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Relational network of innovation ecosystems generated by digital innovation hubs: a conceptual framework for the interaction processes of DIHs from the perspective of collaboration within and between their relationship levels

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Abstract

Collaboration plays a key role in the success attained to date by networks of innovation ecosystems generated around entities known as Digital Innovation Hubs (DIHs), recently created following European Commission initiatives to boost the digitisation of the European economic fabric. This article proposes a conceptual framework that brings together, defines, structures and relates the concepts involved in the collaborative interaction processes within and between these innovation ecosystems to allow comprehensive conceptualisation. The developed framework also provides an approach that helps to tangibilise collaboration as a management process. Here the goal is to ultimately move towards not only qualitative, but also quantitative modelling to bridge the research gap in the state of the art in this respect. The data-driven business-ecosystem-skills-technology (D-BEST) model, devised to configure DIHs service portfolios in a collaborative context, provides the reference basis for the interorganisational asset transfer methodology (IOATM). This is the keystone that structures the framework and constitutes its main contribution. Through the IOATM, this conceptual framework points out collaboration quantification, and serves as a lever for its modelling to deal with collaboration accounting by: turning it into a more controllable management element; guiding practitioners' efforts to improve collaborative processes efficiency with an approach that pursues objectivity and maximises synergies.

Keywords Innovation ecosystem · Digital innovation hubs · Collaboration · Interorganisational asset transfer methodology

Abbreviations

CIGIP	Centro de Investigación en Gestión e Ingeniería de la Producción
CPES	Cyber–physical energy system
CPS	Cyber–physical system
CKTI	Competences, knowledge, technology and infrastructure
CTTE	Cross-domain technology transfer experiment
D-BEST	Data-driven business–ecosystem–skills–technology reference model
DIHs	Digital Innovation Hub
DIH4CPS	Digital Innovation Hubs for Cyber–Physical Systems
EC	European Commission
EDIHs	European Digital Innovation Hubs
Ei2Network	European Network for Interoperability and Innovation
ETB	Ecosystem–technology–business model
ETBSD	Ecosystem–technology–business-skills-data model

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EU	European Union
FTTE	Focused technology transfer experiment
GDPR	General Data Protection Regulation
iAE6	Application experiment number 6 of the DIHCPS project
InnDIHs	Digital Innovation Hubs for the economic promotion of the Valencian Community
IOATM	Interorganisational asset transfer methodology
ITI	Instituto Tecnológico de Informática
I-VLab	European Virtual Laboratory for Enterprise Interoperability
i4OPT	Industrial Production and Logistics Optimisation in Industry 4.0
I4Q	Industrial Data Services for Quality Control in Smart Manufacturing
KTE	Knowledge transfer experiments
MaaS	Marketplace-as-a-Service
MES	Manufacturing execution system
MOM	Manufacturing operations management
M2M	Machine-to-machine communication
OPC UA	Open platform communications united architecture
PAE	Pathfinder Application Experiment
PoC	Proof of concept
R&D	Research and Development
SME	Small- and medium-sized enterprises
UPV	Universitat Politècnica de València
ZDMP	Zero-Defect Manufacturing Platform

Introduction

European small- and medium-sized enterprises (SMEs) generally face a volatile, complex and fiercely competitive global scenario. They have a significant disadvantage in relation to large companies and global corporations, which usually better access financing, resources and skills acquisition; all this enables the latter to compete with higher performance levels and they, therefore, have more sustainability expectations (Bakhtiari et al., 2020). Indeed the obstacles that SMEs usually encounter in acquiring, implementing and exploiting digital technologies and skills respond to this pattern, which implies slowing down their journey towards digital maturity.

SMEs are vital to the European Union's (EU) economy, and account for 99% of all EU companies and two thirds of all private sector jobs. However, only 20% of European SMEs are highly digitised, unlike large corporations whose percentage reaches 50% (Gouardères, 2021). The European Commission (EC) is aware of this. This is why it has been promoting programmes and initiatives for years to foster innovation and to facilitate SMEs' digital transformation, especially those in the most digitally immature sectors. In line with this, a notable support line is to finance projects to create and strengthen a series of regional innovation ecosystems interconnected in a pan-European network. The main drivers of such ecosystems are the so-called Digital Innovation Hubs (DIHs), regional cooperation organisations made up of many diverse partners whose mission is twofold: regionally, to help entrepreneurs in the region to overcome innovation obstacles and digital transformation difficulties by providing them with easy access to knowledge and digital solutions (Miörner et al., 2019), essential tools for success in today's global market; at the European level, to promote the implementation of an interdisciplinary and collaborative network of innovation providers, which will help to keep Europe in a position of technological leadership in today's complex geopolitical scenario.

DIHs were initially conceived by the EC in 2016 as part of the first industry-related initiative of the Digital Single Market package and as one of the most important pillars of the Digitise European Industry effort (Rissola & Sörvik, 2018). Since 2021, this effort is being complemented by the figure of European DIHs (EDIHs) within the framework of the Digital Europe Programme (HaDEA, 2022). This programme initially plans to increase the capacities of the centres selected by each member country to cover activities with a clear European added value based on the collaborative networking of hubs and promoting knowledge transfer. EDIHs will also support companies and public sector organisations in using digital technology to improve the sustainability of their processes and products, particularly regarding energy use and reducing carbon emissions (HaDEA, 2022). DIHs and EDIHs generally provide access to know-how and experimentation, and to the possibility of "try before you invest" by helping companies to improve business/production processes, products or services that employ digital technologies. They also provide innovation services, such as advice on financing, training and skills development, which are necessary for the success of digital transformation (EC, 2022).

This set of innovation-driving entities is generating a relational network within the geographical framework of EU territory in which, from a hierarchical perspective, four relationship levels can be identified (Fig. 1): (i) **DIH level:** that existing within each DIH between the organisations making it up. A DIH is a one-stop-shop type structure that helps organisations to be more competitive by improving processes and innovating products and services via digital technologies. It may include research centres, technology centres, universities, private technology service providers, associations, Chambers of Commerce, incubator or accelerator organisations, regional development agencies, and even governmental organisations (EC, 2022) within a regional scope. It is a space where it offers support services to organisations, usually through a partner platform. The support services

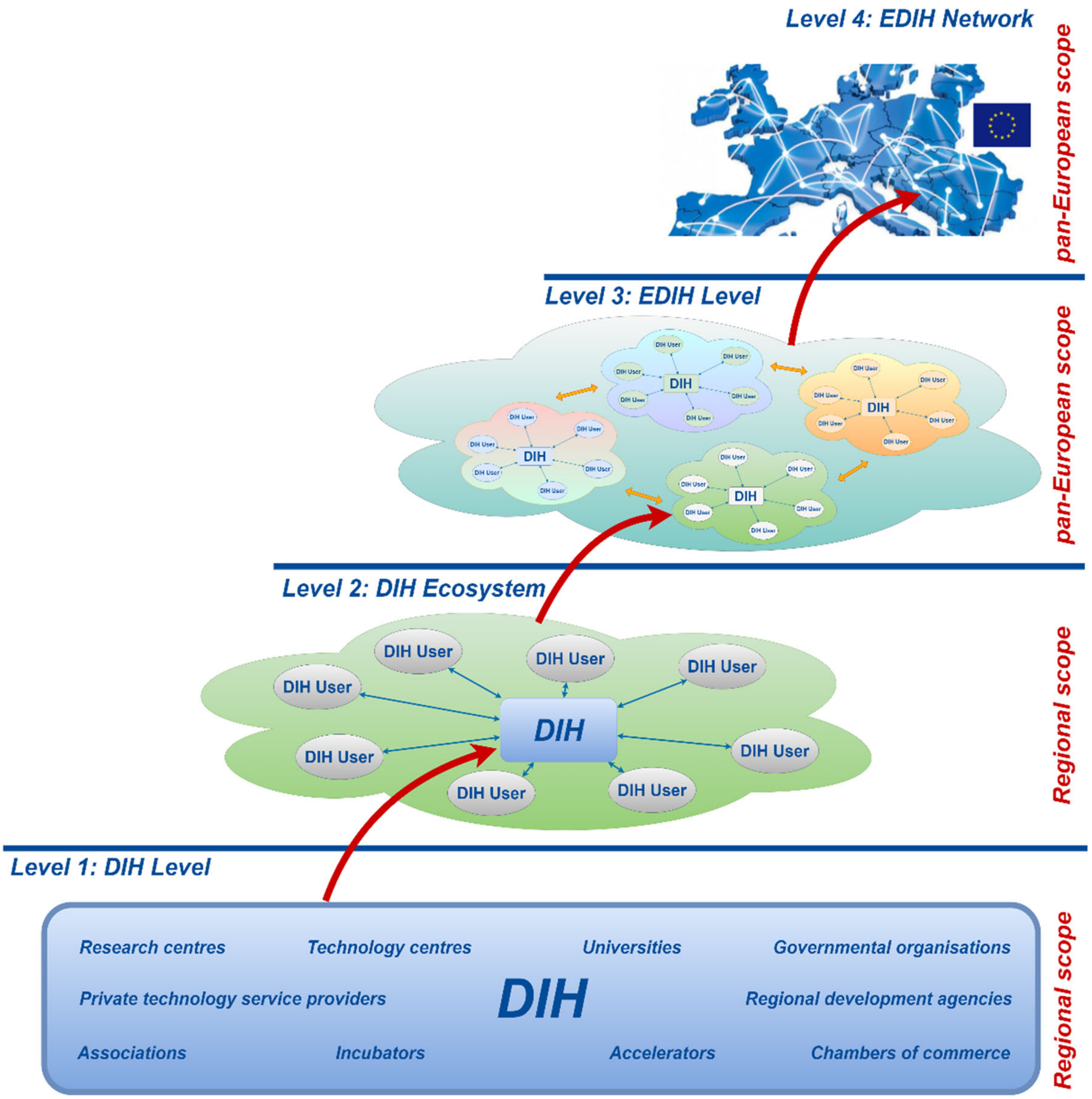


Fig. 1 Relationship levels within the pan-European space of DIHs action

that a DIH can offer include awareness raising of digitisation technologies, innovation exploration, developing visions and strategies for companies, training, access to funds and investments, collaborative research, advocacy and networking events, among others (Georgescu et al., 2021). DIHs have four main functions that characterise them, namely networking, skills and training, pre-investment testing and access to finance (Asplund et al., 2021); (ii) **DIH ecosystem:** that generated in each individual regional innovation ecosystem promoted around a specific DIH between it as an innovation, knowledge, and technology provider, plus the organisations receiving any services included in the DIH portfolio, typically SMEs that need support towards digital transformation, albeit not exclusively; (iii) **EDIH level:** that which integrates a set of networked DIHs into a group and turns it into a collaborative network with presence beyond a specific EU country. Such integration occurs by either belonging to a joint project funded for this purpose or the existence of some other type of transactional agreement between DIHs; (iv) The highest level: the **pan-European EDIH network:** the level of potential interaction in which the different existing DIH groups in Europe, supposedly acting in competition, can create cooperation channels by generating schemes of so-called coopetition (Planko et al., 2019) or similar; e.g. in terms of association or federation to defend their common interests *vis-à-vis* administrations and society at large, which is still an underexplored and underexploited space.

The interaction flows within this relational network depend on several factors. They are mainly determined by the involved actors and their typology, their interests, strategies, objectives, resources, capacities, initiatives, willingness to work in collaboration, and the transactional formal or informal agreements, that exist between actors. They also depend on factors such as: the needs, in terms of digital knowledge and skills, of the regional business fabric in which they operate; the local, regional, national and European legislation applicable in each case; or the degree and sense of governments and public administrations' intervention in the cooperation processes at each interaction level.

The literature does not contain numerous contributions on the study of DIHs. There are also some frameworks and models that address some types of collaborative interaction between elements of some of the mentioned levels of interaction, such as collaboration itself, or derivatives such as cooperation, coopetition, funding, or institutional support, among others. Yet, as far as we know, there is no general conceptual framework that addresses the whole above-described relational network and supports all the possible basic potential interaction flows between all the elements at their relationship levels.

Based on the above, the main objective of this article is to present a conceptual framework that, by building on the above overview of the relational network of European innovation ecosystems driven by EC Digitise European Industry and Digital Europe Programme initiatives, supports the existing interaction processes horizontally along their relationship levels, and vertically between them, from dual qualitative and quantitative perspectives. The research questions posed are the following:

- RQ1 What characteristics define the interactions that take place between the entities making up the DIHs relational network when collaborative processes materialise between them?
- RQ2 What are the key dimensions of the interaction processes between the entities that constitute the DIH relational network; what are their conceptual implications in terms of a quantitative assessment of collaboration?

The rest of the article is organised as follows. Sect. "Literature review" defines the main concepts, delimits the research scope, identifies the correlations between concepts shown by the literature, explains the search method to review the literature, presents the state of the art from the previously explained methodology and selects the most relevant contributions. Sect. "Discussion" firstly presents a conceptual framework by identifying the key dimensions of the interaction processes that take place within a network from dual qualitative and quantitative perspectives. Secondly, it analyses implications in interoperability and sustainability terms. Section 4 presents a use case to provide a practical example of the application of the framework. Sect. "Conclusion" discusses the proposed conceptual framework and analyses the managerial and academic implications that derive from it. Finally, Sect. 6 offers conclusions, including its contribution to theory and practice, along with limitations and possible future research lines.

Literature review

Main concepts

This research focuses mainly on the interrelationships between two types of concepts that pivot around the main one, the DIH concept: (i) those used to designate a type of organisation among those existing in the relational network of European innovation ecosystems; (ii) those used to designate a type of interaction that is potentially possible within the organisations of the relational network of European innovation ecosystems. To gain a better understanding, this section more profoundly introduces the main concepts employed in both categories.

Table 1 introduces the different types of organisations that can be found throughout the relational network of European innovation ecosystems.

All these concepts are closely interrelated and mutually supportive. Thus a DIH and its users form a specific innovation ecosystem herein called the DIH ecosystem. A group of DIHs that work together form a clear example of a collaborative network. The sum of several DIH ecosystems operating as a collaborative network forms an EDIH. The network formed by the set of EDIHs operating in EU territory forms the pan-European EDIH network, an important purpose of the Digital Europe Programme. In any case, these concepts are, on the whole, interconnected around the central "DIH" Concept.

From its own definition, it is clear that both the different collaborative network or innovation ecosystem types that are generated based on DIHs, and the DIH itself, make up complex structures populated by entities of very diverse typologies. This diversity gives rise to a wide range of possibilities for mutual interaction purposes. Hubs, ecosystems and networks, public and private entities, service providers and users, regional, national or pan-European action spaces, and so on, generate a multitude of relationship scenarios with sometimes overlapping, sometimes completely disparate purposes and with a considerable gradient of possibilities between these two extremes. In short, the cosmos originating around the DIH concept is a highly heterogeneous and complex environment where interaction possibilities go beyond simple collaboration. To date, this concept has been the central axis of a large number of the studies, frameworks

Table 1 Organisation types in the relational network of European innovation ecosystems

Organisation type	Definition
Collaborative network	An organisation of a variety of entities (e.g., organisations and people) that are largely autonomous, geographically distributed and heterogeneous in terms of their operating environment, culture, social capital and goals; nevertheless, these entities collaborate to better achieve common or compatible goals (Camarinha-Matos & Afsarmanesh, 2005). Nowadays, collaborative networks are being applied to a wide variety of domains from academic research to manufacturing and other industrial applications. These implementations are supported by a variety of collaboration forms, which range from "supply chains" to emerging dynamic structures in the industry, science and services (Camarinha-Matos et al, 2019)
DIH	A multi-partner collaborative organisation made up of regional entities, itself part of a pan-European network of similar organisations, which, in possession of infrastructure, technology, knowledge, competences, funds, or access to them, and ready to use them to serve regional business and public sector organisations, together with them form an innovation ecosystem in which the hub, as a central role, provides services to support the itinerary of these organisations towards a full and effective digitalisation that makes them more sustainable and competitive
DIH ecosystem	An ecosystem of organisations that is generated from a digital innovation hub as a central actor, where it acts as a source of technologies, knowledge or skills, which it disseminates to the other members that make up the ecosystem to pilot, test and experiment with digital innovations to support their digital transformation processes
DIH network	A collaborative network made up of DIHs that act in coordination to contribute to the development of the regions and countries of the European space from a more sustainable position. This is supported mainly by a larger organisational dimension and by a broader portfolio of knowledge, skills, technologies and solutions than that of its individual members
DIH user	An organisation that, through a transactional agreement, uses the service portfolio of a DIH to receive support for its digital transformation process and thus becomes part of its ecosystem
European DIH (EDIHs)	A specific type of DIH network born from *Digital Europe Programme* calls, with both local and European functions, which has increased capacities to encompass activities with a clear European added value that centre mainly on networking hubs and promoting transfer of expertise. EDIHs also have the stated mission of supporting companies and public sector organisations in using digital technology to improve the sustainability of their processes and products, particularly regarding energy use and reducing carbon emissions. Beyond that and within EDIHs, their DIHs also act as a one-stop-shop to help companies to be more competitive as regards their business/production processes, products or services using digital technologies by providing access to technical expertise and experimentation. Thus firms can "test before invest", and provide innovation services (i.e. financing advice, training and skills development) needed for successful digital transformation (Directorate-General for Communications Networks, Content and Technology of the EC, 2021)
European DIH Network	A set of EDIH networks operating in the EU territory
Innovation ecosystem	An evolving set of actors, activities and artifacts, and institutions and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors (Granstrand & Holgersson, 2020). An innovation ecosystem refers to a loosely interconnected network of companies and other entities that co-evolve capabilities around a shared set of technologies, knowledge or skills, and work cooperatively and competitively to develop new products and services (Nambisan & Baron, 2013)

and models in the literature about DIHs and the arbitration of the relationships between the entities making them up. Some examples are the ecosystem–technology–business model (ETB; Butter et al, 2020) and its two main evolutions, the ecosystem–technology–business–skills–data model (ETBSD; Sassanelli et al., 2020) and the data-driven business–ecosystem–skills–technology reference model (D-BEST; Sassanelli & Terzi, 2022; Sassanelli et al., 2021b). D-BEST aims to act as a reference for the DIH networks specialised in the cyber–physical energy systems (CPES) domain to configure their service portfolios both flexibly and interoperably by integrating their assets (services, competences, skills, technologies) into digital platforms to achieve flexibility and interoperability. Both are critical aspects to achieve DIH networks' sustainability. The D-BEST model is a milestone in the conceptualisation and modelling of collaboration at DIH ecosystem and EDIH levels by triggering the identification and materialisation of service-based cross-collaborative processes between DIH networks on the one hand, and between DIHs themselves and their users on the other. However, it is necessary to further characterise the collaboration concept from a holistic perspective by: (i) firstly defining the concept itself; (ii) secondly placing it in contrast to other types of interaction whose essence, objectives, method and results significantly differ; (iii) finally, by identifying the possible interaction types of among the entities making up DIH structures, their networks and ecosystems that can, to some extent, albeit partially, represent collaboration. Only with this prior characterisation is it possible to bring together, structure and interrelate the components of a comprehensive conceptual framework that addresses the collaboration phenomenon in DIH relational networks.

Regarding the definition of full collaboration used herein as a reference, that chosen is of Wankmüller and Reiner (2020): "Process of strategically working together on a specific business activity where structures are aligned, communication channels are standardised, risks are shared, and resources are pooled in order to make them available for every partner". In short, and according to the perspective provided by this definition, although partners retain their entity, their level of commitment to achieve shared goals is so important that they involve their structures, communication channels and resources, as well as taking risks in the long term.

In contrast to the collaboration notion as a primarily synergistic interaction, in the different environments shaped by DIHs, there may be other formulas of interaction that are significantly removed from this synergy. They range from the simple contraposition of buyer and seller interests in a commercial relationship to the antagonism shown by two competitors. Table 2 sets out the main potential types of interaction that fit this pattern.

With regard to the possibilities for the entities that make up one of the above-mentioned DIH environments to interact according to a formula that denotes a certain degree of collaboration, there are several alternatives. Table 3 presents the most relevant possibilities.

Now that the levels of the relationships in the network of European innovation ecosystems are known, the types of organisations that exist in the network are outlined, and the types of interaction that can potentially take place between the entities making up these organisations are presented, the construction of the conceptual framework herein proposed requires an additional concept, a final piece, for the complete mapping of the relational network: services resulting from collaboration. The entire DIH environment sketched so far holds a prominent circumstance: some entities, those possessing competences, knowledge, technology, infrastructure or funds, or have access to them, offer a service to others, the companies making up the regional business and public sector organisations, to achieve their full and effective digitalisation. Although collaboration is also possible for internal organisational reasons as in any other environment, it is when exercising its main function, providing support services in digital transformation processes, that a deeper understanding of collaboration frameworks and their characteristics becomes valuable for this research. In this sense, it should be stated that the classification of services in an DIH environment is a task already faced by academia, with the D-BEST reference model by Sassanelli and Terzi (2022) being the most evolved and updated exponent of the state of the art. The D-BEST reference model is structured on three levels: macroclasses, types and classes. All the five macroclasses included in the model (ecosystem, technology, business, skills and data) is divided into types of service, and these, in turn into classes of services (Sassanelli & Terzi, 2022) (Table 4).

With the above classification, all the main concepts involved in this research are introduced, and the research scope is also configured (Fig. 2).

Search query and selected results

A search in the Scopus database was performed in accordance with the defined research scope to look for the intersection of the above-indicated semantic fields. The search was done with the title, abstract or keywords of articles, reviews, conference papers and conference reviews published in English in compatible subject areas. For this purpose, we used the search chain TITLE-ABS-KEY [("digital innovation hub") AND (collaboration OR "commercial relationship" OR competition OR cooperation OR coopetition OR coordination OR financing OR funding OR "institutional support" OR investment OR "knowledge transfer" OR partnership OR sponsorship OR "technology transfer")] AND (LIMIT-TO

Table 2 Types of interaction not aligned with the collaboration concept

Interaction type	Definition
Commercial relationship	Any legal relationship of a commercial nature, whether contractual or not, and includes, but is not limited to, a relationship arising from the following transactions: any trade transaction for the supply or exchange of goods or services; distribution agreement; commercial representation, or agency; factoring; leasing; construction of works; consulting; engineering; licensing; investment; financing; banking; insurance; exploitation agreement or concession; joint venture and other forms (Commercial relationship definition, 2013)
Competition	Rivalry between individuals, groups, organisations or nations that arises whenever two parties or more strive for something that they all cannot obtain (Stigler, 1988)
Financing	Money is loaned by an individual or organization for a particular purpose
Investment	The act of putting money, effort, time, etc. into something to make a profit or get an advantage, or the money, effort, time, etc. used to do this (Cambridge Academic Content Dictionary, 2020)

Table 3 Types of interaction aligned with the collaboration concept

Interaction type	Definition
Cooperation	Process of working on independent business activities towards a common (agreed-on) goal in a long-term view, where communication is relatively informal, resources are separated and risks are shared (Wankmüller & Reiner, 2020)
Coopetition	Hybrid behaviour exhibited by two or more competitors that involves cooperative and competitive elements but, instead of fighting one another in fierce competition, consists of organising themselves into, for example, groups or associations, to meet common objectives that would be difficult to achieve individually *vis-à-vis* other organisations. Some examples are other competitors or groups of competitors, administrations, banks, consumer associations, among others. It involves gaining access to additional know-how, skills and resources. This behaviour allows risk sharing and the creation of secure contacts, while protecting one's own assets (Bouncken & Kraus, 2013)
Coordination	Process of aligning, organising and managing actors' operational business activities where private information, risks and resources are shared (Wankmüller & Reiner, 2020)
Funding	Money is given by an individual or organisation for a particular purpose
Institutional support	Support offered by government authorities and institutions, or those directly supported by a government, that comes in the form of policies, plans, laws, regulations, financial or non-financial aid to promote a particular individual or organisation's interests (for the purposes of this research, support of a financial nature, considered separately, is excluded)
Knowledge transfer	The process of transferring experience, skills, and tangible and intellectual property (University of Cambridge, 2009) from an individual or an organisation to another one
Networking	Networking is a form of goal-directed behaviour, both inside and outside an organisation, which focuses on creating, cultivating and utilising interpersonal relationships (Gibson et al., 2014)
Partnership	A partnership is an arrangement in which parties, known as partners, agree to cooperate to promote their mutual interests. The members of a partnership, individuals or organisations, join together to increase the likelihood of each party achieving its mission and broadening its scope (Partnership, Wikipedia, 2022a, b)
Sponsorship	The position or function of a person who or group that vouches for support, advises or helps to fund another person or an organisation or project (Sponsorship, Wikipedia, 2022a, b)
Technology transfer	The process of transferring technology from an individual or organisation that owns or holds it to another one (Technology transfer, Wikipedia, 2022a, b)

Table 4 The D-BEST model service classification (Sassanelli & Terzi, 2022)

Service macroclass	Service type	Service class
1. Ecosystem	1.1. Community building	1.1.1. SME and people engagement and brokerage
		1.1.2. Innovation incitation, awards, and challenges
		1.1.3. Technology scouting
	1.2. DIH innovation development	1.2.1. Communication and trend watching
		1.2.2. Visioning and strategy development
	1.3. Ecosystem governance	1.3.1. Service impact assessment
		1.3.2. Ecosystem management
2. Technology	2.1. Ideas management and materialisation	Ideas generation, assessment, and feasibility study
	2.2. Contract research	2.2.1. Strategic and specific research and development (R&D)
		2.2.2. Technology concept development/proof of concept (PoC)
	2.3. Provision of infrastructure	2.3.1. Access to infrastructure and technological platforms
	2.4 Technical support on scale up	2.4.1. Concept validation
		2.4.2. Prototyping
	2.5. Verification and validation	2.5.1. Product qualification and certification
		2.5.2. Product demonstration
3. Business	Incubation acceleration support	3.1.1. Basic facilities
		3.1.2. Specialised facilities
		3.1.3. Business development
		3.1.4. Guidance
	3.2. Access to finance	3.2.1. Financial engineering
		3.2.2. Connection to funding source services
		3.2.3. Methods and tools
	3.3. Business training and education	3.3.2. Secondment
	3.4. Project development	3.4.1. Identification of opportunities
		3.4.2. Creating consortia
		3.4.3. Development of proposals
4. Skills	4.1. Process and organisational maturity	4.1.1. Maturity assessment
		4.1.2. Maturity strategy development
	4.2. Human capabilities maturity	4.2.1. Human skills maturity
		4.2.2. Skill strategy development
	4.3. Skills improvement	4.3.1. Human up-skilling and re-skilling training
		4.3.2. Educational programmes
		4.3.3. Scouting and brokerage
5. Data	5.1. Data acquisition and sensing	5.1.1. Data acquisition
		5.1.2. Data protection
	5.2. Data processing and analysis	5.2.1. Data storage
		5.2.2. Data analytics
	5.3. Decision-making	5.3.1. Cognitive big data architecture
		5.3.2. Decision support and development
	5.4. Physical-human action and interaction	5.4.1. Collaborative intelligence
		5.4.2. User experience
		5.4.4. Feedback loop
	5.5. Data Sharing	5.5.1. General data protection regulation (GDPR
		5.5.2. Data spaces
		5.5.3. Data Platform

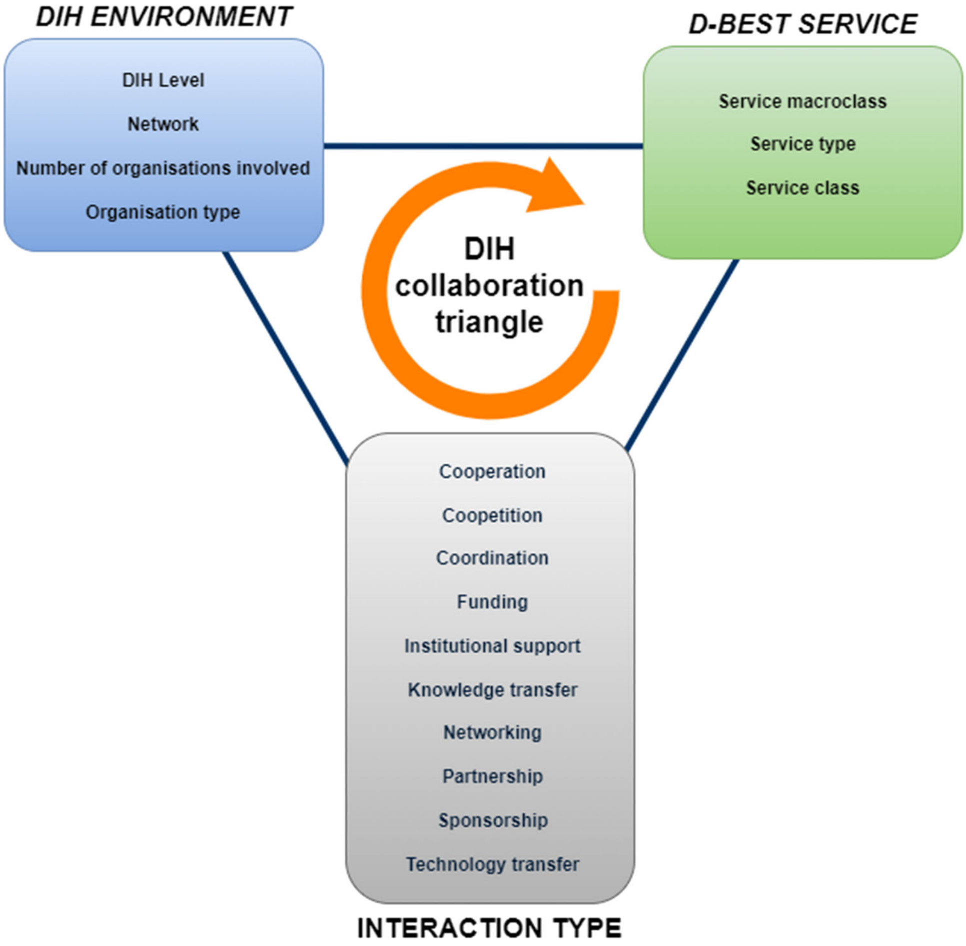


Fig. 2 Research scope representation from the triple perspective of DIH collaboration

(SUBJAREA, “COMP”) OR LIMIT-TO (SUBJAREA, “DECI”) OR LIMIT-TO (SUBJAREA, “ENGI”) OR LIMIT-TO (SUBJAREA, “BUSI”)) AND (EXCLUDE (DOCTYPE, “er”)) AND (LIMIT-TO (LANGUAGE, “English”)). It was not necessary to narrow down the searched time period because all the research publications about DIH are very recent, as is the concept itself. The search for the indicated terms finally yielded 17 results, all of which are limited to the period between 2018 and 2022. The selected results are identified in Table 5.

Thematic analysis

Using the content of the titles and abstracts of the selected literature as a source, a map of co-occurring expressions was drawn up using the VOSviewer v.1.6.16 software application. This allows the concepts present in the literature review with more than three occurrences to be visualised, as well as their dimension and interrelationships (Fig. 3).

Four thematic groups or clusters were automatically identified by VOSviewer: (i) that headed by expression DIHs, which is red-coloured in the figure, grouping others like innovation ecosystem, collaboration, investment, networking, service, service portfolio, training or cyber–physical systems (CPS); (ii) the heading for expression digital transformation, coloured green in the figure, which groups others like cooperation, innovation, digital technology, region, the EC or opportunity; (iii) the heading for expression knowledge, coloured yellow in the figure, which groups others like platform, knowledge transfer, knowledge management, SMEs or medium-sized enterprises; (iv) the heading for expression technology, which is blue-coloured in the figure and groups others, such as technology transfer, flexibility, product, production or robotics.

As expected, as they constitute the thematic axis of the research, the biggest number of co-occurrences appears around expression DIHs, DIH, digital innovation hubs and digital innovations hubs. The highest density of co-occurrences can be seen in the clusters headed by DIHs and digital transformation (red and green); both are related to: several of the concepts under study, such as collaboration, cooperation, investment or networking; service and service portfolio, which are intrinsic concepts to a commercial relationship, and another of the researched concepts; the organisation which, depending on the context, can be

Table 5 Selected results

	Authors	Title
1	Antonopoulos et al. (2020)	Capacity Building Among European Stakeholders in the Areas of Cyber–Physical Systems, IoT Embedded Systems: The SMART4ALL Digital Innovation Hub Perspective
2	Asplund et al. (2021)	Problematizing the Service Portfolio of Digital Innovation Hubs
3	Cotrino et al. (2021)	Industry 4.0 HUB: A Collaborative Knowledge Transfer Platform for Small and Medium-Sized Enterprises
4	Georgescu et al. (2021)	Digital Innovation Hubs: The Present Future of Collaborative Research, Business and Marketing Development Opportunities
5	Hervas-Oliver et al. (2021)	Emerging Regional Innovation Policies for Industry 4.0: Analyzing the Digital Innovation Hub Program in European Regions
6	Lanz et al. (2021a)	Digital Innovation Hubs for Robotics: TRINITY Approach for Distributing Knowledge via Modular Use Case Demonstrations
7	Lanz et al. (2021b)	Digital Innovation Hubs for Enhancing the Technology Transfer and Digital Transformation of the European Manufacturing Industry
8	Lombardo et al. (2018)	Proposal for Spaces of Agrotechnology Co-generation in Marginal Areas
9	Maurer (2021)	Business Intelligence and Innovation: A Digital Innovation Hub as Intermediate for Service Interaction and System Innovation for Small and Medium-Sized Enterprises
10	Pucihar et al. (2021)	Digital Transformation of Slovenian Enterprises
11	Sassanelli et al. (2021b)	Digital Innovation Hubs Supporting SMEs Digital Transformation
12	Sassanelli et al. (2021a)	The D-BEST Based Digital Innovation Hub Customer Journeys Analysis Method: A Pilot Case
13	Sassanelli and Terzi (2022)	The D-BEST Reference Model: A Flexible and Sustainable Support for the Digital Transformation of Small and Medium Enterprises
14	Semeraro et al. (2021)	Interoperability Maturity Assessment of the Digital Innovation Hubs
15	Volpe et al. (2021)	Experimentation of Cross-Border Digital Innovation Hubs (DIHs) Cooperation and Impact on SME Services
16	Zamiri et al. (2019)	Knowledge Management in Research Collaboration Networks
17	Zamiri et al. (2021)	Towards a Conceptual Framework for Developing Sustainable Digital Innovation Hubs

related to coordination; and the EC, the main source of institutional support among DIH networks. The clusters headed by knowledge and technology seem to be less present in the literature, but they also integrate two of the concepts under study: knowledge transfer and technology transfer, respectively. The remaining concepts (competition, coopetition, financing, funding, partnership, sponsorship) do not appear in this thematic analysis. This finding does not directly mean that they are not present in the selected literature, but simply the number of co-occurrences is fewer than three or their presence is indirect.

By taking closer look at the core of the map, the area where the concepts with the most grouped co-occurrences shows that most authors relate DIH to digital transformation, knowledge, technology, service, network and collaboration, and also to opportunity. Such information summarises their overall perception of the central topic (Fig. 4).

State of the art

The contributions of the authors of the selected literature have vastly different objectives, but they generally place DIHs as a central element and address, to a greater or lesser extent, some of the types of interaction that are the subject of this research. Below all these contributions are reviewed from this perspective. At the same time, extracting relevant considerations is done in relation to the interoperability principle and/or its implications in sustainability terms where they are mentioned.

The authors of Antonopoulos et al. (2020), a conference paper, set out and detail their initial objectives regarding the SMART4ALL project. Promoted in its principles by a consortium of 25 partners from various countries, especially from Southern Europe, it aims to offer a way for SMEs to improve R&D capabilities and to integrate new knowledge,

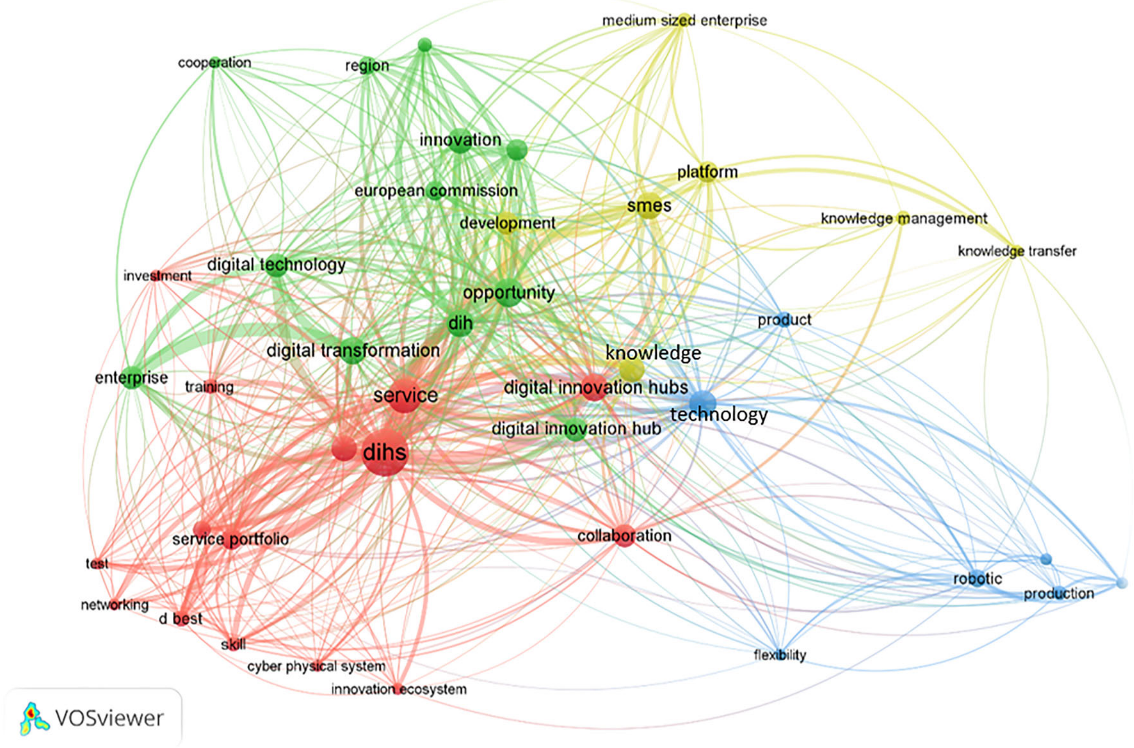
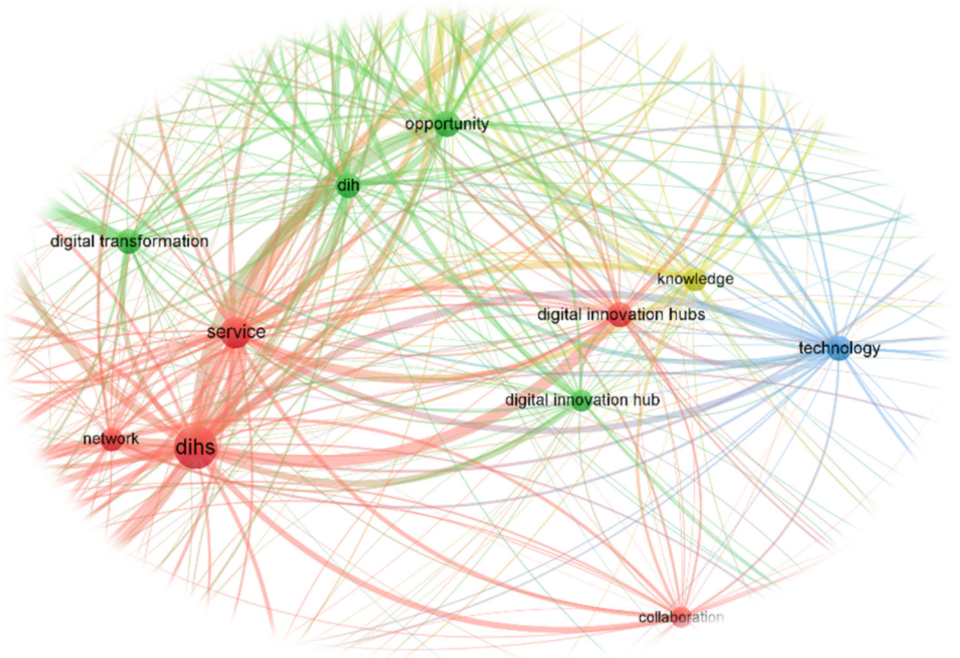


Fig. 3 Co-occurrences map

which comes both from: other knowledge-intensive SMEs and mid-cap companies; and various European research institutions, organisations that, for this purpose, are structured as a DIH network. This paper addresses mainly collaboration at two levels: (i) in the **DIH ecosystem**, firstly with a funded programme called Pathfinder Application Experiments (PAEs; Antonopoulos et al., 2020), which is intended to encourage SMEs to collaborate with one another and with research institutions; secondly with the SMART4ALL Marketplace-as-a-Service (MaaS) platform, an interactive and collaborative web portal; (ii) within the **DIH network**, firstly as an intrinsic requirement of the project itself to form the basis for its sustainability, and secondly through PAEs by encouraging the cross participation of the entities from different ecosystems in each experiment. This project aims to offer competitive advantages on the European market by promoting solutions with high computing power and low energy use in four areas: digitised transport, digitised environment, digitised agriculture and digitised anything. SMART4ALL also expects to constitute itself as a funding network at various levels: (i) the development of each individual DIH with active strategies for attracting venture capital, funding agencies or seed funding, and for providing funding to service providers; (ii) the ecosystem level with users by informing and, sometimes, funding or financing; (iii) at the DIH network level by also facilitating the information flow to partners and users about funding and financing opportunities at regional, national and European levels. Knowledge and technology transfers are addressed in the project at both ecosystem and network levels with three types of specific PAEs: knowledge transfer experiments (KTE), focused technology transfer experiments (FTTE) and cross-domain technology transfer experiments (CTTE).

Drawing on the case studies of the HUBCAP and FED4SAE initiatives, Asplund et al. (2021) pose how the leadership of public innovation ecosystems might fail to support organisations in innovation ecosystems. This study explores these ecosystems to perform four main functions that, according to the authors, characterise DIHs' portfolios: (i) "test before invest"; (ii) "support to find investments"; (iii) "innovation ecosystem and networking"; (iv) "skills and training". From this perspective, the paper addresses the collaboration processes of cooperation, networking and partnership quite tangentially but, in contrast, looks closely at what funding and institutional support mean for ecosystems. In this respect, the research work mentions both the EC funding innovation actions to support to establish DIHs and to provide funding opportunities to the organisations forming part of ecosystems. It is precisely this latter approach type that authors pay more attention to insofar as funding them is often seen as the basis for enabling collaboration, especially in the public–private partnerships area for, e.g., the companies that focus on technology recombination.

Fig. 4 Core of the co-occurrences map



The research of Cotrino et al. (2021) focuses mainly on Industry 4.0 knowledge transfer for SMEs by developing a collaborative web-based Industry 4.0 knowledge transfer platform, referred to as Industry 4.0 HUB. The vision of collaboration in this environment is based on knowledge transfer and networking and, to some extent, also on technology transfer. For these authors, knowledge transfer, as the main theme of their research, is seen as one of the four knowledge flows present in knowledge management, i.e. knowledge creation, retention, transfer and utilisation. For them, communication issues in this cycle appear as a factor of paramount importance for SMEs' transition to Industry 4.0 to effectively take place. To this end, the devised platform is made up of four modules: (i) hub; (ii) roadmap; (iii) community; (iv) collaborate. The last two, the community and collaborate modules, are precisely responsible for facilitating networking and collaboration between partners, with collaboration essentially understood as knowledge transfer.

The study conducted by Georgescu et al. (2021), on the opportunities offered by DIHs in collaborative research, business and marketing development terms, puts forward a different DIH collaboration view because the authors first and foremost think of it as a basis for business and marketing development, and as a springboard for boosting the success of networked relationships. The study is structured around the idea of cooperation as an opportunity to synergistically unleash organisations' potential to remain competitive via a greater exchange of ideas, knowledge, skills, technology and infrastructures that, above all, benefit weaker entities on their journey towards greater digitalisation, especially SMEs. It also attaches vital importance to the funding and support of European institutions to achieve these objectives by DIHs, and thus confers an important role to public–private collaboration initiatives.

Unlike the previous ones, the analysis carried out by Hervas-Oliver et al. (2021) of the DIHs created in European programmes focuses on the first relationship level, i.e. the DIH level, to provide more knowledge on developing regional innovation policies to develop Industry 4.0, especially in the public–private cooperation field, as a master formula for collaboration in regions. According to this analysis, coordination between actors across local and regional industries, which is for the authors a remarkable fundamental interaction type, is a pending issue for most of the analysed DIHs having found that DIHs do not frequently work in coordination with other existing regional initiatives that pursue the same digitisation objective. This work also highlights that, although DIHs perform a wide variety of functions, they are oriented mainly towards facilitating networking between all the different typologies of regional and local actors by focusing on the scope of that context and acting as collective actors. According to this research, DIHs are often organised in a way that allows for bottom-up and negotiated initiatives, rather than traditional top-down policies that take business interests as secondary. This public–private partnership level is seen as positive because this informal understanding allows private sector companies to make decisions and suggestions, and to do agenda-setting. Not surprisingly, DIHs are managed through the collective decisions that contemplate regional and local needs, especially those of SMEs. These public–private partnerships co-design and co-formulate policy directions in Industry 4.0, similarly to those reflected in other place-based policy initiatives, as in China or South Korea.

A very particular point of view of DIH collaboration is that in Lanz et al. (2021a). Their article is based on the initiative known as the H2020 TRINITY project, which focuses on developing an advanced robotic innovation hub based on: (i) agile manufacturing, along with (ii) digital tools and platforms; and (iii) cyber-security technologies. Here the spotlight on DIH collaboration processes is on knowledge and technology transfer. Industrial robotisation is a very specific field on the journey towards greater digitisation and it is only applicable to certain individual cases. Because of this, it presents some particularities from the collaboration processes perspective, which are addressed in the research work. To gain further insight into these particularities, in the TRINITY project, 18 use case demonstrations were carried out by consortium members; to extensively cover local industrial needs, the collaboration of DIH members with local and regional companies, i.e. collaboration within the DIH ecosystem, was essential. This collaboration was articulated through central storage known as the TRINITY Digital Access Point, which also supported disseminating information activities to the general public. A further development of the previous article is that of Lanz et al. (2021b), which also focuses on the TRINITY project. It is noteworthy that it deals with two different collaboration types: (i) human–robot collaboration, typical of those known as cobots, a topic that is completely beyond the scope of this research; and (ii) collaboration typical of the environments configured at the level of DIHs themselves and the local/regional ecosystems that they configure. In the latter, which is the true objective of the present research, this article interprets that innovation ecosystems should be distinguished, among other characteristics, by constituting a European focal point for coordinating and exchanging innovation communities in artificial intelligence, data and robotics, and for transferring knowledge and technology from science to industry, especially SMEs, where the difficulties of recruiting skilled workers are more evident. During such development, the authors also stress the importance of funding at various levels: (i) each EU Member State, co-investing in local/regional DIHs and their ecosystems to support their facilities and services with an impact on the area, and (ii) the EU level or the Digital Europe programme, as it is also called in the article, by funding with this European dimension empowerment of networking between DIHs to enable certain highly specialised facilities and expertise, which are not present in all regions, to become accessible for sharing.

The article by Lombardo et al. (2018) also presents a unique case. Here, inspired by the innovation model of DIHs, they propose that, to push the European agricultural sector towards precision agriculture in marginal areas, the traditional top-down approach, based on transferring knowledge and technology from research centres and universities, should be replaced with a bottom-up approach of open innovation. This would lead to the co-generation of agro-technical technology of products and services in the collaborative spaces generated for this purpose in these specific EU territories. According to the authors, the application of a technology transfer model based exclusively on R&D at universities, research centres and companies has major limitations in marginal territories, which are usually characterised by lack of training and low innovation rates. For this reason, it is considered more appropriate in these areas to start talking about technology co-generation in agriculture, which provides common production among peers, rather than technology transfer, which provides a top-down approach. In this context, Fablab is introduced as an ideal space to implement such an approach. Fablab is a collaborative space that focuses on encouraging experiments with both digital technologies and physical objects, using open-source software and open and big data processing for developing solutions for smart farming. They are spaces where learning to use digital technologies in relation to physical reality is possible. Fablab is, therefore, defined as part of a network, a community, a set of tools, knowledge, processes, but also a service, a business, not a franchise, and is mostly a concept that is still developing. There are four rules that distinguish and define a Fablab: (i) access to the laboratory should be public; (ii) laboratories must sign and show the Fab Charter (http://fab.cba.mit.edu/about/charter/); (iii) the laboratory must have a set of tools and shared processes; (iv) laboratories must be active and participate in the global network. At the time the article was written, there were about 663 Fablabs worldwide. These are yet another example of collaboration to be considered in the certain innovation ecosystems context.

Maurer (2021) raises the characteristics that a DIH should have to act as an intermediary in service interaction and system innovation for SMEs in the Federal State of Vorarlberg, Austria. Although this is very focused research, it is worth noting that the author attaches fundamental importance to collaboration within networks, to the point of going into some detail on this concept from the service science perspective and its specific application to the network formed by a DIH, for which a whole section is employed. Accordingly, it is a service science that provides the philosophical/theoretical basis for ecosystem collaboration, while it is the EC's strategies on the digitisation of European industry that provide the pragmatic direction. A DIH has to carry out a wide variety of activities and tasks, with close cooperation and collaboration of stakeholders in the business sector, and with government and public administrations, civil society and users, and the research and education sector (constituting the so-called quadruple helix stakeholders) is essential to carry them out. In this context, cooperation, coordination, networking and partnership interactions are of paramount importance.

With the survey study conducted by Pucihar et al. (2021) of 125 participating companies, the authors provide insight into the state of digital transformation in Slovenia. Collaborative processes are shallowly dealt with, mainly from the perspective of interaction in cooperation, funding, institutional support and partnership, especially in the DIH field, but also occasionally in the innovation ecosystem space. According to the authors, in Slovenia government investments are made by two different programmes that support the creation and operation of innovation ecosystems: on the one hand, (i) partnerships for strategic development and innovation; on the other hand (ii), the DIH, which was established in cooperation with the Slovenian Chamber of Commerce, universities and businesses. Here funding through grants and co-funding policies is the most discussed collaborative interaction.

The research conducted in the network formed by the members of the DIH4CPS (Digital Innovation Hubs for CPS) project deserves a separate chapter. This project constitutes one of the most remarkable research nuclei in the field of studying DIHs and their collaborative interactions. The objective of DIH4CPS is to create an interdisciplinary network of DIHs and solution providers by focusing on cyber-physical and embedded systems, interlinking knowledge and technologies from different domains and connecting regional clusters in the pan-European DIH expert group. Sassanelli et al. (2021b) present a literature review in an attempt to clearly define and properly group the set of services provided by the DIHs making up their service portfolios. Based on the aforementioned literature review, and using the corresponding theoretical foundations, in this article the authors propose the need to extend the traditional service portfolio of DIHs, fundamentally centred on categories of services related to: (i) the ecosystem; (ii) technology; and (iii) the company. It is known as the ETB model. The proposed extension is to add two categories to the previous model: services related to (iv) skills and (v) data. Based on these five categories, called macroclasses, the consolidation, implementation and final adoption of a new reference model called D-BEST, which aims to shape the service portfolio of DIHs and instantiate them from the digital perspective of Industry 4.0, are cemented. In this modelling context, collaboration between entities also plays an important role. Indeed Sassanelli et al. (2021a) extend the D-BEST model objectives beyond classifying the service portfolios of the DIHs belonging to the network: the authors indicate that the model also allows the identification of opportunities for collaboration between DIHs that foster the creation of pan-European DIH networks. The article focuses on the collaborative interactions that exist in the DIH ecosystem while rendering services between the DIH itself, which forms the ecosystem, and its clients, technology users and technology providers. For both groups, the authors generate the procedures of their specific customer journey by identifying, sequencing and detailing the digital transformation processes that typically take place in each case: (i) in the case of technology users, the processes of observation, awareness, experiment, experience and adoption, (ii) for technology providers, the processes of ideation, design and engineering, minimum viable product, verification and validation, and going to market. Sassanelli and Terzi (2022) propose the D-BEST reference model, which is tested and validated by a survey. The D-BEST model and the customer journey catalyse the digitalisation dynamics of SMEs and define the service chain of DIHs by representing a step of substantial importance to study interaction processes for collaboration between DIHs. This is because their adoption in DIHs' emerging networks would allow flexibility and interoperability to be achieved by fostering the adoption of single digital platforms with which to display and offer services. This would enable the creation of multiple inter- and intracommunications and collaborations between the actors belonging to DIH ecosystems and networks by crucially fostering the exchange and development of joint services. These developments standardise the ultimate purpose of collaboration between entities: the provision of services to SMEs to advance their digitisation. Another group of researchers within DIH4CPS, that of Semararo et al. (2021), emphasises the importance of interoperability for the interactions of collaborative processes in DIH networks. Their article aims to use and adapt a maturity model to define how to assess and improve network interoperability between DIHs and their partners. It does so by: (i) firstly reviewing the state of the art of interoperability frameworks to define DIHs' interoperability requirements; (ii) subsequently identifying the DIHs' main interoperability barriers and DIHs' interoperability concerns; (iii) also modelling an ontology for interoperability assessment; (iv) finally presenting an interoperability assessment prototype. The interoperability assessment as part of the collaborative interactions between DIH networks members is extremely important because these interactions often require the exchange of information, data and knowledge, and the information systems and procedures that they support need to be interoperable. For Zamiri et al. (2019), the focus lies on knowledge management within collaborative research networks like living labs and DIHs. Collaborative research networks can facilitate knowledge transfer between organisations on the one hand, and increase both cross-fertilisation of knowledge and team productivity on the other. Based on the prior development of some theoretical propositions and various sources of evidence from data collection and analysis (observation, interviews, in-depth research, consultations), the authors attempt to improve the ontology of the CARELINK project, which aims to leverage the benefits of research and care tools, and to introduce unique technologies for dementia patients, based on collaboration between entities. The idea is to create an innovation ecosystem in the form of a living lab and, in a second phase, to integrate this living lab into a DIH that focuses on active and assisted living to open up work to a wider community and to integrate other active projects among participants. To conclude, from the collaboration interaction processes perspective, in these ecosystems the research work considers that collaboration is based on networking and knowledge transfer. Zamiri et al. (2021) propose a framework to substantiate DIHs' sustainability by taking into account both the existing literature in sustainability dimensions terms and business models, general objectives and DIHs' demands by studying several of them. The future intention is to apply this framework to various DIHs in the DIH4CPS network in order to lead to further developments. This study does not overtly revolve around the sustainability of DIH collaboration in several of its various forms; i.e. funding, knowledge and technology transfer, networking or sponsorship. The contribution of this work is considered remarkable because it develops a framework to establish and develop sustainable DIHs from five pillars, including environmental, social, economic, governance and technological, and goes on to describe the successful application of the proposed framework in six different DIHs.

The research by Volpe et al. (2021) analyses, from the particular DigiFed innovation initiative scenario, a project funded by EC cross-border collaboration amongst DIHs and between SMEs. The study of this collaboration type is approached first and foremost from the perspective of the cross-border cooperation instruments and their preliminary results. It describes the toolbox of services implemented within the DigiFed project by examining the evaluation results and success rates of collaborative projects (TWIN application experiments) to those from individual organisations (SINGLE application experiments) in the application phase. In this regard, it should be noted that the authors note that smaller companies (1–10 employees) obtain consistently higher success rates in terms of the proposal application to the TWIN-type of application experiments. Similarly, companies with a lower digitalisation maturity level are more likely to apply for collaborative TWIN application experiments. Apart from taking application experiments as tool collaboration, the authors also pay attention to funding as a sort of collaborative interaction through both the so-called cascade funding to SMEs and mid-caps to enhance their assets by including innovative digital technologies, and by experimenting with new funding schemes to support European firms' digital transformation. Another research aim is to further explore the prospects of generalising these instruments to be adopted by other DIH networks by identifying whether DigiFed's support infrastructure serves as a portable example of DIH collaboration to foster similar cross-border partnerships between SMEs and mid-caps across Europe to, thus, obtain increasing returns via innovation enabled by cross-border cooperation. The authors leave for future research the progress made in implementing application experiments and their sustainable exploitation, as well as the evolution of funding mechanisms.

A significant number of conclusions can be drawn from analysing the state of the art, some of which are pointed out in this section. From a global perspective, if among these conclusions we have to highlight those common to all the literature contributions, one would stand out in particular: although these studies follow, the common thread of the processes of collaboration in and between DIHs from various angles and degrees of detail, they all do so in a tangential manner and do not provide an in-depth approach to it. In general terms, the research contributions made to date, which directly or indirectly address the phenomenon of collaboration within innovation ecosystems in general, and in DIHs in particular, consider these interaction processes to be an intangible management element that is difficult to perceive and is not, a priori, measurable. This circumstance may be related to the fact that collaboration or, more specifically the existence of collaboration flows between DIHs and other entities in the ecosystem, has not been taken to date as an asset with its own entity for an organisation. It has, therefore, remained on a secondary plane, usually immersed in other DIH assets, such as competences or skills.

Therefore, it can be stated that, as far as we know after this review, there is still no descriptive or conceptual framework in the literature in the first stage, or a qualitative or quantitative model in a more advanced stage, that addresses the conceptualisation of DIHs' interaction processes from the collaboration perspective both within and between its four relationship levels. The perceived impossibility of measuring collaborative flows between ecosystem entities, as discussed above, is considered to be the main factor that has led to this situation, and has so far prevented ontological, taxonomical, qualitative and quantitative characterisation.

Conceptual framework

Since 2016, when DIHs were conceived by the EC, the European Network of EDIHs and DIHs has continued to grow to a significant size and extent. Yet despite the presence of this network, three important deficits remain in innovation and digital transformation terms. When focusing on the sector, there is a persistent imbalance between the more traditional sectors, which are not very digitised, and the more advanced ones, such as the ICT sector. Moreover in each sector, large companies have easier access to digitalisation and its exploitation than SMEs. Finally from a territorial perspective, there is still a significant difference between the more digitised northern states and those in the south. The joint activity of the European network of EDIHs and DIHs must be strategically oriented towards mitigating the three aforementioned deficits by acting as communicating vessels and allowing extensive knowledge and technology flow. The key to the success of this strategy lies in collaboration. This reality urges us to advance in the understanding of collaboration towards a sort of conceptualisation that does not avoid quantitative characterisation.

This section presents a conceptual framework whose objective is to provide a tool that contributes to identify, characterise, organise and quantify the elements, structure, parameters and variables that determine, as a whole, the interaction processes involved in the collaboration that takes place between the entities making up the relational network of European innovation ecosystems. This framework supports the interaction processes that exist in collaboration between entities: horizontally along their relationship levels, and vertically between them. It is important to note that this framework is developed using a bottom-up approach. This involves initially establishing, from the existing literature, what the core elements are that make up the structure of the construct that the conceptual framework represents, and allow collaboration to be understood as tangible and measurable. This conceptualisation approach is crucial for developing a solidly based conceptual framework. Without a robust approach that provides measurability, collaboration would remain close to abstract and intangible and would, therefore, difficult to model.

The extant literature support this with the D-BEST reference model (Sassanelli & Terzi, 2022). The ultimate purpose of a DIH, as a provider within an innovation ecosystem, is to provide a service to end users. In this context, collaboration between entities has always directly or indirectly been the ultimate purpose of transferring or exchanging some kind of asset among organisations to improve or provide services to end users. From this angle, collaboration is closely related to service provision. According to this basis, an interaction to collaborate implies, as in the provision of services, the transfer or exchange of assets between collaborating service provider organisations, and before and during the provision of a service. This is where the D-BEST model comes into play because it not only identifies what assets are, but the assets that it identifies happen to be measurable in some way.

According to the D-BEST model, the assets required for service provision purposes are classified according to their typology into competences, knowledge, technology, infrastructure and funds (Fig. 5). All these assets are susceptible to measurement in some way and, as the assets they are, can be translated somehow into monetary terms: e.g. competences and knowledge can be measured by the monetary value of the working time spent in exchange; technology and infrastructure by the monetary value of the amortisation time share of the capital invested in them, whose unit is the currency used in the valuation; funds simply for the total amount of money financed, plus its associated costs, regardless of them being interest, fees, stamp duty or guarantees.

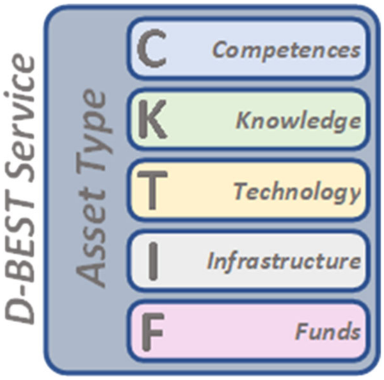


Fig. 5 Elementary asset decomposition of a D-BEST service

As previously mentioned, the D-BEST model divides the possible services that an organisation offers into five macroclasses, and these, in turn, into 20 service types (Table 4), which are identified by two digits: the first one indicates the macroclass, while the second denotes the service type is in the indicated macroclass. Thus with the help of assets as an instrument, it is possible to map all the asset types that an organisation needs to have to cover the complete D-BEST model services catalogue by identifying each service type and its corresponding assets (Fig. 6). This asset map includes 100 categories.

Based on the premise of this categorisation and the mapping of the services provided by the D-BEST model, moving towards the definition of a framework requires considering new elements, especially introducing the asset flow concept, which has not yet been contemplated by research studies to deal with interorganisational collaboration. Materialising collaboration in the collaborative interaction process between two DIH organisations or more occurs by creating a flow of tangible or intangible assets from ceding organisations to beneficiary organisations to alleviate any deficits in the latter and to enable them to provide some specific service types immediately or in the future. This reality is observable in practically all organisational ecosystems, and is the main rationale for a new framework for collaboration.

To facilitate the understanding of the reasoning behind the assets flow concept, the following example is provided: let two organisations decide to undertake a mutual collaboration process to, on the one hand, improve the aptitude of Organisation A for the provision of business training and education services (service type 3.3) in terms of infrastructure, and skills improvement (service type 4.3) in terms of knowledge; on the other, Organisation B to acquire capabilities in terms of providing services for data acquisition and sensing (service type 5.1), data processing and analysis (service type 5.2) and data sharing (service type 5.5), and all in technology terms. Seen the other way around, to materialise this collaborative process, it is necessary for organisation A to act as

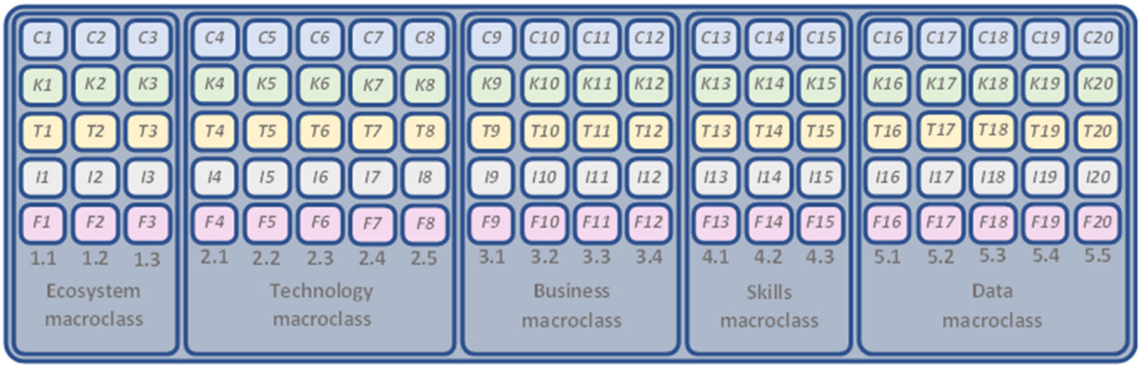
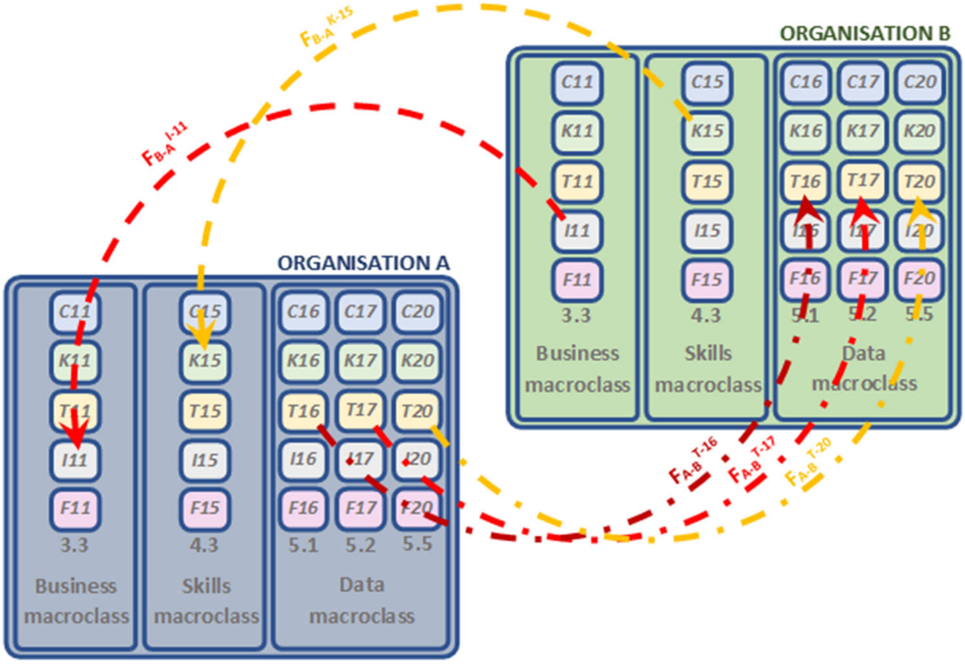


Fig. 6 Asset type map of the D-BEST services catalogue

Fig. 7 Collaboration example between two organisations in a DIH ecosystem



a transferor of some specific enabling assets to Organisation B to provide services types 5.1, 5.2 and 5.5. Organisation B has to transfer them to A to provide service types 3.3 and 4.3. These individual asset flows can be depicted as shown in Fig. 7. They are designated as $F_{O-O'}^{A-T}$, with O being the transferor organisation designation, O′ the beneficiary organisation, A the type of transferred asset and T the service type numbered from 1 to 20. This collective designation indicates that individual flow $F_{O-O'}^{A-T}$ of asset type A is transferred from Organisation O to Organisation O′ to enable the provision of service T.

It is possible to add an additional layer of characterisation to the exchange of collaborative relationships between entities because, for each service type, the D-BEST model provides an additional level of classification called service class (Table 4). By simply counting the number of service classes involved in each individual asset flow, e.g. on a percentage basis, an additional characterisation of collaboration can be provided, which is referred to here as service depth. This aspect is addressed again later in this article.

This approach to define the origin, destination, channel and asset transferred in the collaboration process is called the Interorganisational Asset Transfer Methodology (IOATM). It constitutes the cornerstone of the proposed conceptual framework.

It is pertinent here to comment on or explain this methodology and the relationship levels between the entities making up the network of European innovation ecosystems. Whether it is the transferor or the beneficiary of a certain asset, the fact that an organisation is at a certain relationship level does not prevent it from transferring assets to entities at different levels or, on the contrary, receiving them. The vertical transfer of assets, or the transfer between different levels, is not restricted in actual practice, and although due to the very nature of levels the most usual are horizontal or intralevel transfer processes, collaboration between entities at different levels, especially in the first three, is also common; i.e. DIH, ecosystem and EDIH levels. Accordingly, it should be noted that IOATM, as a potential means to quantitatively assess collaboration between the entities of innovation ecosystems, does not restrict this circumstance in any way and, therefore, confers the framework flexibility in this respect.

This holistic approach, based on defining the origin, destination, channel and transferred asset involved in the asset flow of the collaboration under study, answers research question RQ1, formulated about the characteristics of the interaction that occurs between the entities composing DIHs' relational network when collaboration takes place between them. Thanks to this construct, collaborative processes between organisations can be translated in asset flow terms. This translation is particularly significant because the mapping and identification of the individual asset flows involved in collaboration enable IOATM as a tool for the quantitative assessment of collaboration processes. On the one hand, the possibility of individualising each asset transfer facilitates its characterisation and the establishment of measurable technical specifications, which are crucial for quantifying the gross magnitude T_{mb} acquired by such a transfer; e.g. in purely monetary terms, in terms of the time spent or use of the asset, or by other quantification means. On the other hand, the identification of the individual channel that conducts each individual transfer also helps to characterise it and to establish its specifications. This is fundamental to quantify the performance or efficiency eff_t of the channel in the transfer process; in other words, to quantify organisations' capacity to collaborate. This ability to collaborate, whose value would be between 0 and 1, depends not only on the parameters that define and characterise the transfer channel, especially those related to interoperability, but also on some parameters specific to the intervening organisations, all of which could be the subject of further research. This efficiency eff_t modifies downwardly the gross magnitude of transfer. Thus their joint product leads to the net magnitude of transfer T_{mn}, an artifice that would make it possible to accurately measure collaboration in hypothetical quantitative modelling. From this perspective, both the assets flow and transfer channels can be considered the two key dimensions in collaborative interaction processes, and the elements that most shape the quantitative assessment of collaboration, dimensions around which the other elements of the proposed framework are positioned: the service catalogue, the involved relationship levels, the collaborative interaction types, and origin and destination, all of which essentially do not shape, but condition assessments. This approach provides an answer to research question RQ2, formulated in the Introduction of this article.

Regarding the interaction types aligned with collaborative processes, on the contrary it is necessary to make some distinctions because each type presents its own peculiarities in relation to the involved entities typology or the types of transferred assets: (i) cooperation involves transferring all or some of the first four asset types, i.e. competences, knowledge, technology and infrastructure (CKTI), and admits the exposed methodology without restrictions; (ii) coopetition presents two faces, cooperative and competitive, and the IOATM scope is restricted to collaboration that materialises from the cooperative perspective with the transfer of CKTI; (iii) coordination forces organisations to align and organise business activities by sharing information, risks and resources and, therefore, producing the controlled transfer of CKTI; (iv) in collaboration through funding, basically a money transfer occurs in a unidirectional way; that is, when the ceding organisation transfers the asset, the receiver can, in turn, transfer other assets to the transferor in response, such as knowledge or technology, but not money; (v) Institutional support interactions are characterised by the transferor organisation being a government authority or a public institution, and flow is unidirectional. The assets transferred in this collaboration type are normally skills (indirectly acquired with the support of policies, plans, laws or regulations) or financing; (vi) knowledge transfer is defined by its own name; (vii) networking basically implies transferring knowledge about who to collaborate with and in what subjects; (viii) partnership; it essentially represents the same as cooperation or coopetition, but on a larger scale and in terms of the number of involved organisations, to produce the same type of assets transfer as in these; (ix) sponsorship; a potential formula in which the transferor organisation is a person or group from the private sphere; it is unusual in the innovation ecosystems context; here the assets flow is unidirectional and it may involve knowledge transfer in the form of advice or some type of funding; (x) Technology transfer; its very name characterises it. In any case, albeit with their particular nuances, all collaborative interaction types occupy a place in the methodology advocated by this framework.

Having clarified all this, the conceptual framework can be represented, from a general perspective, by bringing together within a single frame all the aforementioned elements. On the one hand, those elements are based on the D-BEST model, which serves as a platform to develop the conceptual framework: asset types involved in services, macroclasses and service types, and the asset type map of the service catalogue. On the other hand, those new elements that allow the collaboration process between organisations to be shaped: transfer channels or asset flows, the four relationship levels in the network of European innovation ecosystems, collaborative interaction types and, obviously, the ceding and the recipient organisations (Fig. 8). The conjunction of all these and their interrelationships, with a special emphasis on the

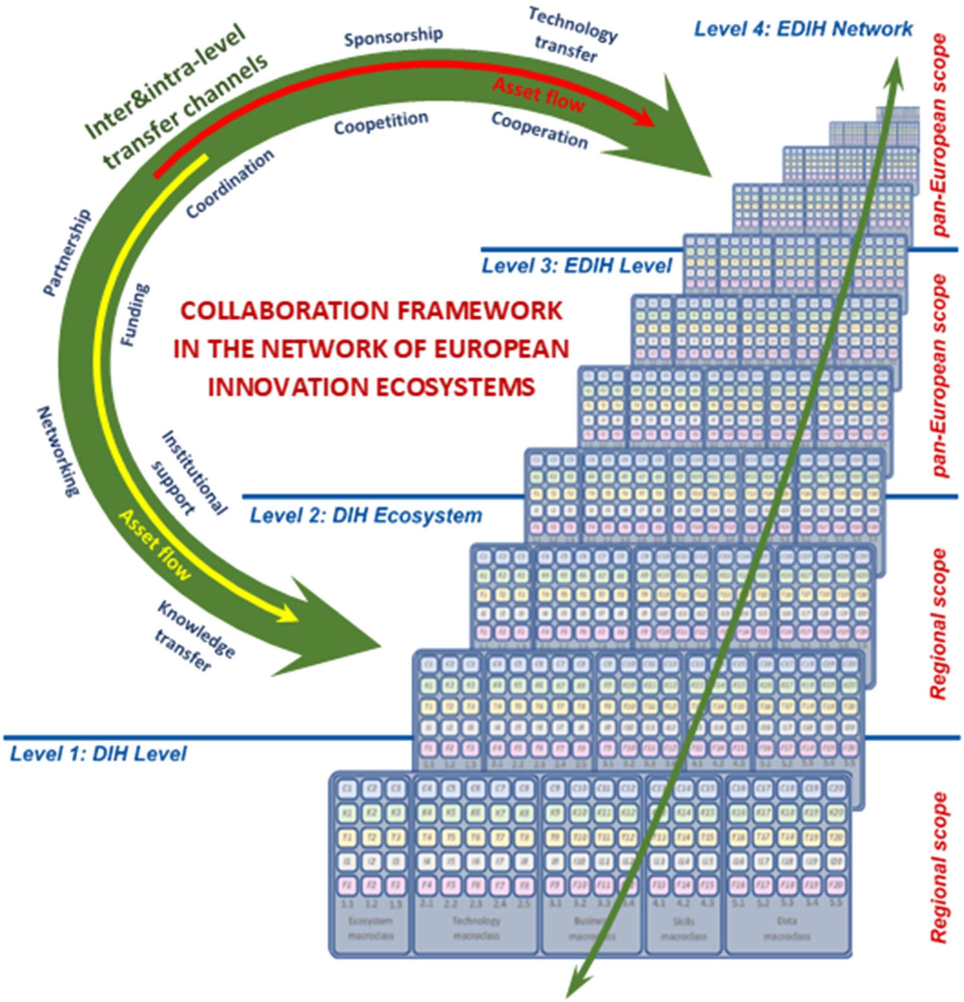


Fig. 8 Collaboration Framework in the Network of European innovation ecosystems

core concept of asset flow as the main rationale, make up the proposed conceptual framework.

Case study: a food processing application experiment for production management and predictive maintenance within the DIH4CPS framework

European project "Fostering DIHs for Embedding Interoperability in the CPS of European SMEs" (DIH4CPS) was an innovation action that received funding from the European Union's Horizon 2020 programme. This created an interdisciplinary network of DIHs) and solution providers specialised in the Industry 4.0 technologies application in SMEs, especially on cyber–physical and embedded systems, interweaving knowledge and technologies from different domains, as well as connecting regional clusters with this pan-European expert pool of DIHs.

When the project finished in December 2022, DIH4CPS's ambition to become a sustainable network materialised early in 2023, when it was instantiated in the European Virtual Laboratory for Enterprise Interoperability (I-VLab) under the name of Ei2Network, which is currently operational.

DIH4CPS integrated its ecosystem with 11 initial DIHs from nine countries from all regions of Europe, and 20 additional DIHs following the first and second open calls, to provide European industry with unprecedented ease of access to world-class domain expertise in developing CPS and embedded systems. The development of this expertise revolved around a core experimentation cluster that consisted of 23 application experiments covering many key industrial sectors and activities.

This use case approaches the collaborative processes in Application Experiment number 6 (iAE6) carried out in the project, which aimed to address the difficulties of those companies that, despite having large and valuable production data generated by powerful automation systems, do not integrate them into the value chain and end up often representing data silos that are barely or no exploited at all. The planned experiment, implemented in practice into an industrial pilot of the food processing sector, supports the development of data-driven value-added services, both related to the manufacturing execution system/manufacturing operations management (MES/MOM) functional areas (e.g. production order control or performance analysis) and predictive maintenance. The experiment facilitated the development of a vertical solution that leverages the production data generated by quality inspection machines for the agri-food sector, especially in the production of olives, cherry tomatoes and other fruit, which was made possible by the integration of value-added services that collect and maximise the process data generated by state-of-the-art machine vision sorting and grading machines to optimise production and maintenance management.

Food processing application experiment iAE6

The application experiment was validated with a pilot at a food processing company specialised in cherry tomatoes (Níjar, Almería, in Spain), on a cherry tomato grading and sorting line (Figs. 9, 10, 11), which was subject to improvement (Fig. 9).

The process of sorting and grading cherry tomatoes involves several steps. Firstly, operators transport pallets containing cherry tomatoes and feed them into the sorting line's roller conveyor. From there, tomatoes move along different feeding belts and enter the Multiscan MGS sorting and grading roller machine. This machine uses computer vision to detect the different features of each cherry tomato, such as shape, colour and size, as it rolls through the machine. In this way it inspects the entire surface of each fruit. The machine classifies them into different quality categories defined by the user through an intuitive user interface, which allows the thresholds for each property and category to be set up. The machine then tracks and guides all the tomatoes to strategically placed slots to place them into separate exits. The objective of the application experiment is to develop data-driven added-value MES/MOM applications to improve manufacturing operations (Figs. 10, 11).

The main components or building blocks making up the system's architecture has allowed the experiment to be developed, which is organised into clusters or tiers according to the different levels of a secure industrial network defined by the IEC/ISA 62443 series of standards as detailed below (Fig. 12).

An embedded server based on the open platform communications united architecture (OPC UA) facilitates the integration of the production data generated and managed by the line inspection machine into external applications. The OPC UA is becoming a standard factor for machine-to-machine (M2M) communications at different industrial network communication levels. By means of OPC UA Service Discovery technology and an ad hoc data model for OPC UA Data Access services, the application experiment delivers a turn-key solution to enable "Plug-and-Play" connectivity. This OPC UA Server allows information from not only the quality inspection machine, but also from other connected manufacturing equipment, to be exchanged. In this way, the embedded OPC UA server allows other services to exchange operational and maintenance data with the quality inspection machine so that it is no longer a data silo, which improves the performance of supply chain processes.

A hybrid edge/cloud service platform provides a run-time platform and a core service to facilitate access to the data generated by the OPC UA to connected applications so that they can provide data-driven added value services. The edge/cloud service platform provides asynchronous data services to access real-time production data and synchronous data services to access historical data. This basis enables the secure access and exchange of the operational and maintenance data between the stakeholders involved through a set of data services designed specifically to support this collaboration. The edge/cloud services also allow datasets to be created for analysis and model training purposes. This edge/cloud platform manages the data storage of industrial data time series at two different levels: on-premises (systems installed within the pilot company's boundaries); in-cloud (systems installed in a private cloud). The platform keeps the on-premises hot data generated in the near past by applying retention policies that have been specifically defined to meet the requirements of the added value services that consume these data. The collected and stored data include the industrial variables describing the process and quality of products. On the one hand, as mentioned data services store above all information, even the information collected from line controllers through the embedded OPC UA servers. This includes all the process information about the real-time status of production equipment and all the product quality-related information generated by the compute-vision grading system. On the other hand, data services allow applications to enrich this information with additional context information, like the information provided by operators in natural language to better describe incidences and machine failures.

The implemented MES/MOM applications are basically web applications that provide the manufacturing execution system and the manufacturing operation management functionalities, backed by the edge/cloud platform services. These MES/MOM applications focus on some demanded key functionalities, which mainly revolve around four milestones: production key performance indicators (KPIs) monitoring, production order control, production batch traceability and production process management.

Finally, the objective of the anomaly detection and predictive maintenance module is to put the maintenance data to good use to provide value data-driven services in this area. Anomaly detection and predictive maintenance allow unexpected events in machine performance to be reported by

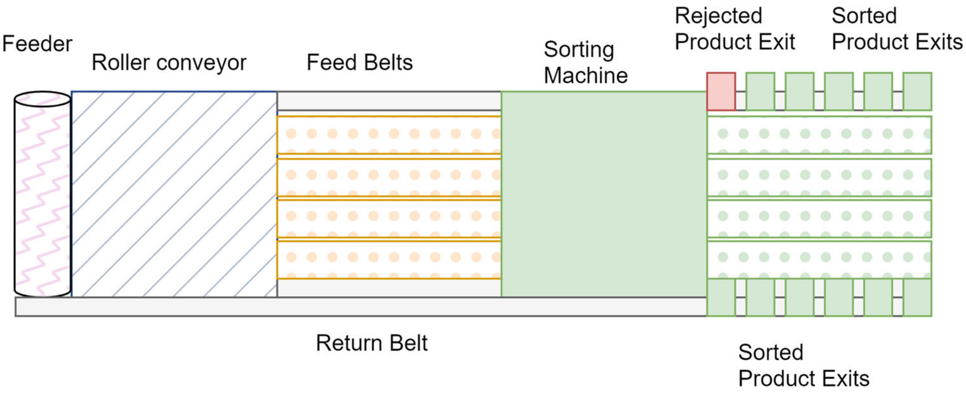


Fig. 9 Scheme of the Multiscan MGS cherry tomato grading and sorting line (*source* DIH4CPS project dissemination archives)

Fig. 10 Multiscan MGS cherry tomato grading and sorting line (*source* DIH4CPS project dissemination archives)

Fig. 11 Detail of Multiscan MGS cherry tomato grading and sorting line (*source* DIH4CPS project dissemination archives)

studying baseline normality trends with contextual information, reporting anomaly detection and the estimated time to failure of machines and predicting any likely failures. In this way, the described module provides a solution to several key issues: (i) detecting and warning in real time when operating parameters deviate from expected machine performance; (ii) studying and adjusting for drift and seasonal variations in performance estimators; (iii) minimising loss of availability due to unplanned repair and adjustment downtime; (iv) reducing operating costs by planning maintenance and stocking appropriate spare parts on site in advance; (v) optimally integrating the planned downtime into the operating schedule. Of the different possible models towards this endeavour, the use of survival models and classifiers was chosen for this project. Survival models are appropriate for obtaining several probability estimations for failure in different future times by allowing maintenance to be adapted according to the taken risk. Besides, classifier models provide different probabilities for each failure type during a given time period.

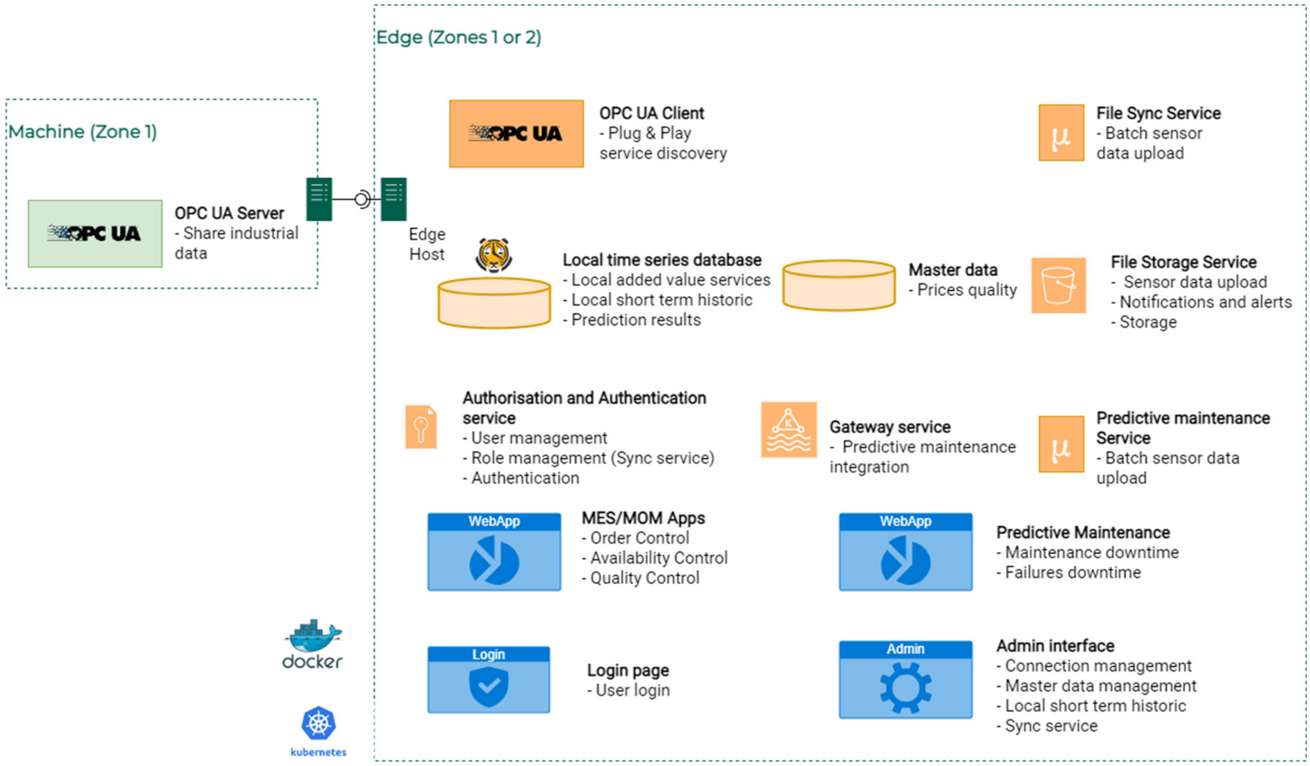


Fig. 12 The iAE6 high-level technical architecture

The pilot was prepared by provisioning plant facilities with laboratory equipment, which consisted of a food processing line simulator, whose main function is to generate values for the different industrial variables from the available historical data. With this simulator, the installation and integration of the different components were validated under laboratory conditions by evaluating the installation procedures and user interfaces to ensure that user requirements and acceptance criteria were met. Once the solution was validated under laboratory conditions, the tested unit was installed on the user's premises and finally commissioned.

Managerial implications of iAE6

From the knowledge acquired during the experiment, several implications for user management processes are worth highlighting: (i) better monitoring of production KPIs; a benefit that comes from the MES/MOM applications. This is because they calculate KPIs from the collected data and display them on comprehensive dashboards designed specifically for different user profiles (operator, production manager or maintenance manager) so that everyone involved in the process can assimilate information; (ii) improved order control due to MES/MOM applications, which provide functions to dispatch production orders to the shop floor (operators and manufacturing equipment), and show the production plan current status to relevant users; (iii) enhanced process management thanks again to the MES/MOM applications by monitoring and controlling the manufacturing process status, and by showing operators the current status of the line and allowing them to specify the cause of stoppage when it is not detected by a machine; (iv) improved production performance, derived from the benefits of anomaly detection and the predictive maintenance system. This vertical solution is expected to be well accepted by the SMEs involved in food grading and sorting, which currently have lower Industry 4.0 maturity levels than larger companies, which usually access technological resources more easily.

Organisational aspects of the iAE6 experiment

Three organisations participated in the design and development of the iAE6 experiment: (i) The Universitat Politècnica de València (UPV), a member of the DIH for the economic promotion of the Valencian Community (InnDIH). It plays the role of team leader, system architect and DIH member that specialises in production management technologies (here mainly MES/MOM technologies) through the Centro de Investigación en Gestión e Ingeniería de la Producción (CIGIP), which belongs to this university. (ii) The Instituto Tecnológico de Informática (ITI), another InnDIH

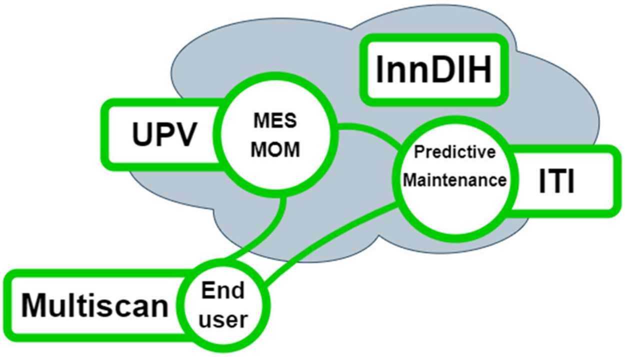


Fig. 13 iAE6 overall organisation

member. It acts as a specialist in machine learning and predictive maintenance technologies. (iii) The company Multiscan Technologies SL. It is the designer, manufacturer, installer and maintainer of the product (Multiscan MGS cherry tomato grading and sorting line of reference PL18007), and is the end user of the solution. It also acts as a specialist in machine vision technology. These three organisations are the intervening actors that play an active role in developing the target solution of this experiment. SAT Costa de Níjar, a company that produces, processes and sells agricultural products, has offered its facilities to run the pilot. However, this company does not play an active role in experiment development, which is why it is not considered in the use case (Fig. 13).

Implementing the collaboration framework

The iAE6 experiment provides a real and sufficiently complex case to constitute a representative example of the collaborative processes that exist in the innovation ecosystems generated around DIHs. The application of IOTAM to this case initially requires defining the source, destination, channels and assets involved in the collaboration process. The example provided by the iAE6 experiment involves, as shown, three collaborating organisations, any of which can act as both the source and destination of assets during the collaboration process. This circumstance provides six potential collaboration channels (Table 6; Fig. 14):

The next step in this bottom-up process is to carry out an analysis to identify the different service types exchanged during the collaboration process, regardless of their origin or destination, into the most elementary services of among the 20 possible types of organisations' services portfolio (Table 7).

Table 7 shows the service macroclasses and service types named and numbered according to the D-BEST portfolio, set out in Table 4, as well as their translation into the IOTAM code, which numbers them with a single digit from 1 to 20 (Fig. 6). Hereafter in this article, the code used will be IOTAM. To follow this process, collaboration activities have

Table 6 Collaboration channels in the use case

Channel	Collaboration origin or asset transferor	Collaboration destination or asset receiver
Channel 1	UPV	ITI
Channel 2	ITI	UPV
Channel 3	UPV	MULTISCAN
Channel 4	MULTISCAN	UPV
Channel 5	ITI	MULTISCAN
Channel 6	MULTISCAN	UPV

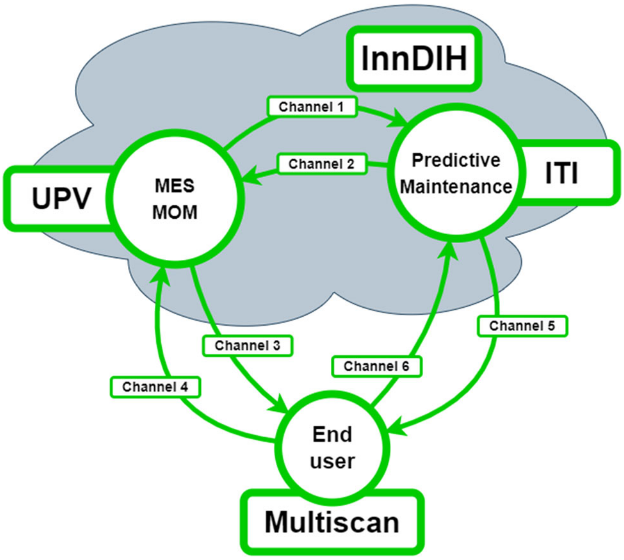


Fig. 14 iAE6 detailed organisation with all the collaboration channels opened among the UPV, ITI and Multiscan

Table 7 List of services identified during the collaborative exchange process

Service Macroclass	Service type	Service type (IOTAM code)	Service type name
Ecosystem	1.3	3	Ecosystem governance
Technology	2.1	4	Ideas management and materialisation
Technology	2.2	5	Contract research
Technology	2.3	6	Provision of infrastructure
Technology	2.4	7	Technical support on scale up
Skills	4.3	15	Skill improvement
Data	5.1	16	Data acquisition and sensing
Data	5.3	18	Decision-making
Data	5.5	20	Data Sharing

to be decomposed channel by channel. In the iAE6 experiment, this decomposition would take the following form (Table 8):

As previously indicated in the conceptual framework presentation, there is the possibility of adding an additional characterisation layer to the exchange of the collaborative relationships among the three entities because, as for each service type, the D-BEST model provides an additional classification level called service class (Table 4). So it is feasible to measure the service depth of collaborative interrelationships by simply counting the number of service classes involved in each individual asset flow, e.g. on a percentage basis. By this approach, let us take a closer look at each elementary service to better understand their rationale from a general perspective. Tables 9, 10, 11, 12, 13 and 14 show the services provided by each collaboration, described per channel as displayed in Table 8 (the truly involved service classes are marked in bold):

After identifying the channels with their respective origins and destinations, decomposing the collaboration process into elementary services, classifying these elementary services into types and calculating the service depth, the next stage in the process is to determine both the assets involved in each elementary service and their typology among the five possible ones: competences, knowledge, technology, infrastructure and funds (Table 15). This provides a first detailed overview of the flow of the assets involved in the collaboration process.

The codes used in columns C, K, T, I and F of Table 15 result from combining the initial letter of the asset name and the IOTAM code of the involved service. For example, code K3 implies knowledge transfer in the Ecosystem Governance

Table 8 Service decomposition of the collaboration process

Channel	Origin–destination	Service Macroclass	Service type	Service type name
Channel 1	UPV → ITI	Ecosystem	3	Ecosystem governance
		Technology	4	Ideas management and materialisation
		Data	16	Data acquisition and sensing (Training dataset acquisition, preparation and sharing)
		Data	17	Data processing and analysis
Channel 2	ITI → UPV	Data	17	Data processing and analysis
		Data	20	Data Sharing (Predictive maintenance model training, building, and sharing)
Channel 3	UPV → MULTISCAN	Ecosystem	3	Ecosystem governance
		Technology	4	Ideas management and materialisation
		Technology	5	Contract research
		Technology	7	Technical support on scale up
		Skills	15	Skill improvement
		Data	16	Data acquisition and sensing
		Data	18	Decision-making
		Data	20	Data Sharing
Channel 4	MULTISCAN → UPV	Technology	4	Ideas management and materialisation
		Technology	6	Provision of infrastructure
		Technology	7	Technical support on scale up
		Skills	15	Skill improvement
		Data	16	Data acquisition and sensing
Channel 5	ITI → MULTISCAN	Technology	5	Contract research
		Skills	15	Skill improvement
		Data	16	Data acquisition and sensing
		Data	18	Decision-making
		Data	20	Data Sharing
Channel 6	MULTISCAN → UPV	Technology	6	Provision of infrastructure
		Skills	15	Skill improvement
		Data	16	Data acquisition and sensing

Table 9 Rationale of the elementary services of Channel 1 UPV → ITI

Service Macroclass	Service type	Service type name	Service class	Service depth	
Ecosystem	3	**Ecosystem governance:** in the role of the iAE6 experiment leader, the UPV provides ITI with both the service impact assessment through the corresponding key performance indicators and ecosystem management, which includes engagement rules and governance structure to ease relationships among organisations	**1.3.1. Service impact assessment** **1.3.2. Ecosystem management**	2 Out of 2	100%
Technology	4	**Ideas management and materialisation:** the UPV, based on the pilot knowledge, generates the idea for the application experiment, evaluates it and analyses its feasibility by subsequently involving ITI in the generated idea	**2.1.1. Ideas generation, assessment, and feasibility study** 2.1.2. Technology readiness assessment	1 Out of 2	50%
Data	16	**Data acquisition and sensing (Training dataset acquisition, preparation and sharing):** training data acquisition for preventive maintenance comes mainly from the MES/MOM management system, which acts as a central hub by collecting and contextualising sensor data	**5.1.1. Data acquisition** 5.1.2. Data protection	1 Out of 2	50%
Data	17	**Data processing and analysis:** Data are prepared in a first stage from the side of UPV according to the requirements of the analytic models for predictive maintenance	5.2.1. Data storage **5.2.2. Data analytics**	1 Out of 2	50%
			Collaboration average depth	5 Out of 8	63%

Table 10 Rationale of the elementary services of Channel 2 ITI → UPV

Service Macroclass	Service type	Service type name	Service class	Service depth	
Data	17	**Data processing and analysis:** Data are prepared from the side of ITI according to the requirements of the front-end systems	5.2.1. Data storage **5.2.2. Data analytics**	1 Out of 2	50%
Data	20	**Data sharing:** ITI, for being responsible for designing the predictive maintenance models, defines both the data space on which data models and data formats are to be used. The security standards adopted in the system architecture enable secure and reliable data exchange. ITI also provides the data and computing infrastructure to enable the training of the model, and provides connection services to ingest the train the datasets delivered by the UPV. The trained models are then deployed using secure interfaces	5.2.2 Data analytics 5.5.1. General Data Protection Regulation (GDPR) **5.5.2. Data spaces** **5.5.3. Data Platform**	2 Out of 3	67%
			Collaboration average depth	3 Out of 5	60%

Table 11 Rationale of the elementary services of Channel 3 UPV → MULTISCAN

Service Macroclass	Service type	Service type name	Service class	Service depth	
Ecosystem	3	**Ecosystem governance:** as the iAE6 experiment leader, the UPV provides the multiscan both the service impact assessment through the corresponding KPIs and ecosystem management, including engagement rules and governance structure to ease relationships among organisations	**1.3.1. Service impact assessment** **1.3.2. Ecosystem management**	2 Out of 2	100%
Technology	4	**Ideas management and materialisation:** the UPV, based on pilot knowledge, generates the idea for the application experiment, evaluates it and analyses its feasibility, and subsequently involves MULTISCAN in the process	**2.1.1. Ideas generation, assessment, and feasibility study** 2.1.2. Technology readiness assessment	1 Out of 2	50%
	5	**Contract research:** as one of the main elementary services of the collaboration carried out in the iAE6 experiment, UPV researches and develops to support the conversion of the initial idea of improving the Multiscan grading and sorting line by implementing MES/MOM systems into a demonstrable concept by applying technological innovation to improve it	**2.2.1. Strategic and specific research and development (R&D)** **2.2.2. Technology concept development/proof of concept (PoC)**	2 Out of 2	100%
	7	**Technical support on scale up:** with this service, the UPV validates the previously researched concept, developed with the participation of Multiscan to confirm its feasibility, firstly in a controlled laboratory environment and then in a real industrial relevant environment for the iAE6 experiment at the pilot company's facilities: SAT Costa de Níjar, Multiscan's customer	**2.4.1. Concept validation** **2.4.2. Prototyping**	2 Out of 2	100%
Skills	15	**Skill improvement:** with this service, the UPV undertakes the task of training and retraining Multiscan's human resources specifically involved in the design, production and maintenance of the MGS cherry tomato grading and sorting line PL18007, in everything related to the MES/MOM systems researched, developed and validated in previous stages. The objective is to acquire the necessary knowledge and technical skills through training, refinement and retraining workshops, both online and on-site, on the pilot's premises. This training includes support for training in the production and maintenance of human resources of Multiscan's customer, SAT Costa de Níjar	**4.3.1. Human up-skilling and re-skilling training** 4.3.2. Educational programmes 4.3.3. Scouting and brokerage	1 Out of 3	33%

Table 11 (continued)

Service Macroclass	Service type	Service type name	Service class	Service depth	
Data	16	**Data acquisition and sensing:** this service refers mainly to the necessary tasks to define the data acquisition methods from the sensors of the sorting and grading line, the pilot's ERP, the production context, etc., to feed the MES/MOM management system	**5.1.1. Data acquisition** 5.1.2. Data protection	1 Out of 2	50%
	18	**Decision making:** with this service, the UPV integrates the tasks needed to generate decision support systems and developments by analysing the data present in the back end of MES/MOM solutions, including prediction, prescription, simulation or formal logic	5.3.1. Cognitive big data architecture **5.3.2. Decision support and development**	1 Out of 2	50%
	20	**Data sharing:** following the rules and methods defined by ITI, the UPV is responsible for the system architecture, and generates the data models and ontologies used in the data exchange of the MES/MOM systems	5.5.1. General Data Protection Regulation (GDPR) **5.5.2. Data spaces** 5.5.3. Data Platform	1 Out of 3	33%
			Collaboration average depth	11 Out of 18	61%

service type; code C15 denotes the transfer of competences in the Skill Improvement service type. All these collaboration interrelationships are graphically represented in Fig. 15.

It is interesting to note some points in relation to Table 15 and Fig. 15. As the purpose of the experiment is for the organisations belonging to the involved DIH, InnDIH (UPV and ITI) to provide support to the end user (MULTISCAN), the two channels where Multiscan was the destination of collaboration were expected to present a greater assets flow, as shown by the aforementioned table and figure. Both were also expected to show at first glance the specific case of the iAE6 experiment to have a strong cognitive and technological component, typical of collaborations whose aim is R&D and innovation. However, this is something that ultimately depends on not only the number of involved assets, but also on their quantification. Another issue to highlight is service depth data, which provide information on how many service types are involved in collaboration. If a service depth is not 100%, it can have two meanings: collaboration does not include all the services in the organisation's detailed portfolio because there is no need for this; or the organisation is not capable of providing them and, if that service type is required, it must be provided by another organisation.

Once each involved asset flow is identified, the last stage of the process is precisely that: quantify asset flows. To do so, organisations must firstly select the most appropriate measurement units for the assessment, which depends on both the asset type and the organisation itself. In our case, all the involved assets can be measured in terms of the time spent by the organisations' different human resources categories (Table 16); e.g. the average persons per month for a period of time, which is usual in research projects like DIH4CPS. Tables 17, 18, 19, 20, 21 and 22 show an example of iAE6 project completion by considering an 18-month period to run the experiment (the given figures are not real and are only intended to show how to complete this process step):

In order to summarise the data about the quantification of asset flows, classified by organisations, a table can be compiled as follows (Table 23):

With all this collected information (without going into further disquisitions about the efficiency of the collaboration channel, which is dealt with more extensively in the next section), it can be stated that the collaboration among UPV, ITI, and Multiscan in the iAE6 experiment is fully mapped, characterised and quantified.

Discussion

The conceptual framework presented and outlined in this article, which has been developed to descriptively address collaboration in the relational network of European innovation ecosystems context, can be discussed on several fronts as herein anticipated: (i) one first aspect to comment on stems from its aptitude as a lever to move towards a solid collaboration model; (ii) a second point to consider arises from its

Table 12 Rationale of the elementary services of Channel 4 MULTISCAN → UPV

Service Macroclass	Service type	Service type name	Service class	Service depth	
Technology	4	**Ideas management and materialisation:** MULTISCAN collaborates with UPV by providing the necessary information for this process	**2.1.1. Ideas generation, assessment, and feasibility study** 2.1.2. Technology readiness assessment	1 Out of 2	50%
	6	**Provision of infrastructure:** Here Multiscan, as the only organisation with a contractual connection to the pilot company, S.A.T. Costa de Níjar, organises everything necessary to provide UPV with access to the infrastructure provided by the pilot company, as well as all the assistance required from the administration, production and maintenance staff of this company	**2.3.1. Access to infrastructure and technological platforms**	1 Out of 1	100%
	7	**Technical support on scale up:** MULTISCAN collaborates with UPV by providing the necessary information for this process	**2.4.1. Concept validation** **2.4.2. Prototyping**	2 Out of 2	100%
Skills	15	**Skill improvement:** MULTISCAN's staff attend the training and retraining activities taught by the UPV related to the MES/MOM solutions	**4.3.1. Human up-skilling and re-skilling training** 4.3.2. Educational programmes 4.3.3. Scouting and brokerage	1 Out of 3	33%
Data	16	**Data acquisition and sensing:** MULTISCAN collaborates with UPV by providing the necessary information for this process, mainly documentation describing how to access the industrial variables available in the OPC UA interface and what information they convey	**5.1.1. Data acquisition** 5.1.2. Data protection	1 Out of 2	50%
			Collaboration average depth	6 Out of 10	60%

connotations regarding interoperability; (iii) to conclude the discussion, a third point worth looking closely at is sustainability repercussions.

A thorough conceptualisation and understanding of the interaction processes involved in the collaboration between the existing entities in an innovation ecosystem, basically and usually formed around DIHs or EDIHs, requires identifying, characterising and organising their elements, structure, parameters and variables, and also providing a quantitative nuance so that the developed framework serves as a lever for solid modelling that facilitates a methodology to assess in practice the magnitude of collaboration between two organisations. As noted in the previous section, this is possible by mapping and identifying each individual asset transfer flow because, once the two ends of the channel are identified and point to a very specific asset type, it is possible to value them and the transfer flow magnitude between organisations, which serves as the primary piece of calculation of any complex case, as seen in the use case. So it is necessary to quantify all the individual asset transfer flows that occur between transferor and receiver organisations.

From the above starting point to quantify the collaboration involving a given $\mathrm{F}^{\mathrm{A-T}}_{\mathrm{O-O'}}$ individual flow of transfer from one organisation O to another O', the first degree of added complexity in quantification terms comes from considering that the collaboration of O with O' covers several fronts and, thus, integrates several individual asset flows. The sum of the magnitudes of the different individual flows involves having to standardise units of measurement. When talking about competences, knowledge, technology or infrastructure, it is possible to use the spent time or the use of assets and the monetary value. However, this is not the case when the asset is funding: in principle, it is only possible to use the monetary value of the transfer as the unit of measurement. Therefore, one aspect to consider in this respect would be that the sum of the magnitudes of transfer flows requires the monetary value

Table 13 Rationale of the elementary services of Channel 5 ITI → Multiscan

Service Macroclass	Service type	Service type name	Service class	Service depth	
Technology	5	**Contract research:** as another of the main elementary services of the collaboration in the iAE6 experiment, ITI researches and develops to support conversion into a demonstrable concept of the initial idea of improving the Multiscan grading and sorting line by implementing a system to detect anomalies in the line's operation and for predictive maintenance by applying technological innovation for these purposes	**2.2.1. Strategic and specific research and development (R&D)** **2.2.2. Technology concept development/proof of concept (PoC)**	2 Out of 2	100%
Skills	15	**Skill improvement:** with this service, ITI undertakes the task of training and retraining Multiscan's human resources specifically involved in maintaining the MGS cherry tomato grading and sorting line PL18007, in everything related to the systems researched for anomaly detection and predictive maintenance, developed and validated in previous stages. The objective is to acquire the necessary knowledge and technical skills through training, refinement and retraining workshops, both online and on-site, on the pilot's premises. This training includes support in the training of the maintenance human resources of Multiscan's customer, SAT Costa de Níjar	**4.3.1. Human up-skilling and re-skilling training** 4.3.2. Educational programmes 4.3.3. Scouting and brokerage	1 Out of 3	33%
Data	16	**Data acquisition and sensing:** this service refers mainly to the necessary tasks to define the data acquisition methods from the sensors of the sorting and grading line and the MES/MOM management system to feed the module for anomaly detection and prescriptive maintenance	**5.1.1. Data acquisition** 5.1.2. Data protection	1 Out of 2	50%
	18	**Decision making:** with this service, ITI integrates the tasks needed to generate decision support systems and developments by analysing the data present in the back end of the module for anomaly detection and predictive maintenance, including cognition, prediction, prescription, simulation, machine learning or formal logic	5.3.1. Cognitive big data architecture **5.3.2. Decision support and development**	1 Out of 2	50%
	20	**Data sharing:** ITI, which is responsible for the system's architecture, designs both the data space on which data models and ontologies that enable secure and reliable data exchange are based, and the data platform that enables the development of the architecture and its components, and provides connection services	5.5.1. General Data Protection Regulation (GDPR) **5.5.2. Data spaces** 5.5.3. Data Platform	1 Out of 3	33%
			Collaboration average depth	6 out of 12	50%

Table 14 Rationale of the elementary services of Channel 6 MULTISCAN → ITI

Service Macroclass	Service type	Service type name	Service class	Service depth	
Technology	6	**Provision of infrastructure:** Here Multiscan, as the only organisation with a contractual connection to the pilot company, SAT Costa de Níjar, organises everything necessary to provide ITI with access to the infrastructure provided by the pilot company, as well as all the assistance required from the administration, production and maintenance staff of this company	**2.3.1. Access to infrastructure and technological platforms**	1 Out of 1	100%
Skills	15	**Skill improvement:** MULTISCAN's staff attend the training and retraining activities taught by the ITI related to the module for anomaly detection and predictive maintenance	**4.3.1. Human up-skilling and re-skilling training** 4.3.2. Educational programmes 4.3.3. Scouting and brokerage	1 Out of 3	33%
Data	16	**Data acquisition and sensing:** MULTISCAN collaborates with ITI by providing the necessary information for this process	**5.1.1. Data acquisition** 5.1.2. Data protection	1 Out of 2	50%
			Collaboration average depth	3 out of 6	50%

to be used as the unit of measurement, unless no funding takes place. This is extensible to more complex cases that involve collaboration between more than two organisations.

The next degree of complexity in the calculation arises when not only organisation O transfers assets to O′, but simultaneously organisation O′ also transfers others to O. Thus both organisations simultaneously act as transferors and receivers. The mutual collaboration involved in this case can be quantitatively analysed from a twofold perspective: (i) on the one hand, the total flow of existing collaboration by the two entities can be calculated by adding the total of the individual transfer values issued in both directions; (ii) on the other hand, it may be useful to obtain the final balance of the collaboration between both entities and find out which one offers collaboration surplus, which presents a deficit, as well as the magnitude of the difference, which implies subtracting the flows from one organisation to another.

Finally, the highest degree of complexity in the calculation occurs when, as is often the case in DIH networks, more than two organisations are involved in a multiple simultaneous collaboration process, as in the use case. IOATM allows this type of problem to be scaled from the simplest above-explained case because any of these complex problems is simply the composition of dual subproblems, i.e. problems formed around two organisations. Therefore, conversely, the problems generated around multiple organisations can be simplified by decomposing them into subproblems formed by pairs of organisations and their corresponding asset transfers. From this point, the valuation of the total collaboration between all the collaborative entities results from adding all the existing dual subproblems. With this in mind, this conceptual framework, therefore, provides a scalable and adaptable tool for modelling collaboration in innovation ecosystems consisting of numerous organisations. Finally, it is worth mentioning that a model developed from this framework should also incorporate some nuance parameters that modify the calculated values, depending on some notable factors that can alter the efficiency of collaboration, such as the harnessing degree of collaboration in the receiving organisation, asset transfer efficiency depending on the interoperability degree that exists through the transfer channel, as discussed later, or the efficiency of the transfer impulsion exerted by the transferor entity (Fig. 16). These three factors can be subject to variations due to the many causes that require an analysis, along with future modelling.

The approach provided within this framework to the collaborative process is based on considering it to be an assets flow from a first organisation to a second one to increase the latter's capabilities to provide services according to the D-BEST model categorisation and using the mapping of asset types as support. As a system, this approach represents a tool to standardise and specify the basic elements that intervene in any collaborative interaction process in an innovation ecosystem. For this reason, it is considered essential to establish the framework. Despite being indispensable, this tool does not

Table 15 Asset flows of the collaborative processes in iAE6

Channel	Origin–destination	Service Macroclass	Service type	Service type name	Service depth (%)	Asset				
						C	K	T	I	F
Channel 1	UPV → ITI	Ecosystem	3	Ecosystem governance	100		K3			
		Technology	4	Ideas management and materialisation	50		K4			
		Data	16	Data acquisition and sensing	50			T16		
		Data	17	Data processing and analysis	50			T17		
Channel 2	ITI → UPV	Data	17	Data processing and analysis	50			T17		
		Data	20	Data sharing	67			T20		
Channel 3	UPV → MULTISCAN	Ecosystem	3	Ecosystem governance	100		K3			
		Technology	4	Ideas management and materialisation	50		K4			
		Technology	5	Contract research	100			T5		
		Technology	7	Technical support on scale up	100		K7			
		Skills	15	Skill improvement	33	C15				
		Data	16	Data acquisition and sensing	50			T16		
		Data	18	Decision-making	50			T18		
		Data	20	Data sharing	33			T20		
Channel 4	MULTISCAN → UPV	Technology	4	Ideas management and materialisation	50			T16		
		Technology	6	Provision of infrastructure	100		K4		I6	
		Technology	7	Technical support on scale up	100		K7			
		Skills	15	Skill improvement	33	C15				
		Data	16	Data acquisition and sensing	50					
Channel 5	ITI → MULTISCAN	Technology	5	Contract research	100			T5		
		Skills	15	Skill improvement	33	C15				
		Data	16	Data acquisition and sensing	50			T16		
		Data	18	Decision-making	50			T18		
		Data	20	Data sharing	33			T20		
Channel 6	MULTISCAN → ITI	Technology	6	Provision of infrastructure	100				I6	
		Skills	15	Skill improvement	33	C15				
		Data	16	Data acquisition and sensing	50			T16		

Abbreviations for assets: C (competences), **K** (knowledge), **T** (technology), **I** (Infrastructure), **F** (Funds)

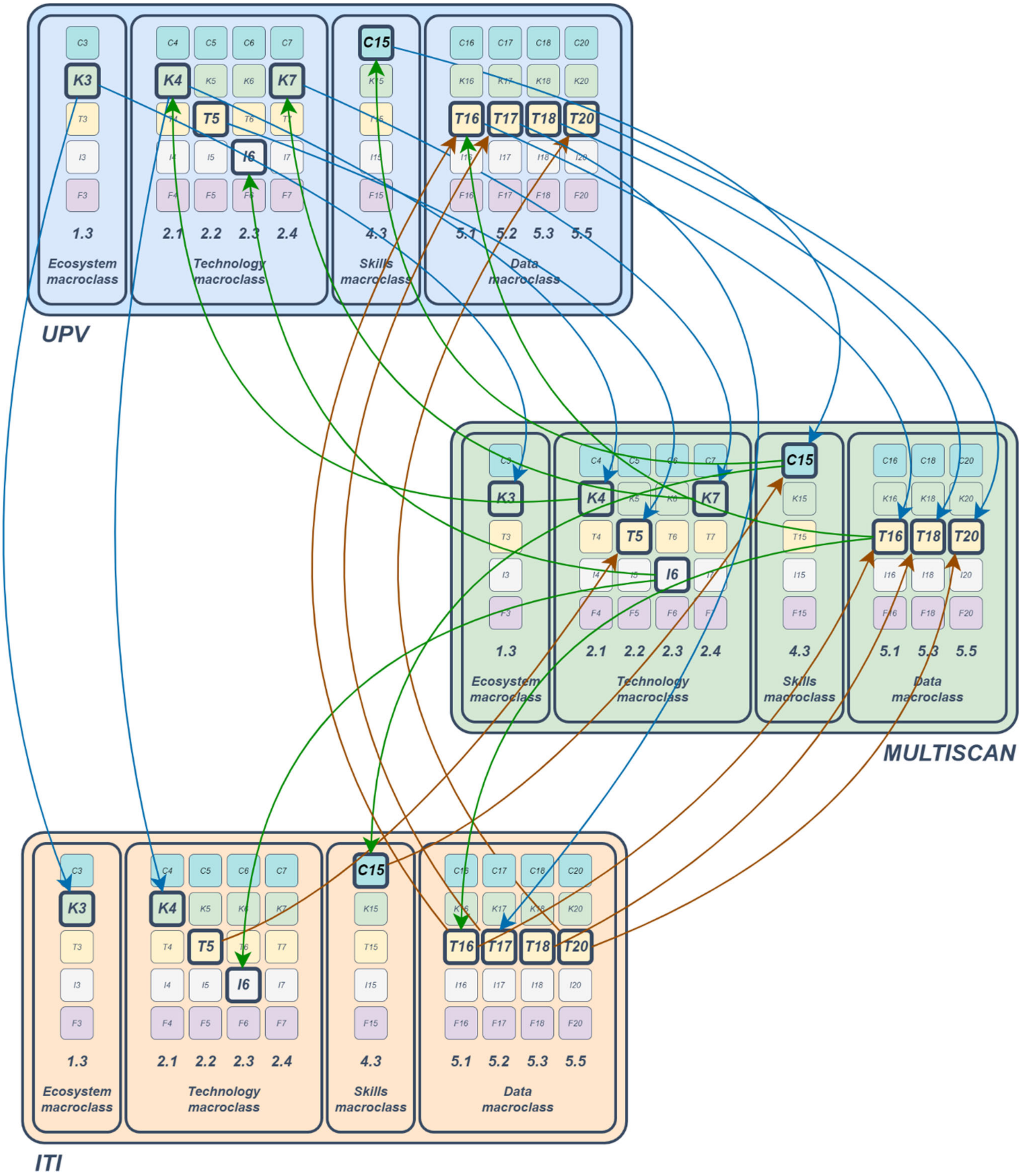


Fig. 15 Asset flow map of the collaboration interrelationships between the UPV, ITI and MULTISCAN

Table 16 Professional categories involved in collaboration

	UPV and ITI	Multiscan
Categories	MR: Main researcher	M: Department Manager
		ST: Senior technician
	PoD: PostDoc researcher	JT: Junior technician
	PrD: PreDoc researcher	SW: Skilled worker

Table 17 Quantification of asset flows of the collaborative processes in iAE6 for Channel 1 UPV → ITI (person × months)

Channel	Origin–destination	Service type	Service type name	K				T			
				Type	MR	PoD	PrD	Type	MR	PoD	PrD
Channel 1	UPV → ITI	3	Ecosystem governance		K3	0.05	0.25	0.90			
		4	Ideas management and mat		K4	0.05	0.15				
		16	Data acquisition and sensing						T16	0.25	
		17	Data processing and analysis						T17	0.20	
SUBTOTALS					0.10	0.40	0.90			0.45	

Table 18 Quantification of asset flows of the collaborative processes in iAE6 for Channel 2 ITI → UPV (person × months)

Channel	Origin–destination	Service type	Service type name	T			
				Type	MR	PoD	PrD
Channel 2	ITI → UPV	17	Data processing and analysis	T17		0.05	0.20
		20	Data Sharing	T20		0.05	0.45
SUBTOTALS						0.10	0.65

constitute a sufficient resource to create a robust model by itself because, although it allows the definition of both the origin and destination of the assets flow and the transferred asset itself, as stated above, it is essential to pay attention to the environment through which the transfer occurs because this medium must be enable an efficient flow for collaboration to optimally materialise. Efficiency here means that the asset flow occurs between both organisations under interoperability conditions and these conditions are sustainable from a comprehensive perspective, i.e. organisations are interoperable at (i) the data level, (ii) the service level, (iii) the process level and (iv) the business level (Fig. 17), and all from the triple dimension of conceptual, technological and organisational barriers (Ducq et al., 2012).

Indeed the value of the transferred assets may be altered by the greater or lesser ability of the organisations involved to access and process data from their multiple sources without losing meaning and subsequently integrating them so that any of them can locate, explore and grasp the structures and contents of datasets. Thus an efficient collaborative process requires the prior assessment of interoperability at the data level. The same applies when the asset transfer is performed through distributed systems, and the ability to cooperate in services that imply data exchanges, despite differences in language, interface and execution platforms (Fang et al., 2004), is also crucial. Hence troubles with the interoperability at the service level can prove to be a disturbing factor that needs evaluation and control, a task that must be done from a comprehensive perspective and involves interoperability sublevels, such as the signature, protocol, semantic, quality and context sublevels (Strang and Linhoff-Popien, 2003). In networked environments, such as the entities making up innovation ecosystems, it is no less important to ensure that the processes of those organisations that interact to collaborate are designed to work together (federated relationship approach) or are even conceived from the outset as a single common process (integrated relationship approach) (Ducq

Table 19 Quantification of asset flows of the collaborative processes in iAE6 for Channel 3 UPV → Multiscan (person × months)

Channel	Origin–destination	Service type	Service type name	C				K				T			
				Type	MR	PoD	PrD	Type	MR	PoD	PrD	Type	MR	PoD	PrD
Channel 3	UPV → Multiscan	3	Ecosystem governance					K3	0.15	0.40					
		4	Ideas management and mat					K4	0.20	0.50	1.05				
		5	Contract research									T5	0.40	1.00	2.05
		7	Technical support on scale up					K7		0.35	0.55				
		15	Skill improvement	C15		0.40									
		16	Data acquisition and sensing									T16		1.25	
		18	Decision-making									T18	0.05	0.70	1.80
		20	Data Sharing									T20		0.55	1.45
SUBTOTALS						0.40			0.35	1.25	1.60		0.45	3.80	5.30

Table 20 Quantification of asset flows of the collaborative processes in iAE6 for Channel 4 Multiscan → UPV (person × months)

Channel Origin–destination		Service type	Service type name	C					K				
				Type	M	ST	JT	SW	Type	M	ST	JT	SW
Channel 4	Multiscan → UPV	4	Ideas management and mat						K4	0.10	0.20		
		7	Technical support on scale up						K7				
		15	Skill improvement	C15		0.50	1.20	4.00				0.05	
SUBTOTALS						0.50	1.20	4.00		0.10	0.20	0.05	

Channel Origin–destination		Service type	Service type name	T					I				
				Type	M	ST	JT	SW	Type	M	ST	JT	SW
Channel 4	Multiscan → UPV	6	Provision of infrastructure						I6	0.05	0.10		
		16	Data acquisition and sensing	T16			0.10						
SUBTOTALS							0.10			0.05	0.10		

Table 21 Quantification of asset flows of the collaborative processes in iAE6 for Channel 5 ITI → Multiscan (person × months)

Channel Origin–destination		Service type	Service type name	K				T			
				Type	MR	PoD	PrD	Type	MR	PoD	PrD
Channel 5	ITI → Multiscan	5	Contract research					T5	0.30	1.00	1.75
		15	Skill improvement	C15		0.40					
		16	Data acquisition and sensing					T16		1.00	
		18	Decision-making					T18	0.05	0.65	2.05
		20	Data Sharing					T20		0.90	2.20
SUBTOTALS						0.40			0.35	3.55	6.00

et al., 2012). Taking this step to address the necessary interoperability at the process level is crucial to safeguard the efficiency of the transfer of such transfer-sensitive assets as knowledge. To succeed in this, a significant part of the effort should focus on modelling network processes and defining system objectives (Ducq et al., 2012) from a collaborative working perspective. Regarding the last interoperability level (that of business), it must be seen as the last link in the chain that joins collaboration to efficiency through interoperability. Collaborative entities must be able to collaborate both organisationally and operationally with their network partners, and regardless of them being at the same or a different relationship level, or if they are to effectively establish, conduct and develop their relationships supported by information and communication technologies to create value in order to prevent that different legislation, corporate cultures, general, specific working procedures, or decision-making methodologies to undermine the effectiveness of the transfer of assets in collaborative processes. At this level and to that end, practicality must prevail. So the task of being interoperable will require addressing four challenges: (i) the interoperability of integrated value networks; (ii) the economic evaluation of business interoperability; (iii) the determination of optimal interoperability levels; (iv) the design of internal and interorganisational systems and process architectures for interoperability (Legner & Lebreton, 2007). All this needs to be taken into account from a managerial viewpoint.

Nowadays, sustainability is, and rightly so, a cross-cutting concern in practically any sector and activity. Collaboration between organisations does not escape this growing

Table 22 Quantification of asset flows of the collaborative processes in iAE6 for Channel 6 Multiscan → ITI (person × months)

Channel Origin–destination		Service type	Service type name	I					C				
				Type	M	ST	JT	SW	Type	M	ST	JT	SW
Channel 6	Multiscan → ITI	6	Provision of infrastructure	I6	0.05	0.10							
		15	Skill improvement						C15		0.45	1.20	3.80
SUBTOTALS					0.05	0.10					0.45	1.20	3.80

Channel Origin–destination		Service type	Service type name	T				
				Type	M	ST	JT	SW
Channel 6	Multiscan → ITI	16	Data acquisition and sensing	T16			0.10	
SUBTOTALS							0.10	

trend, certainly not between organisations willing to network, which is the case of the entities belonging to the innovation ecosystems created in Europe around DIHs and/or EDIHs. It is common for the results of collaboration to fall short of expectations because the ability to obtain satisfactory results depends on many factors that are not often taken into account by organisations. Collaboration can confer organisations mutual benefits by helping to bridge gaps through shared effort. However, these potential advantages should not divert our attention from the fact that collaboration does not always work well, and certainly not in all contexts. Collaborative interaction processes can be misused. It is worth remembering that the complexities involved in collaboration may be used to promote certain vested interests. Actors with resources and skills can use the legitimising power of collaborative initiatives to promote their own agendas. Therefore, the first questions to ask at the beginning of every collaborative practice are: What is the purpose of this collaboration? Whose interests does it potentially serve? To a great extent, the sustainability of a collaborative relationship depends on the answer to these questions. Conduct in collaboration can be determined by monitoring techniques, such as audits or verifications of best practices, at a more qualitative level and, crucially, by quantitative evaluation methodologies based on accounting and statistics (Fadeeva, 2005). This is where the herein proposed framework takes centre stage because it enables these evaluation avenues by taking a quantitative approach.

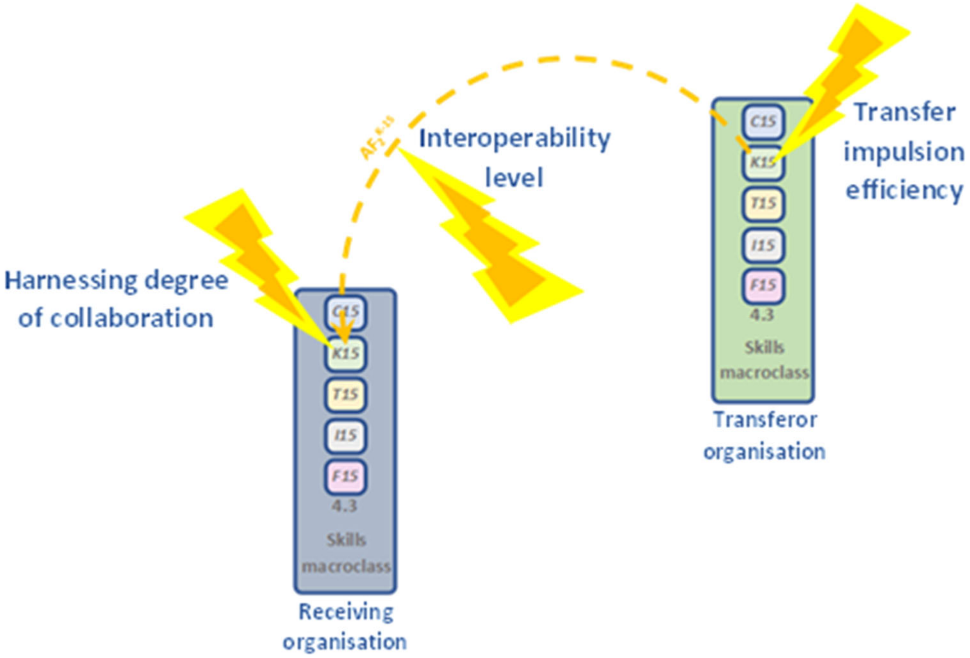
Conclusion

This article presents a conceptual framework that firstly defines and structures the relational network of European innovation ecosystems driven by the EC's Digitise European Industry and Digital Europe Programme initiatives as a whole. Secondly, it provides theoretical and conceptual support to the existing interaction processes horizontally along their relationship levels and vertically between them from a dual qualitative and quantitative perspective. The purpose of this framework is twofold. On the one hand, the initial aim is to bridge the gap in research into collaboration between DIHs by providing a broader conceptualisation of the elements, structure, interrelationships and content making up the materialised interactions between organisations in the collaborative environment that exist in a network generated from DIHs and/or EDIHs. On the other hand, the framework must represent an effective lever for moving towards a model for collaboration in this context. This research can contribute significantly to develop advanced analysis and evaluation tools in collaborative processes, which can provide a robust response to interorganisational interaction problems. From a previous and global definition of the pan-European space of action of DIHs, on which its four levels of relationship are delineated, the article begins by defining the main concepts involved within the scope of this research work: (i) the organisation types existing in the relational network of European innovation ecosystems; (ii) the types of interaction not aligned with the collaboration concept; (iii) the types of interaction aligned with the collaboration concept. Likewise, the article indicates which definition of collaboration is adopted as the first reference for research, whose authors are Wankmüller and Reiner (2020): "Process of strategically working together on a specific business activity where structures are aligned, communication channels are standardised, risks are shared, and resources are pooled in order to make them available for every partner". Subsequently, the classification of the D-BEST model services by Sassanelli and

Table 23 Summary table on the quantifications of asset flows (person × months)

Channel	Origin–destination	Staff categories	Asset					Subtotal	Total
			C	K	T	I	F		
Channel 1	UPV → ITI	MR		0.10	0.45			0.55	1.85
		PoD		0.40				0.40	
		PrD		0.90				0.90	
Channel 2	ITI → UPV	MR							0.75
		PoD			0.10			0.10	
		PrD			0.65			0.65	
Channel 3	UPV → MULTISCAN	MR	0.40	0.35	0.45			0.80	13.15
		PoD		1.25	3.80			5.45	
		PrD		1.60	5.30			6.90	
Channel 4	MULTISCAN → UPV	M		0.10	0.10	0.05		0.15	6.30
		ST	0.50	0.20		0.10		0.80	
		JT	1.20	0.05				1.35	
		SW	4.00					4.00	
Channel 5	ITI → MULTISCAN	MR		0.40	0.35			0.35	10.30
		PoD			3.55			3.95	
		PrD			6.00			6.00	
Channel 6	MULTISCAN → ITI	M			0.10	0.05		0.15	5.70
		ST	0.45			0.10		0.55	
		JT	1.20					1.20	
		SW	3.80					3.80	

Fig. 16 Factors altering the efficiency of collaboration



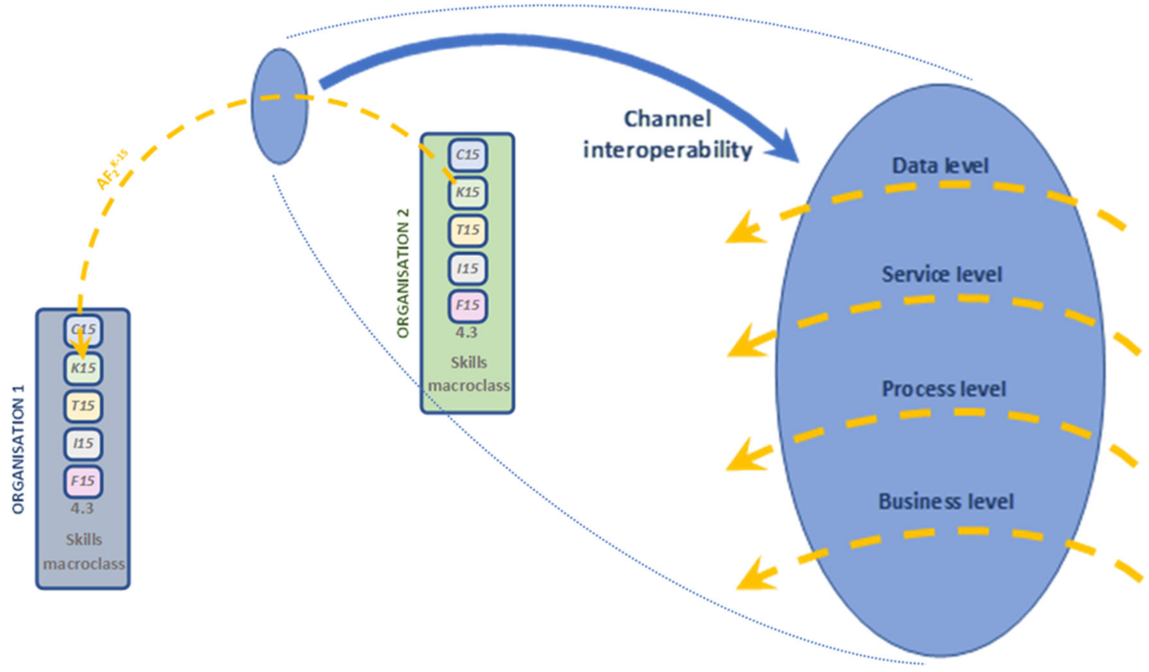


Fig. 17 Components that make up transfer channel interoperability

Terzi (2022) is introduced, which in later sections is crucially important to construct this framework, and the research scope is delimited from the triple perspective of the environment, D-BEST service, and interaction type. On this basis, according to the review of the scientific literature that relates DIH concepts and all the interaction types related to the collaboration process, this research identifies, collects and performs a thematic and content analysis of the 17 selected contributions of the state of the art that is most aligned, partially or totally, and directly or indirectly, with the purpose of the framework. The literature review reaches three main conclusions: (i) most of the selected articles address collaboration between DIHs in a tangential manner; (ii) the research contributions made to date consider the interaction processes for collaboration to be an intangible element of management that is difficult to perceive and, a priori, is not measurable; and (iii) as far as we know from this review, there is still no descriptive or conceptual framework, or a qualitative or quantitative model, that deals with the conceptualisation of the interaction processes of DIHs from the collaboration perspective within and between its four relationship levels. The framework built on a bottom-up approach is presented below. The conceptualisation path guided by this approach starts by explaining the decomposition of the D-BEST services into assets and types. From this decomposition, collaboration can be conceptualised as an assets flow from ceding organisations to beneficiary organisations to alleviate any deficits in the latter and to, thus, enable them to provide some specific service types immediately or in the future. This abstraction, which is called the IOATM, lies at the heart of the conceptual framework and the article for not only establishing the precise origin, destination, channel and transferred asset, but for also representing a theoretical means to quantitatively assess the magnitude of collaboration, which is considered the main contribution of this research. Subsequently, to effectively show how this framework can be implemented in a real situation, a use case that addresses collaborative processes in the iAE6 application experiment of the DIH4CPS project is presented as an example. To do so, all the steps to the full characterisation and quantification of collaboration are detailed. Finally, the contribution of the presented framework is discussed on several fronts: (i) its suitability as a lever for moving towards a strong collaborative model; (ii) its interoperability implications; (iii) its sustainability repercussions.

This approach provides answers to the formulated research questions. The main characteristic to define the interactions that take place between the entities making up the relational DIHs network when collaboration processes materialise between them is the possibility of decomposition into the origin, destination, channel and transferred asset involved in the assets flow of the analysed collaboration, which provides an answer to research question RQ1. From this perspective, both the assets flow and the transfer channels can be considered the two key dimensions in the collaborative interaction processes and the elements that most shape the quantitative assessment of collaboration, dimensions around which the other elements of the proposed framework are positioned: the services catalogue, the levels of relationship involved and the collaborative interaction types, which do not essentially shape, but condition, the assessment. This approach provides an answer to research question RQ2 formulated in the introduction of this article. In the end, the presented framework is discussed on three cardinal fronts: (i) its aptitude as a lever to move towards a collaboration model; (ii) its connotations in interoperability terms; (iii) how it relates to sustainability.

The implications of this framework are substantial. In the academic sphere, it bridges the research gap detected on the analysed topic, and not only contributes a new perspective on collaborative processes in the innovation ecosystems generated by DIHs and/or EDIHs, but also establishes the meaning and interrelationships of the concepts making up its ontology. It provides a nuance that allows quantification, and serves as a lever to model a research object in clear progression, such as collaboration. As for managerial implications, the main one to highlight is that the approach offered by IOATM constitutes the first piece of a future model that will enable dealings with the accounting of collaboration in its multiple facets and, therefore, will turn it into a more tangible and controllable management element. However, it is also worth noting that, in addition, this framework can already constitute a roadmap that helps practitioners to guide their efforts to improve the efficiency of collaborative processes with an approach that pursues objectivity, plus the maximisation of synergies between collaborative entities.

Despite its strengths, the framework presents some limitations that should be outlined here: (i) the D-BEST reference model is specifically oriented to DIHs and, by extrapolation, can work in EDIHs or in organisations that integrate innovation ecosystems in general, such as service providers or end users. Beyond this collaboration scope, the service catalogues and the asset typology may vary that, in turn, implies that the presented framework lacks validity; (ii) it does not offer a plane frame of uniform application for all types of collaboration, but shows variations in interpretation depending on whether interactions are cooperation, coopetition, coordination, etc.; (iii) in multiple collaboration schemes involving more than two organisations, when the transferor organisation simultaneously transfers assets to several receiver organisations, it is not always easy to precisely delimit the assets transferred to each one, especially when intangible assets like competences or knowledge are involved, which implies further effort to specify flows and their direction from their origin through the corresponding mapping. Something similar happens in collaborative processes with several transferor organisations that simultaneously interact with a receiver organisation, which requires additional efforts to delimit asset transfers, this time in the destination.

This research leaves several open doors that can guide future research on the topic under study: (i) the most obvious one is to advance towards modelling the collaborative interaction processes of DIHs and its validation through empirical methods, such as complete case studies or surveys; (ii) in such modelling, it would be very useful to face the challenge posed by the evaluation of the factors that may alter the efficiency of collaboration, such as harnessing degree of collaboration in the receiving entity, asset transfer efficiency depending on the degree of interoperability that exists through the transfer channel, or efficiency of the transfer drive exercised by the transferor entity; (iii) with a view to collaboration sustainability, it also seems appropriate to study in more detail how to monitor and evaluate the behaviours exercised during collaboration processes to avoid misuse, but to mitigate undesired effects on its efficiency.

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Author contributions Julio C. Serrano conceptualised the method described in this framework, implemented it, applied it to the case study, and wrote the main text of the manuscript, tables and figures. José Ferreira provided overall supervision of the text, contributed to the conceptualisation and provided the case study. Ricardo Jardim-Goncalves and Angel Ortiz reviewed the article, contributed to the discussion section and validated the conclusions.

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Data availability The data on which this article is based, including the developed method and case study data, are available upon request. Nevertheless, due to confidentiality considerations, detailed information regarding the development of the pilot used in the case study cannot be publicly disclosed.

Declarations

Conflict of interest No potential conflict of interest is reported by the authors.

Ethical approval Not applicable.

Informed consent Not applicable.

Consent for publication The authors consent that the work entitled “Relational Network of innovation ecosystems generated by digital innovation hubs: a conceptual framework for the interaction processes of DIHs from the perspective of collaboration within and between their relationship levels” for possible publication in the Journal of Intelligent Manufacturing. The authors certify that this manuscript is original and has not been published in whole or in part, nor is it being considered for publication elsewhere.

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