The Architecture and Dynamics of Industrial Ecosystems: Diversification and Innovative Industrial Renewal in Emilia Romagna.

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Abstract

The paper aims at advancing our understanding of the architecture and diversification dynamics of industrial ecosystems, and identifying policies for the innovative industrial renewal of mature economies. Industrial ecosystems are here defined as multi-tiered production systems involving heterogeneous agents operating in sectoral value chains and contributing to the capability domains of the ecosystem (and its participants) with closely complementary but dissimilar sets of resources and capabilities. The geographical boundaries of the industrial ecosystem are shaped by the evolving interdependencies linking organisations within the ecosystem and by the new linkages consolidating beyond that. Thus, the industrial ecosystem is a structured production space centred mainly on its productive organisations, as well as other institutions, intermediaries and demand-side actors, purposefully involved in co-value creation processes along various types of diversification and innovative industrial renewal trajectories. Drawing on a five-year research programme in the Emilia Romagna industrial ecosystem, a number of case studies are introduced to highlight these trajectories and the underpinning structural learning dynamics. The paper concludes by identifying a number of policy implications, focusing on strategies for enhancing the structural readiness of the industrial ecosystem and promoting smart diversification and innovative industrial renewal policies.

Key words: Industrial ecosystem, Production space, Structural readiness, Diversification, Innovative industrial renewal, Industrial policy

JEL classifications: D20, O25, O30

1. Introduction

Over the past two decades, profound structural transformations in the global manufacturing and technology landscapes have reshaped the worlds of production. The geography of production and trade have been redesigned along “glo-cal” networks. Sectoral boundaries have been blurring as a result of global processes of vertical disintegration and industrial reorganisation, while new symbiotic relationships between manufacturing and services have developed. Technological change, technology system integration and the scaling up and diffusion of emerging technologies (robotization and digitalisation in particular) have also led to the ‘genetic mutation’ of traditionally defined sectors (Andreoni and Chang, 2016).

Firms have responded to these transformations by introducing new organizational models characterised by co-opetition and co-value creation, while governments have implemented new industrial policies (Andreoni, 2016). In this context, the rediscovery of the key role of ‘production in the innovation economy’ has been particularly strong in mature industrial economies facing deindustrialisation, industrial commons deterioration, productivity decline and technology lock-in (Pisano and Shih, 2012; Berger, 2013; Locke and Wellhausen, 2014; Andreoni and Chang, 2017; Konzelmann et al., 2017).

In view of disentangling these complex industrial and technological transformations, a new stream of research has proposed various concepts of ecosystems – i.e. entrepreneurial, business, innovation and industrial ecosystem. These approaches share the ‘biological analogy’ of co-evolving systems involving a broad range of interdependent organisations and institutions, co-existing and complementing each other in co-value creation processes.

This paper aims at advancing our understanding of the complex architecture and diversification dynamics of industrial ecosystems and suggesting policies for the innovative industrial renewal of mature industrial economies. Starting from an analytical review of the ecosystem literature and the ways in which it addresses emerging problems in innovation system (IS) studies (Section 2), we advance a new industrial ecosystem framework structured around the concepts of *capability domains* and *sectoral value chains* (Section 3). This new theoretical framework is grounded in complex system thinking and integrates recent ecosystem approaches with resource/capability theories of the firm and industry organisation, structural learning and advancements in evolutionary economic geography, specifically those focusing on related and unrelated diversification. The theoretical framework is the result of a five years research programme on industrial and diversification dynamics in the Emilia Romagna (ER) region. This research adopted a mix-method approach and developed through a number of iterations between theory and evidence. The research programme started in 2013 with a study of the origin, evolution and transformation of the biomedical regional cluster and later in 2015 of the packaging machinery industry and the evolution of regional industrial policies[1].

Within this new framework, section 4 focuses on different types of diversification dynamics responsible for the innovative industrial renewal of industrial ecosystems, either in the form of the ‘emergence’ of new sectoral value chains, or the ‘transformation’ of the existing ones. The ‘decline’ of an industrial ecosystem is thus understood as a transformation failure, that is, the incapacity to govern the transition towards innovative diversification trajectories. Section 5 illustrates these different types of diversification dynamics, and underlying structural learning processes, through company case studies from the ER industrial ecosystem. The industrial ecosystem framework sheds new lights on the ER archetype, specifically its architecture and those diversification dynamics which have made the region able to maintain strong manufacturing and innovation performances for several decades. Section 6 concludes by sketching some industrial policy implications arising from the industrial ecosystem framework, in particular how to enhance the structural readiness of the industrial ecosystem and promote smart diversification and innovative industrial renewal.

2. Industrial and innovation (eco)system thinking: a critical appraisal

Industrial (eco)system thinking can be traced back to the works of Charles Babbage and Fredrick List, and later Alfred Marshall and Allyn Young. Raising concerns about the state of innovation in England, Babbage (1830 and 1835) developed an analysis of (and indicators for) the national IS first, to move then to the study of structural interdependences regulating firms’ scale expansion and, thus, increasing returns in manufacturing systems (Scazzieri, 1993; Andreoni and Scazzieri, 2014). Young (1928) developed this idea further by distinguishing increasing returns arising from roundabout methods of production in *large-scale production* (by large firms or large industries), from those arising from *large production*, that is, an expansion led by increasing reciprocal demand (and supply) in a circular and cumulative causational fashion. List 1885 [1841] advanced a theory of a ‘National System of Political Economy’ where different productive forces (and interests) contribute to the generation of value in the national manufacturing system and the ancillary agriculture and commerce sectors. Marshall (1919 and 1920) recognised that knowledge is ‘the most powerful engine of production’, that ‘organisations aids knowledge’ (1920:138-9) and that there are a number of competitive (mainly learning related) advantages associated with regional agglomerations – thus, the first idea of ‘industrial district’.

Marshall was the first to explicitly highlight the relevance of biological analogies ‘between social and especially industrial organisation on the one side and the physical organisation of the higher animals on the other’ (1920:240)[2]. Specifically, the biology analogy was supposed to help the economist in disentangling processes of compound evolution (as defined by Herbert Spencer; see Niman, 1991) involving heterogenous agents in several rounds of evolution. Despite the fact that Marshall ended building his *Principles* on mechanical analogies, given the impossibility of reconciling heterogeneity with the industry supply curve/cost apparatus (Sraffa, 1926), the biology analogy presents at least three advantages in developing our understanding of industrial dynamics and ecosystems. First, it grounds industrial ecosystems in an evolutionary framework characterised by a complex system of interdependencies linking heterogeneous actors across a number of dimensions (Garnsey, 1998; Garnsey and McGlade, 2006; Dosi and Virgillito, 2017). Second, it suggests the importance of looking at the properties of the ‘habitat’ – i.e. its structure – to understand how and why heterogeneous actors (agency) might be drawn into operating and evolving in a certain direction (structure-induced dynamics). Third, it points to a number of evolutionary (non-linear) dynamics in which divergence and variance arise from (as well as drive) competition, cooperation, adaptation, selection, diversification and speciation[3].

Drawing from the 'biology analogy', a number of scholars have recently rediscovered the idea of ecosystems. The 'ecosystem idea' has been used to embed firms’ value creation internal dynamics within a broader system of co-evolving and interdependent activities performed by multiple heterogeneous players (Garnsey and McGlade, 2006; Teece, 2007; Adner and Kapoor, 2010; Adner, 2012; Pitelis, 2012; Adner et al., 2013; Berger, 2013; Best, 2013; Reynolds and Uygun, 2017). Adner (2012) defines the ecosystem as comprising the set of players (and their complementary assets) that need to be aligned in order for a firm to undertake a value creation process. By focusing on value creation processes, let’s say the production of a new critical product system such as the airbus A380 (Adner and Kapoor, 2010), the ecosystem framework departs from more traditional firm, sectoral and spatial approaches. It does so by redefining the ecosystem around the specific set of interdependent value-creation activities and heterogeneous players involved in the process, including organisations and institutions from industry, government, intermediate institutions and academia as well as markets.

The ecosystem framework does not simply recognise the role of institutions and different types of organisations in shaping innovation and industrial dynamics, it also emphasises two further issues: (i) the fact that the very structure of interdependences among the players in the ecosystem affect their roles and relationships – i.e. their bargaining power, transaction costs, competition and cooperative strategies – and (ii) that these interdependencies are ultimately responsible for path-dependent, co-evolving and emerging processes, as well as auto-reproducing dynamics and positive feedback[4].

The industrial ecosystem approach shares a number of epistemological premises with the IS research programme. The idea of *National IS* (Freeman, 1987; Lundvall, 1992; Nelson, 1993) and *triple helix* (Carlsson and Stankiewicz, 1991) recognise interactions among different players (mainly supply side actors) and different institutions as main drivers of industrial innovation and competitiveness . *Regional IS* (Cooke et al., 2004) as well as localized learning models (Maskell and Malmberg, 1999) assign special relevance to the regional scale and, thus, the role of proximity and localised capabilities. In some cases, these approaches reached out evolutionary economic geography (Boschma and Frenken, 2006), in others rediscovered and systematised important insights from industrial district and clusters research (Marshall, 1920; Becattini, 1989; Brusco, 1982; Breschi and Malerba, 2005). More recently, the *Sectoral System of Innovation and Production* (SSIP) approach (Malerba, 2004; Lee and Malerba, 2017) stressed the importance of sectoral production systems as well as the role of demand side actors in innovation. Finally, the IS framework has been further broadened along the ideas of *Socio-Technical Systems* (Geels, 2004) and better specified in terms of system functions within the *Technological Innovation Systems* research agenda (Hekkert et al, 2007).

Despite their important contributions, alongside a number of problems raised elsewhere (Weber and Truffer, 2017), there are at least five critical challenges that IS frameworks are increasingly facing in interpreting the new worlds of production. The ecosystem approaches present some advantages in dealing with some of these new challenges, at least in terms of their capacity to provide a more flexible, dynamic, systemic and value creation centred representation of innovation and industrial dynamics. Let’s then look at these challenges and how they have been addressed by IS research and what alternatives ecosystem approaches offer.

First, the changing geography of production makes increasingly difficult to identify the ‘real boundaries’ of a national or regional system. While these geographical scales are politically relevant, they tend to undermine more complex configurations and various types of production, technological and market linkages across regions and nations. Thus, while the national and even more the regional scale remains a useful starting point, different criteria are required to identify the most relevant boundaries of the system. Differently from the regional IS literature, in the ecosystem framework, the geographical boundaries of the ecosystem are defined by the value creation processes and the relevant structure of interdependences linking relevant players. To the extent that a supply-side or demand-side player is involved in these processes, then it will be considered integral part of the ecosystem independently from its being (or not) co-located in a certain regional system. The geographical boundaries of the industrial ecosystem are thus shaped by the evolving interdependencies linking organisations and institutions within the ecosystem, and by the new linkages consolidating beyond that through processes of value creation and capture. This dynamic perspective contrasts with the ‘relatively static’ picture offered by regional IS (Reynolds and Uygun 2017).

Second, sectoral boundaries are constantly redefined by global value chains integrating different companies in complex multi-layered structures, while the same companies are undergoing forms of ‘genetic mutation’. For example, a leading company like General Electrics (GE), traditionally specialised in the production of heavy industrial machineries, aviation, power engines, has been undergoing dramatic processes of diversification and, ultimately, mutation with respect to its areas of specialisation. GE is increasingly becoming a leading digital company specialised in the development of industrial sensors and software, mechatronics and digital systems, technology platforms for industrial internet. Differently from the SSIP approach, the ecosystem framework is centred on value- creation and capture processes and activities resulting from interdependent value chains. Given that at each link of the chains, each heterogeneous player can operate across multiple value chains (performing the same or different technology and production functions), the ecosystem framework can better capture co-evolving dynamics triggered by changes across sectoral boundaries of the economy.

Third, understanding technological change in ISs today requires a stronger production-engineering focus on technology platforms, that is, the different types of technologies constituting them, as well as the ways in which challenges in the scaling up of emerging technologies and their commercialisation affect value creation and capture dynamics (Tassey, 2007 and 2010). The tendency in IS studies to focus mainly on innovation, and much less on industrial production, has limited their understanding of technologies and innovation itself. On the contrary, by focusing on issues such as ‘co-innovation risks’ and ‘adoption chain risks’ (Adner 2012), the ecosystem approaches have re-assigned centrality to the production-innovation nexus, including problems associated with product commercialisation and production scaling up.

Fourth, while IS research tends to focus on relations and networks among heterogeneous actors, the structure of these networks often remain underexplored, and in some cases there is a tendency to rely on horizontal/flat network representations. In industrial district research, for example, by overlooking the structural configuration of the production system a number of critical changes in the industrial districts have been missed (Piore and Sabel, 1984; Becattini et al, 2009; Dei Ottati, 2018). The ecosystem approach embraces a truly multi-level complex system representation of innovation and industrial dynamics, thus acknowledging the co-existence of both horizontal and vertical relationships among heterogeneous actors (Oh et al. 2016).

Fifth, and finally, while industrial district research and transition studies have assigned relevance to the culture and society of districts and evolving socio-technical systems, the political economy of these systems has remained largely unexplored in both IS and ecosystem approaches. However, linking production/ISs studies to political economy analysis is a fundamental condition for the formulation of feasible industrial policies, as the distribution of power among organisations (and networks of powerful organisations) is unequal and policies have to govern conflicting interests, especially in systems in transition (Andreoni and Chang, 2019).

Classical political economy has traditionally focused on the conflicting interests between different nations and, within them, of different economic sectors or social classes. In the classical schema, the national system-level interests are intrinsically linked (and not reduced) to the interests expressed by its composing sectors and groups. However, to the extent that in today's global economy, the geographical and sectoral boundaries are blurring, classical political economy approaches struggle in mapping out the power relationships and conflicting interests expressed by different interest groups and sectors *within* and *across* countries. For example, regional value chains connect companies from sectors in different countries and each of these companies expresses interests which are beyond one sector and its country of reference.

While the proposition of a fully-fledged political economy theory of industrial ecosystem is beyond the scope of this paper, the industrial ecosystem approach suggests to look at sectors as composed by heterogeneous players whose interests are interdependent but different. For example, within the same sector, along the value chain, firms of potentially different size and with different shareholders and corporate governance structures are expression of different interests (sometimes conflicting even more than across sectors) and might have different organisational power. The corporate governance rules determining the relationships within firms and across interdependent players along value chains in the ecosystem is also central. The corporate governance and institutional settlements tend to determine who are the players in the value chains who capture value, as well as the extent to which value is retained and redistributed in the ecosystem. For example, corporate governance might determine firm level financialisation and offshoring decisions which have an impact on the overall ecosystem.

3. The Architecture of the Industrial Ecosystem

Industrial ecosystems are complex systems. Therefore in advancing a new definition and framework for the analysis of industrial ecosystems, we start drawing on complex system theory. We then move to the analysis of the two main axes around which the industrial ecosystem is structured – that is, its capability domains and sectoral value chains. We then conclude by providing an integrated framework linking capability domains and sectoral value chains, what we call here the *production space* of the industrial ecosystem.

3.1 Industrial Ecosystem: A complex system theory definition

In his seminal contribution 'The Architecture of Complexity', Herbert Simon (1962:468) introduces the idea of a complex organised system as 'one made up of a large number of parts that interact in a nonsimple way' and one where 'the whole is more than the sum of the parts … in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not trivial matter to infer the properties of the whole'. More critically, Simon identifies two properties of complex systems: (i) complexity takes the form of hierarchy; (ii) hierarchies have the property of near decomposability[5].

By a *hierarchic system* Simon (1962:468) means 'a system that is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem'. Hierarchy does not necessarily imply subordination relations, instead it means that complex systems present a multi-tiered system structure characterised by the co-existence of both vertical and horizontal relational structures. The same organisations are embedded in multiple and multi-tiered structures. In industrial ecosystem, this means that firms might be operating within one or more traditionally defined sectors along different value chains, and performs different production/technology functions in each of them.

Near-decomposability allows us to distinguish interactions *among* and *within* sub-systems (i.e. among the parts of those subsystems), and the different orders of magnitude of these interactions. In social systems, according to Simon (1962:475-7), it is rare that 'each variable is linked with almost equal strength with almost all other parts', while it is the case that '[i]ntracomponent linkages are generally stronger that *intercomponent* linkages'. For example in business organisations, members of a department (sub-system) tend to communicate and influence other members within the department more than members in other departments, both trough formal and informal mechanisms and channels (Teece, 1996). Therefore, the principle of near-decomposability suggests that while all players in the industrial ecosystems interact in some way or another, and thus they are interdependent, some players are more interdependent than others and this can involve one or more dimensions.

Within the industrial ecosystem multi-tiered structure, each productive organisation, intermediate institution, demand-side actor is embedded in a web of structural interdependencies which are at the same time constraining, enabling and shaping their behaviour. This means that their decisions and value creation activities are not simply path dependent, more fundamentally they are ‘induced’ and ‘triggered’ by the ecosystem structure in which they are embedded and their interdependencies. Specifically, at the firm level, organisations administer and constantly extract new services (capabilities) from their resources to capture new production opportunities in the market and develop new ‘areas of specialisation’ (Penrose, 1959; Teece, 1996; Dosi, 1997; Lazonick, 2010). In doing so, production resources and structures – their imbalances, bottlenecks, similarities and complementarities – operate as learning ‘inducement mechanisms’ or ‘focusing devices’ within productive organisations – i.e. *structural learning* (Richardson, 1960 and 1972; Rosenberg, 1969; Andreoni, 2014).

The industrial ecosystem is composed by many of these firms undergoing processes of structural learning in production as well as in the market through continuous interactions with demand-side actors – i.e. learning by using (Rosenberg, 1982). Demand-side actors and markets are critical in shaping the industrial ecosystem. The reason is that changes in the ‘quantity’ of demand (both final and intermediate demand) as well as the ‘quality’ or composition of demand (resulting from changes in income distribution) open (and shape) productive opportunities for firms in the ecosystem. The extent of the market – especially the intermediate demand of components – is particularly relevant in the context of an ecosystem as it is responsible for specialisation, further division of labour and increasing returns.

As a result of the structural interdependencies linking supply- and demand-side organisations in the industrial ecosystem, each of them (even competitors) will be involved in some processes of co-value creation. The cumulative process of learning and accumulation of capabilities to perform different production/technology functions generates what we call here the capability domains of the industrial ecosystem, that is, a distinctive pool of resources and capabilities (section 3.2).

The value creation processes of learning and diversification, and the structural interdependencies they involve, also shape the ‘real’ boundaries of industrial ecosystems. While industrial ecosystems might be well centred around a regional core of dense interdependencies (near-decomposability), this does not exclude the fact that (i) some of its organisations cannot establish and consolidate linkages at the ‘glo-cal’ interface with other systems of production, knowledge creation and resource flows; and that (ii) regionally co-located organisations might be completely disconnected from the industrial ecosystem despite their geographical proximity.

Therefore, the ‘real boundaries’ of an industrial ecosystem can be only identified by tracking the network of value creation linkages involving organisations around a regional core and those value linkages spanning out from the regional core. The identification of *structural holes* in the ecosystem is equally important: there might be a number of co-located organisations that are disconnected from the ecosystem which do not benefit from their co-location despite their proximity. They might be exactly those firms specialised in mature industrial sectors, thus, those in need of innovative industrial renewal policies. Structural holes might also refer to the lack of organisations with closely complementary but dissimilar capabilities. The identification of the real boundaries of the ecosystem become then critical for governments interested in supporting industrial ecosystems and their transformation.

Industrial ecosystems can be defined as multi-tiered production systems involving heterogeneous agents operating in sectoral value chains and contributing to the capability domains of the ecosystem (and its participants) with closely complementary but dissimilar sets of resources and capabilities. The industrial ecosystem is thus a structured production space centred mainly on its productive organisations, as well as other public actors, intermediaries and demand-side actors, purposefully involved in co-value creation processes along various types of diversification and innovative industrial renewal trajectories. The geographical boundaries of the industrial ecosystem are shaped by the evolving interdependencies linking organisations within the ecosystem and by the new linkages consolidating beyond that.

3.2 Capability domains

The capability domains of an industrial ecosystem are distinctive clusters of resources and capabilities developed by heterogeneous organisations and institutions, including firms, intermediaries and demand-side actors embedded in the ecosystem. In order to specify the nature and relationship among these different clusters of capabilities, we propose to start from analysing the most critical organisation of the industrial ecosystem – i.e. the firm.

According to Penrose (1959:109-110; italics added) 'at all times a firm has a foothold in certain types of production and in certain types of markets […] called *areas of specialization* of the firm. Each type of productive activity that uses machines, processes, skills, and raw materials that are all complementary and closely associated in the processes of production we shall call a *'production base' or 'technological base'* of the firm, regardless of the number or type of products produced. A firm may have several such bases, […] the significance of distinguishing such groupings lies in the fact that a movement into a new base requires a firm to achieve competence in some significantly *different area of technology*'.

The production/technology bases of the firm are therefore pools of resources from which firms extract specific services (capabilities) to create value products and capture opportunities in the market. In an industrial ecosystem, the combination of the different production/technological bases of its firms – thus their resources and capabilities (alongside the resources and capabilities embedded in other organisations, institutions and demand-side actors), give rise to various clusters of closely complementary but dissimilar capabilities (beyond the individual firm) that we call here *capability domains*.

Each capability domain of an industrial ecosystem thus defines a distinctive combination of resources and a distinctive way to use them – i.e. capability. Indeed even regions initially endowed with similar clusters of resources/capabilities can follow different diversification trajectories and, in turn, differentiate their capability domains (see for example Best, 2013 and 2016 for the Greater Boston ecosystem; Reynolds and Uygun, 2017 for Massachusetts; Broekel and Brachert, 2015 for the German industrial ecosystem). These resources/capabilities are contributed by heterogeneous players, can be deployed across different sectors of the economy and are reflected in the variety and quality of products produced by the firms in the ecosystem.

Capability domains include different *types of technologies*, that is, generic technologies, proprietary technologies, infra-technologies and production technologies. Infra-technologies such as measurement, testing and prototyping tools, are critical in leveraging the development and efficient use of these generic technologies from R&D to manufacturing processes and commercialisation. Finally, production technologies are indispensable in manufacturing and innovation processes, as well as scaling-up and commercialisation of new product systems (Tassey, 2007). Some of these generic technologies enable a broad range of activities, thus, they find application in multiple sectoral value chains.

In industrial ecosystems firms have multiple options for developing their production/technology base, including a myriad of inter-firms cooperative arrangements. Since the seminal work of Richardson (1972), research in industrial organisation and regional agglomeration, have stressed how (under specific conditions) firms would have an advantage in establishing inter-firms cooperative arrangements if the development of a new production/technology base require closely complementary but dissimilar capabilities (Teece, 1996; Best, 1999; Pitelis, 2012; Andreoni, 2014). This means that a large part of linkages between firms (and their production/technology bases) in the ecosystem will be triggered by the need (and opportunity) to access closely complementary but dissimilar capabilities and will be organised around multiple sectoral value chains.

The capability domain concept can be operationalised starting from a list of general technology areas and mapping out the type of distinctive resources/capabilities that firms and other relevant actors in a certain industrial ecosystem have been able to develop starting from these general technology areas (see section 5 for an application in the ER industrial ecosystem). These resources/capabilities will be reflected in the products and services provided to the markets by the firms in the ecosystem. Thus, by analysing these outputs – the features, functionalities and quality of products and services – it is possible to infer and validate the list of capability domains of the ecosystem, at least with respect to the revealed capabilities and the diversification potential of the existing resources/capabilities.

3.3 Sectoral value chains

Within an industrial ecosystem, firms might be operating within one or more traditionally defined sectors along different segments of the value chain, and perform different production/technology functions. Although sectors have been key units of analysis in industrial economics, they are becoming increasingly problematic as ways of aggregating productive units and studying value creation and capture dynamics.

Nathan Rosenberg was among the first to point out how sectors are compositional heuristics that very often hide more than reveal production and technological dynamics. 'For many analytical purposes it is necessary to group firms together on the basis of some features of the commodity as a final product; but we cannot properly appraise important aspects of technological developments in the nineteenth century until we give up the Marshallian concept of an industry as the focal point of our attention and analysis. These developments [rapid technical change in the American production of machine tools] may be understood more effectively in terms of certain functional processes which cut entirely across industrial lines in the Marshallian sense…' (Rosenberg 1963:422; italics added).

Similar observations inspired the work of Giacomo Becattini (1989) who distinguished at least three concepts of industry (or sector): one built on the idea of 'satisfaction of needs'; another on the idea of 'technological similarity'; finally, a sociological concept based on the idea of 'awareness of belonging' to a particular industry. The latter led to the definition of the *Marshallian industrial district*, as a 'complex and tangled web of external economies and diseconomies, of joint and associated costs, of historical and cultural vestiges, which envelops both interfirm and inter-personal relationships [and tend] towards the multi-sectorial' (Becattini, 1989:9). Along the same lines, by embracing a more structuralist perspective, Dahmen (1989:132) developed the idea of *development blocks* as 'a sequence of complementarities which by way of a series of structural tensions, i.e., disequilibria, may result in a balanced situation'. Both the concept of industrial district and development block identify complementarities across sectors as a key relationship for grouping production units, although they do not provide explanations regarding how (i) these different sectors are linked along different sectoral value chains, and (ii) how heterogeneous players performing distinctive technology/production functions operate within and across value chains.

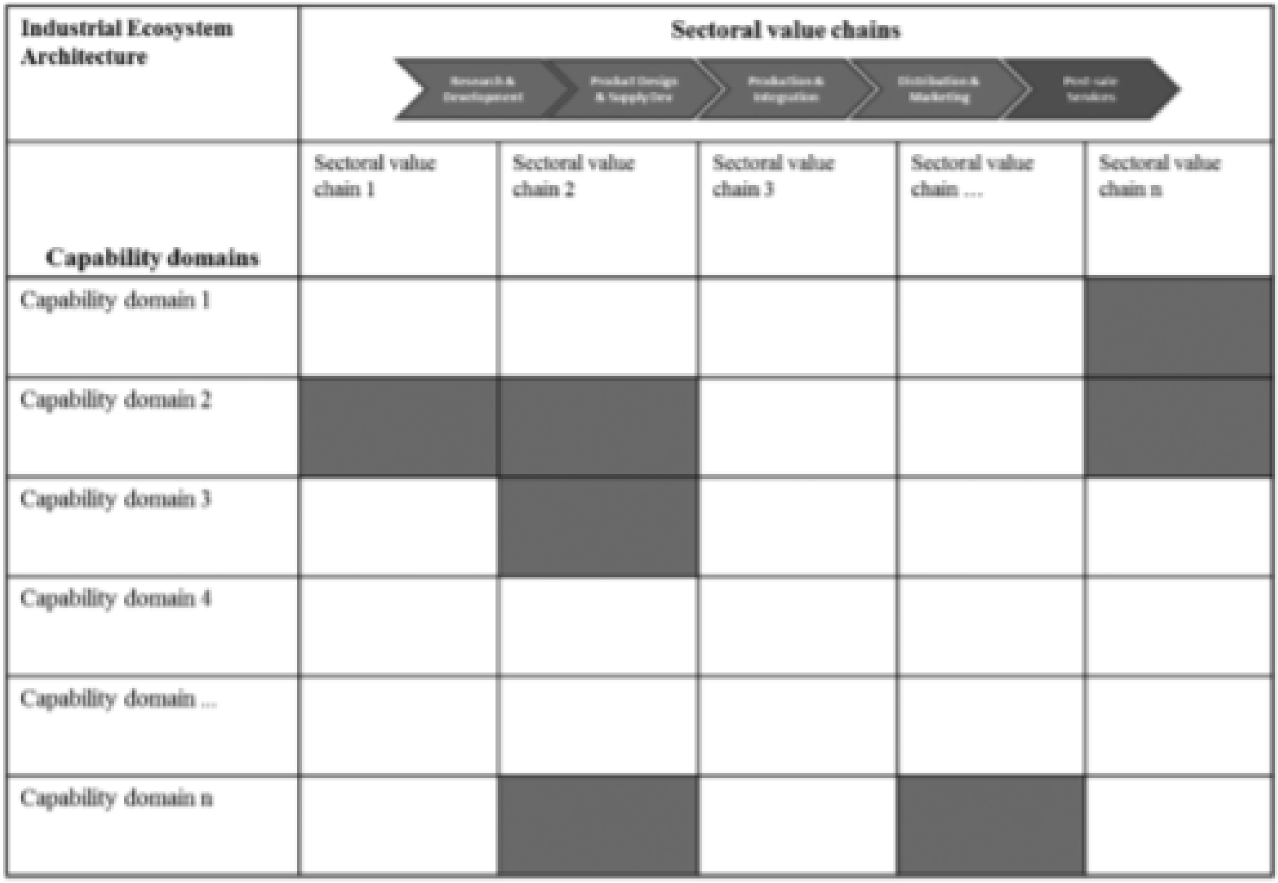
While recognising that in some cases sectoral distinctions still matter (for example the fact that the machine tool sector is the main producer of production technologies makes it different from a sector which is simply deploying them), the ecosystem approach suggests to adopt a value chain open system unit of analysis. It distinguishes different organisations – focal firms (also called system integrators), suppliers and complementors (including specialist contractors) – as well as institutions, according to the relative location of activities (and functions) they perform along the value chains. These value chains maintains some sectoral distinctive features, but are treated as open systems which cannot be narrowly defined by traditional sectoral boundaries. Drawing on this approach, we can identify different *sectoral value chains* structuring the industrial ecosystem. Each sectoral value chain is connected with the others via both *horizontal* and *vertical linkages*, that is, horizontal and vertical flows of inputs and outputs linking heterogeneous actors performing different production/technology functions. Some of them operate mainly within one or a few sectoral value chains, while others provide production/technology services across multiple sectoral value chains.

System integrators are focal firms in a sectoral value chain as they orchestrate the production and technological activities of multiple suppliers and complementors, as well as customers. They can draw on (but also nurture) the capability domains in the industrial ecosystem by establishing inter-firm cooperation networks and by adopting different governance modes (Richardson, 1972; Teece, 1996; Pitelis, 2012). The governance modes are particularly important as they determine the extent to which system integrators in the ecosystem co-create value, capture the value and retain/redistribute part of that value in the ecosystem. The governance modes in the industrial ecosystem might be affected by multiple factors, in particular they tend to reflect the types of system integrators (e.g. local/foreign) in the ecosystem, their internal corporate governance (e.g. ownership structure) and supply chain development strategies, as well as the broader institutional and regulatory setting in which they operate (e.g. IPRs; corporate governance regime).

The industrial ecosystem architecture opens opportunities for the emergence of truly multi-sectoral firms whose specialisation is in combining and recombining different capability domains, and trigger various forms of pollination across sectors. Among suppliers and complementors, specialist contractors tend to be the main *pollinators* of the ecosystems. By providing technology intensive services to several firms in the ecosystem and by drawing on different capability domains, specialist contractors are well positioned to discover opportunities across sectoral value chains. Moreover, by operating at the interstices of different sectoral value chains and redeploying technical solutions arising from different sectoral value chains or competitors within the same value chain, specialist contractors may trigger various forms of indirect (and often hidden) cooperation. Indeed indirect cooperation may involve heterogeneous actors operating across different sectoral value chains but also competitors within the same sectoral value chain.

3.4 Production Space: A structured space of opportunities and constraints

The production space of an industrial ecosystem can be thought as a matrix where heterogeneous organisations operating in one (or more) sectoral value chains draw on one (or more) capability domains (and the different types of technologies they include) to perform a number of production and technology functions in processes of co-value creation, diversification and innovative industrial renewal. In the production space matrix (Figure 1), columns distinguish different types of sectoral value chains, and the corresponding cells identify the different capability domains on which actors in the sectoral value chain draw from. Rows, instead, list different capability domains underpinning different sectoral value chains in the industrial ecosystem. A number of capability domains are particularly pervasive or transversal, that is, they constitute the bases for production and technological processes for many organisations in multiple sectoral value chains.



Industrial Ecosystem Architecture	**Sectoral value chains**				
Capability domains	Sectoral value chain 1	Sectoral value chain 2	Sectoral value chain 3	Sectoral value chain …	Sectoral value chain n
Capability domain 1					▨
Capability domain 2	▨	▨			▨
Capability domain 3		▨			
Capability domain 4					
Capability domain …					
Capability domain n		▨		▨	

Fig. 1. *Industrial ecosystem architecture*

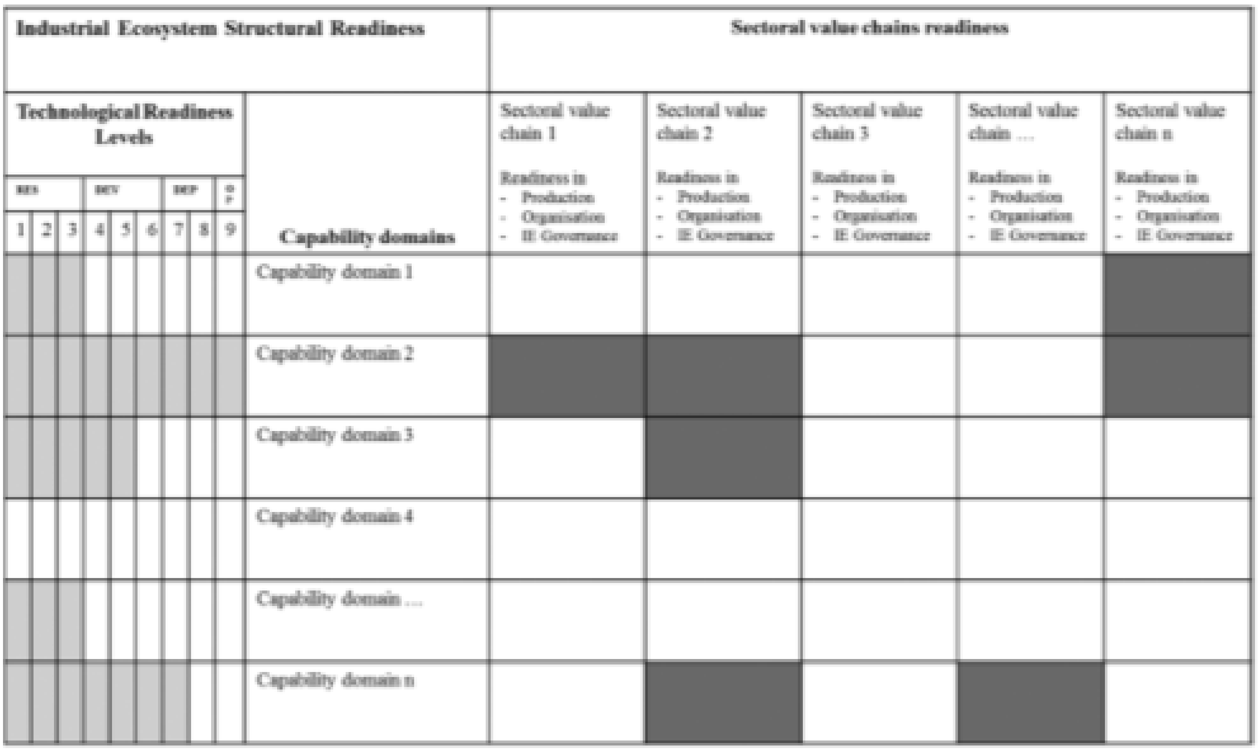
Source: Author

The production space is a structured space of opportunities and constraints. Beyond the map of ‘existing’ sectoral value chains and related combinations of capability domains, there are a number of ‘potential’ productive opportunities, especially at the interstices of the matrix, which can be exploited by the same or different firms in the industrial ecosystem. Indeed, in a Penrosian fashion, as pointed out by Best (1999:109-113), the productive opportunities that a firm is not able to exploit ‘are not lost but instead are shifted into market interstices and become opportunities for other firms, existing and new. […] Abandoned possibilities are simultaneously opportunities for new divisions within subsidiaries or spin-offs, or for new firm creation’.

However, the production space may also act as a constraint leading to *transformation failures* and the decline of the ecosystem. Specifically, the industrial ecosystem might be characterised by a limited *structural readiness to change*, both with respect to its capability domains and sectoral value chains. From a capability domains perspective, at the firm level, constraints might arise from technological path dependencies and asset specific commitments which might limit organisations in the ecosystem in capturing potential opportunities (Maskell and Malmberg, 1999). Over time, this lack of technological readiness in one (or more) capability domain(s) might even lead to situations of technological lock-in, especially because of the existence of interdependent investment commitments in specific assets (Chang and Andreoni, 2016).

Structural holes in the ecosystem might also reduce its structural readiness. For example, the lack of (or failure in developing) a critical capability domain (let’s say capabilities in ICT technologies) might undermine the integration of emerging technologies (adaptive automation) in promising new products (robots). The lack of this critical capability domain might depend on different problems in the technological innovation chain such as the lack of specific infratechnologies to scale up a new emerging technology. The ‘technological readiness levels’ (TRLs) are today widely used metrics which focus on the technology innovation chain and allows to assess the extent to which technologies (e.g. machinery, equipment or software) are ready to be deployed in production in an operating plant[6].

From the sectoral value chains perspective, the structural readiness of the industrial ecosystem might be negatively affected by the adoption of organisational models constraining the development of its heterogeneous actors (especially suppliers, complementors and specialist contractors around the focal firms), or by the lack of industrial policies nurturing the ecosystem with investments in quasi-public good infratechnologies (Andreoni et al., 2017).



Industrial Ecosystem Structural Readiness										Sectoral value chains readiness				
Technological Readiness Levels										Sectoral value chain 1 Readiness in - Production - Organisation - IE Governance	Sectoral value chain 2 Readiness in - Production - Organisation - IE Governance	Sectoral value chain 3 Readiness in - Production - Organisation - IE Governance	Sectoral value chain … Readiness in - Production - Organisation - IE Governance	Sectoral value chain n Readiness in - Production - Organisation - IE Governance
RES			DEV			DEP		OP						
1	2	3	4	5	6	7	8	9	Capability domains					
░	░	░							Capability domain 1					■
░	░	░	░	░	░	░	░	░	Capability domain 2	■	■			■
░	░	░	░	░					Capability domain 3		■			
									Capability domain 4					
░	░	░							Capability domain …					
░	░	░	░	░	░	░			Capability domain n		■		■	

Fig. 2. *Industrial ecosystem structural readiness*

Source: Author

According to their structural readiness, industrial ecosystems might undergo processes of emergence, decline or transformation. The *emergence* of a new industrial ecosystem can be triggered by the rise of new organisations developing existing or emerging technologies (technology push), or the establishment and consolidation of new interdependences which expand the boundaries of the ecosystem. New organisations can also emerge in response to market/demand pull dynamics and develop new strategic sectoral value chains and, in turn, new capability domains. On the contrary, a limited degree of structural readiness combined with increasing competitive pressures may lead to the *decline* of some of the organisations in the ecosystem, starting with those specialised in mature sectoral value chains (or tasks/product segments), to end with the decline of the entire ecosystem. Thus, new industrial ecosystems can emerge, while others can decline. More often, however, industrial ecosystems undergo processes of *transformation* along different diversification and innovative industrial renewal trajectories.

4. Diversification and Innovative Industrial Renewal Dynamics: A micro-structural perspective

Diversification dynamics at the firm, regional and national levels have been studied in organisation studies (Penrose, 1959; Teece, et al.1994), evolutionary economic geography (Boschma, 2017), and seminal contributions in development economics (Hirschman, 1977). Despite notable differences, the literature has been biased in two respects.

First, diversification dynamics have been mainly understood with reference to the concept of 'relatedness' and, in particular, the idea of a branching process triggered by a principle of 'similarity' among resources/capabilities requirement, more than 'complementarity' (Andreoni, 2014; Broekel and Brachert, 2015; Boschma, 2017). The *similarity principle* states that two (or more) activities are related if they require similar sets of resources and capabilities, such as skills and technologies. This does not exclude the fact that activities might present some degree of dissimilarity or strangeness. Activities would be considered similar to the extent that the resources/capabilities (or cognitive) distance remains limited, that is, companies can draw on the same set of resources/capabilities to perform the stated activities. Diversification is thus defined as a branching process where firms fully exploit their capabilities by deploying them in similar activities.

The *complementarity principle*, instead, points to a branching process in which in order to diversify firms must learn to perform closely complementary but dissimilar activities. The fact that these activities are dissimilar is made evident by the fact that companies will require either developing (learning), controlling (M&A) or accessing (cooperation) different resources/capabilities. The fact that these activities are not simply dissimilar, but also closely complementary, gives companies an opportunity for developing a new production/technology area, as defined by Penrose. In both branching processes of diversification, similarities and complementarities are not pre-determined, but are discovered in the structural learning process (Andreoni, 2014).

Second, the study and measurement of relatedness has been mainly based on an inductive approach based on 'revealed diversification'. For example, at the firm level, (Teece et al., 1997) capture the technological relatedness between products (thus, the fact that they require similar capabilities) by looking at the frequency of co-occurrence of products in firms' portfolios. Building on the same idea, at the regional and national levels, other scholars assumed that if a certain region (or nation) shows co-location of a number of sectors (or co-export of a number of products), then these sectors (or products) must be related, that is, must require similar capabilities and resources. The idea of the 'product space' of nations built around countries' export baskets is a notable example (Hidalgo et al., 2007). Alternatively, at the regional level, the relatedness leading to diversification has been studied focusing on the frequency of co-occurrence of technology classes on patent documents, the so called 'technology space' (Rigby, 2015).

While these approaches are appealing, they might also be misleading, especially at the regional and country levels. First, co-location does not imply a 'genuine relatedness amongst agents, technologies, firms and sectors in a spatial context' (Kogler, 2017); secondly, relatedness is not symmetrical, in fact there is likely to be asymmetry (Boschma, 2017); third, it does not inform us about the nature of these alleged relationships, thus, they are not actionable from an industrial policy perspective (Andreoni and Chang, 2019). Finally, while the principle of similarity is a powerful focusing device, its exclusive use might limit our understanding of 'unrelated' diversification, that is, one requiring new capabilities/resources (Saviotti and Frenken, 2008). In fact, unrelated diversification is likely to be better explained in terms of complementarities.

The problematisation of the two conventional standpoints discussed above – focus on 'similarity' and 'revealed diversification' – is a necessary, although not sufficient, step in opening up the back box of diversification in industrial ecosystems. The development of a micro-structural perspectives shall start from the consideration of the diversification motives and strategies of firms (Penrose, 1959), as well as an analysis of firm-level processes of structural learning and their propagation across sectoral value chains and markets (Rosenberg, 1963, 1969 and 1979; Hirschman, 1977; Teece, 1996; Dosi, 1997; Andreoni, 2014). Specifically, we suggest first to look at the different *types* of micro-processes triggering both related and unrelated diversification, in particular the role of complementarities and technology recombination/integration. Second, we stress the importance of considering *potential relatedness* in the production space, that is, potential diversification pathways embedded in the ecosystem, and what is the structural readiness to change of the ecosystem.

At the firm level, Penrose (1959:110) distinguishes between diversification *within* the same areas of specialisation – i.e. production of more products based in the same technology *and* sold in the firm's existing markets – from diversification *beyond* existing areas. The latter might be of three kinds: (i) entry in *new markets* with *new products*, but using the *same production/technology base*; (ii) expansion in the *same market* with *new products*, based in a *different area of technology*; (iii) entry in *new markets*, with *new products*, based in a *different area of technology*. There also other diversification activities in which firms expand the number of products produced (also subcomponents, or production technologies) for the firm's own use.

Drawing on its unused resources/capabilities, the Penrosian firm constantly chooses among these different opportunities for expansion and diversification, also in response to changes in the external conditions, in particular changes in the quality and quantity of demand. For example diversification 'is often virtually forced on a firm as it tries to maintain its position in a given field' (Penrose, 1959:137) or is a response to unfavourable movements in demand conditions, sometimes temporary, in other cases permanent. In the long term the firm will have to specialise in a number of 'relatively impregnable bases' and distribute its internal resources accordingly (Penrose, 1959:137).

Therefore, at any time, firms have a 'variety of inducements', both internal and external, to expand and diversify in one or more directions. Specifically, '[c]omplex technologies create internal compulsions and pressures which, in turn, initiative exploratory activity in particular directions' (Rosenberg, 1969:4). The theory of structural learning (Andreoni, 2014) explicitly points to these inducement and triggering mechanisms embedded in the firm's production processes and structures, in particular, the existence of similarities, complementarities and bottlenecks (such as indivisibilities). In fact, as documented in Rosenberg (1963, 1969 and 1979; see Andreoni, 2014 for a systematic analysis), the industrial revolution started from the widespread application of a 'relatively small number of similar processes' and technologies to a large number of industries, as well as the development of complementary technological innovations, as 'innovations hardly ever function in isolation' (Rosenberg, 1979:2). In turn, technological innovations trigger organisational reconfigurations within firms (Andreoni, 2014) as well as at the inter-firms level (Klepper, 2007; Pitelis, 2012; Andreoni et al., 2017).

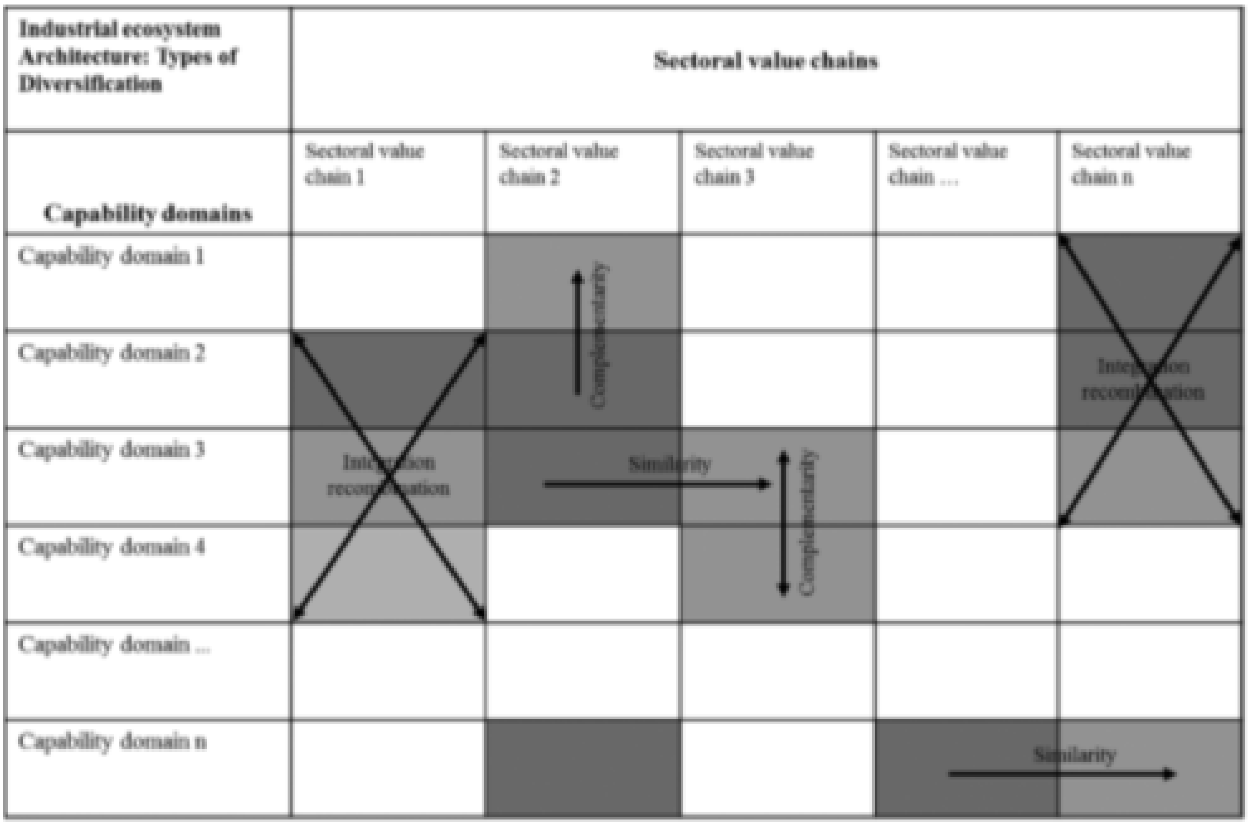
At the level of the industrial ecosystem, diversification opportunities in the production space will be induced and triggered by its capability domains (and interstices), that is, the different pools of resources/capabilities distributed among heterogeneous actors in the ecosystem, and their interdependencies. We propose to focus on three main *types of diversification* in the production space triggered by similarities, complementarities and recombination/integration respectively.

First, diversification may be induced by *similarities*, that is, the application of the same pool of resources/capabilities (let's say a technological solution for automation) to a number of similar products or processes within the same or across different sectoral value chain (let's say pharma packaging machinery, agricultural machineries and medical device). Thus, diversification induced by similarities starts from a certain capability domain and results in the application of a set of resources/capabilities (from the same capability domain) to a number of activities within the same or across different sectoral value chains (see Figure 3).

Second, diversification may be induced by *complementarities* within and across sectoral value chains and their underpinning capability domains. Indeed complex and critical product systems (let's say medical devices, airplanes or robots) tend to rely on more than one capability domain as defined here (let's say advanced materials, mechanics and ICT). In developing a new product or process which require different clusters of resources/capabilities, firms will tend to face a number of constraints or bottlenecks determined by the fact that the interdependent activities they have to perform rely on resources/capabilities from different capability domains. Firms may respond to these constraints along different branching processes of diversification, that is, either building these new resources/capabilities internally or by acquiring/accessing them externally through M&A operations (e.g. absorbing an innovative SMEs) and establishing collaborations. As a result of this complementarities-induced diversification, companies will end up combining their resources/capabilities from one capability domain with those in another capability domain.

In some cases, either this complementarities-led branching process or a purposeful firm strategy can also result in completely new forms of integration and recombination of resources/capabilities far beyond two capability domains, indeed in some cases can lead to the development of a new capability domain or processes of technological speciation (Fleming, 2001; Frenken, et al. 2012). This integration-recombination branching processes are our third type of diversification.

Firms in the industrial ecosystem might experience one or more of these different types of diversification dynamics, indeed some of them are one the prosecution of the other. That is, some firms start from related diversification based on similarities towards increasing forms of unrelated diversification based on complementarities and recombination/integration. The fact that the type of diversification based on similarity is often described as ‘related’ diversification depends on the fact that similarities make relatedness more evident and direct. Instead, ‘unrelated’ diversification proceeds along complex indirect connections, bottlenecks, complementarities and purposeful recombination/integrations which remain largely hidden. The following figure 3 maps the three different types of diversification identified here against the production space of the industrial ecosystem.



Industrial ecosystem Architecture: Types of Diversification	**Sectoral value chains**				
Capability domains	Sectoral value chain 1	Sectoral value chain 2	Sectoral value chain 3	Sectoral value chain …	Sectoral value chain n
Capability domain 1		Complementarity			
Capability domain 2					Integration recombination
Capability domain 3	Integration recombination	Similarity	Complementarity		
Capability domain 4					
Capability domain …					
Capability domain n					Similarity

Fig. 3. *Types of diversification in industrial ecosystems*

Source: Author

From an industrial ecosystem perspective, while similarities are an important inducement mechanism, complementarities are even more so. The reason is that complementarities induce firms in both exploring/moving beyond their existing areas of specialisation and establishing inter-firm collaborations with firms endowed with closely complementary but dissimilar capabilities. As a result, diversification will enrich the capability domains and strengthen interdependencies. Similarly, in the industrial ecosystem, the existence of a production space built on different capability domains induce even more opportunities for effective recombination/integration of capabilities for improving existing products or creating new ones (i.e. technological speciation; Levinthal, 1998; Cattani, 2006). The possibility of drawing on closely complementary but dissimilar capability domains and developing integration capabilities is particularly important, given that products are increasingly becoming complex product systems, thus, they integrate multiple sets of technologies and depends on effective technological interfaces (Hobday, 1998; Tassey, 2007 and 2010; Best, 2016; Andreoni et al., 2017; Andreoni, 2017).

5. The Emilia Romagna industrial ecosystem archetype: a case study

The industrial ecosystem framework offers new analytical lenses to revisit the Emilia Romagna (ER) archetype and investigate its diversification and innovative industrial renewal dynamics. The architecture of the ER industrial ecosystem is characterised by five distinctive capability domains (Table 1) and several sectoral value chains (Table 2).

Starting from the identification of its capability domains, we can distinguish five different capability domains: (i) bio, food and agro-technologies; (ii) advanced materials; (iii) mechanical systems and automation; (iv) ICT and embedded systems; (v) biopharma and medical technologies. These capability domains cut across traditionally defined sectors and go beyond the production and technology bases of individual companies *and* traditionally defined industrial districts.

Table 1. *The capability domains of the ER industrial ecosystem*

Capability domains	Distinctive clusters of resources and capabilities	Cross-sectoral value chains applications
Bio, food and agro-technologies	• Characterisation and selection of new raw materials, their quality and safety • Design and validation of equipment and plants for food processing and packaging • Agro-food process and product optimisation • Agro-food biological resource improvement and valorisation • Mechanic and functional augmented food • Improvement of the nutritional characteristics of food • Agro-food-specialised industrial equipment and mechanical plants • Food packaging, including innovative materials for packaging, quality and hygiene, environmental impact of packaging • Advanced plants and technique for food and drug packaging, including active packaging • Molecular traceability and traceability systems • Agro-food-relevant microorganism • Food quality, safety and health, including use of non-destructive analysis methods • Valorisation of typical productions • Assisted improvement platform for the seed industry • Agro food industry by-products and rejects value recovery • Dedicated energy crops and residual biomass in agriculture • Biomass evaluation mapping and modelling for energy uses • Energy conversion systems	• Food and beverage industries • Suppliers of raw materials and semi-finished products • Producers of sensors and packaging materials • Seed industries • Mills • Ingredients and semimanufactures • Fruit and vegetable consortia • Phytosanitary product manufacturer • Packaging • Chemical industry • Rubber and plastic • Pharmaceutical industry • Machines and plants for the food industry • Waste treatment and disposal
Advanced materials	• Material sciences (all material application) • Development and characterisation of new materials • Design, processes, synthesis and characterisation on organic and inorganic and hybrid materials • Advanced materials, design and photonic applications • Advanced functional materials • Structured and/or composite materials for advanced applications • Surface treatments	• Advanced manufacturing • Automatic machinery • Agricultural machinery • Automotive and transport • Electronics • ICT industry • Hydraulics • Industrial mechanics • Mechatronics for industrial and civil use • Machine tools • Packaging • Mechanical components

Table 1. *Continued*

Capability domains	Distinctive clusters of resources and capabilities	Cross-sectoral value chains applications
	• Polymers and injection moulding technologies • Metallurgy, corrosion and polymeric materials for the environment • Ceramics • High performance, functionally augmented and low-recycling-cost ceramic materials • Recycled materials technology	• Energy and environment
Mechanical systems and automation	• Industrial design for mechanics • Precision engineering • Mechanical design, prototyping and e-testing • NVH (noise, vibration, harshness) • x-tronics, automation, mathematical models • x-tronics, automation, logic models • x-tronics, actuators, control electronics, power electronics • x-tronics, hydraulic actuators • x-tronics, sensors • Automation, robotics and mechatronics: actuators and sensors • Virtual prototyping and experimental modelling of mechanic systems • Tracking and tracing of products and processes • Augmented and virtual reality • Collaborative design validation, digital mock up, virtual prototyping exploration and real-time simulation for the design of new products • Mechanical properties, in particular tribological (fiction and wear), surface and multiscale coatings • Coating engineering for mechanics • Coating engineering at the macro–micro scale • Processing and nanofabrication • Configuration and management of integrated production systems • Industrial applications of materials and innovative technological processes • Machining technologies for the automotive and aeronautical sector • Fluid dynamics • Thermo – fluid dynamic, engines, car and vehicles • Thermo – fluid dynamic, machines and energy conversion systems	• Advanced manufacturing • Automatic machinery • Agricultural machinery • Automotive and transport • Electronics • ICT industry • Hydraulics • Industrial mechanics • Mechatronics for industrial and civil use • Machine tools • Packaging • Mechanical components • Food industry • Civil construction • Industrial construction • Chemical industry • Pharmaceutical industry • Biomedical industry • Logistics and transport • Safety • Defence

Table 1. *Continued*

Capability domains	Distinctive clusters of resources and capabilities	Cross-sectoral value chains applications
ICT and embedded systems	• Electronic components • Embedded systems • Software engineering and software architecture • Interoperability, protocols and standards • Automation and control • Algorithms, data and signal processing • Mechatronic systems and applications • Robotics • Integration in components and systems • Men-machine interfaces • Computer vision and pattern recognition • Sensor and monitoring/control systems • Information and communication systems and network infrastructure • Knowledge management and semantic-based systems • Cloud computing, mobile and pervasive computing • Internet of things • Bioinformatics	• Advanced manufacturing • Automatic machinery • Agricultural machinery • Automotive and transport • Electronics • ICT industry • Hydraulics • Industrial mechanics • Mechatronics for industrial and civil use • Machine tools • Packaging • Mechanical components • Food industry • Civil construction • Industrial construction • Chemical industry • Pharmaceutical industry • Biomedical industry • Logistics and transport • Multimedia • Pubic Administrations • Safety • Defence
Biopharma and medical technologies	• Biosensors • Medical devices • Drug delivery and quality by design • Drug discovery • E-care • OMICs and bioinformatics for 'OMICs' • Pre-clinic trials • Diagnosis technologies • Development and pre-clinic validation of biological therapeutic agents (antibody drugs) • Personal health technologies • Therapy technology • Advanced therapies • 2D and 3D scaffolds • Regenerative medicine and tissue engineering in orthopaedics • Pharmaceutical innovation • Translational medicine, especially for innovative diagnosis and treatment of degenerative disease of the nervous and cardiopulmonary systems • Industrial applications of genomic and mitochondrial medicine • Biocompatibility, technological innovation and advanced therapies • Computational bioengineering • Nanobiotechnologies • Clinic bioinformatics	• Health services • Pharmaceutical-biotechnological • Biomedical and biomaterials • Nanotechnological • ICT • Cosmetics • Food industry

Source: Own elaboration based on several sources including ASTER sectoral and technology studies, High Technology Network data, and personal interviews with ASTER and companies in the ER ecosystem.

From a historical perspective, 'Mechanical systems and automation' (in particular machinery and mechanical components) and 'Advanced materials' (in particular plastics and ceramics) are the most distinctive capability domains of the ER industrial ecosystem, alongside 'Bio, food and agro-technologies'. These capability domains have found application in both advanced manufacturing and more traditional sectoral value chains, including food and agro-processing. The development of the two capability domains pertaining 'ICT and embedded systems' and 'Biopharma and medical technologies' started in the late 1980s. The development of these latter capability domains have had a pervasive effects across all sectoral value chains, in particular by establishing close complementarities with the 'Mechanical systems and automation' capability domain.

The existence of such a rich set of capability domains is the cause (and the result) of the existence of multiple sectoral value chains populated by a plurality of heterogenous players, including public sector institutions. Regional industrial policies have equipped the industrial ecosystem with a rich and diffused complex public-private technology infrastructure including 10 centres of excellence, 38 research labs, 11 centres for innovation and technology transfer, 23,000 researchers, of which 13,000 in the private sector. ER is the 3rd Italian region for investment in R&D and the first one for the number of EPO patents (ASTER, 2017; see also Andreoni et al. 2017).

The ER's industrial ecosystem has been traditionally organized around industrial districts among which automotive, machinery, packaging, biomedical, agro-tech, food, textile, ceramics and plastics. Originally industrial districts emerged as regional (and often sub-regional) networks of companies specialised in specific sectors and products, and linked by multiple backward and forward linkages. Despite the increasing emergence of major domestic players leading sectoral value chains (automotive, packaging and automation), and the attraction of international companies operating as system integrators (e.g. in medical device and pharma), the organisational structure of the ER industrial ecosystem is still dominated by horizontal linkages across the main sectoral value chains. This means that even when the sectoral value chains and the access to the international markets became mainly mediated by big system integrator firms, the regional suppliers and contractors maintained a relatively high degree of independence and explored similar and complementary productive opportunities, both within and across sectoral value chains (Table 2). As a result, for a number of sectoral value chains, the boundaries of the ER ecosystem have expanded to involve players from the other two major industrial regions in the north of Italy – Lombardia and Veneto (especially for biopharma and medical technologies), and even regions in other countries (e.g. Baden Wurttenberg in Germany for packaging machineries).

The ER industrial ecosystem is characterised by a variety of focal firms operating as system integrators, but also complementors, suppliers and specialist contractors (including KIBSs) 'joining up' and 'pollinating' the industrial ecosystem. In 2015 we counted a wide range of small (31.7% with 10-49 employees) and medium-size enterprises (24% with 50-249 employees) organised around a smaller number of big-size enterprises (24.8% with more than 250 employees) and operating across well-articulated sectoral value chains. The dominant 'governance mode' in the region has favoured the reproduction of the ER industrial ecosystem and the capacity of its different actors to contribute to co-value creation. For example, (Andreoni et al., 2017) documents how IMA – a leading system integrator company in packaging machinery – played a key role in nurturing its suppliers and complementors (especially during the recent financial crisis) and, thus, nurturing the capability domains on which their co-value creation processes were built.

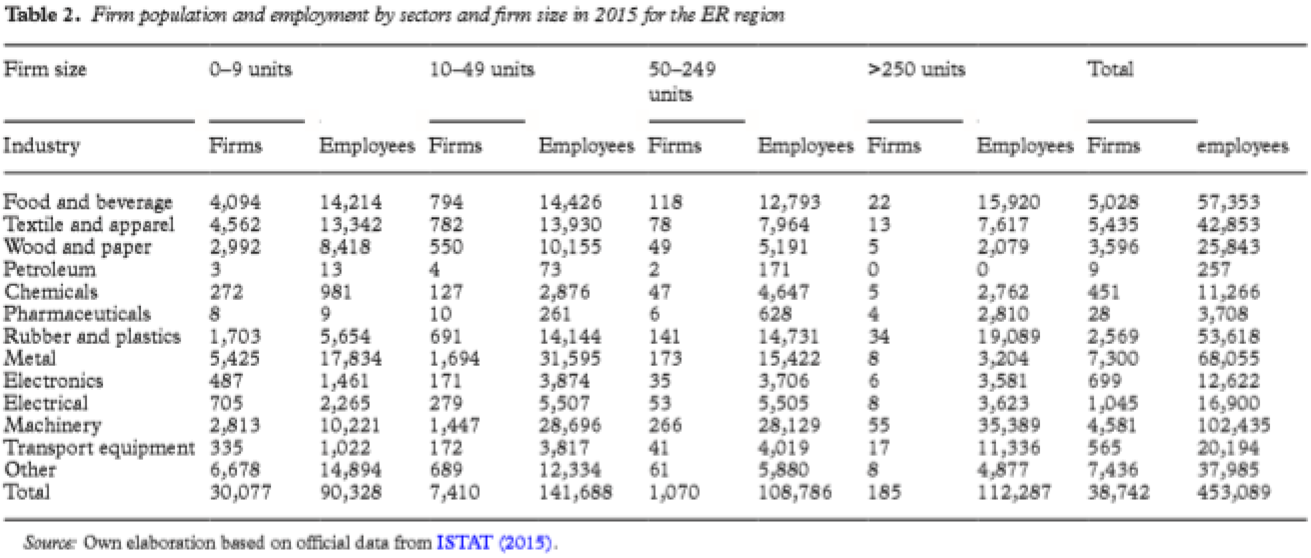


Table 2. *Firm population and employment by sectors and firm size in 2015 for the ER region*

Firm size	0–9 units		10–49 units		50–249 units		>250 units		Total	
Industry	Firms	Employees	Firms	Employees	Firms	Employees	Firms	Employees	Firms	employees
Food and beverage	4,094	14,214	794	14,426	118	12,793	22	15,920	5,028	57,353
Textile and apparel	4,562	13,342	782	13,930	78	7,964	13	7,617	5,435	42,853
Wood and paper	2,992	8,418	550	10,155	49	5,191	5	2,079	3,596	25,843
Petroleum	3	13	4	73	2	171	0	0	9	257
Chemicals	272	981	127	2,876	47	4,647	5	2,762	451	11,266
Pharmaceuticals	8	9	10	261	6	628	4	2,810	28	3,708
Rubber and plastics	1,703	5,654	691	14,144	141	14,731	34	19,089	2,569	53,618
Metal	5,425	17,834	1,694	31,595	173	15,422	8	3,204	7,300	68,055
Electronics	487	1,461	171	3,874	35	3,706	6	3,581	699	12,622
Electrical	705	2,265	279	5,507	53	5,505	8	3,623	1,045	16,900
Machinery	2,813	10,221	1,447	28,696	266	28,129	55	35,389	4,581	102,435
Transport equipment	335	1,022	172	3,817	41	4,019	17	11,336	565	20,194
Other	6,678	14,894	689	12,334	61	5,880	8	4,877	7,436	37,985
Total	30,077	90,328	7,410	141,688	1,070	108,786	185	112,287	38,742	453,089

Source: Own elaboration based on official data from ISTAT (2015).

In other sectoral value chains in the ER industrial ecosystem, for example the one around complex haemodialysis medical devices, system integrators such as international companies like Gambro, Baxter, Fresenius, Bellco and BBraun have adopted very different governance modes and strategies which have impacted the evolution of the industrial ecosystem, within and beyond their main sectoral value chains. Some of them (especially in the early 1990s) played a key role in promoting the spin-off and development of specialist contractors (also known as small knowledge intensive business services companies, KIBS), whose areas of specialisation were drawing on different capability domains and a specialised capability in technology system integration. These specialist contractors were then used by system integrators to work out innovative solutions in critical system components for electro medical machines, infusion, transfusion and surgery (sensors, pumps, micro-tubing, filtration systems), as well as related production technologies (co-injection moulding; rapid prototyping and control systems for micro-tubing and critical systems) (Andreoni and O'Sullivan 2014; Klepper, 2007; Probert et al, 2013).

For example, starting from the medical device companies in the ER region we identified a number of 'pollinators' operating at the same time with multiple companies at the interstices of sectors like automotive, aerospace, medical device, pharma, food, construction and chemicals. In the ER industrial ecosystem, the strong demand pull for luxury sports cars (Ferrari and Lamborghini) and other consumer products, played an important role in developing the capability domain around plastics and production technologies for polymers. Companies specialised in plastics became also important in the development of medical device disposable components and, later, other medical device product systems. Medical devices, however, require more sophisticated plastics. Thus, as a result of this technology push, capabilities around polymers were further developed by medical device companies. Eventually these new capabilities in advanced materials found applications in other sophisticated products, including luxury cars. Therefore, companies in the industrial ecosystem have been indirectly cooperating across sectoral value chains and capability domains of the ecosystem.

Given the presence of a rich combination of different capability domains and a variety of supply and demand side actors, the ER industrial ecosystem has shown over the years a strong degree of structural readiness. In particular, firms have developed different production/technology bases and related areas of specialization along different branching processes of diversification and innovative industrial renewal. For example a capability domain in plastics and injection moulding has found applications in automotive and medical devices; fluid system, including filtration and pumps, in food processing machinery, medical device and automotive; sensors, biosensors and mechatronic system in medical devices, pharma, automated and adaptive machineries.

The production space matrix presented in section 3.4 is a useful tool in mapping out and distinguish the different types of diversification dynamics which have characterised the evolution and transformation of the ER industrial ecosystem. The following are a number of illustrative company cases drawing on firm-level longitudinal evidence (see Figure 4).

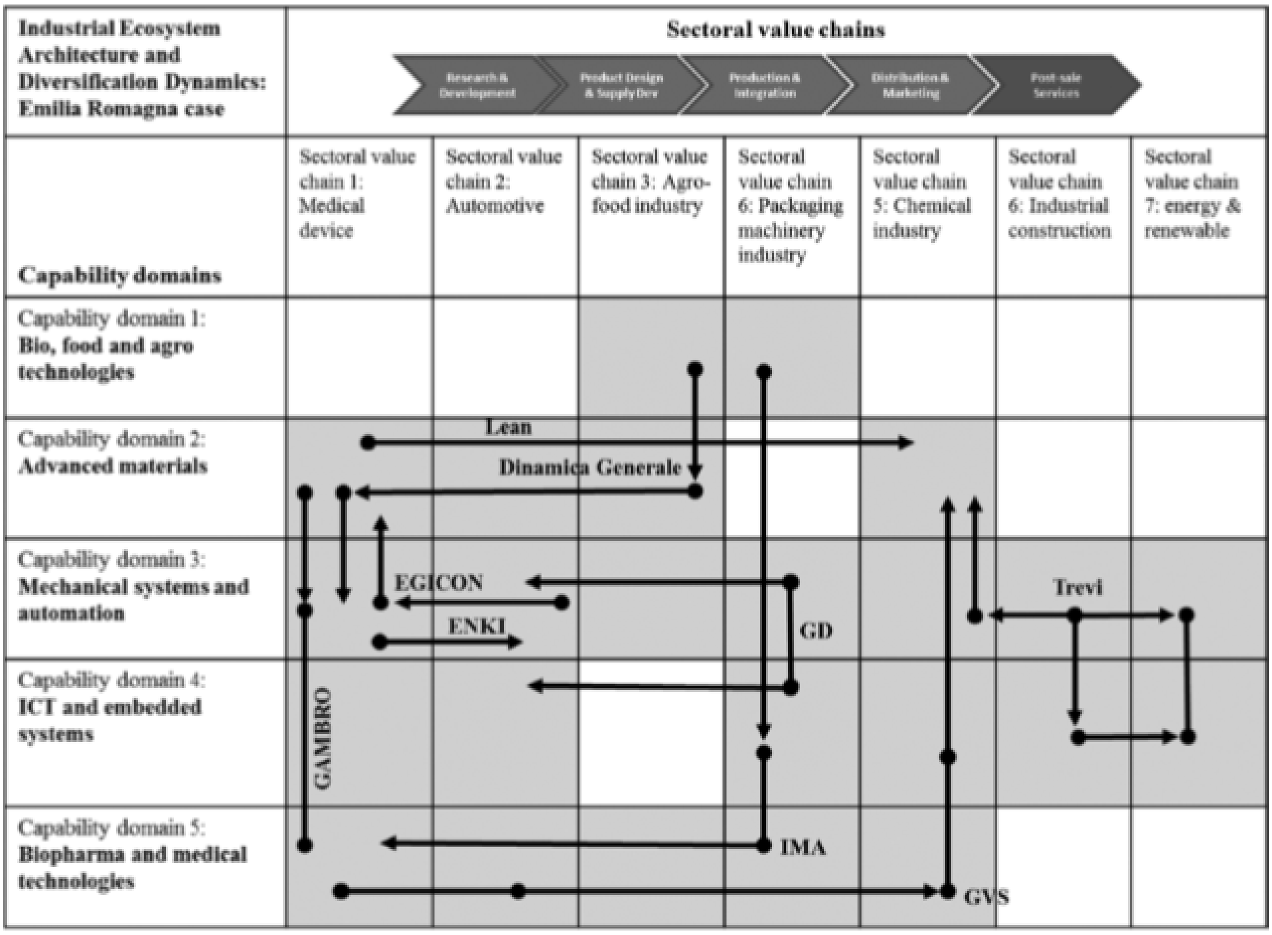


Fig. 4. *The ER production space matrix and diversification dynamics: illustrative company cases*
Source: Author

Starting from diversification processes triggered by similarities, specific automation solutions have been adopted in a broad range of machineries as well as critical product systems. Similarly, in the so called ‘plastic valley’ (Patrucco, 2005), capabilities in injection moulding technologies have been used to move from the production of plastic components for machine tools and automotive, to a broad range of plastic disposables and micro-tubing for medical devices as well as aerospace components. Similarly, capabilities in flow systems hardware (pumps, tubes, etc.) – and increasingly in complementary software (sensors) – have allowed companies to diversify their portfolio along various similar products, sometimes increasing their quality or expanding their functionalities (see the cases of companies like ENKI, Lean, EGICON and Dinamica Generale).

We can then find several cases of diversification processes triggered by complementarities, especially at the interface of the “Mechanical systems and automation” and “ICT and embedded systems” capability domains. Companies specialised in precision engineering and automated systems such as packaging – IMA, GD, SACMI and Marchesini – had to expand their technology/production bases to combine their traditional automation mechanics-related resources and capabilities with others more related to electronics/embedded systems. In the production of packaging machineries, for example, in order to move towards the high-value product segment of packaging machinery for pharmaceutical products, a world-leading company like IMA had to develop specific resources and capabilities in mechatronics which allowed to increase operational and computational speed as well as data tracing (Andreoni et al., 2017).

Finally, with respect to diversification dynamics triggered by integration/recombination, we find interesting cases around the "Advanced materials" capability domain. For example, the company GVS started its diversification trajectory by integrating capabilities in plastic moulding and automation to develop an innovative integrated technique for automatic co-moulding on horizontal presses (i.e. 'All in-Mould' technology). This innovative recombination and integration of two of the most important capability domains in the ER ecosystem, led to the creation of advanced medical filtering (e.g. blood transfusion and haemodialysis applications) and, from there, filters and components for anti-lock braking systems (ABS) in automotive, petrol injection systems and fuel tanks, safety and biohazard (respiratory and antiviral protection) and molecular filtration (chemical protection).

There are finally cases of companies who diversified along all three types of pathways described above. This is the case of the Trevi Group, a company who started specialising in foundation engineering (special foundations), tunnel excavation and soil consolidations, which then diversified in the drilling field (oil, gas and water) as well as design and execution of multi-story automatized and underground car parks, and renewable energies (offshore wind power and geothermal). To operate in such a diverse set of fields, the company had to develop, acquire and access resources/capabilities from different capability domains in the ecosystem and recombine/integrate them in innovative ways.

6. Towards an industrial ecosystem policy agenda for innovative industrial renewal

In mature economies, industrial ecosystems are transformed over time by different types of diversification and innovation processes along different cyclical trajectories (Andreoni et al., 2017 introduce the concept of "structural cycles; see also Lee and Malerba, 2017 on "catch up cycles"; see also Boschma et al., 2017 on the need to link regional diversification and transition studies). For example, since the classical analyses of the ER model (Brusco, 1982; Piore and Sabel, 1986), the ER region has undergone significant transformations along different structural cycles (Andreoni et al., 2017; De Ottati, 2018).

The policy challenge of keeping industrial ecosystems along a trajectory of diversification and innovative industrial renewal is of paramount importance in mature economies. As highlighted, there are multiple factors which can lead to a transformation failure in the industrial ecosystem and result in its decline. Decline might be determined by the presence of structural holes in the production space; failures in developing closely complementary capabilities; failures in catching-up with emerging technologies; extractive governance models which do not support co-value creation processes. With respect to the localised capabilities, Maskell and Malmberg (1999) also points to situations of asset erosion, substitution (when new technologies rapidly devalue former investments) and failures in 'un-learning', that is, escaping from path-dependency (especially in mono-industrial regions).

The industrial ecosystem framework presented here provides a starting point to systematise a number of industrial policy interventions focused on promoting diversification dynamics and innovative industrial renewal. As stressed by Kogler (2017), new tools for designing diversification strategies which take into account the complex architecture of the industrial ecosystem are needed. The production space matrix introduced in section 3 is a mapping tool to represent the existing architecture of the industrial ecosystem. More critically, as discussed in section 4, it might help in identifying a number of embedded opportunities and constraints at the interstices. Different metrics to assess the structural readiness of the industrial ecosystem (TRLs, but also governance models, value chain etc.) are also potentially useful prioritisation tools.

The industrial policy debate in mature industrial economies has progressed significantly over the last decade, although a number of new challenges have been highlighted (Andreoni, 2016; Chang and Andreoni, 2016). The industrial ecosystem framework introduced here aims at addressing some of these challenges by focusing on a number of both proactive and reactive policies for the innovative industrial renewal of mature economies. Five sets of issues deserve particular attention. While not exhaustive, they point to an industrial ecosystem policy agenda for innovative industrial renewal.

First, given the blurring of sectoral boundaries, sectoral industrial policies and technology policies should be complemented by policies 'targeting capability domains', as well as specific promising 'productive opportunities at the interstices' of the production space. These policies would support companies in the exploration of different diversification trajectories in the production space which would remain unexplored otherwise, towards the creation of new technologies, products and markets – i.e. smart diversification. The focus on local 'technology platforms' and 'catalogues of competences' in the ER regional industrial policy are examples in this direction (Andreoni et al., 2017)

Second, given the difficulties in identifying the real geographical boundaries of traditionally defined regional and national ISs, the industrial ecosystem suggests policies targeting variable geometries, that is, policies centred around industrial ecosystems, within and across regions and countries. Indeed, the smart specialisation agenda in Europe is a first attempt in this direction. However, variable geometries call for innovative governance models and careful alignment of different policy instruments, including new ways of composing different interests. This is one of the political economy challenges that the smart specialisation agenda in Europe has not been able to address so far (Andreoni and Landesmann, 2018).

Third, while mature economies have been increasingly targeting emerging technologies, in order to capture these new opportunities it will not be sufficient to concentrate efforts on the financing of basic research. More systemic efforts are required in addressing all sorts of potential constraints in the industrial ecosystem, and proactively increase its structural readiness to change. This might mean focusing on a number of apparently non-cutting edge technology efforts, such as reforming skills training, providing quasi-public good technologies, offering production services (technology intermediaries) or demand incentives (procurement) at different stages of the technology innovation chain.

Fourth, reforms in corporate governance and inter-firms contracting might be critical in promoting co-value creation and value retention in the industrial ecosystem, ultimately its structural readiness to change. In the industrial ecosystem, system integrators operate as focal points as they orchestrate processes of value creation and value capture in global markets. Smaller scale firms providing critical production and technology services are equally critical in co-value creation processes, although they tend to be more vulnerable to external demand shocks, financial crisis, financialisation of focal firms, etc. Industrial policy in combination with corporate governance reforms might become effective tools in reducing these vulnerabilities and guarantee value retention in the ecosystem.

Fifth, and finally, while processes of creative destruction are at the core of innovation dynamics, productive organisations are the result of long social processes of co-learning and collective capabilities development. While a number of companies might have reached points of no return and therefore industrial policies should smooth their ‘exit’, there are many other situations when industrial policy might re-set these organisations towards new paths of innovative industrial renewal. Processes of smart diversification as those suggested within the industrial ecosystem framework should be explored fully, to favour transformation or mutation. In fact it is often forgotten how many of today’s successful companies, as well as industrial ecosystems, have gone through multiple crises and the rumours around their death has been greatly exaggerated.

While being far from a comprehensive agenda, the integration/recombination of some of these analytical and policy insights with the current industrial policy discussion might lead to innovative and more effective industrial policy in mature industrial economies.

Notes

1 The in-depth longitudinal case study analysis included four rounds of data collection and more than 50 in-depth company interviews. Calibrated samples of companies and snowball sampling techniques were used to capture companies missing from traditional sectoral and regional datasets.

2 The biology analogy is intrinsically related to the idea of division of labour. Indeed Darwin was influenced by the zoologist Milne-Edwards who, in turn, drew on Adam Smith's idea of competition and division of labour, and applied an 'industrial analogy' in the biological context first (Schweber 1980).

3 However, as pointed out by Penrose (1952:808-19), the biological analogy should not lead to undermine the 'conscious willed decision of human beings' or 'treating innovations as chance mutation'. In fact, 'firms not only alter the environmental conditions necessary for the success of their actions, but, even more important, they know they know that they can alter them and that the environment is not independent of their own activities' (Penrose, 1959:42).

4 This emphasis on interdependencies is germane to the idea of "untraded interdependencies" used by Storper (1995) to highlight the way in which 'an industrial complex is an enacted system generated by knowledgeable participants who are subject to structural pressures but who are also collectively capable of transforming their environment' (Garnsey, 1998:371).

5 Many of the challenges in IS studies arise from the analytical management (and awareness) of these systemic complexities and, thus, the more or less explicit way in which different de-composition heuristics are adopted in the characterisation of multi-tiered system structures. In particular, thinking about an industrial ecosystem as a hierarchic and nearly-decomposable system helps us in identifying the different set of possible interactions (and interdependencies) among *heterogeneous actors* in a multi-tiered structure system, as well as its *boundaries*, without committing to any pre-determined list of organisations and institutions, geographical or sectoral boundaries (Simon, 2000)

6 TRLs are a nine-point scale based on a qualitative assessment of maturity, clustered around four main phases: research (TRL 1-3), development (TRL 4-6), deployment (TRL 7-8) and operations (TRL 9). TRLs are useful metrics in assessing the extent to which an ecosystem might find difficult to evolve as a result of limited technological readiness in specific areas.

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