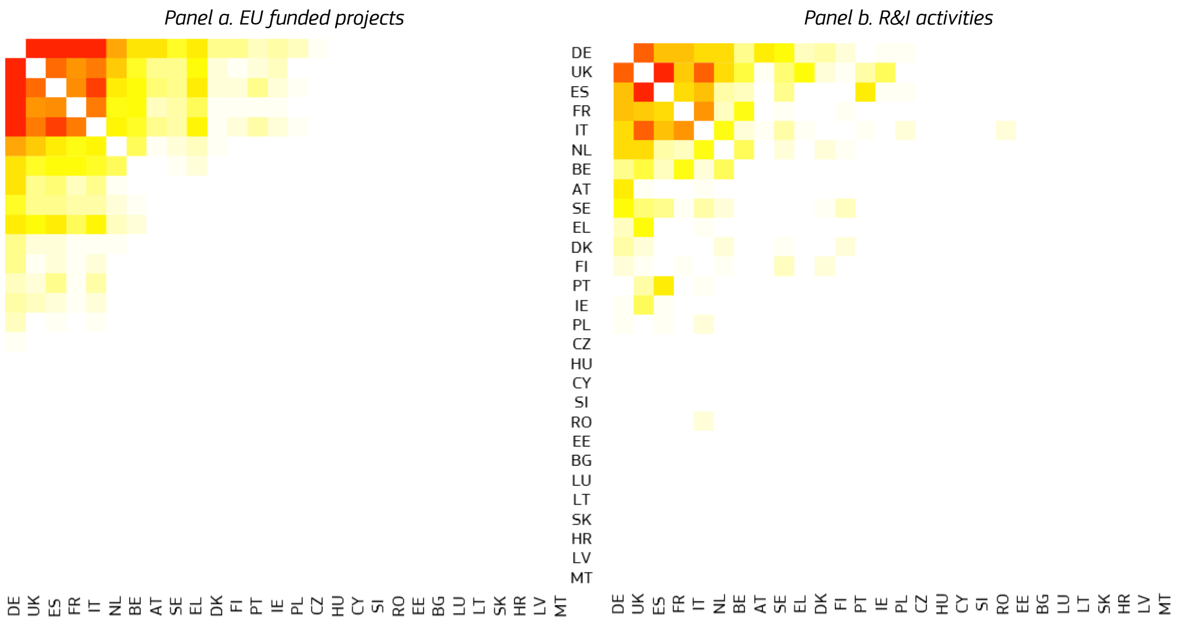
([36]) The UK is included to maintain comparability with the information related to FP7 and H2020 (thus, pre-Brexit).

help better understand how knowledge is generated and transferred within the European digital ecosystem, and to what extend this is in line with EU's policy priorities.

Figure 23, Panel a. gives an idea of the intensity of collaborations in the network of EU funded projects, considering players located in EU MS and in the UK (the diagonal is left blank, as internal collaborations – that is, across players located in the same country – are disregarded). The closer to red is the colour of a cell, the higher is the number of collaborations across two countries. Collaborations turn out to be rather concentrated: more intense collaborations in EU funded projects are observed between Germany, France, Italy, Spain and the UK, which together cover the largest number of EU projects. If we look at the digital domains associated to the collaborative EU-funded projects, most of them fall under the digital area of "Artificial Intelligence" (20%), "Data, Dynamic data" (12%), and "Infrastructure, cloud computing, digital platform, IaaS, SaaS, PaaS" (10%). This composition is very much in line with the three main digital areas in the whole EU digital ecosystem (see section 3.2).

It is informative to compare the network of collaboration in EU-funded projects with the 'spontaneous' network of collaboration in R&I activities (Figure 23, Panel b.). The comparison of the two parts of Figure 23 shows that the collaborations in EU funded projects across EU MS are more spread out than the ones in R&I, which concentrate in fewer countries. In fact, collaborations in R&D (Panel b.) occur mostly between the UK, Italy, Spain and Germany and are less intense for the rest of the players. This is revealed by the overall lighter colours of the cells in Panel b., which implies that a more intense collaboration is taking place in co-participation in EU-funded projects rather than in R&I activities. This suggests that countries that are not much involved in collaborations on R&I activities may be benefitting relatively more from engaging in collaborative EU-funded projects. EU-funded activities strengthen collaboration across EU MS and help balancing the geographical distribution of digitally-relevant activities. Hence, EU funded programs such as FP7, Horizon 2020 and Horizon Europe may contribute to reducing gaps across EU players in the digital ecosystem (Righi et al., 2021).

Figure 23. Collaborations in EU funded projects and R&I activities, total number (2009-2022)

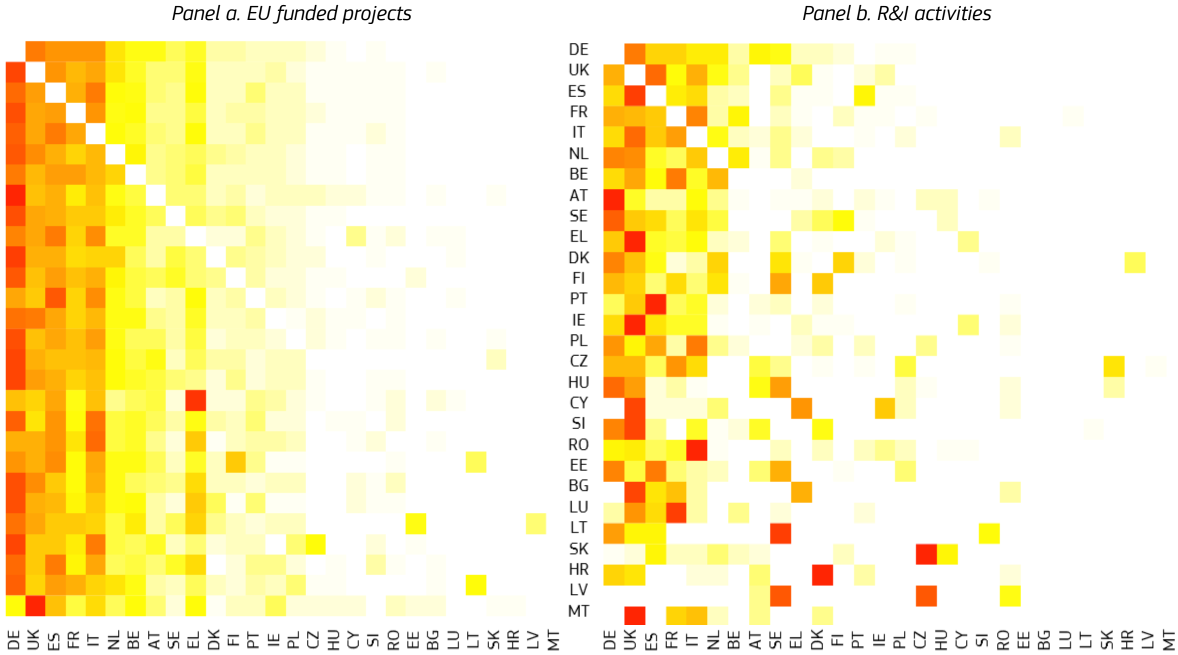


Note: The EU-funded programs considered are FP7, H2020, Horizon Europe. In both Panel a. and b, each cell shows the number of collaborations in EU funded projects (Panel a.) or R&I activities (Panel b.) across players located in two countries (bilateral) in fractional count, where the value assigned to each collaboration is equal to 1/binomial coefficient of the number of players involved in the collaboration[37]. All values in the matrix have then been normalized within a range 1 (max value) - 0 (min value), so that the largest value takes value 1 and the smallest 0. A cell takes a colour closer to red (white) the closer the underlying value is to 1 (0).

(37) The binomial coefficient of a number *n* correspond to the number all possible unordered combinations of size 2 (i.e. in pairs) of the number *n* of participants in a shared activity, so that the sum of all the bilateral collaborations determined by the same activity is always equal to 1.

Figure 24 displays the same information of Figure 23, with the difference that bilateral collaborations are considered in terms of their relative number in each country (by row) – in other terms: the closer to red is the colour of a cell, the higher is the number of collaborations across two countries with respect to the total number of collaboration of the considered country (i.e. the country on the row). All countries display relatively high number of collaborations in EU funded projects (Panel a.) with only five countries (which are the same where most EU funded collaborations concentrate, see Figure 23, Panel a.): Germany, France, Italy, Spain and the UK. A comparison of the two parts of Figure 24 also allows highlighting the differences in terms of geographical coverage between collaborations in EU funded projects (Panel a.) and in R&I activities (Panel b.): while in R&I collaborations each country seems to have very few "favourite" partners, with which it performs most of R&I activities and nothing (or almost) with the others, in EU funded projects collaboration are more geographically distributed.

Figure 24. Collaborations in EU funded projects and R&I activities, number by country (2009-2022)



Note: The EU-funded programs considered are FP7, H2020, Horizon Europe. In both Panel a. and b, each cell shows the number of collaborations in EU funded projects (Panel a.) and R&I activities (Panel b.) across players located in two countries (bilateral) in fractional count, where the value assigned to each collaboration is equal to 1/binomial coefficient of the number of players involved in the collaboration. The values in the matrix have then been normalized by row within a range 1 (max value) - 0 (min value), so that the largest value in each row takes value 1 and the smallest 0. A cell takes a colour closer to red (white) the closer the underlying value is to 1 (0).

5 Conclusions

Digital transformation is reshaping the horizon of technological, social and economic development. In a scenario of accelerated technological change, mastering emerging digital technologies is essential to grant the EU competitiveness and a leading role in the global technological and industrial landscape. Attaining digital leadership is, thus, the condition for the successful implementation of the twin transition.

DGTES responds to a call for an appropriate scientifically-based and policy relevant analytical tool to map, explore, analyse and better understand the digital ecosystem within the scope of the digital transformation.

This report presents an overview of the global digital ecosystem covering the time period between 2009 and 2022. Relying on the graph structure of the DGTES database, it also proposes a preliminary exploration of the policy-relevant issue of digital leadership from a network perspective. As summary, some take-home messages can be highlighted.

- The global digital ecosystem is geographically concentrated. Three geographical areas – China, the US and the EU – host more than 70% of activities and players. This does not mean that other geographical areas do not play any role, but their ability to influence and steer the evolution of the global digital ecosystem is likely to be limited - and possibly constrained around specific subdomains. The weight of China in the digital ecosystem has been growing remarkably since 2015, coinciding with the implementation of initiatives fostering patent applications in emerging digital technologies.
- The digital ecosystem does not have a specific "flavour", in the sense that it is not dominated by a prominent technological domain. This does not imply that activities are very homogeneously distributed across digital areas: while the first five digital domains ("Data, Dynamic data", "Artificial Intelligence", "Cloud computing, digital platform, services", "Autonomous systems, robotics", and "Semiconductors, power electronics") cover 65% of all activities, the last three ("Blockchain", "Advanced computing", "Quantum technologies") correspond to only 3.5%. This figure may reveal different degrees of technological maturity, where emerging digital areas still represent "niche" domains and do not have (yet) reached a sizeable "critical mass" in the digital ecosystem. At the same time, this may also mirror a different level of engagement in terms of investments and public funding to support specific digital technologies. The relevant efforts of the EU on artificial intelligence and related applications may be an example of the latter.
- The EU digital ecosystem is rather heterogeneous. Five Member States (MS) - Germany, France, Spain, Italy, and the Netherlands - account for more half of players and activities (including EU-funded projects). This implies that the other 22 countries share the other half. Also, the composition of the digital ecosystem varies remarkably from country to country, as well as the importance of EU-funded projects - for example, the participation in EU-funded projects goes from 72% of activities in Greece to 10% in Slovakia.
- Besides providing insights about the differences across MS, DGTES helps shed light on the effectiveness of policy instruments addressing internal cohesion within the EU. The presented analysis of the collaborations on EU-funded projects across players in the EU and the UK shows how these are more uniformly geographically distributed than collaborations in R&I activities, which tend to concentrate in fewer countries and fewer players. This suggests that, by strengthening collaborations, EU-funded projects manage to mobilize and engage those MS that would otherwise remain at the margins of the digital ecosystem, thus helping balance the geographical distribution of digitally-relevant activities within the EU. This confirms that the EU-funding programmes contribute to building capabilities needed for a vibrant European digital ecosystem.
- Looking at the global digital ecosystem with a network approach can provide novel insights to the discussion on EU's digital leadership from the angle of strategic autonomy. Although the EU plays a similar role than China and the US in shaping the overall activity of the digital ecosystem, thanks to the structure of its R&I collaborations it occupies a strategic position as connecting bridge or as bottleneck, with the potential to influence and control the flow of knowledge across the network. Looking deeper into subdomains of the digital ecosystem that are critical for Europe's twin transition, this report contributes to informing about the risks of overdependence in the domains of cybersecurity and raw materials, where the EU occupies a marginal and non-strategic position. In autonomous systems, Europe does not engage in a large share of activities, but the dense structure of EU's collaborations grants it a more strategic position in the network representing R&I collaborations in this subdomain.

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List of abbreviations and definitions

AI	Artificial Intelligence
BC	Betweenness centrality
EC	European Commission
EU	European Union
DGTES	Digital Techno-Economic ecoSystem
GDP	Gross domestic product
JRC	Joint Research Centre
IaaS	Infrastructure as a service
IDITES	Impact of Digital Transformation on the Economy and Society (project)
MS	Member State
NLP	Natural language processing
PaaS	Platform as a service
PREDICT	Prospective Insights on ICT R&D (project)
RCA	Revealed comparative advantage
R&D	Research & development
R&I	Research & innovation
SaaS	Software as a service
SMEs	Small and medium enterprises
TES	Techno-Economic ecoSystem
WBC	Weighted betweenness centrality

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Annexes

Annex A – List of repositories

The repositories of textual documents used to identify the activities entering the DGTES database presented in this report are:

- For business activities: Dow Jones, Orbis, Crunchbase
- For innovation activities: Patstat, Cordis for EU-funded projects (FP7, Horizon 2020, Horizon Europe)
- For research activities: Scopus (selected journals, see Appendix B).

Annex B – List of journals

This appendix contains the list of journals (in alphabetical order) that were used for the semi-automatic keyword extraction of research activities. The purpose of having a limited list of journals is to obtain as much relevant coverage as possible of the digital world, focusing on journals that are as horizontal as possible.

The number of journals used in the report has been limited to 121, taking into account: i) the relevance of each journal with respect to a given digital area (after a look at the journal description and some selected papers appearing in the journal); ii) the relevance of the journal for its scientific community of reference, given by a set of indexes defining the ranking score of the journal (i.e. the H-Index and the Impact Factor, where available).

Advanced Engineering Informatics
Advances in Applied Microbiology
Applied Clinical Informatics
Applied Linguistics
Applied Linguistics Review
Applied Mathematical Modelling
Applied Microbiology and Biotechnology
Artificial Cells, Nanomedicine and Biotechnology
Artificial Intelligence
Artificial Intelligence Review
Big Data Research
Big Earth Data
Biochemical Engineering Journal
Biocybernetics and Biomedical Engineering
Bioresource Technology
Bioresources and Bioprocessing
Biotechnology Advances
Biotechnology and Bioengineering
Blockchain: Research and Applications
Business Horizons
Communication Research
Computational Geosciences
Computational Linguistics
Computer Law and Security Review
Computer Methods and Programs in Biomedicine
Computers and Security
Computers and Geosciences
Computers and Structures
Computers in Biology and Medicine

Critical Reviews in Biotechnology
Critical Reviews in Environmental Science and Technology
Current Opinion in Biotechnology
Data and Knowledge Engineering
Decision Support Systems
Digital Business
Electronic Commerce Research and Applications
Energy
Engineering in Life Sciences
Environmental Modelling and Software
Environmental Technology Reviews
Focus on Surfactants
Foundations and Trends in Machine Learning
Future Generation Computer Systems
Geo-Spatial Information Science
Health Care Manager
Health Information Management Journal
IEEE Computational Intelligence Magazine
IEEE Electrification Magazine
IEEE Journal of Biomedical and Health Informatics
IEEE Journal of Emerging and Selected Topics in Power Electronics
IEEE Multimedia
IEEE Power and Energy Magazine
IEEE Robotics and Automation Letters
IEEE Transactions on Neural Networks and Learning Systems
IEEE Transactions on Pattern Analysis and Machine Intelligence
IEEE Transactions on Power Systems
Information and Management
Information Economics and Policy
Information Sciences
International Business Review
International Journal of Applied Earth Observation and Geoinformation
International Journal of Computer Vision
International Journal of Information Management
International Journal of Intelligent Systems
International Journal of Medical Informatics
International Journal of Multimedia Information Retrieval
International Journal of Systems Science, Operations and Logistics
Internet of Things
Journal of Artificial Intelligence and Soft Computing Research
Journal of Biomedical Informatics
Journal of Biotechnology
Journal of Complexity
Journal of Computational Design and Engineering
Journal of Computational Science
Journal of Corporate Finance
Journal of Environmental Management
Journal of Intelligent Transportation Systems

Journal of Medical Systems
Journal of Nanobiotechnology
Journal of Network and Computer Applications
Journal of Parallel and Distributed Computing
Journal of Pathology Informatics
Journal of Power Sources
Journal of Strategic Information Systems
Journal of Systems Architecture
Journal of the American Medical Informatics Association (JAMIA)
Knowledge-Based Systems
Machine Translation
Medical Image Analysis
Methods of Information in Medicine
Modeling Earth Systems and Environment
Natural Language Engineering
Nature Biomedical Engineering
Nature Biotechnology
Nature Energy
New Biotechnology
Online Social Networks and Media
Pervasive and Mobile Computing
Primary health care research and development
Professional Case Management
Progress in Quantum Electronics
Quality Management in Health Care
Remote Sensing of Environment
Reviews in Environmental Science and Biotechnology
Robotics and Autonomous Systems
Robotics and Computer-Integrated Manufacturing
Simulation Modelling Practice and Theory
Smart Health
Social Networks
Software and Systems Modeling
Spatial Information Research
Statistical Methods in Medical Research
Sustainable Energy Technologies and Assessments
Swarm and Evolutionary Computation
Synthetic and Systems Biotechnology
Telecommunications Policy
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