The Evolution Path to Collaborative Networks 4.0

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Abstract. The last two decades have witnessed considerable boost in emergence of a networked society, reflecting the increasing growth in hyper-connectivity among the organizations, people, smart machines, and intelligent systems. This trend was enabled by advances in ICT and more specifically in computer networking. In this context, new forms of coworking and collaboration in networks, composed of distributed, autonomous, and heterogeneous entities have emerged, which first led to the formation of Collaborative Networks (CN) as a new discipline, and then followed by series of milestones leading to its gradual evolution.

Nowadays CNs play a key role in the ongoing process of digital transformation in industry and services. Although it is relatively young, a number of "generations" can be identified through the last decades for the CN discipline. We are now at the beginning of what can be identified as the Collaborative Networks 4.0, characterized by features such as: hybridization in CNs, collaboration between humans and intelligent autonomous systems, collaborative distributed cognitive systems, reflecting on collaborative accountability, handling ethics and coping with risks and disruptions faced in CNs, managing large amounts of collaborative data, monetization of collaboration, creating a collaboration culture, supporting collaboration creativity, handling mass collaboration, and supporting collaborative value creation through new business models, among others.

The IFIP WG 5.5, through its annual conference the PRO-VE, which is now in its 21st edition, has played a determinant role, along these two decades. It has contributed to shaping, promoting, and extending the CN research and development community and its practices; thus, consolidating this area, and identifying and introducing new directions and preserving it as an active research agenda.

Keywords: Collaborative Networks, Virtual Organizations, Virtual Enterprises, Digital Transformation, Business Ecosystems

1 Introduction

Along the last few decades there has been a noticeable increase in networking, which has enabled a big increase in collaboration activities supported by computer networks.

From an initial focus on collaboration among humans or organizations, the scope has been expanding to include collaboration with and among smart machines and systems. This trend results from a progressive integration of the physical and cyber worlds, namely Cyber-Physical Systems / Internet of Things (CPS/IoT), leading to what can be called a hyper connected world. Complementarily, more and more systems, devices and machines embed higher levels of intelligence, reflecting higher levels of autonomy [1].

Besides the technological drive, the collaboration trend has also been motivated by a number of other factors such as the need to strive in turbulent and even disruptive scenarios, increase in global competition, stronger environmental concerns, push for tailored and one-of-a-kind small products by customers, and tougher quality requirements, as well as the consumer demographic shifts, etc. [2], [3], [4].

Understanding and supporting collaboration activities requires contributions from multiple disciplines and areas, including computer science and engineering, industrial engineering, electrical engineering, management, economics, sociology, law, ethics, and even natural ecosystems and biology, etc. Although the subject has attracted considerable attention in different research communities, realizing the need to study and adopt all these contributions has caused a confluence towards developing an interdisciplinary perspective of the area. As such, during the last decades, the collaborative networks (CN) area has emerged and evolved as an established scientific discipline, whose first manifesto can be traced back to 2004/2005 [5], [6].

In parallel with research and development initiatives, a large number of application cases have emerged and become operational in virtually all sectors of the society. Often new experiments on collaboration have emerged even before the publication of their scientific basis is out. This has been induced and motivated by the possibilities offered by new technology and new market needs. Applications of collaborative networks in industry represent one of the largest groups, starting with the evolution of traditional supply chains to more dynamic value chains and global supply networks, including extended enterprises, virtual enterprises, business ecosystems, etc. [7]. This trend can be seen in manufacturing, namely in the so-called Industry 4.0 [8], [9], [10], [11], but also in construction, agribusiness, energy, and many other areas. The same has emerged in the area of services, with integrated multi-supplier business and software services in a large variety of sectors including commerce, tourism, insurance, healthcare, elderly care, education, and journalism, among others. Similarly, in the governmental sector for providing better services to citizens, through the integration of service offerings from different governmental organizations. We can also observe the emergence of public-private-social networks to address major societal problems which cannot be solved by any single organization.

In times of global crises, such as the case of COVID-19 pandemic, what becomes particularly noticeable is the high number of collaborative networks emerging worldwide. In different sectors such initiatives may use different terminologies, but a set of common underlying principles can be identified to be shared by all of them, showing that the CNs are nowadays widespread to all sectors of activity in the society.

This chapter aims to give an overview of the various types of CNs, a summary of current developments in the area, and a panorama of their evolution, and emerging directions and challenges.

2 A Classification of Collaborative Networks

There are currently many "manifestations" of collaborative networks in multiple sectors. Nevertheless, all these cases show diverse characteristics e.g., in terms of their structure, duration, purpose, internal agreements, external liabilities, and membership regulations, among many others. In order to facilitate understanding the specific characteristics of each case it is relevant to establish a taxonomy of collaborative networks.

A frequently used taxonomy (Fig. 1) was originally proposed in [12] and has been updated in more recent publications [7], [11], [13]. At its upper level, this taxonomy introduces two main classes:

- *Collaborative Networked Organizations* (CNOs) – to include all cases for which an organizational structure for the set of network members is designed and specified explicitly.
- *Ad-hoc collaborative networks* – to include those manifestations of CNs that emerge in a quasi-spontaneous way, without predefined organizational structure.

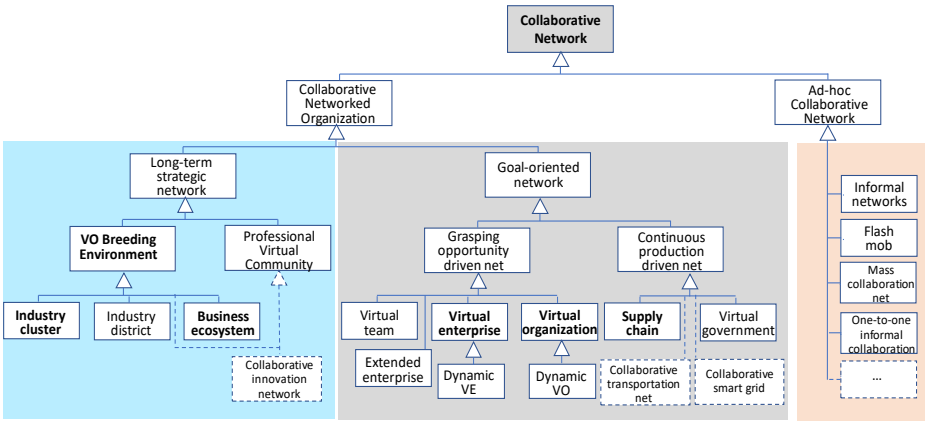

Fig. 1. A taxonomy of Collaborative Networks

CNOs include two main sub-classes:

- *Long-term strategic networks* – these are associations of entities, usually established with a very long duration in mind, and whose main objective is to help their members prepare for effectively working together whenever relevant new collaboration opportunities arise. In other words, these associations aim to facilitate the rapid and agile formation of goal-oriented networks in response to new opportunities. In order to accomplish such preparedness for collaboration, the involved entities invest in establishing common or interoperable ICT infrastructures / platforms, agree on common business principles, define rules for sharing and working methods, and providing high level of mutual awareness about the competencies and resources of the members, accompanied by trust building processes, etc.

- *Goal-oriented networks* – these are typically established within and through long-term strategic networks, in order for its involved entities to jointly achieve a given goal, such as realizing a specific project, developing a (complex) product, or providing a service, etc.

According to this taxonomy, the long-term strategic networks are further divided into *Virtual organizations Breeding Environments* (VBEs) [14] and *Professional Virtual Communities* (PVCs), depending on whether the main membership type is respectively organizations/enterprises or people (e.g., free-lancers). Today, some variants of VBEs include *Industry Clusters*, *Industrial Districts Business Ecosystems*, etc. As exceptions, there are some cases of networks that might be considered as both sub-class of the VBE and the PVC, e.g., *Collaborative Innovation networks*.

Goal-oriented Networks include the cases of (i) response to a single opportunity (*Grasping opportunity driven network*), which involves a temporary association of entities that join capabilities and resources to better satisfy the opportunity and that dissolve after the goal is achieved (typically project-oriented); and (ii) continuous production of a product or delivery of services (*Continuous production driven network*). Examples of case (i) include *virtual enterprise* (VE), *virtual organization* (VO), and *extended enterprise*, among others. Examples of case (ii) include *supply chains*, collaborative *virtual government*, etc.

Ad-hoc Collaborative Networks, which often rely on new mobile communication facilities and social networks and are characterized by some kind of "spontaneous emergence" without an apparent (strong) organizational structure. Some of these cases are triggered by some social event or sudden need, or even by human socialization needs. Under this class we can include, for instance, flash mobs, mass collaboration, informal networks, etc.

Considering that CNs are still young phenomena, many new forms are still emerging, namely induced by new technologies. As such, a taxonomy of CNs needs to remain open and subject to continuous expansion and evolution. The presented taxonomy has been used by the research community as a "working taxonomy". It was however defined at the early stage of this area, and it might be natural for other taxonomies to be proposed as new collaboration experiments pop-up once it becomes difficult to link them to the current classes. Furthermore, other taxonomies might also appear as a result of using different classification perspectives. For instance, in [15] Durugbu suggests a classification that uses mainly the same sub-classes but at the upper level they are organized in three different main groups: (1) Organization-driven, including VBEs and dynamic VOs; (2) Business-driven, including Extended Enterprise and Virtual Enterprise; (3) Professional-driven, including PVCs, eScience, and Virtual Labs. Then the class VO is defined as a member of the three groups.

We might also observe in time some transformation of classes. For instance, some ad-hoc cases, with a long duration, are likely to become organized and thus moved to the class of CNOs. That is the situation we observe for some cases of mass collaboration, such as in the Open source and Wikipedia development communities, which have evolved to a more structured cases and could better be classified as a sub-class of continuous production driven network.

3 Generations of Collaborative Networks

Collaborative Networks have been playing a key role in the ongoing process of digital transformation in industry and services. Despite CNs being a relatively young discipline, various development stages or as recently called "development generations" can be identified for it (Fig. 2). These stages/generations can be labelled as follows:

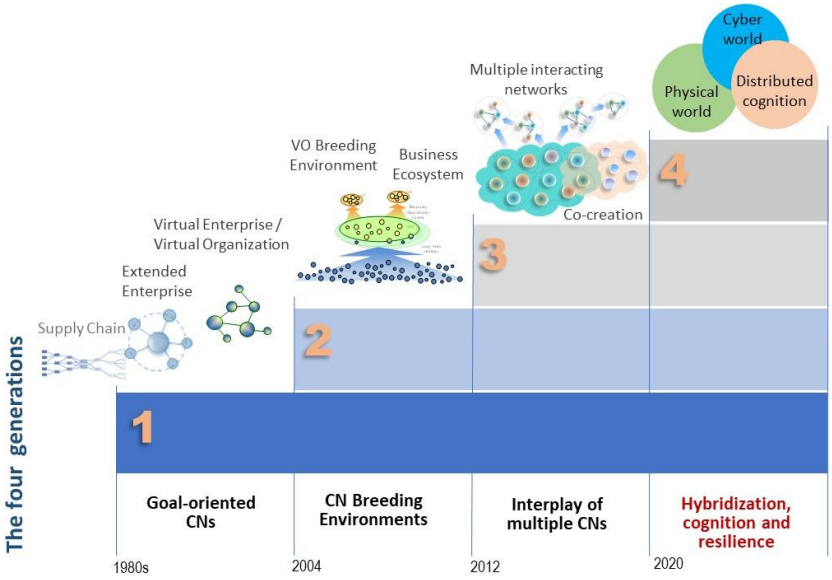

Fig. 2. Collaborative Networks Generations

- **Collaborative Networks 1.0** – corresponding to the early stage of the CNs, which was mostly focused on goal-oriented networks and that has covered the beginning manifestations of dynamic supply chains, extended enterprises, virtual enterprises, and virtual organizations.
- **Collaborative Networks 2.0** – mainly characterized by the introduction of the notion of VO breeding environment as a strategic network, encompassing business ecosystems, industry clusters, industrial districts, and professional virtual communities as sub-classes.
- **Collaborative Networks 3.0** – focused on addressing the interplay among multiple CNs, including hybrid value systems networks, co-creation and open innovation networks, and narrowing down on issues of multiple levels of membership, inheritance and transition between CNs, multi-supplier "servitization", etc.

At present however, we are entering a new stage of the CNs, whose precise characteristics are still not completely clear, but can so far be tentatively specified as follows:

- **Collaborative Networks 4.0** – primarily capturing: hybridization and collaboration between humans and intelligent autonomous systems, while addressing innovation in handling and support for distributed cognitive systems, reflection on accountability, ethics, coping with risks and disruptions, handling large amounts of data, monetizing collaboration, creation of collaboration culture, collaboration creativity, mass collaboration, collaborative value creation, and defining new business models among others.

In terms of research and development most ongoing challenges are in fact related to this generation.

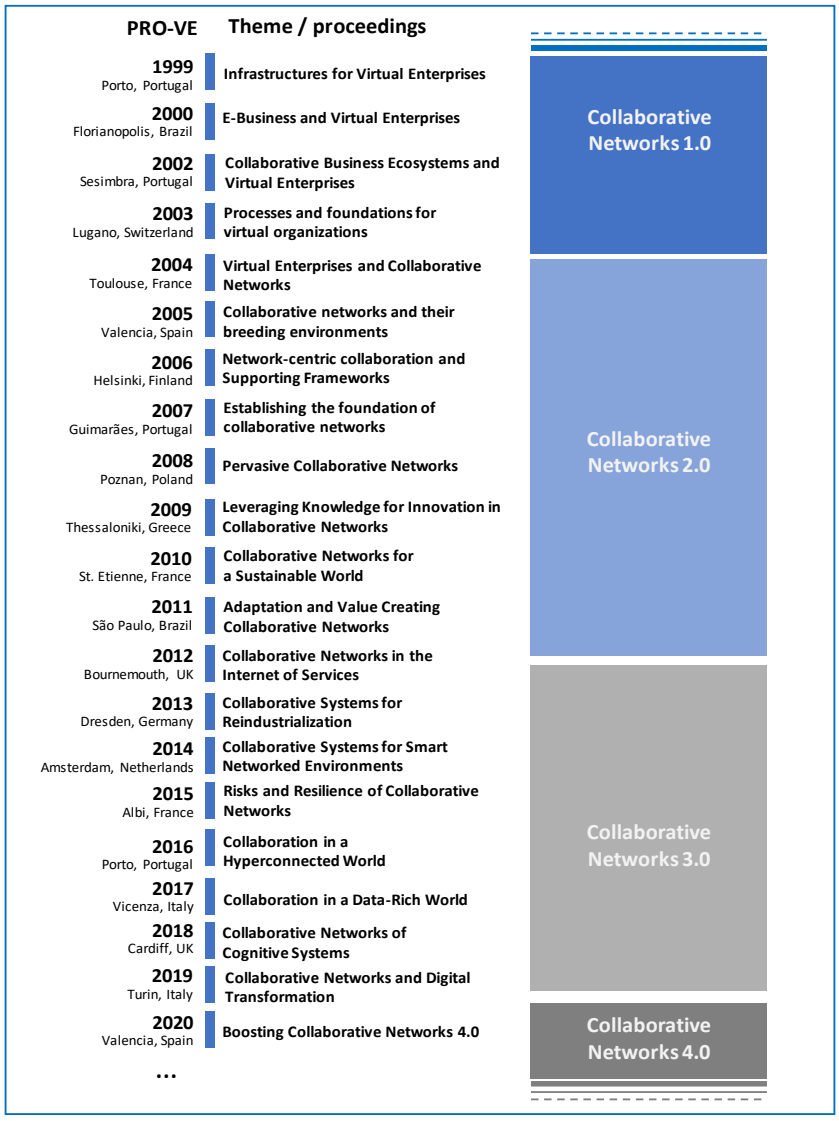

Fig. 3. The role of IFIP WG5.5 and PRO-VE in shaping the Collaborative Networks area

The IFIP WG 5.5, as reflected in its annual conference PRO-VE (Working Conference on Virtual Enterprises), has played a determinant role, along the last two decades, in formation and shaping of the related research community and its practices, consolidating the area, and pointing to new research and development directions, thus keeping an active research agenda (Fig. 3) [16]. Further to knowledge sharing and promoting a multi-disciplinary convergence, the PRO-VE series acquired a crucial role in the identification of needs, setting the trends, building a research community, and contributing to education.

4 Ongoing Developments, Trends, Challenges and Expectations

Research and development in CNs in the last decades covered a wide spectrum of activities from which a large number of achievements can be pointed out, including development of concepts, models, methods and tools, and their application to a variety of cases. Fig. 4 gives a brief high-level view of the main branches of developments on these past works.

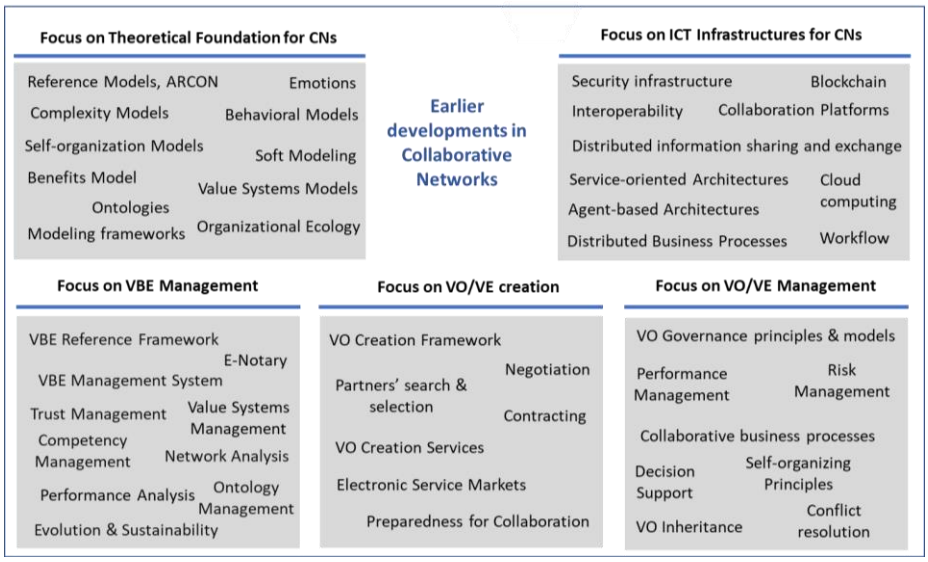

Fig. 4. Some earlier developments in Collaborative Networks

More recent and ongoing works involve a greater convergence of knowledge areas and technologies, in line and to some extent influenced by current trends in digital transformation and Industry 4.0 movement [11], eventually leading to a new generation of CNs.

In order to present the leading-edge areas of developments and trends that have revolutionized the CN, as well as the main challenges and expectations which these

have raised, we introduce three main categories for the research work in CN. These include addressing: (i) CN's scope, membership, organization, and governance, (ii) CN's support platforms, tools, and infrastructures, and (iii) CN's collaboration culture, strategies, and business models. Furthermore, for each of these categories, we provide a cross section among the sub-dimensions of the category against their related emerging trends and raised challenges. As such, Sections 4.1 to 4.3 represent each category and provide a set of significant examples within each of their respective cross section tables.

4.1 Evolution in Scope, Membership, Organization and Governance

While earlier works on CN were focused on networks of organizations or people, the same concepts are being extended to other types of collaborative networks. In Fig. 5, the main sub-dimensions of the evolution introduced in this area are mentioned, and for each sub-dimension, their recent trends as well as their main raised challenges are exemplified. A summary of our introduced aspects related to each sub-dimension is also described below.

Evolution in scope, membership, organization and governance

Sub-dimension	Recent and ongoing trends	Some emerging challenges
a. Evolution of scope	• Starting to address collaboration among components in complex CPS & SoS • Starting to address collaboration in digital twins	• Identify liability & responsibility borders • Further embed collaboration in digital twins • Transition from control-orientation to collaboration-orientation
b. Hybridization	• Human-Machine collaboration (e.g. collaborative robotics) • Understanding CNs as socio-technical systems • Early models of emotions in CNs	• Explore affective computing & emotions in CNs • Extend Machine-Machine collaboration • Extend human-digital twin concept to enhance H-M collaboration
c. Inspiration in Nature	• Ecosystem metaphor applied to businesses • Stigmergy and self-organization • Identification of structures, behavioral models & enhancement mechanisms	• Better understand collaboration mechanisms and principles • Replicate effective mechanisms and organizational structures from Nature
d. Multi-level networks	• Hyper-connectivity • Co-existence of formal and informal networks • Hybrid value systems	• Support inter-dependence of co-existing CNs • Develop governance for interacting networks • Better understand self-organization, co-evolution, power dynamics, value systems
e. CN Identification and differentiation	• Identification and differentiation of CNs from co-working situations analysis • Identification of collaborative behaviors	• Concisely specify collaborative behaviors • Identify and characterize emerging collaboration forms
f. Resilience & antifragility	• Identification of capabilities and strategies to support resilience and antifragility • CN developments in disaster management	• Find strategies & implementation approaches to enhance resilience and antifragility • Develop new relevant assessment indicators for resilience and antifragility
g. Collaboration – Competition	• Characterization of *coopetitive* environment • Positioning the *coopetitive* notion in CNs	• Better understand interactions collaboration – competition • Develop new collaborative behavior models • Incentives and expectations management
h. Sustainability	• CNs as an enabler of sustainability • Green collaborative networks • CNs in circular economy • Sustaining the collaboration	• Progress from enterprise-centric to ecosystem-oriented perspective • Align developments with standards & UN Agenda 2030 • Seek synergies with social innovation actions

Fig. 5. Overview of Evolution in Scope, Membership, Organization and Governance

a) Evolution in scope

CN concepts are penetrating the area of Cyber-Physical Systems / Internet of Things (CPS/IoT). Previous works on such systems were mostly focused on issues of integration and interoperability, safe communications, control, and energy management. As systems grow in complexity, becoming systems-of-systems (SoS), and involve very large numbers of interconnected components, collaborative networks also offer a new perspective on how to organize and manage them.

Examples include the emerging notion of Collaborative CPS [17], and new approaches to integrated systems-of-systems [18, 19]. In fact, some earlier ideas in this direction can be traced back to [20] which adopted the notions of VO and VBE to materialize agility and reconfigurability of the shop floor, but the approach is attracting more attention recently, as more and more sub-systems embed high levels of intelligence and autonomy [21].

b) Evolution towards hybridization

Collaboration between humans and machines gained a new boost with recent developments in collaborative robotics [22] and facilitated by new interfacing and sensing technologies. But nowadays, more extended scenarios are envisioned, involving collaboration among multiple humans and machines / sub-systems [11], taking advantage of the best capabilities of each. In fact, this idea revisits the notion of "balanced automation systems" [23], [24], which can get new realization through advanced digital twins.

Complementarily, understanding CNs as socio-technical systems allows to borrow concepts from social sciences to better model social interactions among network members. One example is reflected in addressing the notion of emotion in CNs [25], which opens new directions for effective governance of networks.

c) Seeking inspiration from collaboration cases in Nature

Nature offers a large display of collaboration cases, which appear to have a high degree of sustainability and optimization [13]. These cases have been studied in various disciplines including ecology, biology, zoology, etc., from which we can get new knowledge on effective collaboration mechanisms, roles, behavior, and organizational structures.

One of the most popular classes of collaborative networks, the business ecosystems, are in fact inspired on natural ecosystems [26], [27]. Stigmergy is another example of mechanism that has been adopted namely in mass collaboration [28], [11].

d) Evolution towards multi-level networks

With the increasing hyper-connectivity among organizations, people, machines, and smart systems, typically multiple networks co-exist and interact. These networks have different durations, can be at different stages of their life cycle, and often share some members and resources. Some of these networks are formal and regulated by contracts, while others are informal and led by social interactions. Frequently these networks comprise members with very different value systems. As such, it is important to understand their complexity, support the interplay among these networks [29], and devise appropriate governance and analysis methods applicable to them.

One example can be found in [30], where multiple virtual organizations play a role along the life cycle of a complex product such as a solar power plant.

e) Identification and differentiation of CNs
With the diversification in interconnection and socialization mechanisms, new forms of collaboration have emerged. In this context it is important to devise approaches and mechanisms to identify (make visible) and characterize emerging CNs. Examples in this direction include [31] focused on recognition and modeling of collaborative situations, and [32], which addresses the agile operation of small collaborative teams in the context knowledge organizations.

f) Evolution towards resilient and antifragile CNs
Society and its organizations face increasing number of disruptive events, which appear with increasing frequency with potentially large impacts. Such extreme events can be caused by economic crises, pandemic situations, climate change, political instability, terrorism, demographic and immigration shifts, changes in regulations, or high dependency on advanced complex technologies, among others. From industry point of view, these can easily disrupt the global supply chains as well as the local business ecosystems. In order to cope with such events, CNs need to develop high resilience, i.e., the capability to absorb shocks and recover [33], and antifragility, i.e. the capability to not only absorb shocks, but to enhance and become better afterwards [34].

An overview of mechanisms and capabilities to build resilience and antifragility in collaborative business ecosystems can be found in [4]. Other examples include [35], which addresses resilience in service-oriented architectures for virtual enterprises, and [36] that proposes a method for formalization and evaluation of resilience in collaborative networks. Regarding antifragility, an example work is [37], which addresses edge-attack and local edge-repair response mechanisms in complex networks.

g) Interactions collaboration – competition
The combination of collaboration and competition that often, while in an apparent paradox, take place within the same environment, led to the term “coopetition” and is attracting increasing attention [38].

Characterization of *coopetitive* environments and a better understanding of the behavior of their involved actors can help devising more effective governance for CNs. Complementarily, proper incentives policies and expectations management need to be better developed [39], [13].

h) Increased focus on sustainability
CNs have been always pointed out as a core enabler for preserving sustainability [40], and mainly in the sense that resolving the involved challenges in the market and society require collaboration among multiple stakeholders. In this direction, more recently, a number of works introduced the two notions of green virtual enterprise and green VO breeding environment and have further addressed the relation between these two concepts and the circular economy [41], [42], [43].

Complementarily, the issue of sustainability of the collaboration itself is addressed in [44] for the context of collaborative business ecosystems. Furthermore, various initiatives are looking into the role that can be played by CNs in the fulfillment of the set of objectives set in the UN Agenda 2030 for Sustainable Development [45].

4.2 Evolution in Support Platforms, Tools, and Infrastructures

The information and communication technologies have always constituted a core enabler for collaborative networks. Therefore, advances in these technologies naturally impact the evolution of CNs, as highlighted in Fig. 6, through a set of main sub-dimensions. In relation to each sub-dimension, the recent set of trends as well as the main raised challenges are then exemplified and briefly described below.

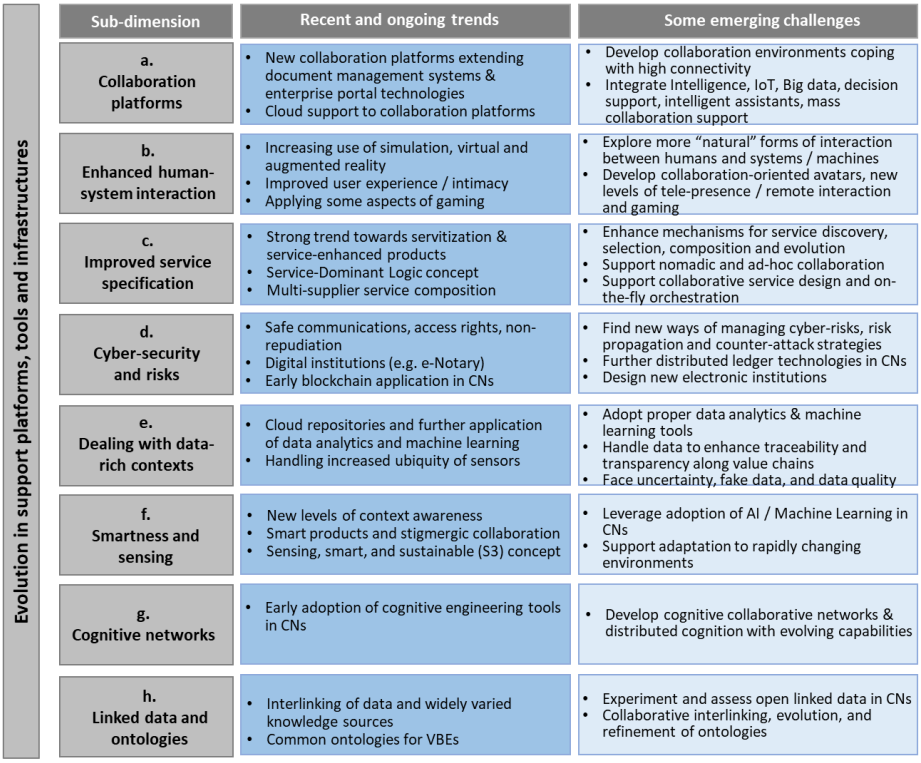

Fig. 6. Overview of Evolution in Support Platforms, Tools, and Infrastructures

a) Towards a new generation of collaboration platforms

New collaboration platforms, mainly focused on collaboration among humans, are primarily resulted from progressive evolution and convergence between document management systems and enterprise portal technologies. Additionally, cloud computing provided these platforms with more elastic resources management and

remote access, which is crucial for geographically distributed systems such as the CNs [46].

The combination of various other technologies, including the big data, sensing, IoT, and the AI / ML, offer new possibilities for richer collaboration environments, featuring real-time context awareness, decision-support and intelligent assistance, data handling, analysis and visualization, and data services [47], [48].

b) Enhancement of human-system interaction

The increasing adoption of augmented and virtual reality, simulation, and the so-called "natural user interfaces" allows for better human-machine interaction and system interface. The development of collaboration-oriented avatars [49], [50] adoption of gaming mechanisms, and remote interaction with resources also contribute to improving the user experience and establishing more effective interaction among network members.

c) Improved service specification

There is a strong trend towards "servitization" as reflected in the notions of service-enhanced products [51], product-service systems [52], [53], smart product, and service-dominant logic [54], [55], [56].

In recent times, there has been a special focus on the provision of integrated services and combining multi-supplier contributions, which implicitly requires addressing the collaborative networks for service provision [57]. Other directions include development of novel mechanisms for service discovery, service selection, service composition [58], and service evolution in order to adapt to the evolving user requirements as well as the technology evolution [57]. Collaborative design of services, complemented with the "de-construction" / transformation of traditional software systems into collections of services [59], is another trend that attracts research work.

d) Improved handling of cyber-security and communication risks

Dealing with cyber-security has been a continuous concern since the early stages of the CN discipline [60]. Various mechanisms for safe communications, access rights management, non-repudiation, authentication, etc. have been addressed. Complementarily, some experiments on electronic institutions were carried out [107]. One example is the electronic notary as an additional facility to support VO creation in VBEs, and as a tool supporting in VBE / business ecosystems management [62].

Further trends include approaches to preclude risk propagation and exploitation of distributed ledger technologies, such as the block-chain [63], [64], [48].

e) Dealing with data-rich contexts

The hyper-connectivity among organizations, people, devices, and systems, combined with increased usage of sensors, is leading to data-rich environments which enable better and timely decision-making, and development of new services. In this context, new challenges emerge regarding the adoption of proper data storage, visualization and analytics tools, and applicable machine learning techniques [11], [47]. One relevant point to mention here is the possibility for increased traceability and transparency of the contributors along the value chains [11]. But this new context also

poses new challenges regarding data privacy, data ownership, quality of data, fake data identification and handling, and how to cope with uncertainty that may rise in the CNs [65], [47], [66].

f) Increased smartness and sensing
Ubiquitous sensing allows for higher levels of context awareness which combined with progressive adoption of AI and ML leads to increasing the smartness, autonomy and self-adaptability capabilities of the infrastructures, systems, and machines. Such contexts support the design of "sensing, smart and sustainable (S3)" networks [67], [68] and thus resulting CNs that feature distributed intelligence. Some examples of applying these ideas to the design of novel collaborative platforms in manufacturing and smart products can be found in [69] and [70].

g) Towards cognitive networks
An additional level of integration of AI and machine learning elements in CN infrastructures and tools is emerging by the first attempts to embed cognitive engineering tools in such systems. One example is [71], which envisages cognitive-based collaborative networks to support mobile health services. In [72] the Cognitive Model of Creativity is explored to bring computational creativity to manufacturing networks. Another example [73] attempts to deploy cognitive capabilities in a CN for the delivery of public services.

These early examples illustrate a trend that may bring CNs to a form of collective intelligence or distributed cognition.

h) Exploring linked data and ontologies
In a hyperconnected world heterogeneous data and knowledge sources abound. The development of new methods to interlink and explore those sources, namely open ones, can enhance collaboration among members of CNs and open the opportunity for creation of new services. Additionally, the interlinking existing ontologies defined by different members in the CN, as well as collaborative refinement and evolution of the shared ontologies for the CN, is also important to facilitate common understanding.

As an example, in [74] linked data methods are used as the bases for development of advanced collaboration spaces. Another example [75] addresses collaborative editing of linked data. An early example of research and development for engineering and evolution of VBE ontology can be found in [76]. Another example [77] discusses extensions of a standard ontology for robotics and automation (CORA) for collaborative robotics and collaboration between humans and cyber-physical systems. A method for ontology evolution is illustrated in [61].

4.3 Evolution in Collaboration Culture, Strategies and Business Models

The third complementary area of evolutions in CNs focuses more on the soft issues related to this paradigm. In Fig. 7, a set of main sub-dimensions for the evolution introduced in this area are mentioned, and for each sub-dimension their recent trends

as well as their main raised challenges are exemplified. A summary of our introduced aspects related to each sub-dimension is also described further below.

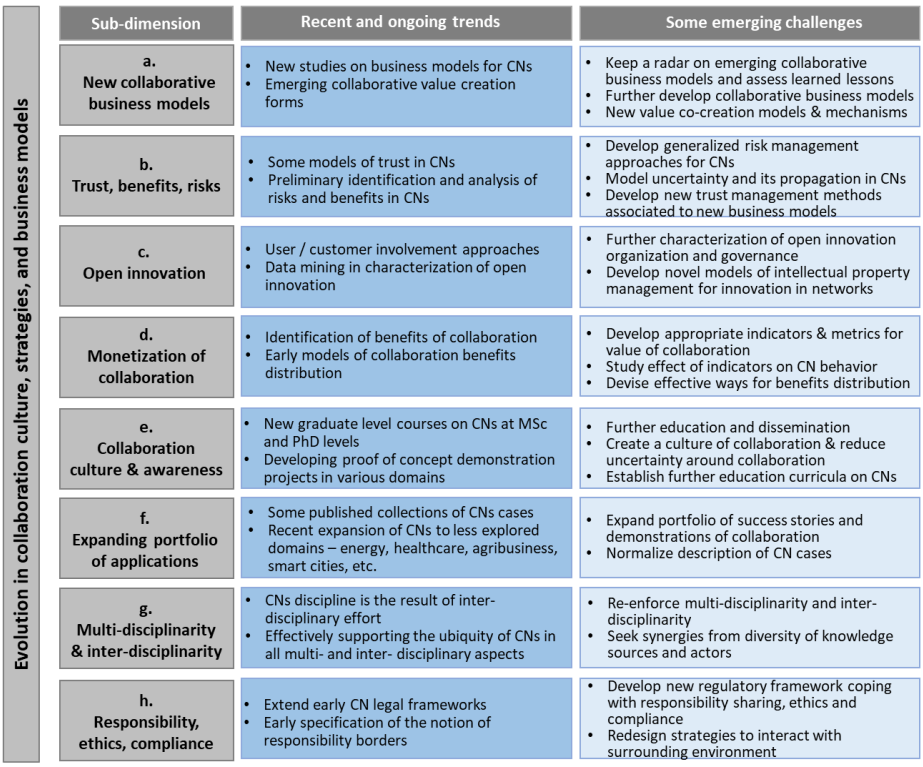

Fig. 7. Overview of Evolution in Collaboration Culture, Strategies and Business Models

a) New collaborative business models

The ongoing digital transformation processes and the associated convergence of multiple technologies induce new collaborative business models and value co-creation approaches. This trend is reflected in the emergence of concepts such as co-creation, co-innovation, customer intimacy, *glocal* enterprise, shared economy, *servitization*, and hybrid value chains, among others [11], [78], [79], [80].

The continued emergence of new collaboration forms raises the challenge of keeping a radar on such new business models, assessing lessons learned, and further modeling and structuring the involved mechanisms [81].

b) Further addressing of trust, collaboration benefits and risks

Trust management has been a classical topic in CN research. Various issues have been addressed, such as rational trust modeling, assessment, and management [82], trust monitoring [83], evaluation of the social dimension of trust [84], etc. With the emergence of new collaboration forms it also becomes important to pursue new approaches for trust management in relation to new business models.

The benefits of collaboration are often mentioned in the CN literature. However, there is little work on methods to make a fair distribution of benefits among the CN members. Some early examples include methods based on the Shappley value [85], [86], and a proposal for modeling the "social contributed benefits" and "external (received) benefits", together with a list of their relevant metrics [87]. Nevertheless, further developments of models for fair benefits distribution are still lacking.

Risks of collaboration is another issue that has been intuitively discussed and for which some methods have been proposed addressing the risk analysis and propagation, risk identification, and risk assessment and reduction [88], [89], [90], [91], [92]. Yet, a more generalized risk management approach for CNs is still needed, namely in order to cope with new the forms of CNs, and the complexity of multi-level networks.

c) Evolution in collaboration for open innovation

Collaboration for the purpose of innovation in an open setting has been another active research topic [92], [93], [94]. A comprehensive analysis of interactions between the two areas of collaborative networks and innovation/open innovation is provided in [95].

Customer involvement in CNs, and namely in co-creation / co-innovation processes, has been particularly focused on in recent years [30], [93], [96],[97].

Despite of these recent developments, further characterization of the open innovation processes, and their organization and governance, together with novel approaches to handle the rights to intellectual property in this context, remain open challenges.

d) Towards monetization of collaboration

Collaborative work adds certain overhead to the activities of its involved actors, e.g., the communication, reporting, and information exchange costs, the additional needed process formalization efforts, and the conflict resolution, among others. At the same time, various benefits generated through collaboration are difficult to measure and thus may easily be overlooked, e.g., the access to new knowledge, triggering innovative ideas, increased prestige, higher reputation, achieving diversity, as well as improving the potential of risk taking, acquisition of additional competencies, and agility, among others.

It is, therefore, important to devise ways of making collaboration benefits more explicit and measurable. Some earlier attempts in this direction can be found in [85] and [87] which address the modeling of collaboration benefits and identifying its main relevant indicators. Nevertheless, further work is still needed to appropriately define these indicators and introduce metrics for measuring the value of collaboration [11], in other words, to "monetize collaboration". Furthermore, it is also important to study the effect of such indicators on the behavior of the CN members [44].

e) Creation of collaboration culture and awareness

The effectiveness of collaboration does not depend solely on technological solutions. Considering the socio-technical nature of the CNs, it is fundamental to increase the general awareness about the main issues in CNs and to promote formal education on

this discipline. Various universities have launched graduate courses related to the CN subject at MSc/MBA and PhD levels. One of the first reported examples can be found in [98] and a preliminary proposal for a reference curriculum for CN education is provided in [99]. But further education curricula need to still be established [11] and sharing of experiences and educational resources needs to be promoted.

f) Expanding the portfolio of application domains

As part of a wider knowledge dissemination and awareness creation efforts for CNs, it is important to organize and make available collections of (real) case studies of CN applications. One example of such collection is available in [100], but an expansion of this portfolio would be highly beneficial for CN researchers, practitioners, and educators.

In recent years we have noticed a growing expansion of CNs to less explored domains, such as energy [101], health and elderly care [57], agribusiness [102], smart cities [47], etc. In order to facilitate the understanding and sharing of experiences across sectors, it is also important to reach some normalization on the description of the case studies.

g) Re-enforcing multi-disciplinary / inter-disciplinary approaches

The CN discipline itself is the result of an inter-disciplinary convergence [5], [6]. With the expansion of CN application to diverse domains and the involvement of new players as the result of ongoing digital transformation process [11], it is necessary to re-enforce the CN's multi-disciplinary and inter-disciplinary dialog, seeking synergies from diverse knowledge areas. Besides the traditional areas of technology and the social sciences involved in the CNs, it is increasingly important to also extend this dialog to natural sciences that study collaboration forms in Nature [13].

h) Progressing on responsibility, ethics, and compliance

Legal frameworks for regulating the creation and operation of several classes of CNs have been so far discussed, e.g., in [103], [104], [105], and various countries already have specific laws addressing both the "long-term strategic networks" and the "goal-oriented networks".

With the increase in hyper-connectivity as well as in the intelligence / autonomy of machines and systems, it is necessary to further invest on regulatory frameworks coping with issues of responsibility, ethics, and compliance [11] among all entities involved in the CNs. For instance, in [106] there is some discussion on liability and "responsibility borders" in the case of multi-supplier systems-of-systems, but these issues need further developments as we move towards hybridization of CNs.

5 Conclusions

Currently, research and development on collaborative networks are growing in a pervasive manner, as manifested in covering a large number of collaboration forms and CN applications in multiple sectors of the society. Induced by new possibilities offered by advances in information and communication technologies, and motivated

by the current digital transformation movement, it is likely that various other new forms of CN will also appear in the coming years. As such, it is important to the CN taxonomy is open, in order to properly allow positioning various types of CNs in relation to one another.

Along the last 2-3 decades, R&D in this area has co-evolved in parallel to the evolutions in ICT developments, the new market, and the societal needs, thus introducing a number of significant leaps in this area. In analogy with the industrial revolutions and the ongoing Industry 4.0 trends, four "generations of CNs" can also be identified. The currently emerging 4th generation is still in its early stages. Nevertheless, it can already be roughly characterized by various dimensions as well as the trends and challenges that once achieved, will boost the CN 4.0. As such, in this chapter an extensive list of trends and challenges is identified, which are organized along three main dimensions of: (1) Evolution in scope, memberships, organization and governance, (2) Evolution in support platforms, tools and infrastructures, and (3) Evolution in collaboration culture, strategies, and business models. The set of trends and challenges that are mentioned and exemplified in relation to each of the above dimensions and their sub-dimensions, also constitute the elements of a research agenda for the coming years in this area.

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