



Innovation intermediaries in the digital transformation process. A comparative case study of research and technology organisations in the US and the UK

Guendalina Anzolin^{*}, Eoin O'Sullivan

Centre for Science, Technology and Innovation Policy, Institute for Manufacturing, University of Cambridge, UK

ABSTRACT

Research and Technology Organisations (RTOs) are innovation intermediaries that support knowledge transfer between science and industry, with a strong focus on applied research aiming at scaling up technologies characterised by a systemic failure in their pre-production phase. They aim to fulfil the knowledge transfer function embedded in their mission. Recently, there has been a growing literature about RTOs' role, especially in relation to how they respond to the changing innovation and production environment. In this paper, we empirically explore (i) how RTOs' activities are changing as a response to the increasing complexity of manufacturing technology systems, and with a focus on the particular case of digital manufacturing, which demands higher scope for the role of RTOs' activities; (ii) if there is any attempt to align and coordinate such activities with other intermediary actors in the ecosystem. Our analysis reveals that existing activities (mainly technology development) are evolving to respond to new challenges, and new activities are emerging as part of RTOs' services to firms (e.g., workforce development and, to a lesser extent, supply chain development activities). RTOs face challenges in coordination with other intermediaries; targeted funding can provide the space to experiment with new forms of collaboration.

1. Introduction

Over the past decade, the process of innovation has become more complex, with digitalisation involving the use of multi-level and multi-platform technologies, whose efficient use lies in the availability of a panoply of competencies and skills. To deliver the promises of high productivity and high innovation levels, digital technologies require deep inter-organisation collaboration, where value co-creation is critical (Suominen et al., 2021). In a complex, multidisciplinary and collaborative space, digital innovations are characterised by a knowledge transfer process that requires strong complementarity between actors and increasing levels of intermediation (Howells, 2024; Javernick-Will and Levitt, 2010; Kirkels and Duysters, 2010; Villani et al., 2017). Such intermediation aims at filling the gaps (e.g., funding for infrastructure, applied research, protocol, standards, and training) along the innovation process, providing a solution to challenges that could undermine innovation and, thus, the adoption of digital technologies (Chen and Lin, 2018; Lichtenthaler and Lichtenthaler, 2010).

In this process, the space and role of organisations that bring together different actors of the innovation ecosystem and provide activities to fill the capabilities gaps along the innovation process are expanding (Caloffi et al., 2023; Holland et al., 2024). Mostly known as innovation

intermediaries, such organisations are characterised by a high flexibility and adaptability of their mission, something that contributes to the reshaping of their functions and activities over time (Arnold et al., 2010; Miller, 2014). This paper explores how changes brought about by the digital innovation processes are shaping the overall function and especially the activities of Research and Technology Organisations (RTOs). RTOs are a specific and underexplored subset of innovation intermediaries aiming to support the knowledge transfer between science and industry, with a strong focus on applied research (De Silva et al., 2018; Hales, 2001; Van Lente et al., 2003). RTOs have been historically centred around knowledge transfer functions, with a prevalence of technology development activities such as reconfigurable pilot lines (and different types of testbeds), test labs and other testing facilities and services whose cost is too high for single firms.

RTO's activities have been changing and broadening over time (Miller, 2014); their intermediary role is critical to address the challenges coming from the integration of digital data-centric technologies with physical machinery, especially given the combination of technology systems that is required for the efficient adoption of digital technologies. Digital manufacturing has been widely explored in innovation intermediaries' research, focusing on institutional elements, governance and business models (Colovic et al., 2024; Colovic et al., 2025; Holland

^{*} Corresponding author.

E-mail addresses: gma39@cam.ac.uk (G. Anzolin), eo252@cam.ac.uk (E. O'Sullivan).

et al., 2024; Howells, 2024; Sala-Vilar et al., 2024); yet an analysis of RTOs as a specific type of innovation intermediary acting in digital manufacturing and a focus on the shifting nature of their activities is missing.

Our work goes in the direction of building a typology of innovation intermediaries (Howells, 2024), by focusing on RTOs and their unique role in filling the gaps across the *valley of death* (Yin et al., 2022; Ellwood et al., 2022); while existing literature refers to a generic knowledge transfer type of activities for RTOs (Ciapetti and Perulli, 2018; Taverdet-Popiolek, 2022), we adopt a functional approach that explores the set of activities within the knowledge transfer function, e.g., technology development, deployment, workforce activities. This approach helps to provide a functional, up-to-date definition of RTOs (Farina and Preissl, 2000) and continue the effort to chart a typology of functions and activities over time (Howells, 2024). In addition, we provide preliminary evidence on a neglected field of research, which is the collaboration between different types of innovation intermediaries; this is critical in digital manufacturing, characterised by high complexity and multilayered systems that require collaboration and coordination between actors. While there are few contributions focused on the coordination mechanisms that RTOs build with some stakeholders in the ecosystem, such as firms and universities (Albors-Garrigós et al., 2014; Giannopoulou et al., 2019), there is a lack of empirical analysis about the coordination between RTOs and other types of innovation intermediaries that respond to the knowledge transfer function (see section 2.2.) with different activities along the innovation life cycle (an exception is the Hales, 2001 study on KIBS and RTOs). Our two research questions are: how have RTOs' activities changed to guarantee the knowledge transfer process of digital technologies? Is there any coordination (in the sense of any *division of labour*) between RTOs and other actors that provide an intermediary type of activities?

Our research explores these questions by looking at two case studies of RTOs in the UK and the US, which are the top two countries in the academic interest on this topic (Zhang and Liu, 2023). We selected two RTOs, MxD (Manufacturing Times Digital) in the US and the High-Value Manufacturing Catapult (HVMC) in the UK; they act in the digital manufacturing space, which is an interesting case given how digital manufacturing pushes the system complexity element (i.e., integration of hardware, software and connectivity) and the pace of change (e.g., in terms of the workforce required). Our study provides a comparative analysis of RTOs in the UK and the US to better understand their differences and their comparative elements. To the best of our knowledge, no previous study has gathered primary data on these RTOs' activities.

The rest of the article is structured as follows. The next section reviews the existing literature on RTOs, characterising their 'special' role in the ecosystem, reviewing what existing studies mention in relation to RTOs functions and activities, and on any evidence about their coordination role with other intermediaries active in the knowledge transfer process. Section 3, departing from the research gaps identified in the literature review, introduces the conceptual framework and the research questions. Section 4 presents the methodology and the case study selection. Sections 5 and 6 present the context and analysis of the two case studies. Section 7 compares and discusses the results, and section 8 puts forward conclusions, limitations and suggestions for future research.

2. RTOs in the literature

In this section, we focus on three strands of the RTOs literature. The overall underpinning theoretical background lies in the innovation system literature and especially in the sub-field of technology innovation systems, which focuses on actors and institutions that influence the development and diffusion of technology (Carlsson and Stankiewicz, 1991; Lynn et al., 1996; Watkins et al., 2015). Such literature acknowledges the collective dimension of innovation and the key role that government plays in orchestrating the generation and diffusion of innovation. First, we analyse and critically contribute to the

understanding of the unique role that RTOs have within the broader literature of innovation intermediaries. Second, we delve deeper into the activities that characterise RTOs, particularly looking at how the changing features of the digital innovation process are reshaping how RTOs operate. Third, we review the literature on the coordinating role played by RTOs, assessing the role of RTOs both as a self-standing organisation and as an 'orchestrator type of organisation' in the ecosystem. In this section, we intend to review the literature and to identify gaps.

2.1. RTOs as a special sub-set of innovation intermediaries

RTOs are a subset of the broader category of innovation intermediaries. Despite playing a critical role in innovation systems of industrialised and emerging economies (Suominen et al., 2021), RTOs have received less attention than other types of innovation intermediaries, such as university incubators, technology transfer offices, open innovation intermediaries, knowledge knowledge-intensive business services (KIBS) (Borrás et al., 2024; Caloffi et al., 2023; Crow and Bozeman, 1987; Hertog and Pim, 2002).

Existing literature on RTOs suggests conceptualising them as 'super intermediaries' because of their unique multiple intermediary role in the triple helix of government, industry and academia (Meyer et al., 2019; Sheikheldin, 2021). In order to emphasise their place at the interfaces where innovation, science and policy actors meet to contribute to technologies scaling up, they are also called 'boundary organisations' (Chataway et al., 2019; Hanlin et al., 2018). Yet RTOs are more than the intersection of different organisations' boundaries; they are dynamic institutions that adapt and change together with the broader system of innovation and technology diffusion. One of the most significant changes for RTOs has been the severe cut in public finances since the early 1990s (Preissl and Farina, 2000); this led to a revision of their functions and their role in the ecosystem. While such decline has been more than compensated by the number of contracts and cooperative projects with industry (Larrue and Strauka, 2022), the different nature of the funding had implications on the types of activities conducted. RTOs are highly adaptive and they tend to respond to changes in the institutional and industrial space; Preissl (2006) showed that RTOs in Europe changed their modes of operation as national economies shifted towards service economies, and recent literature confirms further changes related to the digital economy (Elia et al., 2020; Rossi et al., 2022; Shapira and Youtie, 2017).

The existing literature gap on RTOs is mainly due to their diversity in terms of legal status, governance structure, activities performed, and funding models, all of which make it difficult to handle RTOs as a consistent category in analytical work (EARTO, 2015; Larrue and Strauka, 2022; Preissl and Farina, 2000). The European Association of RTOs (EARTO) defines RTOs as "*non-profit organisations whose core mission is to harness science and technology in service of innovation, to improve quality of life and build economic competitiveness*". Three features make RTOs unique in the space of innovation intermediaries.

First, despite the different configurations, RTOs remain distinctive from both universities and firms, but they often have tight links with both (Albors-Garrigós et al., 2014; Giannopoulou et al., 2019; Suominen et al., 2021). Being distinctive, they are also highly flexible, and it is argued that they can increasingly play a problem-solving role at the intersection of industrial challenges, as per their original mandate – i.e., purely technology transfer between science and industry – and societal challenges, increasingly including 'wicked problems' beyond purely innovation challenges (Schot and Steinmueller, 2018; Uyerra et al., 2020). RTOs operate between a science base and a series of businesses, with the role of spanning gaps in the knowledge transfer process; according to the UK Hauser Review (Hauser, 2010), which recommended the set-up of the Technology Innovation Centres (named Catapults), they are organisations "focused on the exploitation of new technologies, which bridge activities between research and technology

commercialisation". Such gaps and bridging activity have been persistent in the so-called valley of death, the phase of the innovation process where innovations that are ready from a scientific and technical point of view struggle to attract private funding for the scaling-up phase (Islam, 2017). This phase of the innovation process is often reported also in terms of Technology Readiness Levels (TRLs) 4–6. De-risking the process by filling this gap, where RTOs operate at the interfaces of key actors of the innovation and industrial systems, is the core of their mission to speed up the translation of innovation to market (Holland et al., 2024). As reported by a recent survey, the increased translational role is confirmed by a shift towards more knowledge exchange and transfer activities (Larrue and Strauka, 2022), where the main input for such change is mostly related to changing demand from clients (i.e., firms requesting different types of services/activities from the RTOs).

Second, despite a drop in public resources, RTOs tend to receive substantial funding from the government and the private sector, and they tend to be non-profit (Van Lente et al., 2003). Historically, many RTOs depended mostly on government budgets and focused mainly on scientific missions; some RTOs started out as testing/safety centres (e.g., LGC in the UK) or as industry membership-based centres (e.g., PERA and TWI¹), which were able to raise private funding and work on projects with firms. Today, the latter type has become more common, and research projects developed with firms are at the core of RTO operations (Albors-Garrigós et al., 2014; Hales, 2001). A consequence of the drastic decrease in public resources raises questions of an optimal division of labour between mostly publicly and/or mostly private organisations (Farina and Preissl, 2000). This paper considers RTOs that receive a portion of their funding from the government (national and/or regional).

Third, regarding their business model, RTOs do not provide services for the industry in terms of delivering ready-for-use knowledge and solutions. RTOs and firms collaborate mostly through the development of engineering or R&D projects (Mas-Verdú, 2007). Within these projects, RTOs perform their role as "hard intermediaries," providing technology testing activities, certification and standards, and research facilities (De Silva et al., 2018; Van Lente et al., 2003). The Hauser Review (Hauser, 2010) argued that RTOs should be where there is a case for developing a research and pre-commercialisation capability and acting to fill gaps (e.g., infrastructure, equipment, and skills, which would not otherwise be in place) and bring these activities together. This activity has changed over time. While in the past RTOs were conceived as agencies that actively participated in the technology programmes of mainly SMEs, over the years, the relation between RTOs and their SMEs began to show "symptoms of alienation" (Nath and Inalini, 1996), and to move in favour of medium and big companies. Among the structural causes that contributed to loosening the ties between RTOs and SMEs (Araoz, 1996), there is the need to update capabilities and to create new skills following the rapid changes in new digital technologies.

2.2. RTOs functions and activities

One of the reasons why it is complex to classify RTOs is that the knowledge transfer function has been expanding over time, and the resulting number and types of activities are very heterogeneous.

Existing literature tends to conflate the concept of functions and activities, often using them interchangeably; in this paper, we refer to *functions* concerning the innovation process. Building on existing literature, we use knowledge transfer as an overarching function, specifying that it can materialise into more (or less) knowledge development,² knowledge diffusion, and knowledge adaptation functions; each

function can be underpinned by different *activities* meaning the services that RTOs deliver as part of their overall knowledge transfer function (e.g., technology activities such as testbed facilities, standard development, workforce activities such as training, hiring guides and learning courses, etc). There is a consensus that RTOs focused, at least until recently, on knowledge transfer functions mainly in terms of knowledge development and that most of their activities fall within applied industrial research and encompass services such as certifications and standards, provision of research facilities, technical assistance, SMEs collaboration projects (De Silva et al., 2018; Georghiou et al., 2003; Loikkanen et al., 2011; Readman et al., 2018).

Existing literature on the functions and activities of RTOs is scarce. To clarify this aspect, we conducted a systematic literature review on the functions and activities of RTOs using the Elsevier-Scopus database and the following keywords: 'Research and Technology Organisations' AND 'function*' , 'RTO*' AND 'function*', 'Research and Technology Organisations' AND 'activit*', 'RTO*' AND 'activit*'.³ The keyword search was performed in all areas (title, abstract, keywords), limiting the research to the following subject areas: business, management and accounting, social sciences and economics, econometrics and finance. The result was a total of 98 articles. We excluded articles non-related to our subject (for example, RTO is also used as 'Recovery Time Objective' or 'Real Time Optimisation'), and we obtained 58 articles. After excluding duplications, we had 34 articles, which we read and examined, particularly examining functions and/or activities of RTOs. Functions and activities are often used interchangeably, increasing the grey area around RTOs modes of action. The 34 papers refer to activities that RTOs perform, mostly R&D activities, testbeds, metrology and certification (naming these as technology development activities), and other 'softer' activities such as training and networking. Although an in-depth analysis of the evolution of activities is lacking, interestingly, a recent paper refers to training and workforce types of activities as becoming more common in RTOs (Giannopoulou et al., 2019; Gonzalez-Urango et al., 2024; Thurner, 2017; Zaichenko, 2018). Functions of RTOs are rarely examined; knowledge (or technology) transfer and diffusion are referred to as the main functions of RTOs, with their scope increased over time, showing a more downstream orientation towards applied research. We read each article and examined the functions and activities of RTOs. Table 1 in Appendix 1A presents the main findings of the systematic literature review.

There is increasing evidence that activities are both changing and expanding (Zhang and Liu, 2023). This is related to two main reasons. First, in the 1990s, RTOs changed in many countries due to deregulation policies, privatisation and lower availability of funding. In parallel, and partially as a consequence, changing requirements in the industrial structure emphasised the increasing importance of technology transfer and the application or integration of technologies in existing systems (Farina and Preissl, 2000). Second, an implicit requirement to strengthen coordination between different actors given the increasing speed, complexity and co-innovation mechanisms that characterise digital technologies innovation. Both aspects had consequences; starting from the first, the increasing pressure in terms of financial sustainability had three important consequences: (i) the need to maintain large technology infrastructure and equipment specialised in certain technologies, which led to an increasing openness to a broader range of users; related to this, (ii) a movement towards downstream activities (from more upstream research activities that dominated in the past), and which contributed to the strengthening of technology transfer activities to industry (Leitner, 2005); (iii) the movement towards knowledge diffusion

¹ <https://www.airto.co.uk/about/members/>.

² Knowledge development in this paper refers to a function that is done in collaboration (e.g., collaborative R&D) with businesses, thus transferring knowledge to firms.

³ Although the term RTO has been more used in Europe, where it is more common, there is increasing evidence of contributions that use the term and study RTOs across different countries, including for example: Singapore (Ng et al., 2023); Tanzania (Sheikheldin, 2021); Taiwan and Thailand (Intarakumnerd, 2011); Brazil (Figuereido et al., 2005).

Table 1
Interviews across the UK and the US. Source: Authors.

Country/ Code	Organisation	Role
1_US	MxD	Strategy & Engagement
2_US	MxD	Membership & External Relations
3_US	MxD	MxD Learn
4_US	MxD	Projects & Engineering
5_US	MxD	CTO
6_US	MxD	CEO
7_US	MEP Illinois	CEO
8_US	MEP Rhode Island	Senior Workforce Manager
9_US	JARC	President
10_US	AMNPO/Gov	Founding Director
11_US	Georgia Institute of Technology	Expert involved in the design of the Manufacturing USA Institutes CTO
12_UK	HVMC	CTO
13_UK	HVMC	Technology Strategy Manager
14_UK	HVMC	Director for Strategic Development
15_UK	HVMC	Particulate Engineering Group Technology Leader
16_UK	HVMC	Chief automation officer/Head of Digital
17_UK	BEIS	Senior civil servant in charge of a key policy program
18_UK	Made Smarter Adoption	Program Manager
19_UK	HVMC/Made Smarter	Expert in HVMC board and involved in the design of the Made Smarter
20_UK	HVMC	Director of Research

type of activities has also implied a shift into different areas, such as education, training services, support to start-ups with activities that are increasingly complementary to core activities of technology development (Gonzalez-Urango et al., 2024; Nath, 2008). Relatedly and regarding collaboration reinforcing, the speed at which digital technologies have to be commercialised is not comparable to what happened a few decades ago. It used to take many years for academic discoveries to be commercialised, and much of this effort used to happen in the so-called corporate R&D labs, which have been largely dismissed (Arora et al., 2015; Hauser, 2010). Digital technologies have expanded the activities required from RTOs, reshaping opportunities and challenges across the innovation process, where the transformation of knowledge is as complex and fuzzy as the generation of knowledge (Mrinalini and Nath, 2000). The high technology interdependence between different yet complementary technologies requires organisations such as RTOs to be capable of dealing with different elements belonging to existing and new structures changing at different speeds (Elia et al., 2020; Landesmann and Scazzieri, 1996). One of the main challenges in this sense is the ability to provide activities in an exploratory phase (Landry et al., 2013) while fostering collaboration (Readman et al., 2018) and still being able to conduct high-level research (Zaichenko, 2018). In other words, RTOs are increasingly required to balance long-term activities (exploratory research), short-term activities (projects with firms), and medium-term activities (exploring knowledge base in collaboration with industry) (Arnold et al., 2010; Larrue and Strauka, 2022).

2.3. RTOs 'orchestrating role' in the innovation process

The combination of activities and the multiple actors involved, together with the interdependence embedded in digital technologies, require high and increasing coordination at the level of technologies developed by the effort of multiple actors and of different intermediaries that fill gaps along different functions of the innovation process (e.g., technology development, technology adoption, technology diffusion). Collaboration has become particularly critical for firms that lack sufficient internal R&D resources, thus being more dependent on inter-organisational collaboration (Kim et al., 2010; Knockaert et al., 2014; Lin, 2003). This is not only something that characterises small firms but also big companies that have, over time, reduced (or eliminated) more

applied types of research, a tendency that increased the value and the opportunity for RTOs, whose 'techno-economic' capabilities became key for a continuous provision of cutting edge research tools for knowledge transfer and to ensure effective co-investments by government and private firms (Barge-Gil et al., 2007; Bordoloi et al., 2024; Tassej, 2014).

Since RTOs are known to be "practitioners in the art of collaboration" (Readman et al., 2018), their role not only as collaborators but also as facilitators and orchestrators of the innovation network is critical (Albors-Garrigós et al., 2014). The literature discussed the role of RTOs as "hubs", using their prominence and power to perform a leadership role in pulling together the dispersed resources and capabilities of companies and their network (Dhanaraj and Parkhe, 2006; Rossi et al., 2022). RTOs are observed to increasingly play an 'orchestrating'/'innovation system hub' role (Gonzalez-Urango et al., 2024; Holland et al., 2024; Larrue and Strauka, 2022); such a role is particularly suited to RTOs since, as a boundary-bridging organisation, they can draw on their convening capacity to create bridges between different actors building on their knowledge repository enriched over time by the different projects. RTOs should take advantage of their role as neutral convenors to identify and help address wider barriers to innovation and commercialisation (Hauser, 2014). The coordination (and collaboration) between RTOs and other intermediaries remains largely unexplored in the existing literature, especially the peculiar orchestrating role that they play at the interfaces of actors interested in technology transfer (TRLs 4–6). This represents an important gap, especially in light of the co-creation and coordination capabilities needed to generate innovation (Kreiling and Paunov 2021). Both RTOs, which we could define as *shapers*, and other types of intermediaries, which we could define as *supporters* (Randhawa et al., 2022), are key in shaping ecosystem configuration, and supporters are critical in identifying which capabilities actors need to drive innovation (Nenonen et al., 2019; Teece, 2007).

Addressing a wide range of activities between partners in close collaboration, to complement and not duplicate, becomes instrumental in successfully deploying relevant disruptive innovations in emerging technologies areas. The need for such coordination between intermediary organisations that operate at different TRLs also has implications in terms of different funding schemes designed across the entire value chain; an effective collaboration would ensure that different organisations provide complementary activities across the innovation cycle and specifically the technology development and adoption phases (Larrue and Strauka, 2022).

2.4. Research gaps

The literature on RTOs tends to primarily analyse them as a sub-category of innovation intermediaries, often discussing their role in a prescriptive way and reinforcing the need to understand how organisations actually work and how they are reshaping their activities. A recent contribution based on a computational analysis of the types and functions of innovation intermediaries does not include RTOs among the main innovation intermediaries (Caloffi et al., 2023). Some authors argue that their broader scope makes classifying RTOs challenging (Larrue and Strauka, 2022), while others tend to conflate RTOs with KIBS, given their enhanced service character (Thurner and Zaichenko, 2015). We point to two gaps in RTOs literature: the first one is about the activities that RTOs perform to fill capabilities gaps along the innovation cycle, and these have not been explored concerning the recent evolving nature of RTOs in digital manufacturing. The second one is the coordination (i.e., their division of labour) between RTOs and other innovation intermediaries that perform similar activities at different levels of the innovation cycle, i.e., at different TRLs. The coordination between RTOs and other innovation intermediaries is largely underexplored, and it is key to understand how the co-innovation and co-value creation dynamics are reflected across different innovation intermediaries. Both gaps are an attempt to respond to work needed in this field, specifically

looking at activities that contribute to defining RTOs as a distinct organisational form and at their role as 'animateurs' in their ecosystem (Howells, 2024).

3. Conceptual framework building

We now introduce our conceptual framework based on the literature discussed in section 2. First, our analysis departs from how digital production technologies shape the activities required to support firms along the innovation life cycle. Digital manufacturing technologies requires shared infrastructure layers, interoperability and standards, which are key for interoperability, thus combining technologies at different maturity levels (Alqoud et al., 2022; Pedone and Mezgar, 2018). Such combinations raise the complexity that firms face, thus shaping the activities they demand to intermediary organisations like RTOs (Cohen and Levinthal, 1990). Second, by building on the existing literature on activities performed by RTOs, we explored if and how they are changing. For example, in the case of the UK and the US – our two case studies detailed below – RTOs have been set up to fill capabilities gaps along the so-called valley of death (TRLs 4–7). We intend to explore whether this initial focus has changed and in which direction, assuming that an increased sophistication in digital manufacturing requires broader and more activities for a knowledge transfer process that keeps on promoting the provision of collective goods (Carlsson and Stankiewicz, 1991; Colovic et al., 2024). Understanding the possible generic similarity of activities has become key to understanding RTOs, as it is a way to focus on the capability-building element (Nath and Inalini, 1996). Third, we consider other actors (i.e., organisations) involved in filling gaps along the innovation life cycle by helping firms with various activities/services. Interactions within and between institutions are key in facilitating knowledge exchange (Lundvall, 1992); such interactions and dependencies are critical because intermediaries influence the activities of one another (Hernández-Chea et al., 2021) and because any ambiguity in their role can hinder value co-creation (Mele et al., 2018). We will explore if and how RTOs coordinate with other intermediary actors in the digital manufacturing innovation space, considering the strong coordination that is required to efficiently deploy digital technologies; thus, we investigate RTOs' coordination with other organisations that aim to fill gaps at higher TRLs levels (i.e., 8–9) and in the adoption/-diffusion space. The focus on evolving activities and actors is in line with recent conceptualisations of the innovation ecosystem (Granstrand and Holgersson, 2020). In Fig. 1, we represented the conceptual framework, which stems from the literature review with three layers, (I) the role of RTOs in filling gaps along the innovation life cycle, (II) the activities that RTOs perform as part of their role, (III) RTOs' coordination with other innovation intermediary actors. The first research question builds on I and II, RQ1 How have RTOs' functions and activities expanded to support digitalisation across the innovation life cycle?; the second research question builds on II and III, RQ2 Is there any coordination between different actors that provide intermediary type of activities?

While most RTOs were set up for knowledge transfer with, in many cases, an almost exclusive focus on supporting technology development activities, in the realm of digital production technologies, characterised by high complexity and multiple technologies that have to be integrated

to exploit their opportunities fully, this is not the case anymore. Other activities are becoming critical to fully responding to the knowledge transfer function. RTOs have been increasingly required to leverage their capabilities to undertake workforce development activities, which are key to creating the competencies to absorb and learn new technologies. More recently, supply chain development has also become a key area in activities development within RTOs⁴; such activities are becoming critical to ensuring that value created in the early stages of the innovation process gets captured along existing supply chains.

4. Research design, method and data

This paper adopts a qualitative approach to investigate the research questions introduced in the previous section (Eisenhardt and Graebner, 2007; R. K. Yin, 2009). Specifically, we conducted a comparative analysis of two RTOs, applying a purposeful sampling procedure where we selected our cases based on their likelihood to provide relevant insights to advance the understanding of RTOs activities in digital manufacturing and their role in the ecosystem. Due to the scarcity of academic research on RTOs and given the specificities of countries characterised by different innovation processes, an exploratory case study analysis offers the preferred method to gather insights into empirical phenomena and their contexts and to contribute to the theory-building process. The conceptual framework defined in section 3 guides our analysis, emphasising the conceptual elements (Strauss and Corbin, 1990) and providing structure and rigour to the inductive analysis of the cases (Johnson and Duberley, 2015).

We studied RTOs based in the US and UK (Appendix 1C). Similar to other experiences where RTOs were founded in response to specific socio-economic needs and changes (e.g., after the Second World War) (EARTO, 2007), the RTOs at the core of our analysis belong to two networks that were founded a few years after the Global Financial Crisis (GFC). Both countries, characterised by 'radical innovation' processes and a reluctance to government intervention (Konzelmann et al., 2010), realised the heavy consequences of decades of deindustrialisation and the severe challenges firms faced to translate early-stage innovation into commercial products. The two RTOs networks founded are the National Network for Manufacturing Innovation (today called Manufacturing USA Institutes) in the US and the Catapult Network in the UK.⁵ In both countries, the M-USA and the Catapults were established with the aim of filling gaps in the scaling up and commercialisation process, providing supporting activities for firms to go beyond the valley of death (Ellwood et al., 2022; Y. Yin et al., 2022). Against this backdrop, we selected one institute in each network using as selection criteria institutes that act in the digital manufacturing space. As discussed in the previous section, digital manufacturing pushes the system complexity element concerning the integration of multiple layers of technology and it has contributed to

⁴ For example, the RAMI Act (2015) in the SEC34 indicates that "Activities of a center for manufacturing innovation may include the following: a) Research, development, and demonstration projects, including proof-of-concept development and prototyping, to reduce the cost, time, and risk of commercializing new technologies and improvements in existing technologies, processes, products, and research and development of materials to solve precompetitive industrial problems with economic or national security implications; b) Development and implementation of education, training, and workforce recruitment courses, materials, and programs; c) Development of innovative methodologies and practices for supply chain integration and introduction of new technologies into supply chains.

⁵ The networks were introduced in 2012 in the US after a recommendation of the United States President's Council of Advisors on Science and Technology and in 2011 in the UK, following the independent Hauser proposal in 2010 that recommended the establishment of technology and innovation centres.

The conceptual framework

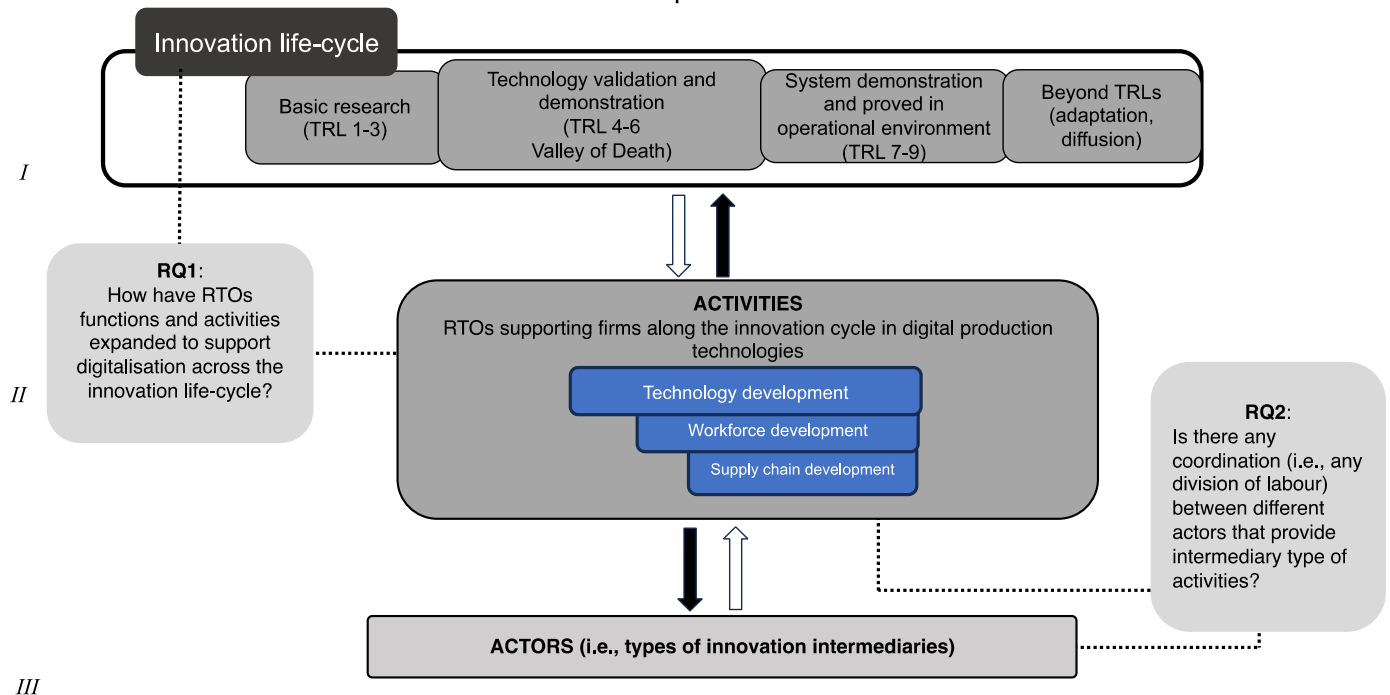


Fig. 1. Manufacturing USA institutes.

increasing the pace of change, thus calling for a demand for new activities (Esmailian et al., 2016).

The two institutes are the *Manufacturing x Digital* (MxD) in the US and the *High-Value Manufacturing Catapult* (HVMC) in the UK.⁶ MxD is one of the 17⁷ Manufacturing USA Institutes and one of the 9 Department of Defence-funded institutes; the HVMC is a group of seven pre-existing centres that have been characterised by a high level of activities in their ecosystems. Within the HVMC, we focused on MTC, which specialises in digital manufacturing, additive manufacturing, automation, and robotics, as well as intelligent automation; we also conducted a few interviews with the AMRC centre, given the senior role overlap between the centres and HVMC. Given our interest in the downstream phase of digital innovation and the 'division of labour', especially concerning technology adoption activities, we also conducted interviews with other actors active in the technology diffusion space. Specifically, we looked at the Manufacturing Extension Partnership (MEP) in the US and Made Smarter Adoption in the UK. The former is a network of 51 centres across the US and Puerto Rico, characterised by high heterogeneity in their modes of operation but aiming to enable manufacturing firms to increase competitiveness through technology support services, workforce development, lean and process improvement. The first MEP was set up in 1989 and the rest followed in the early 1990s. The latter, Made Smarter Adoption, is a program set up by the UK government firstly as a regional pilot in 2018 in the North West to promote the adoption of digital technologies across SMEs. In 2020 the programme was rolled out

⁶ We chose MxD over the other smart manufacturing institute called CESMII because MxD was created in 2014, and it was one of the first institutes, while CESMII came up in 2017; selecting an institute that has been there since the early days gave us the opportunity to understand how activities and functions evolved over time. A similar reason applies to the HVMC and the Digital Catapult, which were created in 2011 and 2013. In addition, the Digital Catapult has dealt with manufacturing to a much lesser extent than the HVMC and only recently with supply chains

⁷ There are now 18 institutes with the recent addition of SMART USA (Semiconductor Manufacturing and Advanced Research Twins USA), which is under the DoC.

to three additional regions, and it now covers seven regions.⁸ Despite providing similar services, it is important to acknowledge the structural difference between MEPs and Made Smarter Adoption, as the latter is a recent program and not an established network as MEPs. The UK counterpart of MEPs, the Manufacturing Advisory Services, was dismantled in 2015 as a result of austerity policies.

The data collection process was done over two years (January 2023–April 2024), and it involved different data sources. An initial policy review of the documents related to the introduction and the regulation of both roles and activities of both M-USA and the Catapults was conducted; secondly, an in-depth analysis and review of all information available on MxD and HVMC website allowed further clarification on the type of activities, and thus of projects, performed by the organisations. We then conducted two scoping interviews with policy stakeholders who participated in the networks' founding process. Lastly, we conducted 20 semi-structured interviews, reaching as many actors as necessary to achieve meaning saturation, which was indicated by the stability and consistency of the responses given by the interviewees (Hennink and Kaiser, 2022). Semi-structured interviews have been characterised by an introduction by the interviewer providing definitions of terms and explaining the main research questions of the project; we adopted an open interview protocol, leaving interviewees free to indicate additional/different directions and to enrich their responses with contextual elements (see Appendix 1D). In addition, we also conducted two shop-floor visits both at MxD in Chicago (US) and at MTC in Coventry (UK); introductory presentations about the organisations often accompanied such guided tours. The interviews were collected between May 2023 and February 2024, and they are listed in Table 1.

In terms of data analysis, we transcribed interviews using *Otter* software; it was not possible to record when we had on-site interviews at MxD and MTC (due to internal protocols). For these interviews, notes and comments were transcribed within 24 h after the interviews and follow-up emails were exchanged, to clarify existing doubts. Coding interviews immediately after conducting them was also key to realise

⁸ <https://www.madesmarter.uk/adoption/>.

meaning saturation. We proceeded with our content analysis from both interviews' transcripts and notes, categorising the thematic areas emerging from our questions. Given the nature of our data, we proceeded with a qualitative content analysis; in this way, we supported the proposition of new theoretical elements about RTOs activities (Vaismoradi et al., 2013). Information coming from the recording and the notes was discussed by the authors, and it was triangulated with secondary data sources from the organisations and from the extensive number of policy and program documents. Internal and external materials were critical to making the process highly iterative and providing a unique description of the ecosystem where the institutes operate.

5. Analysis of the US case

5.1. Overview

MxD is one of the 17 Manufacturing USA Institutes (M-USA)⁹ and it is dedicated to spurring digital manufacturing competitiveness in key technologies. It was established in 2014¹⁰ and it is located in Chicago (IL), where it employs around 75 people, and it has dedicated facilities with a 22,000 square foot shop floor with some of the most advanced manufacturing equipment in the world. We interviewed the six top managerial figures in MxD, focusing our questions on whether (and how) the overall function and the activities they provide to companies have changed and how they interact with other actors in the ecosystem. For the latter aspect, we mainly focused on the interaction between MxD and the Manufacturing Extension Partnerships (MEPs), which are a network of public-private partnerships with centres in all US states (and Puerto Rico) established in the 1980s dedicated to serving SMEs struggling with technological and organisational aspects. MEPs are part of the US technology policy and are key actors in filling the gaps, for example, in building the preconditions firms need to engage in digitalisation (Fromhold-Eisebith et al., 2021; Shapira, 2001).

5.2. Evolution of activities

All interviews conducted at MxD reveal that the challenges firms face with digitalisation have contributed to reshaping the activities needed to fulfil the knowledge transfer mission. Originally funded to perform technology development activities specifically targeting the valley of death (that space of the innovation cycle identified with Technology Readiness Levels 4–7 (DOC, Department of Commerce, 2016), MxD activities evolved towards accelerating the adoption of technologies. As the CTO explained:

“In addition to [being] an R&D centre, and especially with SMMs, we are now 100% focused on demonstration and promoting opportunities to improve the manufacturing process, as there is the need to broaden the focus from R&D to demonstration and implementation” (#US_4).

Other interviewees from MxD supported the view that the main challenge firms face today is not in the technology development per se but rather in the process of technology adoption and diffusion, where the opportunity to provide demonstration activities to firms is critical. Demonstration is vital because:

“Most of the technologies that companies need to increase productivity today are mature, but firms don't know how to use them” (#US_5).

Two examples where they focus on technology demonstration come

from current technology projects: (i) a digital twin project with a focus on implementation, where MxD works with a consortium of firms to show them the barriers for digital twin implementation; (ii) a data architecture project, concerning the complexity of aggregating data from the shopfloor deriving from the lack of standards; for the first step of data gathering and analysis, and MxD shows firms (also SMEs) that the use of a data gathering sensor placed (even) on older equipment can provide benefits to the business (#US_5). The outcome of MxD projects is a guidebook and/or an implementation guide, which better responds to the shift towards technology demonstration and implementation.

The shift towards demonstration and implementation went in parallel with a stronger focus on workforce development activities, which complemented an effective engagement with digital technologies. Despite being in the government recommendations since M-USA's inception, workforce development activities were outside the core of the first years of activities. This is both because core funding coming from the government (i.e., Department of Defence) was limited to technology development activities (TRLs 4–7). One interviewee noted:

“Despite the institute being free to look for other sources of funding, during the first years of life it was very much focused on exploring the ecosystem and on the main activity of technology development” (#US_3).

In 2019, after a rebranding of MxD, a new and clear strategy for workforce development emerged as a key priority [#US_6 and #US_3]. A workforce advisory committee was introduced in 2019. The institute designs workforce-related projects in two ways: (i) through grant proposals (defined as a proactive way) and (ii) through funding coming from other branches of the government and/or not-for-profit organisations (defined as a reactive way), where MxD has more freedom on the content.¹¹ The main outcome of workforce projects is a hiring guide, which maps future jobs reflecting companies' needs. More recently, in 2023, MxD received \$US 6 million in federal funding to scale up a collaborative program they designed with universities called CAPITAL (Curriculum and Pathways Integrating Technology and Learning). As one interviewee explained:

“There has always been the need for workforce development, but there was no real funding before, so we had to find other ways ... but the situation is different today”. (#US_3).

In the future, MxD aims to increase its capacity to train people within its facility; given the key role of demonstration-related projects, being able to train the workforce to demonstrate the scope of digital technologies is an area where there is high demand.

Lastly, when asked about supply chain development activities, our interviewees mentioned that despite being an area with increasing attention, firms are resistant to engaging due to data-sharing requirements. MxD has started looking at supply chain projects through the development of a workforce project; more specifically, they embarked on a project with an OEM that wanted to assess skills across three of their suppliers to upgrade the supply chain. Although this is a first project, it reflects the importance of using supply chain lenses to fully encompass the knowledge transfer function at the technology and workforce levels.

5.3. Collaboration with other actors across activities

Technology development and workforce development activities have thus been changing considerably over the last years, reshaping and

⁹ The institutes were introduced by the Obama administration under the name of National Network for Manufacturing Innovation (NNMI), the today M-USA are funded by the Department of Defence (10), the Department of Energy (6) and the Department of Commerce (1)

¹⁰ Previously called DMDII – Digital Manufacturing and Design Innovation Institute – it became MxD in 2019

¹¹ There are three requirements when MxD designs workforce development programmes: Three things when evaluate projects on workforce: i) industry voice at the table and they make sure that they are there from ideas to deployment ii) they prefer community driven (middle school and high school building from the network) iii) it would need to reach a population that is undertaken (in terms of areas of action).

responding to changing demands from firms. Yet such changes do not happen in a vacuum, and they also impact other boundary organisations active in the knowledge transfer process in the same ecosystem, which are different from MxD in their mandate. We consider the collaboration between MEPs, which have been in charge of helping SMEs increase productivity and build the conditions to adopt new technologies. We found that there is increasing collaboration between MxD and MEPs. We interviewed the MEP based in Illinois, and we complemented our research by interviewing another MEP (Rhode Island) once it became clear that the interaction between MxD and MEP does not happen on a regional basis but more in relation to the scope and the nature of the project. Starting from technology development activities, this is an area where there is a coordinated division of labour between the two organisations because they respond to different business models, with MxD working on a project-based model and with a membership system focusing on “enabling the technology” [#1_US]. Differently, MEPs have a consultancy-based model, and they provide services by sending experts to firms to solve their more urgent challenges. Thus, MxD works on medium- and long-term projects, while MEPs tend to have quicker responses and shorter-term projects. As a sign of increasing collaboration, it has become more common for MEPs to receive the implementation guide from MxD to facilitate their jobs with SMEs “as part of an ongoing and growing collaboration” [#7_US].

As for workforce development activities, the space for collaboration is less defined. MxD and MEPs boundaries are quite defined from their business model, with MxD outcome being most often a hiring guide or a certificate, while MEPs provide a more immediate action for workforce needs, tackling urgent issues that require a quick response. Yet, the availability of less core funding for workforce development made collaboration through projects coming from different sources a more common reality for workforce-related projects. Thus, MxD has collaborated with roughly 12 MEPs based on different projects; MEPs are independent and very heterogeneous organisations (e.g., some MEPs are part of a university like the MEP in Georgia Tech), with different funding (both in scale and scope) with a fair amount of autonomy, which result in different sets of capabilities that become the real basis for MxD to engage with them. For example, MxD started a Connecticut project about building online curricula with and for their members, and the MEP Connstep was the only channel through which to complete this project. Another example comes from a collaboration between MxD, ARM (which is another DoD-funded M-USA) with the MEP in Rhode Island for a workforce project on automation and cybersecurity. It was reported that:

“The MEP in Rhode Island has developed unique capabilities on workforce development due to a high demand from shipbuilding and submarine” [#8_US].

Our interview with IMEC – the MEP based in Illinois close to MxD – confirmed that there is an ongoing collaboration and that they receive support from MxD to assist their clients. Finally, according to our interviewees, supply chain activities are at an early stage, and there is no ongoing collaboration.

Overall, collaboration is increasing despite the unclear division of labour about technology and workforce activities between MxD and MEPs. The increasing collaboration happens mainly through projects designed based on funding availability at the federal and state levels. The US government has been insisting on more collaboration and coordination; for example, NIST (National Institute of Standards and Technology, which is part of the Department of Commerce and where both M-USA and MEP programs belong) awarded funding to each M-USA in operation in 2017 for a two-year project that embedded MEP staff within each M-USA, to facilitate awareness and understanding of the recently created M-USA.¹² Another policy measure came from NIST

(both AMNPO and MEP offices) with a pilot program in 2016 to include smaller members’ perspectives about the technologies available in the M-USA institutes, to make SMEs aware of the technological opportunities within MEPs, and to connect them. The program was also a success in making clear to the institutes the needs of smaller manufacturers (GAO, 2020). One of the most recent signs of collaboration is a five-year program/partnership between MxD and the whole MEPs network with a focus on accelerating digital technology adoption by SMEs.

6. Analysis of the UK case

6.1. Overview

The HVMC is one of the nine institutes of the UK Catapult network, which was set up between 2011 and 2023, with funding from Innovate UK to bring closer together conceptualisation/innovation and commercialisation (Uflewaska et al., 2024). The HVMC comprises seven centres,¹³ with different areas of technological specialisation, with a total of 2114 employees. We interviewed leading figures in the HVMC focusing on analysing if (and how) the functions and activities changed and to which extent they interact with other actors in the ecosystem. For the latter aspect, given that the UK government abolished the Manufacturing Advisory Services in 2015 (which were an attempt to replicate MEPs in the UK), we focused on the Made Smarter Adoption program introduced in section 4.

6.2. Evolution of activities

Similarly to the US case, all interviews conducted in the UK confirmed that the HVMC¹⁴ has been responding to digitalisation challenges with a reshaping of the activities they perform, yet this has been much slower and more nuanced, also given lower funding availability. The focus of HVMC is still very much on the ‘Valley of Death’ technology development, yet one interviewee mentioned that they have a broader scope, going from TRL 3 to 7:

“[We refer to these as] ‘crevices of death’ ... and we try and convey the thoughts, needs and challenges [TRL 3] but also pull the technology through [TRL 7] and mature the technology” [#UK_18].

Overall, the relationship between HVMC and universities appears strong with HVMC’s fundamental research activities being more present in certain areas. Differently from MxD in the US, where the movement towards technology demonstration has been stronger, HVMC seems to maintain the focus on both technology development and technology transfer/demonstration. In the UK, there tends to be fewer technology demonstration type of activities because few centres of HVMC have demonstration production lines on their shop floor. One interviewee described how they distinguish between “innovation” and “adoption”:

“I’d use innovation versus adoption [to describe their activities]; the former is more centred to OEM and tier 1 that have the money and ability to enter into the technology development space, while adoption is more related to getting the technology off the shelf, de-risking businesses to make the transition” [#UK_18].

Within technology development activities, HVMC’s preferred approach is challenge-based rather than a technology development project. For example, a recent project was proposed to develop an automated vision system to inspect a difficult geometry. At first, they rejected it because there were no capabilities to develop the technology.

¹³ The seven centres are: Advance national Research Centre, CPI, Manufacturing Technology Centre (MTC), National Composites Centre, National Manufacturing Institute Scotland, Nuclear AMRC, WMG

¹⁴ When referring to the HVMC we refer in this paper to both MTC and AMRC centres, when it is not specified.

¹² The program was concluded in 2020 (GAO).

Yet, analysing the challenge behind the request, which was the need to inspect a hole to see whether it was clear of debris, they helped the firm not by developing an automated vision system but by inducing a vacuum and measuring the fall-off. With this example, they pointed to the fact that for most challenges faced by firms, technologies already exist, and there is a high need for technology adoption to different production processes. Technologies demonstration is thus becoming more important given the challenges brought by digitalisation, which contributed to shaping the perceptions of the role of the centres:

“We are classed as innovation, not invention centres, and innovation is [has become] very much about novel ways of integrating existing technologies ... dealing with technologies that don't actually interoperate, this is where our development goes.” [#16_UK].

As for workforce development activities, the interviews suggest that they are becoming increasingly central to their knowledge transfer function. As a caveat, it is important to remember that although the Catapult network was set up in 2011 with the main mandate to do technology development activities (TRL 4–7), most of the centres that form the HVMC – more precisely 5 (including the two represented in our interviews) out of 7 – had pre-existing training centres.¹⁵ This has contributed to a situation where training was done *anyway*, yet not as part of the HVMC functions, thus enlarging the gap between technology development/adoption activities and workforce development activities. These activities should instead be combined, given that workforce activities are key to fully enabling the knowledge transfer projects. One interviewee explained:

“Skills have always been part of AMRC strategy, finally now InnovateUK acknowledges it” [#UK_18].

This comment refers to the recent openness from InnovateUK about recommendation 10 of the 2021 Independent Catapult Review, which proposed introducing skills development into the following funding phase of Catapults (BEIS, 2021). This is reinforced by the 2023 Review, which emphasises that Catapults will drive skills fore-sighting and development in collaboration with the rest of the ecosystem.¹⁶

Lastly, in terms of supply chain activities, this is at a very early stage, but it is imperative to expand HVMC activities in that direction [#18_UK]. One of the HVMC centres mentioned how supply chain activities have always been part of their portfolio, yet in quite a narrow way, mainly looking at supply chain mapping at the product level to better understand the level of capabilities already in the UK for a specific product.

6.3. Collaboration with other actors across activities

Relatively to their counterpart in the US, the HVMC has a low level of collaboration with other players in the ecosystem and with other Catapults. To understand the role played by actors that deal with digital technology transfer with SMEs, we analysed the case of Made Smarter Adoption. Differently, from the relationship between MxD and the MEPs

¹⁵ Training centres are not identical, but they are shaped by the ecosystem demand and sectoral focus. For example, AMRC and MTC analysed in this paper, provide both training centres and apprenticeships.

¹⁶ Together with Levelling Up, equality diversity and inclusion and expansion of the network, skills are the fourth pillar of the future objectives of Catapults. <https://www.gov.uk/government/publications/catapult-network-review-2021-how-the-uks-catapults-can-strengthen-research-and-development-capacity>.

in the US, the scenario is different in the UK, where Made Smarter is not an organisation but a program, and the program is specifically targeted to favour companies' adoption of a pre-defined set of digital technologies.¹⁷ This has created challenges, indicating that the attempts to collaborate often fail. One interviewee stated:

“We try to work with the Catapult, but it is very hard, sometimes they think Made Smarter should be one of their services” [#UK_16].

Being two different legislative creatures, the coordination appears more challenging. Two elements emerge from our interviews. First, the HVMC is referred to be quite isolated from the rest of the ecosystem;

“My perception of the HVMC is that it likes to buy new shiny things and then they try to understand what they can do with it ... that's fine if you have their funding model, but the people we deal with [SMEs] don't have that money” [#18_UK].

This is also linked to the different business models and sets of clients, yet it remains problematic because SMEs are the primary target for Made Smarter Adoption, but they would also require technology demonstration type of activities beyond what Made Smarter can deliver. Once directed to the HVMC, the success is limited because “there is limited funding to work with SMEs and to collaborate” [#20_UK].

Three interviews mentioned that the abolition of MAS (Manufacturing Advisory Services) in 2015 left a void in the knowledge transfer process, particularly regarding lean and other technology and organisational activities that often constitute a precondition to engaging with more sophisticated technologies. When asked about collaboration on the workforce side, interviews refer to no collaboration taking place despite the training centres in most HVMC centres and a specific branch of Made Smarter directed towards skills, mainly referring to the lack of funding. One interviewee mentioned that “the skill situation in the UK is utterly confused, and the landscape is generally broken” [#19_UK].

Finally, collaboration between Catapults is also scarce, despite getting better over time, with competition forces that are decreasing. One interviewee explained:

“We are trying to develop mechanisms where we can identify the centres that should be involved in different projects ... initially there was a fear of missing out and everyone [every centre] was trying to do everything. Over time we realised that there are many areas where many centres are involved (e.g., digital, additive manufacturing) and collaboration may play out better” [#UK_14].

Fig. 2 summarises the findings on the innovation intermediaries' activities and their coordination with other actors in the ecosystem across the UK and the US. Defining the set of activities on the left, we represent our results as coloured bubbles of varying sizes; as for the first panel (RQ1), the bubbles' size respectively indicates the movement towards higher TRLs in technology development activities and an increasing focus (with different intensities, i.e., different sizes) in workforce and supply chain development activities. In the second panel (RQ2), the size of the bubble indicates the intensity of collaboration on the different activities, with a cross indicating no ongoing collaboration.

Legend: The bubble size qualitatively indicates the magnitude of the findings across the two countries. The cross indicates no ongoing collaboration.

¹⁷ Examples of technologies that are included in the Made Smarter program are: Additive manufacturing, the Industrial Internet of Things (sensors), artificial intelligence and cognitive learning, mobile devices and wearable technology, data and systems integration, robotics and process control automation, virtual, augmented and mixed realities, industrial cybersecurity, big data and analytics.

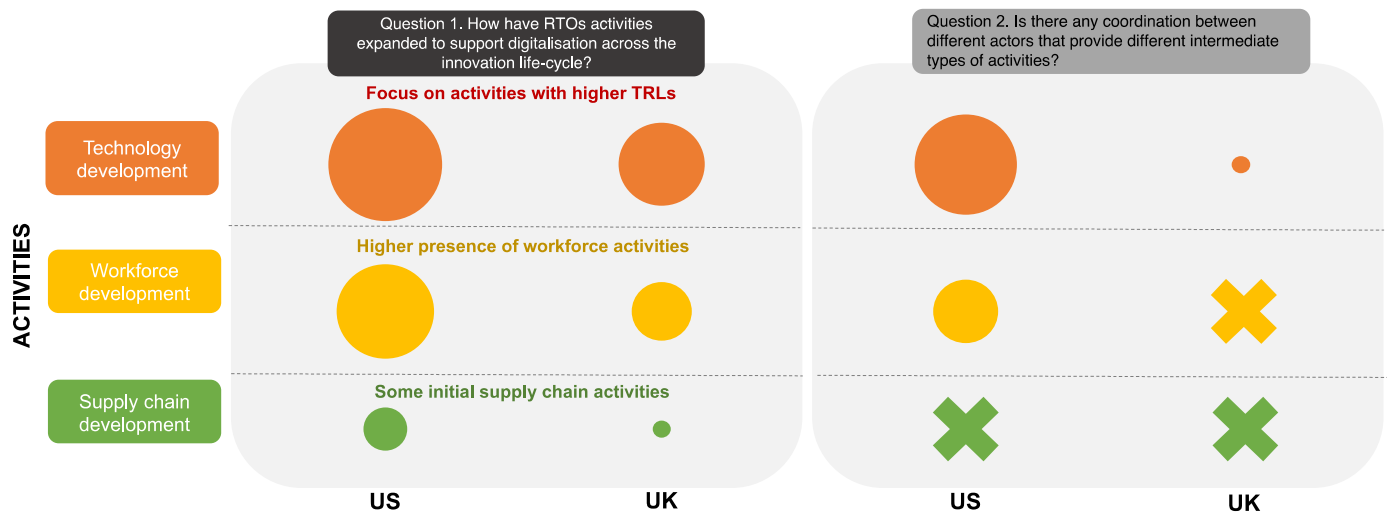


Fig. 2. Catapult network centres.
Source: Catapult network website

7. Comparative findings and discussion

The cases analysed reveal that activities within RTOs are changing, yet there are challenges in terms of rapidly adjusting to what firms require to fill capabilities gaps in a constantly changing knowledge transfer process. The 'orchestrating' role of RTOs is mottled, with processes of error and trials that emerge spontaneously and as a result of policy programs and have been part of how RTOs operate with other actors involved in the knowledge transfer process. Funding availability tends to soften such challenges to clarify scope and objectives, providing more room for collaboration engagement.

The US case of MxD and its collaboration with (multiple) MEPs indicates that the intermediary role for digital production technologies is de facto interpreted as a technology demonstration/technology implementation, with MxD providing support mostly through activities that correspond to TRLs level 7–8. This has allowed MxD to better respond to firms' changing needs and to target different gaps along the knowledge transfer process; the digitalisation process requires demonstration activities to promote technology diffusion. MxD is also quickly adapting to workforce development activities to meet the increasing demand and acknowledges the importance of developing supply chain activities, which are only at early stages. Collaboration with other intermediary actors involved in complementary knowledge transfer activities (i.e., technology development, technology deployment, technology adoption) happens more often and MxD is increasingly taking the role of ecosystem 'shaper' (Randhawa et al., 2022). The main channel is the opportunity to tap into funding opportunities, which require building collaboration with other actors (e.g., through consortia). This tendency would confirm the role of top-down policies in fostering collaboration, providing the funding opportunity for different organisation to leverage their capabilities and collaborate.

In contrast, in the UK case, the evolution of technology development activities, i.e., more towards technology demonstration and implementation, is slower, and strong relations with universities maintain the core activities of the organisation anchored to lower TRLs. The HVMC centres acknowledge the requirement to move towards demonstration and implementation activities, especially in light of firms' requests, yet this is challenging also because organisations are less equipped for these activities, e.g. most centres lack production lines and infrastructure for demonstration activities. Workforce development is performed in a siloed way, given that some of the Catapult centres can provide workforce activities outside of the core funding they receive from the government, thus preventing a truly interconnected technology and workforce project; different from the US case, in the UK, it is hard to tap

into other sources of funding to develop non-technology development related activities, such as workforce or supply chain activities. The scarce collaboration between the HVMC and programs such as Made Smarter Adoption indicates an overall isolation of the HVMC from the rest of the system. Also, four interviewees unanimously report that the UK faces a significant gap in simulation and lean production, a gap left by the abolition of MAS and the lack of funding to target these specific failures in the knowledge transfer process. This latter point is very different from the US, where the longstanding program of MEPs across the country and their expanding activities cover lean manufacturing and technology adoption challenges (Wessner, 2013).

In the rest of the section, we provide a reference to how our analysis fits with and contributes to the broader literature on the topic. Starting with the activities of the two examined RTOs, our study indicates that the activities of RTOs are going through a reshaping process (both in the number and in the type) to respond to new challenges coming from digital technologies. Although this was discussed by previous literature (Holland et al., 2024; Rossi et al., 2022), our study indicates not only the change but also its direction. Digital technologies present challenges that are heavily related to deployment and adoption, rather than technology development, and RTOs' activities evolve as a response (Saad et al., 2024); while this indicates a certain level of technology maturity, it may cause issues if RTOs are not ready for a smooth adjustment to a different set of activities, e.g., insufficient funding and lack of adequate infrastructure, for example, for demonstration activities, as in the case of the UK (Charles et al., 2015). When discussing technology development activities, our research aligns with recent findings, confirming a stronger emphasis on applied research, with a focus on deployment and adaptation (Larrue and Strauka, 2022). Despite a prescriptive focus on the workforce since institutes' inception in 2011 and 2013 (more consistent and stronger in the US policy documents),¹⁸ workforce development activities started to play a major role only recently; more efforts at the policy level (both funding and coordination mechanisms) confirm that RTOs' success in the knowledge transfer process strongly depends on its workforce (Thurner, 2017). This is one of the most interesting and novel findings of our research; RTOs as part of the different requirements of digital technologies, are required to do more workforce activities to respond to firms' requests. This indicates that technical knowledge and human/workforce knowledge are intrinsically linked to fulfilling the

¹⁸ This is true especially in the US context where workforce development activities are present in the legislation of the past ten years about M-USA. Workforce has also been a critical aspect for MEPs (Wessner, 2013: p. 113).

knowledge transfer objective, yet MxD and HVMC faced challenges given that their core funding coming from the Department of Defence (US) and Innovate UK could not be used for activities other than technology development (TRLs 4–6). More recently, both agencies have moved towards a more flexible approach and workforce activities are central to future strategies of funding agencies and their RTOs.¹⁹

Supply chain activities are at an initial stage, and they mainly refer to value chain mapping to understand gaps and missing elements. Supply chain becomes a sort of lens that can be used to design technology and workforce projects; in other words, as the example from the US shows (the first supply chain project emerged to be a workforce project adopting supply chain lenses, see section 4.2), mapping the supply chain is often a requirement to ensure capabilities at the technology level and the competences emerging from workforce activities are captured across specific value chains. Workforce activities and the initial work at the supply chain level require to be combined with technology deployment/adoption activities to fulfil the knowledge transfer function (Larue and Strauka, 2022).

Regarding the collaboration and division of labour in the ecosystem, our study indicates that despite RTOs possessing the resources and the knowledge to act as facilitators in the ecosystem, the occasions to do so are rare and mostly based on opportunities coming from random funding made available by specific programmes (e.g., the exchange of workforce between M-USA and MEPs). RTOs and other organisations can nicely and effectively combine two neighbour types of expertise, creating synergies they obtain from mutual feedback between their focus areas (Farina and Preissl, 2000). The technical skills, know-how, infrastructure and institutional memory that RTOs have built over time make them key ecosystem actors (Martins et al., 2023; Sheikheldin, 2021), not (only) because of their long-standing position but because of the critical interfaces they work across. They have the potential to be more market makers, shaping the technology in the direction where there is more demand, facilitating relationships in the ecosystem, playing a unique orchestrating role across universities and key business actors, being able to know and fill the gaps coming from different ends of the spectrum (Colovic et al., 2025; Giannopoulou et al., 2019). Literature from the early 2000s looked at how organisations that provide similar activities do it efficiently, especially when the sources of funding are different. Hales (2001) and (Preissl and Farina, 2000), present evidence on the division of labour between RTOs and KIBS, arguing that their functions and collaboration are very country specific. For example, in the UK there was a very clear-cut division of labour – this referred to RTOs that existed before and were privatised (Hales, 2001). Our research, for the first time, explored the division of labour between organisations that receive a portion of their funding from public bodies and that are in charge of different gaps along the innovation cycle, and it indicates that much can be done in this space to promote efficient use of resources and a better response to technical challenges.

Finally, our findings point to the critical role of policy, at least under three aspects. Policy measures are critical to provide firms with the right incentives to build absorptive capacity by fostering the adoption of digital technology for productivity increases and upgrading. During the UK data collection, it emerged how companies struggle to make investments since they do not see the real value of new technologies (one interviewee mentioned that the UK is the biggest second-hand equipment from Germany). Second, modern industrial challenges require resources to provide public organisations with the tools to respond to an evolving set of challenges (Borrás et al., 2024). Third, innovation policy programs (such as the ones designed by NIST in the US that promoted

the exchange of employees across different organisations) are a tool to enforce organisational collaboration, as they acknowledge that innovation policy needs to be systemic, i.e., it needs to focus on multiple actors from different parts of an innovation system that learn from each other while performing different activities and functions.

8. Conclusions

Digital technologies affect the innovation process, redefining the space and scope for government intervention. The multiple sets of technologies that are part of digital systems present higher failures and complexity, redefining the type of services and support that firms require from RTOs. A new space has been opening with higher specialisation and increased scope; within this space, RTOs have moved from exclusively technology development activities to technology demonstration and implementation with a stronger focus on workforce and supply chain activities.

This paper delves into RTOs, providing new evidence on the changing nature of knowledge transfer activities in digital innovation, on the relevance of demonstration and workforce activities to support absorptive capacity and on an evolving division of labour with other intermediary actors. These insights advance our understanding of how RTOs, firms, and policymakers can adapt and respond to changes in the innovation process.

Our research contributes to the existing literature in three main ways. First, it provides evidence of how RTOs supporting digital manufacturing are adapting to new activities and how their coordinating role is increasing in the ecosystem where they operate. We thus build on previous literature, which emphasises the critical role of flexible and adaptive missions of RTOs (Kim et al., 2010; Preissl, 2006) that are increasingly required to expand their activities to respond to recent technological and innovation challenges (Noviaristanti et al., 2023; Rincón Díaz et al., 2017; Rossi et al., 2022). In addition, we contribute to the systematisation of the RTOs literature regarding *old* technology activities and the emergence of *new* workforce activities. A further theoretical contribution is through an initial assessment of the 'division of labour' of innovation intermediaries in the ecosystem (Martins et al., 2023; Alborns-Garrigos et al., 2010), and how they try to organise their interactions with top-down and bottom-up approaches.

Second, our empirical analysis of the UK and the US provides data on organisations that have not been studied before; our empirical investigation, which allows for the first time to gather comparative data across two RTOs in the US and the UK, provides a unique source of knowledge regarding the type of activities that RTOs perform, as well as their challenges. Specifically, by engaging with the managerial board of both RTOs, we have a clear picture of the type of activities that RTOs perform and their most recent challenges. We provide evidence that MxD and HVMC's main function of knowledge transfer remains at the core, yet to succeed, their activities are evolving and increasing in scope. According to our interviews with policy stakeholders, such broadening of activities is common to other institutes in the respective networks.

Our third and last contribution is at the policy level. There are three specific policy recommendations in this area. It is critical to gather evidence that can inform policymakers about gaps along the innovation cycles; in this way, they can strategise for specific technology domains targeting different organisations for a more efficient knowledge transfer process. RTOs similar to the ones analysed in this research (i.e., non-profit and that receive a proportion of their funding from the government) are a critical tool to navigate barriers across the often disconnected parts of the innovation process, their knowledge repository role across innovation actors gives them a unique position to collaborate and 'serve' the policymaking process providing valuable inputs. A second critical policy implication is that RTOs funding agencies should allow the use of core funding for workforce development activities, providing room for a flexible use of resources based on the evolving gaps and challenges; it is clear from the numerous skills programmes across

¹⁹ DSIT (2023). 2023 Update to the 'Catapult Network Review'. An update on developments since the Catapult Network Review (2021). See recommendation 10 and relative response on workforce <https://assets.publishing.service.gov.uk/media/6503184897d3960014482f14/catapult-network-review-2023-update.pdf>.

countries that strategising for a technology domain requires workforce development as a parallel dimension to the technical one. Third, policymakers should incentivise RTOs' orchestrating role as this would increase alignment and a more defined 'division of labour' between the different actors. In the US, for example, NIST started to design specific programmes for collaboration between MxD (and other institutes) and the MEPs network.²⁰

Our paper has intrinsic limitations. The first and most critical one is that we studied two individual RTOs, making it hard to generalise given the high heterogeneity that characterises these organisations. There are two main challenges. We focused on RTOs that support digital manufacturing, so it is hard to draw parallels for RTOs that operate in different industrial domains, even when within the same networks (in the case of the US, the other important difference regards the funding agency, while in the UK the funding agency is one across the network in the US there are three different Departments with different policy priorities). Existing policy documents across the two countries point to a certain level of similarity given by the common innovation and production systems these organisations operate in at the country level, but there are technology and local specificities that can hardly be overcome. In addition, it is hard to conclude that RTOs based in other countries will have similar features. However, we analysed the case of digital manufacturing, and we observed that there are some common trends between the UK and the US. We observe similar challenges across the two RTOs, for example, a stronger focus on deployment activities and

workforce activities, indicating that the technology area (i.e., digital in our case) can be a predictor of similar challenges. Our limitations pave the way for future research, at least in two directions. First, it would be critical to understand to which extent an increased focus on other activities (i.e., workforce development and supply chain development) goes beyond the UK and the US and how it evolves in countries where, for example, government intervention in these areas has been more common (e.g., in Germany, Japan or France). Second, it is crucial to gather data on a more consistent base; the reports commissioned by EARTO to OECD (Larrue and Strauka, 2022) went in that direction with an initial survey of major RTOs in Europe, yet more data, collected more consistently across time and available to the broader scientific community would benefit more research in this area.

CRediT authorship contribution statement

Guendalina Anzolin: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization.
Eoin O'Sullivan: Methodology, Funding acquisition, Conceptualization.

Acknowledgements

This work was supported by Gatsby Charitable Foundation [GAT3816].

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.technovation.2025.103200>.

Appendix 1A: Systematic literature review

Authors	Title and type of publication	Functions and/or activities' references
Barge-Gil et al. (2007)	Research and technology organisations: How do they manage their knowledge? [Article]	<ul style="list-style-type: none"> • RTOs perform R&D activities and offer a wide range of technological services, aimed to improve firms' competitiveness by encouraging their technological and innovative performance • Examples: information exchange and promotional activities like technology and commercial fair attendance, diffusion journeys, informative sessions; innovation activities to support firms; sector oriented and/or technology-oriented activities.
Barlatier et al. (2010)	Service portfolio design for service innovation management: The case of a Luxembourgish research and technology organization [Conference paper]	<ul style="list-style-type: none"> • RTOs perform R&D activities in a collaborative way to improve and strengthen the innovation capabilities of private and public organisations.
Borsi (2021)	The Balanced State of Application-oriented Public Research and Technology Organisations [Article]	<ul style="list-style-type: none"> • Knowledge creation activity that aims at solving practical problems; research and non-research related activities; support activities • Examples: Quality of the research and ICT infrastructures, organizational knowledge; management practices, progressive HR management practices, funding and administration of activities).
Dufva and Ahlqvist (2015)	Elements in the construction of future-orientation: A systems view of foresight [Article]	<ul style="list-style-type: none"> • Foresight activities
Fechtelpeter et al. (2018)	Supporting the planning phase of SME-tailored technology transfer projects [Conference paper]	<ul style="list-style-type: none"> • Technology transfer activities
Gershman et al. (2019)	Open innovation in Russian state-owned enterprises [Article]	<ul style="list-style-type: none"> • Innovation activities
Giannopoulou et al. (2019)	Same but different? Research and technology organisations, universities and the innovation activities of firms [Article]	<ul style="list-style-type: none"> • Activities that support industrial research and the transfer of science and technology to business • Examples: (i) bridging the gap between science and industry to facilitate innovation, dissemination, and uptake of new technologies; (ii) strategic applied R&D activity targeted at specific sectors or technologies; (iii) development and/or dissemination of scientific and technical standards and information; (iv) best-practice initiatives, training, consultancy, and dissemination of information to raise firms' competitiveness in the global market.

(continued on next page)

²⁰ This is an example of a recent programme <https://www.mxdusa.org/2023/10/18/mxd-announces-partnership-with-nist-manufacturing-extension-partnership/>, and a concept note of their increasing collaboration here https://www.manufacturingusa.com/sites/manufacturingusa.com/files/2021-09/MEP_MFGUSA_infograph_ic_final_web_ready.pdf.

(continued)

Authors	Title and type of publication	Functions and/or activities' references
Gonzalez-Urango et al. (2024)	Toward institutionalization of responsible research and innovation: insights from case studies of technological centres in Spain [Article]	<ul style="list-style-type: none"> •Facilitators of technological activity; activities with undefined boundaries; training and education management as core activities.
Hecklau et al. (2021)	Technology Audit: Procedure for the Assessment of the Technological Maturity of Applied R&D Organisations [Conference paper]	<ul style="list-style-type: none"> • Generic reference to research activities
Hecklau et al. (2022)	Assessment Dimensions and Items for the Evaluation of the Technological Maturity of Applied R&D Organisations [Conference paper]	<ul style="list-style-type: none"> • Generic reference to R&D activities
Hecklau et al. (2023)	Quantitative Evaluation of Assessment Items of the Technology Audit Method for Research and Technology Organisations (RTOs) [Conference paper]	<ul style="list-style-type: none"> • Generic reference to R&D activities
Hecklau et al. (2020)	Requirements for a methodology for the analysis and assessment of technological capability in research and technology organisations [Conference paper]	<ul style="list-style-type: none"> • Activities between TRL3 (detection concept of critical functions and/or properties) to 6 (model demonstration of critical functions in relevant environment)
Hecklau et al. (2020)	Analyzing the role of research and technology organisations (RTOs) in national innovation systems (NIS) [Conference paper]	<ul style="list-style-type: none"> • Main activities are to provide product and process solutions in applied research. • Examples: Research (basic research, applied research, contract research); Development, demonstration and production: product development, prototyping, proof of concept, compliance, technical support, pilot projects and equipment, production process development; IP protection and commercialisation: patenting, IP portfolio management, licensing, commercialisation; Business and market development: entrepreneurship and start-up support, market analysis, etc.
Hyland et al. (2006)	Sources of Innovation and Ideas in ICT Firms in Australia [Article]	<ul style="list-style-type: none"> • No reference to RTO activities
Khelifaoui and Bernier (2023)	Research and technology organisations as entrepreneurship instruments: the case of the Institut National d'Optique in the Canadian optics and photonics industry [Article]	<ul style="list-style-type: none"> • Examples of activities that RTOs perform both research based, and service based: intellectual property development, protection and commercialisation or business and market development, including entrepreneur- ship and start-up support.
Kidschun and Hecklau (2021)	Towards a Framework for Impact Assessment of Research & Technology Organisations [Conference paper]	<ul style="list-style-type: none"> • No reference to RTO activities/functions
Koens et al. (2018)	Making knowledge work: The function of public knowledge organisations in the Netherlands [Book chapter]	<ul style="list-style-type: none"> • No reference to RTO activities/functions
Leung et al. (2014)	Eureka!: Lessons learned from an evaluation of the idea contest at Deltares [Article]	<ul style="list-style-type: none"> • No reference to RTO activities/functions
Miller (2014)	The strathclyde technology and innovation centre (TIC) in Scotland's innovation system [Article]	<ul style="list-style-type: none"> • Functions of RTOs have broadened over time. In addition to their traditional R&D 'hard' functions such as technology testing, they are now promoted as service assets in regions, and provide 'soft' business services such as networking and consultancy • Essential enabling functions in the innovation process.
Mrinalini and Nath (2000)	Organizational practices for generating human resources in non-corporate research and technology organisations [Review]	<ul style="list-style-type: none"> • Knowledge generation function process followed by knowledge application, where knowledge is finally transformed for use in the production sphere. • Identify and prioritize the areas of its research activities and the delivery of research results to the clients
Mrinalini and Nath (2008)	Knowledge management in research and technology organisations in a globalized era [Article]	<ul style="list-style-type: none"> • Critical function between linking the organisation and the users; focus on what is needed to have the RTO maintaining the core research activities • Training is an activity that can orient the industry.
Osborne et al. (2021)	A Hierarchical Approach to Technology Roadmapping within an RTO Environment [Article]	<ul style="list-style-type: none"> • No reference to RTO activities/functions
Preissl (2006)	Research and technology organisations in the service economy: Developing analytical for changing innovation patterns [Article]	<ul style="list-style-type: none"> • Functions in the upstream segments of innovation processes (basic and applied research, product/process development).
Riegler and Höllerschmid (2006)	Voluntary disclosure on project intangibles from R&D in business reporting: A principles-based approach for R&D intensive companies [Article]	<ul style="list-style-type: none"> • No reference to RTO activities/functions
Sassanelli and Terzi (2022)	Building the Value Proposition of a Digital Innovation Hub Network to Support Ecosystem Sustainability [Article]	<ul style="list-style-type: none"> • Knowledge creation and knowledge transfer functions • Applied research activities
Suominen et al. (2021)	'Gold', 'Ribbon' or 'Puzzle': What motivates researchers to work in Research and Technology Organisations	<ul style="list-style-type: none"> • Function of RTOs are related to basic research and development, certification and standards, and the provision of research facilities and contributing to technology transfer.
Taverdet-Popiolek (2022)	Economic Footprint of a Large French Research and Technology Organisation in Europe: Deciphering a Simplified Model and Appraising the Results [Article]	<ul style="list-style-type: none"> • RTOs activities through spending and employment on the one hand, and the economic leverage of knowledge transfer activities through contract research, spin-offs and the outflow of staff on the other hand
Thurner (2017)	Transfer Revenues of Research and Technology Organisations (RTOs) in times of economic crisis [Article]	<ul style="list-style-type: none"> • Knowledge transfer activities, and non-R&D activities are of vital importance for the implementation and success of the innovation. • Examples: collaboration activities, R&D performance, and recruitment activity; education and training activities.
Thurner and Zaichenko (2014)	Research and technology organisations (RTOs) in the primary sector: Providing innovation to Russia's mines and corn fields [Article]	<ul style="list-style-type: none"> • The function is the provision of S&T and of expertise and innovation for public agencies; • RTOs provide bridging functions for the dissemination and uptake of new technologies between science and their client (through transfer activities) • Both R&D and non-R&D activities; the latter are of vital importance for the implementation and success of the innovation; education and training activities.
Thurner and Zaichenko S. (2018)	Technology transfer into Russia's agricultural sector-Can public funding replace ailing business engagement? [Article]	<ul style="list-style-type: none"> • Function of bridging between science and production line • Technology transfer activities, focusing on the creation and distribution of new knowledge and technologies.
Thurner and Zaichenko (2016)	Sectoral differences in Technology Transfer [Article]	<ul style="list-style-type: none"> • Function of knowledge development • Function of knowledge diffusion and use of technology

(continued on next page)

(continued)

Authors	Title and type of publication	Functions and/or activities' references
Thurner and Zaichenko (2015)	The feeding of the nine billion - A case for technology transfer in agriculture [Article]	<ul style="list-style-type: none"> • Technology transfer activities • Functions of technology creation and technology diffusion; bridging function between science and production; core activity lies in enhancing firms' competitive advantages through technology uplifting. • Activities of monitoring technology developments; RTOs are more active in upstream activities of the innovation process, and less with the implementation of new technologies at their clients; Semi-public RTOs show more downstream orientation through applying their technical competences to better serve their clients; innovation activities; technology transfer activities.
Zaichenko S. (2018)	The human resource dimension of science-based technology transfer: lessons from Russian RTOs and innovative enterprises [Article]	<ul style="list-style-type: none"> • Functions of technology transfer in terms of both the ability to outsource firms' R&D and to customize R&D outputs. • Basic research, applied research and development activities. • Technology transfer activities and publication activity, including less formal categories including training activities, scientific publications, professional mobility of researchers, academic networking. • S&T services (like metrology and certification offices, engineering and design centres, etc.)
Ciapetti L.; Perulli O. (2018)	New tech spaces for old tech places? Exploring the network of research and technology organisations across North Italian Regions [Article]	<ul style="list-style-type: none"> • Knowledge transfer and knowledge diffusion functions. • This function of knowledge gatekeeping has been originally conceived as a key activity of the R&D organization; technology diffusion activities in the network and involvement in tacit knowledge exchange

Appendix 1B: RTOs analysed in the paper

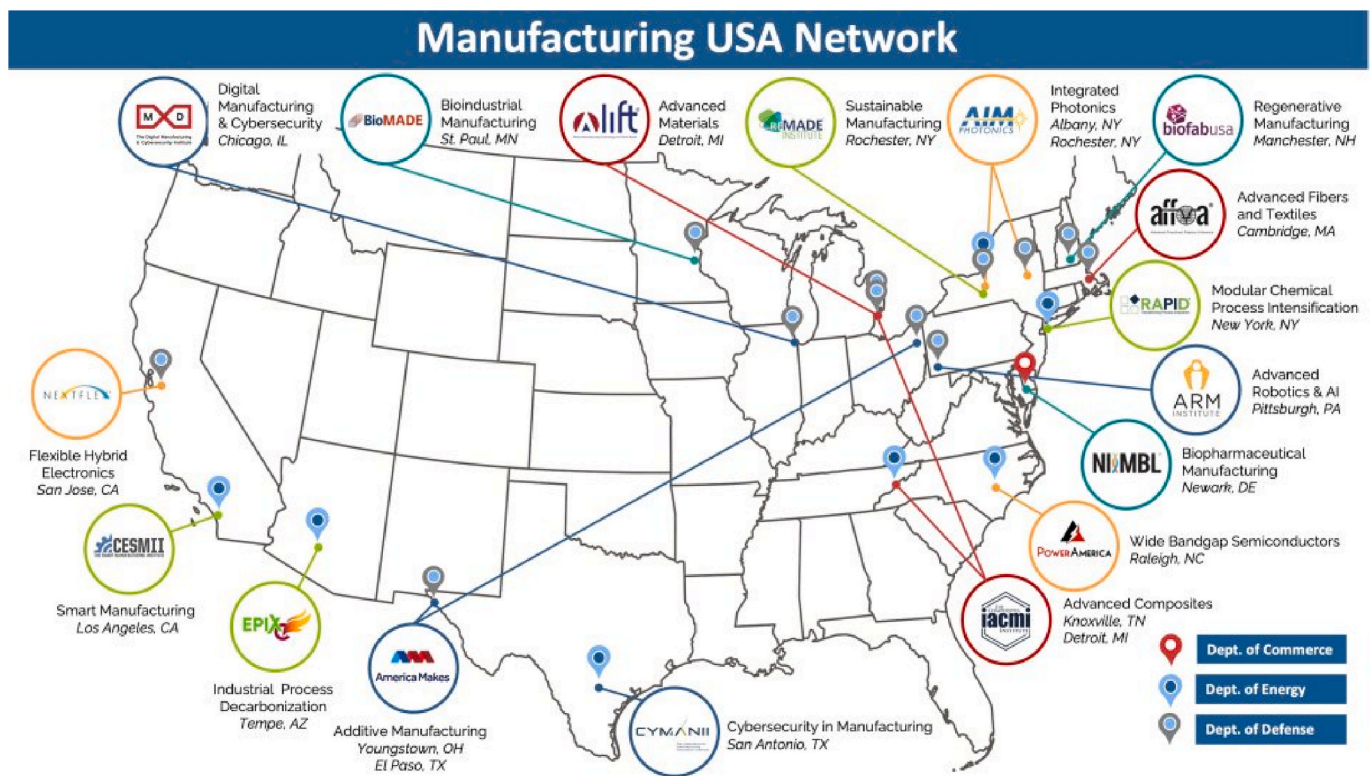


Fig. 1. Framework and research questions. Source: Authors

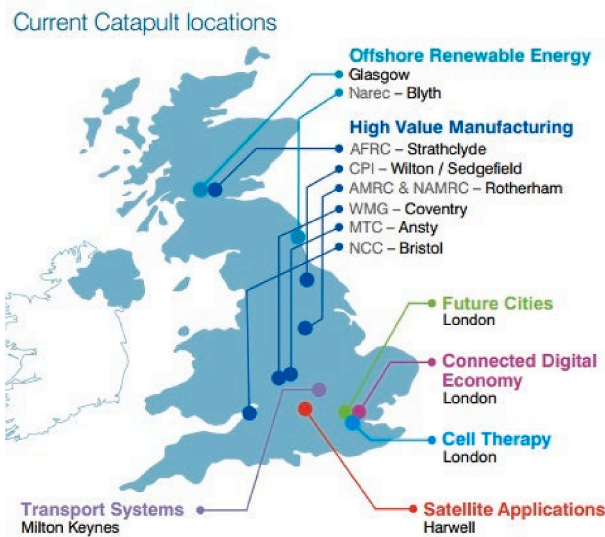


Fig. 2. Summary of the findings.
Source: Authors.

Data availability

Data will be made available on request.

References

- Albors-Garrigós, José, Diaz, Rincon, Carlos, A., Igartua-Lopez, Ignacio, Juan, 2014. Research technology organisations as leaders of R&D collaboration with SMEs: role, barriers and facilitators. *Technol. Anal. Strat. Manag.* 26 (1), 37–53.
- Alqoud, Abdulrahman, Schaefer, Dirk, Milisavljevic-Syed, Jelena, 2022. Industry 4.0: a systematic review of legacy manufacturing system digital retrofitting. *Manuf. Rev.* 9, 32.
- Araoz, Alberto, 1996. Revitalization of industrial technology research Institutes in developing countries. In: Qureshi, M.A. (Ed.), *Human Resource Needs for Change in R&D Institutes*.
- Arnold, Erik, Clark, John, Jávorka, Zsuzsa, 2010. 'Impacts of European RTOs', A study of social and economic impacts of research and technology organisations. In: *A Report to EARTO*. Technopolis Group Ltd.
- Arora, Ashish, Belenzon, Sharon, Pataconi, Andrea, 2015. Killing the Golden Goose? The Decline of Science in Corporate R&D. *National Bureau of Economic Research*.
- Barge-Gil, Andres, et al., 2007. Research and technology organisations: how do they manage their knowledge? *Int. J. Enterpren. Innovat. Manag.* 7 (6), 556–575.
- BEIS, 2021. *Catapult Network Review How the UK's Catapults can strengthen research and development capacity*. BEIS Research Paper Number 2021/013 Available at: <https://assets.publishing.service.gov.uk/media/6065a7a9d3bf7f0c8d06b811/catapult-network-review-april-2021.pdf>.
- Bordoloi, Tausif, Shapira, Philip, Mativenga, Paul, 2024. Industrial policy initiatives in manufacturing: examining cross-country interventions through an evolutionary typology of technology systems. *Sci. Publ. Pol., scae026*
- Borrás, Susana, Gerli, Francesco, Cenzato, Rebecca, 2024. Technology transfer offices in the diffusion of transformative innovation: rethinking roles, resources, and capabilities. *Technol. Forecast. Soc. Change* 200, 123157.
- Caloffi, Annalisa, et al., 2023. Innovation intermediaries' types and functions: a computational analysis of the literature. *Technol. Forecast. Soc. Change* 189, 122351.
- Carlsson, Benny, Stankiewicz, Rikard, 1991. On the nature, function and composition of technological systems. *J. Evol. Econ.* 1, 93–118.
- Charles, David, Stancova, Ciampi, Katerina, 2015. *Research and Technology Organisations and Smart Specialisation*.
- Chataway, Joanna, et al., 2019. Science granting councils in sub-saharan africa: trends and tensions. *Sci. Publ. Pol.* 46 (4), 620–631.
- Chen, Shih-Hsin, Lin, Wei-Ting, 2018. Analyzing determinants for promoting emerging technology through intermediaries by using a DANP-based MCDA framework. *Technol. Forecast. Soc. Change* 131, 94–110.
- Ciapetti, Lorenzo, Perulli, Paolo, 2018. New tech spaces for old tech places? Exploring the network of research and technology organizations across North Italian Regions. *Eur. Plan. Stud.* 26 (1), 192–211.
- Cohen, Wesley M., Levinthal, Daniel A., 1990. Absorptive capacity: a new perspective on learning and innovation. *Adm. Sci. Q.* 35 (1), 128–152.
- Colovic, Ana, et al., 2024. *Innovation Intermediaries and Emerging Digital Technologies*, vol. 133. Elsevier, 103022.
- Colovic, Ana, et al., 2025. Institutionalising the digital transition: the role of digital innovation intermediaries. *Res. Pol.* 54 (1), 105146.
- Crow, Michael M., Bozeman, Barry L., 1987. A new typology for R&D laboratories: implications for policy analysts. *J. Pol. Anal. Manag.* 6 (3), 328–341.
- De Silva, Muthu, Howells, Jeremy, Meyer, Martin, 2018. Innovation intermediaries and collaboration: knowledge-based practices and internal value creation. *Res. Pol.* 47 (1), 70–87.
- Dhanaraj, Charles, Parkhe, Arvind, 2006. Orchestrating innovation networks. *Acad. Manag. Rev.* 31 (3), 659–669.
- Díaz, Rincón, Augusto, Carlos, Garrigós, Albors, José, 2017. Research and technology organizations' mobilizers of the regional environment: competitive strategies. *Eur. J. Manag. Bus. Econ.* 26 (2), 180–198.
- DoC, Department of Commerce, 2016. Strategic plan executive office of the president national science and technology Council advanced manufacturing national program office. *National Network For Manufacturing Innovation Program*.
- EARTO, 2007. *Research and Technology Organisations in the evolving European Research Area, a status report with policy recommendations*. EARTO report.
- EARTO, 2015. *EU R&I policy & data-driven decision making. Knowing your innovation ecosystem actors: data on European RTOs*. EARTO report.
- Eisenhardt, Kathleen M., Graebner, Melissa E., 2007. 'Theory building from cases: opportunities and challenges'. *Acad. Manag. J.* 50 (1), 25–32.
- Elia, Gianluca, Margherita, Alessandro, Passiante, Giuseppina, 2020. Digital entrepreneurship ecosystem: how digital technologies and collective intelligence are reshaping the entrepreneurial process. *Technol. Forecast. Soc. Change* 150, 119791.
- Ellwood, Paul, Williams, Ceri, Egan, John, 2022. Crossing the valley of death: five underlying innovation processes. *Technovation* 109, 102162.
- Esmailian, Behzad, Behdad, Sara, Wang, Ben, 2016. The evolution and future of manufacturing: a review. *J. Manuf. Syst.* 39, 79–100.
- Fromhold-Eisebith, Martina, et al., 2021. Torn between digitized future and context dependent past—How implementing 'Industry 4.0' production technologies could transform the German textile industry. *Technol. Forecast. Soc. Change* 166, 120620.
- Georghiou, Luke, et al., 2003. *A comparative analysis of public, semi-public and recently privatised research centres-summary final report*. European Commission/DG Research.
- Giannopoulou, Eleni, Barlatier, Pierre-Jean, Pénin, Julien, 2019. 'Same but different? Research and technology organizations, universities and the innovation activities of firms'. *Res. Pol.* 48 (1), 223–233.
- Gonzalez-Urango, Hannia, et al., 2024. Toward institutionalization of responsible research and innovation: insights from case studies of technological centers in Spain. *Journal of Responsible Innovation* 11 (1), 2322754.
- Granstrand, Ove, Holgersson, Marcus, 2020. Innovation ecosystems: a conceptual review and a new definition. *Technovation* 90, 102098.
- Hales, Mike, 2001. *Birds were dinosaurs once-The diversity and evolution of research and technology organisations*. RISE final report, CENTRIM Brighton.
- Hanlin, R., et al., 2018. Science granting councils as boundary organisations: evidence from a political economy study of five countries in sub-saharan africa. *Conference Paper*, Presented at *GlobeLics 2018*, pp. 24–26.
- Hauser, Hermann, 2010. *The current and future role of technology and innovation centres in the UK*. A Report for the Department For Business Innovation and Skills.
- Hauser, Hermann, 2014. *Review of the Catapult Network-Dr Hermann Hauser-The Rt Hon Dr Vince Cable MP*.
- Hennink, Monique, Kaiser, Bonnie N., 2022. Sample sizes for saturation in qualitative research: a systematic review of empirical tests. *Social science & medicine* 292, 114523.

- Hernández-Chea, Roberto, et al., 2021. Moving beyond intermediation: how intermediary organizations shape collaboration dynamics in entrepreneurial ecosystems. *Technovation* 108, 102332.
- Hertog, Den, Pim, 2002. Co-producers of innovation: on the role of knowledge-intensive business services in innovation. *Productivity, Innovation and Knowledge in Services*, pp. 223–255.
- Holland, Claire, et al., 2024. Innovation intermediaries at the convergence of digital technologies, sustainability, and governance: a case study of AI-enabled engineering biology. *Technovation* 129, 102875.
- Howells, Jeremy, 2024. Innovation intermediaries in a digital paradigm: a theoretical perspective. *Technovation* 129, 102889.
- Islam, Nazrul, 2017. Crossing the valley of death—an integrated framework and a value chain for emerging technologies. *IEEE Trans. Eng. Manag.* 64 (3), 389–399.
- Javernick-Will, Amy, Levitt, Raymond E., 2010. Mobilizing institutional knowledge for international projects. *J. Construct. Eng. Manag.* 136 (4), 430–441.
- Johnson, Phil, Duberley, Joanne, 2015. Inductive praxis and management research: towards a reflexive framework. *Br. J. Manag.* 26 (4), 760–776.
- Kim, Kyonghwan, et al., 2010. The role of intermediaries on technological risk management and business development performance in Korea. *Technol. Forecast. Soc. Change* 77 (6), 870–880.
- Kirkels, Yvonne, Duysters, Geert, 2010. Brokerage in SME networks. *Res. Pol.* 39 (3), 375–385.
- Knockaert, Mirjam, Spithoven, André, Clarysse, Bart, 2014. The impact of technology intermediaries on firm cognitive capacity additionality. *Technol. Forecast. Soc. Change* 81, 376–387.
- Konzelmann, Suzanne J., Fovargue-Davies, Marc, Schnyder, Gerhard, 2010. Varieties of Liberalism: Anglo-Saxon Capitalism in Crisis? Available at: SSRN 1929627.
- Kreiling, Laura, Paunov, Caroline, 2021. Knowledge Co-creation in the 21st Century: A Cross-Country Experience-Based Policy Report.
- Landesmann, Michael A., Scazzieri, Roberto, 1996. s. Production and Economic Dynamic.
- Landry, Réjean, et al., 2013. Technology transfer organizations: services and business models. *Technovation* 33 (12), 431–449.
- Larrue, Philippe, Strauka, Orestas, 2022. The Contribution of RTOs to Socio-Economic Recovery, Resilience and Transitions.
- Leitner, Karl-Heinz, 2005. Managing and reporting intangible assets in research technology organisations. *R&D Management* 35 (2), 125–136.
- Lichtenthaler, Ulrich, Lichtenthaler, Eckhard, 2010. Technology transfer across organizational boundaries: absorptive capacity and desorptive capacity. *Calif. Manag. Rev.* 53 (1), 154–170.
- Lin, Bou-Wen, 2003. Technology transfer as technological learning: a source of competitive advantage for firms with limited R&D resources. *R&D Management* 33 (3), 327–341.
- Loikkanen, Torsti, Hyytinen, Kirsi, Kontinen, Jari, 2011. Public research and technology organisations in transition—the case of Finland. *Sci. Technol. Soc.* 16 (1), 75–98.
- Lundvall, Bengt-Ake, 1992. National Systems of Innovation: towards a Theory of Innovation and Interactive Learning, vol. 242. London Pinter.
- Lynn, Leonard H., Reddy, N Mohan, Aram, John D., 1996. Linking technology and institutions: the innovation community framework. *Res. Pol.* 25 (1), 91–106.
- Martins, Jorge Tiago, Singh, Hukampal, Sonal, 2023. Boundary organisations in regional innovation systems: traversing knowledge boundaries for industry 4.0 regional transformations. *R&D Management* 53 (3), 364–390.
- Mas-Verdú, Francisco, 2007. 'Services and innovation systems: European models of technology centres'. *Service Business* 1 (1), 7–23.
- Mele, Cristina, et al., 2018. Shaping service ecosystems: exploring the dark side of agency. *J. Serv. Manag.* 29 (4), 521–545.
- Meyer, Martin, et al., 2019. Towards new Triple Helix organisations? A comparative study of competence centres as knowledge, consensus and innovation spaces. *R&D Management* 49 (4), 555–573.
- Miller, Stephen, 2014. The Strathclyde technology and innovation centre (TIC) in Scotland's innovation system. *Regional Studies, Regional Science* 1 (1), 145–151.
- Mirinalini, N., Nath, Pradosh, 2000. Organizational practices for generating human resources in non-corporate research and technology organizations. *J. Intellect. Cap.* 1 (2), 177–186.
- Nath, Pradosh, 2008. Knowledge management in research and technology organizations in a globalized era. *Perspect. Global Dev. Technol.* 7 (1), 37–54.
- Nath, Pradosh, Inalini, N., 1996. 'Best practices of research and technology organisation: towards a more responsive R&D'. *Sci. Technol. Soc.* 1 (2), 351–362.
- Nenonen, Suvi, Storbacka, Kaj, Windahl, Charlotta, 2019. Capabilities for market-shaping: triggering and facilitating increased value creation. *J. Acad. Market. Sci.* 47, 617–639.
- Ng, H.Y., Luo, Y., Park, H., 2023. The role of intermediaries in nurturing innovation ecosystems: a case study of Singapore's manufacturing sector. *Science and Public Policy* 50 (3), 382–397.
- Noviaristanti, Siska, Acur, Nuran, Mendibil, Kepa, 2023. The different roles of innovation intermediaries to generate value. *Management Review Quarterly* 1–33.
- Pedone, Gianfranco, Mezgár, István, 2018. Model similarity evidence and interoperability affinity in cloud-ready Industry 4.0 technologies. *Comput. Ind.* 100, 278–286.
- Preissl, Brigitte, 2006. Research and technology organizations in the service economy: developing analytical tools for changing innovation patterns. *Innovat. Eur. J. Soc. Sci. Res.* 19 (1), 131–146.
- Preissl, Brigitte, Farina, Claudio, 2000. Research and Technology Organisations in National Systems of Innovation (DIW Discussion Papers).
- Randhawa, Krithika, Wilden, Ralf, Akaka, Melissa Archpru, 2022. Innovation intermediaries as collaborators in shaping service ecosystems: the importance of dynamic capabilities. *Ind. Mark. Manag.* 103, 183–197.
- Readman, Jeff, et al., 2018. Positioning UK research and technology organizations as outward-facing technology-bases. *R&D Management* 48 (1), 109–120.
- Rossi, Federica, et al., 2022. New business models for public innovation intermediaries supporting emerging innovation systems: the case of the Internet of Things. *Technol. Forecast. Soc. Change* 175, 121357.
- Saad, Abi, Elie, Tremblay, Nathalie, Agogue, Marine, 2024. A multi-level perspective on innovation intermediaries: the case of the diffusion of digital technologies in healthcare. *Technovation* 129, 102899.
- Sala-Vilar, Ròmul, Luís, Li-Ying, Jason, Trauneker, Tim, 2024. How do innovation intermediaries' business models cope with their need to develop new digital services? *Technovation* 131, 102950.
- Schot, Johan, Steinmueller, W Edward, 2018. 'Three frames for innovation policy: R&D, systems of innovation and transformative change'. *Res. Pol.* 47 (9), 1554–1567.
- Shapira, Philip, 2001. US manufacturing extension partnerships: technology policy reinvented? *Res. Pol.* 30 (6), 977–992.
- Shapira, Philip, Youtie, Jan, 2017. Institutions for technology diffusion and the next production revolution. *The Next Production Revolution: Implications for Governments and Business. Organisation for Economic Co-operation and Development*, pp. 243–275.
- Sheikheldin, Gussai H., 2021. Research and technology organizations as super intermediaries: a conceptual framework for policy and a case study from Tanzania. *Frontiers in Research Metrics and Analytics* 6, 691247.
- Strauss, Anselm, Corbin, Juliet, 1990. *Basics of Qualitative Research*. Sage publications).
- Suominen, Arho, Kauppinen, Henni, Hyytinen, Kirsi, 2021. Gold, 'Ribbon' or 'puzzle': what motivates researchers to work in research and technology organizations. *Technol. Forecast. Soc. Change* 170, 120882.
- Tassey, Gregory, 2014. Competing in advanced manufacturing: the need for improved growth models and policies. *J. Econ. Perspect.* 28 (1), 27–48.
- Taverdet-Popiolek, Nathalie, 2022. Economic footprint of a large French Research and Technology Organisation in Europe: deciphering a simplified model and appraising the results. *J. Knowl. Econ.* 13 (1), 44–69.
- Teece, David J., 2007. Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance. *Strateg. Manag. J.* 28 (13), 1319–1350.
- Thurner, Thomas Wolfgang, 2017. Transfer revenues of research and technology organizations (RTOs) in times of economic crisis. *Int. J. Innovat. Manag.* 21 (2), 1750017.
- Thurner, Thomas Wolfgang, Zaichenko, Stanislav, 2015. Knowledge inputs to science- and development-based regimes: evidence from the behaviour of Russian RTOs. *Int. J. Innovat. Manag.* 19 (1), 1550003.
- Uflewskia, Olga, Wong, T.C., Ward, Michael, 2024. 'Capability management of manufacturing research centres: challenges and opportunities'. *Int. J. Manuf. Technol. Manag.* 38 (2), 143–171.
- Uyarra, Elvira, et al., 2020. 'Public procurement, innovation and industrial policy: rationales, roles, capabilities and implementation'. *Res. Pol.* 49 (1), 103844.
- Van Lente, Harro, et al., 2003. Roles of systemic intermediaries in transition processes. *Int. J. Innovat. Manag.* 7 (3), 247–279.
- Villani, Elisa, Rasmussen, Einar, Grimaldi, Rosa, 2017. How intermediary organizations facilitate university–industry technology transfer: a proximity approach. *Technol. Forecast. Soc. Change* 114, 86–102.
- Watkins, Andrew, et al., 2015. National innovation systems and the intermediary role of industry associations in building institutional capacities for innovation in developing countries: a critical review of the literature. *Res. Pol.* 44 (8), 1407–1418.
- Wessner, Charles W., 2013. *21st Century Manufacturing: the Role of the Manufacturing Extension Partnership Program*. National Academies Press.
- Yin, Robert K., 2009. *Case Study Research: Design and Methods*, vol. 5. sage.
- Yin, Yue, Yan, Ming, Zhan, Qiushi, 2022. 'Crossing the valley of death: network structure, government subsidies and innovation diffusion of industrial clusters'. *Technol. Soc.* 71, 102119.
- Zaichenko, Stanislav, 2018. The human resource dimension of science-based technology transfer: lessons from Russian RTOs and innovative enterprises. *J. Technol. Tran.* 43 (2), 368–388.
- Zhang, Cuihong, Liu, Ning, 2023. Innovation intermediaries: a review, bibliometric analysis, and research agenda. *J. Technol. Tran.* 1–31.
- GAO (2020), *Innovation Institutes Report Technology Progress and Members Report Satisfaction with Their Involvement. Report to Congressional Committees*. Available at: <https://www.gao.gov/assets/gao-22-103979.pdf>.