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Thinking (in) Complexity: (In)definitions and (mis)conceptions

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Abstract

The rise of the Complexity Sciences has led to the development of new language about systems. Concepts such as ‘complex systems thinking’ or ‘complexity thinking’ have appeared in the literature appealing to ways of thinking (in) complexity. The notion of ‘complex thinking’ as introduced by Edgar Morin, refers to a mode of thinking more congruent with the complexity of the world. The widespread and sometimes undifferentiated usage of these concepts results in a lack of clarity and terminological confusion, which jeopardizes their heuristic and pragmatic value. We identify literature using terms related to thinking (in) complexity and use a combination of computational and qualitative methods to extract definitions and analyse their usage. We map the relationships of the concepts and their usage across different intellectual communities. Our goal is to clarify these concepts and to strengthen their pragmatic value for the promotion and management of positive changes in complex systems.

Keywords: Complex thinking; Complexity thinking; Complex systems thinking; Bibliometric analysis; Qualitative analysis

Introduction

Systems thinking (e.g. Checkland, 1999) initiated a revolution in the dominant western modes of thinking based on mechanistic worldviews and reductionist approaches to knowledge production (Capra, 1996). Systems thinking has a long tradition in the literature and in practice (Reynolds & Holwell, 2010; Arnold & Wade, 2015) but the advent of Complexity has brought to the literature a diversity of new concepts such as 'complex thinking', 'complex systems thinking' or 'complexity thinking'. The "complexity turn" (Urry, 2005) has not just continued but expanded the revolution initiated by systems thinking calling attention to particular properties of the world. Properties such as non-linearity, recursiveness, emergence and self-organisation, amongst others, and unpredictable dynamic behaviours have been associated with systems that are 'complex' (Kaufmann, 1996; Érdi, 2008; Stepney, 2018; Thurner *et al*., 2018).

The study of complex systems has produced a body of knowledge hosted under the umbrella of an emergent Complex Systems Science(s) or Complexity Science(s) including a set of assumptions and key concepts associated with Complexity Theory as a general framework to understand complexity (Castellani & Hafferty 2009; Byrne & Callaghan, 2013).

New worldviews began to emerge and with them the call for the development of new modes of thinking capable of grasping this complexity (Waddington, 1977; Morin, 2005). These should, in principle, be more capable of supporting the investigation of complexity and the design of interventions aimed at promoting or managing change in the "real-world" (e.g. Bar-Yam, 2004; Senge, 2006; Blinded for review).

In relation to the developments of the Complexity Sciences, Edgar Morin introduced the notion of Complex Thinking as a new mode of thinking that attends to and integrates some aspects of the complexity of the world (Morin, 2005). In principle, more complex modes of thinking could support a better understanding and management of change in the world. Morin argues that even within the scope of Complexity, science may operate with modes of thinking grounded in very different ontological and epistemological framings (Morin, 2007). Indeed, Morin has called attention to the fact that a significant amount of work conducted under the realm Complexity Sciences may be trapped in what he calls "restricted complexity", a scientific approach operating within a paradigm of simplification not so dissimilar to that of traditional science. Within this framework the goal is to "decomplexify" complexity, focusing on the goals of control (of complex systems) and the uncovering of universal laws. Morin positions these modes of thinking, largely translated into modelling and simulation techniques, in the tradition of the Santa Fe School, in contrast with ideas of complexity that focus more on the organisational aspects of knowledge and broader ontological and epistemological implications. He has called attention to the fact that the modes of thinking underlying much of the computational approaches to complexity, by neglecting the core organisational aspects of systems underlying properties such as emergence, may not, in themselves, be complex. He sees the necessity for a type of logical complexity capable of integrating the complementarities that are necessary to describe different dimensions of the world (e.g. part-whole; order-disorder) and the dynamic interplay between them that sustains it as a complex whole (Morin, 2007). In the sense of calling for approaches to a more "generalised complexity", Morin has also contributed to deepen the

broader reductionist/antireductionist debate. Although outside the scope of this paper, overviews of Morin's work are available elsewhere (e.g. Montuori, 2004, 2004).
Different approaches to complexity may, then, confer different meanings to concepts associated with thinking (in) complexity. It is possible that similar terms are used to refer to distinct or complementary modes of thinking and that distinct concepts are used interchangeably. Clarifying the ways in which thinking (in) complexity is conceptualised in the literature, and how different concepts are related, may be important steps towards exploring possible complementarities and synergies between approaches. This type of conceptual clarification and mapping may be important to support the development of strategies, tools and resources for the promotion and evaluation of different modes of thinking, as well as their coordination, applied to the understanding and management of real challenges and their complexity. One way to approach a preliminary mapping of the literature is to identify different intellectual communities, distinguished by their use of common references, and to analyse how they use key concepts.
Morin's work has somehow contributed to an important distinction between complexity theories (i.e. theories aimed at describing, explaining and predicting complexity) with their respective contents and concepts (e.g. emergence; self-organisation; autopoiesis; criticality) and complex thinking as the extent to which the thinking (process) is organised according to the same principles that sustain the complexity of the world. Morin (1992, 2005, 2014) has proposed the notion of ("generalised") complex thinking as a way of thinking complexity through a set of key principles related to the complexity of the world, namely (i) the *dialogical principle*, through which one may "maintain duality in the context of unity" (Morin, 2005, p. 99) and integrate complementary aspects of reality, that appear as antagonistic (e.g. parts-whole; order-disorder) ; (ii) the *principle of organisational recursion or recursivity*, whereby a process is simultaneously the product and producer of itself (Morin, 2014, p. 17); and, finally, (iii) the *hologrammatic principle*- where the parts are represented and contained in the whole and the whole is represented and contained in the parts.
This leaves open the possibility of distinguishing between thinking complexity and thinking in complexity.
The field of Complexity Science has been expanding and, in that expansion, the vocabulary related to the thinking is differentiating (e.g. complex thinking; complexity thinking; complex systems thinking). There might be different modes of thinking complexity and different concepts that relate to this notion of complex thinking in similar or different ways. In this paper, we identify literature that uses target terms related to thinking (in) complexity and use a combination of quantitative and qualitative methods to identify intellectual communities, extract definitions of these concepts, investigate their usage and how they are differentiated or connected across different intellectual communities.

Methods

Corpus Creation

We used the Web of Science search engine to search the Core Collection (WoSCC) and Scielo databases for documents that use any of the target terms: "complex thinking" (CT) OR

"complexity thinking" (CyT) OR "complex systems thinking" (CST) OR "pensée complexe" (PC). (PC is included as Morin predominantly published in French and only limited works have been translated into English). The WoSCC was chosen as it covers a broad scope of the scientific literature; Scielo represents a complementary resource of literature written in Portuguese and Spanish originating principally in South America, Portugal and Spain.
The search results were downloaded in Bibtex format and then filtered to remove duplicate papers and any that did not have an abstract available in English (necessary for our qualitative analysis). The resulting corpus of 478 documents comprising 420 journal articles, 57 conference articles and 1 book; 378 of these documents were found in WoSCC with 100 from Scielo. For 358 (~75%) of the documents in the corpus, we were able to manually download a full text PDF.

Characteristics of the Corpus

The corpus contained documents from the period 1972 to 2018 from 376 different journals. The documents had a total of 1065 different authors with an average of 2.23 authors per document with 176 articles being single-authored. The average number of documents per author was 0.45, with a maximum of 8. The number of citations per year grew over the period at a rate of 12.7%, with a total of 62 articles published in 2017. Further summary information on the Corpus can be found in Supplementary Information S1.

Full-text analyses: Co-occurrence of Search Terms in the Corpus

To determine which papers used the different terms, including in what combinations, we searched in the full text of 358 of the papers. The search was carried out by first extracting the text from the PDF version of the paper, and then searching that extract text for occurances of the four terms individually. The text was extracted and searched using a software tool specifically developed for the task developed in Java (Blinded for review). Measures were taken to clean the extracted text of artifacts that might result in the tool missing the terms, such as new lines or double spaces. The papers were then tagged as to whether each of the terms occured at least once anywhere in the extracted text.

Network Analysis

Network production and analyses were performed using the Bibliometrix package in R (Aria & Cuccurullo, 2017) which has functions to read the data exported from WoSCC and Scielo and to produce, analyse and visualise bibliometric networks.

Network Production

We assume that patterns of citation are characteristics of different intellectual communities that can be explored in relation to their usage of target concepts. Hence, we analysed the corpus to produce a citation coupling network (Trujillo & Long, 2018). The network is composed of nodes that correspond to the documents, and edges that indicate that two documents cited at least one document in common (a co-occurrence of a citation); coupling analysis has been shown to be an effective methodology for mapping scientific fields (Boyack & Klavans, 2010). Edges can be weighted to indicate the number of co-occurrence

citations, although in the analyses we treat the network as unweighted. We interpret co-occurrence of citations as an indication of the degree to which any two papers are drawing from the same body of knowledge or intellectual tradition.

Network Metrics

Node degree centrality (degree) is the number of edges that a node has connecting it to other nodes. In this context, a high value of degree indicates that a document shares citations with many other documents within the network (which may be suggestive of a review article). (Node) betweenness centrality is a measure of the number of shortest paths (paths with the lowest number of edges connecting any given pair of nodes) between all nodes of the network that go through a particular node. In this context, a high betweenness could arise for a document that bridges domains of study by citing documents across distinct intellectual communities (see below). The hybrid measure of betweenness/degree for a node gives an indication that it is important in connecting across the network, but may have a relatively low number of connections to other nodes: we denote nodes of this character as important "brokers". Further accessible explanation of network metrics and analyses can be found in Borgatti et al. (2018).

Network Structure

The coupling network of the corpus has 328 nodes and 1060 edges (150 nodes had no edges). The overall network contains 14 components (components are connected subgraphs of the network) that contain more than 1 node. The single largest component has 292 nodes (representing 61% of the corpus). The two next largest components contains 7 and 4 nodes, whilst 11 components contain 2 or 3 nodes. We chose to analyse only the largest component as this represents a significant proportion of the total corpus and allows us to analyse a single connected network of potential communities. Hereafter the largest component is referred to as the "core component" and is the principal focus of subsequent analysis.
The community structure of the core component was determined using the WalkTrap algorithm (Pons & Lapaty, 2006). There are 20 communities with more than 3 documents and 6 communities with 10 or more documents.

Qualitative analyses

In order to identify how the concepts are used across the literature we selected a sample of papers for qualitative analyses, targeting the 6 communities that contained 10 or more source documents (ids: 1, 4, 10, 13, 17 and 21). A visual inspection of the core component revealed a region that was not covered by these 6 communities. Two additional communities (ids: 5 and 9), with 8 documents each, were identified in this region and added to the target communities sample. A third community with 8 papers was located in the main region of the core component. However we could not access the corresponding full text documents and did we did not consider it for analysis. An additional set of 5 papers was chosen as key "brokers" in the core component based on high values of node betweenness/degree.

Identifying community themes: thematic content analysis

We conducted a thematic analysis in order to identify pattern themes (Braun & Clarke, 2006) that connected the documents in each of the 8 target communities. We coded the abstracts and lists of keywords (the "Keywords Plus" ascribed by ISI) attempting to answer the questions: "what are the more salient themes", "what are the patterns/themes that connect the documents within a community?", and "what distinguishes the different communities". We used an inductive approach and annotated the responses to these questions as themes/codes and then looked to characterize overarching themes that best expressed the specific identity of each community. This analysis was conducted independently by two team members, who compared their individual coding and theme extraction and negotiated a consensus to label each community. Table 3 contains the total number of documents in each community.

Evaluating the clarity of the definition of concepts: directed content analysis

From each targeted community, we selected a sub-sample of documents to conduct a directed content analysis aimed at identifying how the target concepts "complex thinking" (CT), "complex systems thinking" (CST) and "complexity thinking" (CyT) are defined and used in the literature.

A sub-sample of 25% of documents was chosen from each targeted community corresponding to the documents with the highest degree value relative to the overall network (for which full text was available) plus the additional set of 5 papers chosen for the relation betweenness/degree. This allowed for the retrieval of a total of 44 papers. A list of these sample documents is available in Supplementary Material.

We conducted a directed content-analysis (Hsieh & Shannon, 2005) of the selected documents to classify the extent to which they provided Explicit or Implicit definitions of the target concepts or whether they were Undefined. We searched the full text pdfs for the target concepts and analysed the paragraphs where the concepts appeared. We coded the paper according to the following criteria:

- Explicit definition: the authors clearly state what they conceive the concept to refer to, for example "CT/ CST/CyT *is*" or "we consider "CT/ CST/CyT *as*". A document could be coded as presenting an 'Explicit' definition (E) even if it appeared vague or imprecise to the extent that there was an explicit attempt to state what it refers to. If a definition was considered vague, the full paper was analysed to ensure that any implicit definition was captured in the exploratory open coding of definitions and to explore the extent that it validated the explicit coding.

- Implicit definition: Whenever an explicit definition was not presented, we read the full document to identify to extract an 'Implicit' definition by deducing meaning from other key concepts used in the text and how they seem to relate to each other. Whenever it was possible to extract a meaning or a theme we coded the paper as presenting an Implicit definition of the target concept.

- Undefined: This code was applied when even after reading the full text it was not possible to extract any particular implicit definition or attached meaning that could define its usage or when it seemed to be used in common sense to mean something that is 'elaborated' or 'complicated' or as a rhetorical device.

A sub-sample of documents was analysed by at least two team members who then discussed their ratings and tried to reach an agreement on the classification. In those cases where individual team members were able to definitely attribute a specific coding, there was full agreement across team members. Whenever there was uncertainty about which code to assign, usually between "Explicit vs Implicit" and "Implicit vs Undefined", the team members discussed their doubts and negotiated an agreement. At this stage, 7 documents were rated by three team members, 20 documents were rated by 2 team members. A remaining 13 documents were rated by one team member, after the criteria for coding were made clearer.

Identifying patterns of usage of concepts: exploratory open coding

We used a general holistic coding approach (Saldana, 2015) to identify themed patterns (Braun & Clarke, 2006) of latent meanings or definitions by attempting to respond to the question: "the authors seem to use the concept as pertaining to x/ as if it was x /meaning x/as if it relates to x". The extracted codes, which are described in the Results section, should be read as corresponding to the "x" in these sentences and represent different usages of the concepts. Each team member first generated a list of initial codes (open coding) (Braun & Clarke, 2006; Saldana, 2015) corresponding to extracted meanings or types of usages associated with the explicit or implicit definitions of the target concepts. A process of constant comparison was adopted in order to differentiate and relate the extracted definitions. The lists were then discussed by two team members in order to identify themes/patterns and subsume some codes under broader categories (Braun & Clarke, 2006; Saldana, 2015). A visual concept map was generated to organise the meanings associated with the usage of the concepts and organise them according to how they appear related, their closeness similarities and overlaps.

Results

Prevalence of the Target Concepts

The results of the full-text analysis for all available full-text documents in the whole corpus (n=358 out of 478) are shown in Table 1. Most commonly used terms are 'complex thinking', followed by 'complexity thinking'. A small proportion of documents includes more than one concept, with the most common co-occurrence being the use of 'complex systems thinking' with 'complexity thinking' (2.23%), followed by 'complex thinking' with 'complexity thinking' (1.11%) and 'complex systems thinking' and 'complex thinking' (0.56%). No document used more than two of the target concepts.

Table 1. Full text analysis: Proportions of the full text documents (n= 358) with at least one occurrence of the target concepts.

<<Insert table 1 around here>>

Structure of the Coupling Network

The general properties of the core component of the network are shown in Table 2. The low edge density (proportion of observed edges to total number of possible edges) indicates that it is sparsely connected. The high transitivity (proportion of observed edges to total possible edges between all pairs of nodes connected to common node) contributes to the low average

path length (how many edges, on average, it takes to connect any pair of nodes). The maximum node degree is 41, 65% of nodes have a degree of 5 or less (a plot of the degree distribution can be found in Supplementary Information SI.2). The overall layout and community structure of the core component of the coupling network is shown in Figure 1. The nodes corresponding to the most populated communities (see Methods) are identified and named as a result of the detailed qualitative analyses that are described below.

Table 2. General Properties of the Core Component of the Coupling Network
<<Insert table 2 around here>>

-Insert Figure 1 around here-

Definitions, Usages and Mapping of Target Concepts

The qualitative analysis identifies the communities as pertaining to domains or fields where concepts related to complexity and thinking are applied in the understanding of a given phenomenon (Table 3) . Community 1 is characterised by a consistent focus on complex thinking used as a conceptual lens influenced by 'complex systems science' or 'complexity science' to conceptualise health and health systems. The concepts of CyT and CST are used without an explicit definition. In Community 4, the focus is on social systems. A diversity of concepts related to complexity and thinking related to complexity are used, sometimes explicitly, sometimes implicitly. Community 10 has a clear focus on complexity as a property of cognition. The concept of CT is applied in a very restricted and clearly defined way and the properties of the complexity of the thinking are elaborated explicitly. In community 13 the focus is more philosophical and more guided by an explicit use of concept thinking, often informed by Morin's contributions. The domains are diverse but issues are addressed with an epistemological focus. Topics related to knowledge and inter/transdisciplinarity are common. Community 17 is focused on developing and applying frameworks that afford an understanding and opportunities for action in relation to complex problems and challenges posed by the real-world with a focus on complex thinking as guiding concept. Community 21 resembles community 4 but the focus is on education and educational systems. The terms CST and CT are used mostly explicitly. Communities 5 and 9 correspond mostly to qualitative nursing studies where CT appears as a key concept, defined both explicitly and implicitly and from which key principles are elaborated that shape the use of the methods and the interpretative frameworks used to grasp or attend to the complexity of the phenomena at hand. The documents in the 'brokers' set use mostly CT as a key term.

Table 3. Summary of the targeted communities, with identification of themes and classifications of concept usage
<<insert table 3 around here>>

Table 4 shows the distribution of the classification of the concepts in relation to the type of definition showing the relative percentages and number of documents rated in each category.

Table 4. Distribution of the classification of concepts regarding the type of definitions.
<<Insert table 4 around here>>

While there are more concepts explicitly defined than otherwise, in comparative terms, CYT is more often defined explicitly than 'CT' and it was never classified as undefined. For CST, there are more implicit than explicit definitions.

Table 5 presents the main categories of themes associated with the different usages of the concepts, and the corresponding definitions. Some of these broad themes are divided into sub-themes which are represented in Figure 2 and described below.
<<Insert table 5 around here>>
In this section, we italicised the words that correspond to coded themes. The labels of the main categories of coded themes are presented between simple quotation marks, capitalised and italicised. The sub-themes, within each main category are presented in italics. Figure 2 presents a conceptual map of how the different target concepts appear related to each other regarding the different meanings/definitions extracted from our sample. It shows the overlap of meanings/definitions between concept terms but also how some concepts are used in distinctive ways. The boxes with the white background correspond to main categories of themes and the coloured boxes to sub-themes.

-Insert Figure 2 around here-

As represented in the figure, the term CT is sometimes used in ways that apply also to CyT while CyT is more often used in ways that apply to CST. There is a clear distinction between the top right part of the figure and the bottom left with the former being more associated with contributions from the study of complex systems, in the *tradition of the Santa Fé school*, and the later being more directly associated with the work of Edgar Morin and his conception of complex thinking. To some extent, the former is better represented under the umbrella of "restricted" complex(ity) (thinking) while the latter would better fit Morin's notion of "general" complex(ity) (thinking). This distinction is highlighted by the different colours used as borders for the boxes in the figure, corresponding to the difference between concept usages that more associated with the content of the thinking (what one thinks about) and those that more associated with the process of thinking (how one thinks about). While CST is more often used as referring to content, CT has a more processual meaning. The usage of CyT reveals both orientations.
CyT shares certain usages with CST. Both CyT and CST are sometimes used to refer to the '*Contents of the Thinking'*.

> "At the same time, ' complexity thinking' and 'complexity ideas' have diffused into several areas of the social sciences (...)." (Martin, 2007. Page 575)

CST is also used to refer to the '*Contents of the Thinking'* that is associated with modelling and simulation and to refer to the *modelling decisions* and choice of methods.

> "Complex systems thinking is often defined in relationship to computational systems modeling (...)(Jacobson and Wilensky 2006)." (Berland, 2015. Page 628)

> "complex systems thinking can be used to describe a student's ability to think in terms of systems of elements (...) in this paper, we focus on a specific form of complex systems thinking called levels thinking (Wilensky and Resnick 1999). Levels thinking describes the

> ability to think with and from complex systems theories and models in terms of component aspects (which we term ‘‘agents’’), groups of those agents (which we term ‘‘aggregates’’), and the models and meaning that emerge from their relationships." (Berland 2015. Page 630)

The target concepts are sometimes used to refer to an an academic ‘*School/Paradigm*’, albeit they may refer to different orientations. CST and CyT appear used as references to a type of thinking that follows the tradition of the *Santa Fe School* (www.santafe.edu) in approaching complexity and is more focused on the *contents of the thinking* associated with modelling

> “ Such a theory would perhaps only be possible at a very high level of abstraction and generalization, which presumably is why some adherents of complexity thinking—including the Santa Fe school, and many others (such as Krugman, 1996)—seek to establish formal mathematical principles of complex behaviour." (Martin, 2007. Page 7)”

On the other hand, when CT is used to refer to a ‘School/Paradigm’ it tends to align to an intellectual tradition built upon *Edgar Morin’s concept of complex thinking* as organised by particular principles associated with complexity. It appear as a (complementary) alternative to the School of “restricted complexity” and encompasses a more *philosophical approach,* namely epistemological. Within this tradition, CT is approached as a basic way of thinking about complexity guided by key principles that organise complex systems. As an *alternative paradigm* it also addresses the *narrative dimensions of human systems, embraces a metaphorical approach and integrates qualitative methods in exploring complexity*.

> "From the interpretive perspective, chaos and complexity are metaphors that posit new connections, draw our attention to new phenomena and help us see what we could not see before (Rorty, 1989) (...) Such a perspective departs radically from the established orthodoxy, which is derived mainly from the Santa Fe Institute (Waldrop, 1992). Whereas most Santa Fe scientists tend to conceive of complexity in the classic reductionist manner of searching for the common principles underlying a variety of utterly different systems (see for example Holland, 1995), the perspective adopted here seeks to generate new insights, and thus contribute to expanding the possibilities for thought and action, through the use of the narrative perspective and of the metaphor of complexity (Morgan, 1997; Rorty, 1989)." (Tsoukas, 2001. Page 981).
>
> "A qualitative approach was used, associating complex thinking with the theme-field perspective, and analyzing the production of meanings in daily life, through discursive practices" (Bedin and Kochenborger Scarparo, 2012. Page 90).”

When referring to a ‘*School/Paradigm*’ include a focus on the *integration of knowledge* under a metaphor of complexity. The integration of knowledge is presented as dependent on CT as a way of thinking that is organised by key principles and recognises the role of the thinking subject.

> "He [Morin] poses a new kind of harmonic relationship with the world that comes from the discovery of complexity in science (Morin, 2008). (...) Complex thinking deeply confronts the principles of reduction, disjunction, and determinism of the classical non complex science dating back to Galileo and Newton, which is prior to the “paradigm shift” advanced by information theory, cybernetics, and systems science." (Malaina, 2015. Page 2)
>
> "General complexity” comprises a broad community of philosophers, thinkers, and scientists from many different disciplines and fields of knowledge. The complex thinking of Edgar Morin would be the perfect synthesis of this transdisciplinary epistemic perspective (Morin, 2005a).' (Malaina, 2015. Page 2)

CST and CyT are also used to refer to the application of a ‘*Conceptual Lens*’ in the understanding of a target system that highlights particular types of contents or properties in

the system of interest. This type of usage of the concept may align with the *Santa Fe tradition* and the *contents produced by what have been called "Complex Systems Science" (the study of complex systems), "Complexity Science" or "Complexity Theory"*.

> "We draw on the theoretical perspectives of complexity thinking (also known as complexity science and complexity theory, see for example, Davis, Sumara & Luce-Kapler, 2008; Richardson & Cilliers, 2001) to further explore personal narrative writing assignments as complex, pedagogical phenomena." (Laidlaw, 2013. Page 103)"

> "The point of departure of critical complexity thinking is provided by insights from mainstream complexity theory, as developed during the past 30 years within information theory and neural network theory, by the members of the Santa Fé school." (Kunneman, 2016. Page 421)"

When referring to a '*Conceptual Lens*', the concept terms may refer to a type of thinking that is organised around a certain number of assumptions about how complex systems operate and that are used to guide the (re)conceptualisation of a target system as complex or to build a different understanding of its processes of change.

> "Complexity thinking, which is derived from complexity theory, is a powerful conceptual framework in education that draws on the qualities of complex systems to characterize learning systems (e.g. Davis and Sumara 2006). As such, with its organic, non-linear, relational and holistic features, complexity thinking presents a stark point of departure for contemporary educational research thinking (Morrison 2006). (...) a variety of good exemplars are hard to find for newcomers contemplating the use of complexity thinking as a conceptual framework." (Forsman, 2014. Page 68)

> "Ultimately, complexity thinking acknowledges the " messiness" that we seek to control in healthcare and encourages us to embrace it. This means seeing challenges as opportunities for adaptation, stimulating innovative solutions to ensure positive adaptation, (...) acknowledging that these adaptive actions are part of system behaviour just as much as periods of stability are." (Khan, 2018. Page 1)

> "[implicit] "and that many health system interventions, especially when considered in context, show many features of 'complex systems'. Reforming such systems requires approaches to change management that foster innovation, adaptation and learning." (Husain, 2017. Page 2)"

Once a system is identified or (re)conceptualised as a complex system, a '*Conceptual Lens'* informed by complexity science can continue to be applied to further promote a deeper (i) understanding; or support the (ii) the planning of further actions both in terms or research strategies and methods and in terms of practice or intervention strategies. The '*Conceptual Lens*' can also be refer to a process of thinking (in the case of CyT) that highlights particular ways of investigating a system to ensure congruence or fitness with its properties. However, CyT appears mostly as a '*Conceptual Lens*' that highlights contents (that may, on some occasions, be processes organising CS), more than calling for a certain process of thinking about those contents as when the concepts refers to the '*Enactment of Complexity*' y (cf. ahead). As a '*Conceptual Lens*' the thinking may highlights processes but may not be processual or dynamic.

A particular type of '*Conceptual Lens*' may result type of '*Discourse*'. The term CyT is sometimes used to refer to a type of narrative and contents about complexity that identity a particular type of discourse.

> "complexity thinking as a discourse or a way of thinking and acting that assumes we live in a complex and inter-connected world with multiple and unpredictable outcomes (Davis & Sumara, 2006)." (Hussain 2018. Page 479)

Thinking as a '*Discourse*' of '*Conceptual Lens*' may allow for concepts to be articulated and coordinated and theoretical frameworks to emerge. Sometimes, however, CyT and CT as

terms that refer to a '*Conceptual Armoury*'. They correspond to the content of the thinking and they may be integrated in '*Conceptual Lens*' or '*Discourses*', in which case they are articulated in a coherent framework or set of assumptions. A '*Conceptual Armoury*' refers to contents that are used in 'looser' and less articulated way or given as a starting point for thinking.

> "Complexity thinking refers to a cluster of concepts popularized in several branches of science, primarily in the physical sciences but increasingly in the social sciences."; " books appeared in the 1980s and 1990s that popularized a group of concepts in science: specifically the concepts complexity, chaos, self-organization, emergence and dynamic systems" (Sherblom, 2017. Page 10)

The concept CT is oftentimes used to refer to an '*Intellectual Stance e and a Framework of Principles for Organising the Thinking*'. In this sense, CT is presented as a *process of thinking* organised by key principles that relate to features/properties of complex systems. It refers to an attitude of being sensitive to the need to make the process of thinking congruent with the complexity of the world and that is attuned to some of its critical properties.

> "[Morin (2002) describes the method [of complex thinking] as an intellectual attitude, a strategy-creation of the relation with theory. It is a "thinking activity" through which one seeks the integration of knowledge] (Bedin and Kochenborger Scarparo, 2012. Page 91)" [translated by authors]

When used in this sense, the concept of CT approximates the notion of CT as the '*Enactment of Complexity*' but pertains more to a sensitivity to complexity. CT refers to a *set of principles for organising the thinking* that highlight, and are congruent with, complex properties of the world, has a strong connection to CT as a '*School/Paradigm*' that is influenced by Morin's work and his proposal of key principles for CT (dialogic principle, hologrammatic, recursiveness, self-eco-organisation, emergence, recognition of the cognisant subject in knowing). As a *guiding and interpretative framework* CT supports the construction of lenses and tools for describing and interpreting the world as well as research methods that respect such principles.

To some extent, this resembles the usage of CyT as a '*Conceptual Lens*' but it is more clearly process-focused. Whereas CyT as a '*Conceptual Lens*' operates as a filter that highlights contents (which may be processes), CT used as an '*Intellectual Stance and Framework of Principles for Organising the Thinking'* is less prescriptive in contents but offers more guidance in the form of a set of principles for engaging with that reality in a way that is congruent with its complexity.

> "The three fundamental principles that guide complex thinking are the followings: the hologrammatic principle (according to which not only the part is in the whole but the whole is also in the part), the dialogical principle (according to which two principles could be at the same time antagonistic and complementary), and the recursive principle (according to which, following a generating loop, the products and effects are themselves producers and causes of what produces them)." (Malaina, 2015. Page 2)

It may lead to the development of principled pragmatic tools for research and practice. For example, the integration of a dialogic principle would lead to a type of thinking that is based and formulated in terms complementary 'dualities' (process) while attending to the contents or processes of a system that may be complementary (a lens that is derived from this process).

> "The analysis led to the understanding of each data in the perspective of the hologram, this is, understanding it as a part of the whole that contains in itself its inscription (Morin, 2007a). Therefore, we achieved a thematic analysis that afforded the creation of 'themes of meaning' (Menegon, 2000). The analysis contemplated the perspective of integrality (...) even though

> separate, the themes are constantly associated, in a way as not to lose sight of the complexity of the object. Holograммatically each theme integrates the part and the whole" (Bedin and Kochenborger Scarparo 2012. Page 93) [Translated by the authors]

Both CT and CyT are used as terms referring to the '*Enactment of Complexity*' through the thinking activity embodies the principles of complexity. They refer to modes of thinking organised according to similar properties of CS and congruent with them. They are closely related to the usage pertaining to an '*Intellectual Stance and Framework of Principles for Organising the Thinking*' but does not just prescribe principles for portraying and describing complexity but represents, in itself, an expression of complexity.

> "Complexity is not only a feature of the systems we study, it is also a matter of the way in which we organize our thinking about those systems. This second-order complexity invites consideration of the modes of thinking we use to theorize about complexity (...)." (Tsoukas, 2001. Page 979)"

CT is also used to refers to the '*Enactment of Complexity*' associated with *cognitive complexity*. When used in this sense it has a very specific meaning and describes particular properties of the process of thinking. Different sets of properties describe different types of complexity (e.g. 'dialectical complexity' and 'elaborative complexity'). It is more associated with a particular research domain within the tradition of the cognitive sciences.

> "[Dialectical complexity as a type of cognitive complexity] "involves implicitly recognizing the tension between different dimensions as they relate to a focal topic" (...); "[elaborative complexity] occurs when a singular, dominant theme is developed in a complex way. Elaboratively complex statements do not illustrate the validity of multiple perspectives but rather defend one perspective in a complex way". (Conway, 2008. Page 1030)

Closely related to the usage of CT as the '*Enactment of Complexity*' is CT as pertaining to '*Thinking the Role of the Observer in Complexity*', the process of *thinking about how we observe the complex* and the *thinking about the complexity of the observer*, including their own contribution to the complexity of the world.

> "We argue that the features of complex systems described by complexity theory (...) can only be appreciated and acted upon from the position of second-order complexity. This claim is based on our assumption that the features of complexity are descriptions and interpretations assigned by complex observers to systems whose existence itself is a matter of definitional agreement" (Tsoukas, 2001. Page 988)

> "Morin is in agreement with the "sciences of the complexity", that we need to rethink reality as a complex totality, that is, as a whole that is woven in common, because everything is interrelated, everything is deeply "inter-fecundated". But at the same time, he invites us to think that totality, without excluding from it the one who thinks it. Because of it, the complex thought in Morin´s perspective, seeks to understand the "subject" that knows in a complex way, and installs the "subject" (humanity) as an epiphenomenon of that complexity." (Osorio Garcia, 2011. Page 141)

Even though it was possible to extract several explicit definitions for the different terms some were vague, imprecise or are insufficiently operational to inform action (e.g. assessment or intervention tools). Examples of the different implicit and explicit usages are available as Supplementary material. In some cases, the target concepts were used more as rhetorical devices or applied without ever being defined and it was not possible to infer any implicit meaning.

It is beyond the scope of this paper to do a thorough secondary analysis of how each community uses different definitions of the concepts. However, based on the sample of papers that we analysed, it is possible to present a crude mapping (Figure 3) of how the

different usages of the concepts is distributed across communities. In Figure 3, the circles, corresponding to communities, are located in the regions corresponding to the usages of concepts presented in Figure 2. We note that communities 4 and 21 not only use diverse terms (Table 3) but also that the same concept terms often appear to used with different meanings (Figure 3).

-Insert Figure 3 around here-

Discussion

This study explored the use of concepts related to thinking (in) complexity in the scientific literature using an interdisciplinary approach incorporating the use of text mining, network analysis and a series of qualitative analyses. The construction and analysis of the coupling network afforded the identification of different intellectual communities through patterns of common literature citations. The largest of these communities relates to the general domain of social sciences, with other large communities in the areas of health and education (and health-related education). Other communities are distinguished by their particular approaches to thinking (in) complexity.

Through detailed, staged qualitative analyses of samples of papers from the most populated communities, the landscape of definitions and conceptions has emerged. Although we found greater conceptual consistency and preference for particular terms in some communities over others, the overall landscape is best characterised as a conceptual muddle, with the same concept terms being used differently and different concept terms being applied with similar meanings within and between communities. More often than not the definitions are vague and lack an operational orientation from which to derive clear directions in terms of the development of tools or resources to improve our capacity to understand and intervene in the complex world. The concepts are diffuse and their meanings overlap, limiting their pragmatic value. In many usages the connection with ‘thinking’ is limited. Many definitions are associated more with contents than processes providing little guidance as to how to organise our ways of coupling with the world through the ways we think of it. This state of affairs poses several challenges.

The challenges currently faced by humanity reveal, on the one hand, the failure and limitations of the traditional modes of thinking and, on the other hand, the need to develop new modes of thinking that are sufficiently complex to cope with their complexity and to manage change in positive ways. While a diversity of modes of thinking complexity may be desirable the clarity of the concepts and how they are used is, nevertheless, fundamental for the development of strategies and tools aimed at evaluating and promoting the complexity of our thinking. It seems necessary to explore the conceptual boundaries of the different, but related, terms and the potentialities and limitations associated with the different ways that they might be distinguished and related. This clarity is as important both to promote developments within domains and to facilitate interdisciplinary dialogues and collaborations, widely recognised as fundamental to address our most pressing real-world challenges. We believe the initial mapping of definitions resulting from this study can provide a starting point for their refinement and for the development of the necessary work to establish solid

theoretical foundations to address how we think (in) complexity.

Limitations and Future studies

The scope and findings of this study are dependent on the choice of search terms. We chose to limit terms to those explicitly relating to complexity, though we acknowledge the closely related (and diverse) body of systems thinking and anticipate the existence of other modes of thinking that do not use the term complex, whilst perhaps employing in process/content concepts that may be considered to be complex. Having put thinking (in) complexity in focus, we are now in a position to broaden the scope of consideration. Other terms related to thinking in complexity could be included in future studies (e.g. Thinking with complexity). Future studies could also explore the differences of definitions within each community or domain.

On a technical note, one of the key issues in bibliometric analyses is the matching of cited references (see e.g. Olensky et al., 2016). Although matching is likely to be more accurate when considering documents from a single database (e.g. WoS), a variety of inconsistencies are still present and will influence any matching process. We believe these effects are mitigated in our study as we do not employ detailed (citation-match derived) edge weights in the network or community decomposition and the network is principally used to inform the document sampling for the downstream qualitative analyses. As a result we believe the general findings in terms of the classification of definitions and their usage is robust.

Data Accessibility Statement

The corpus used is available by searching with the provided terms in the Web of Science Core collection and the Scielo collection (via the Web of Science interface); this will produce an up-to-date version of the database. The R package and the bibliometrix package are open source and freely available. Access to full text PDFs will be dependent on institutional provision; distribution by the authors is not permitted.

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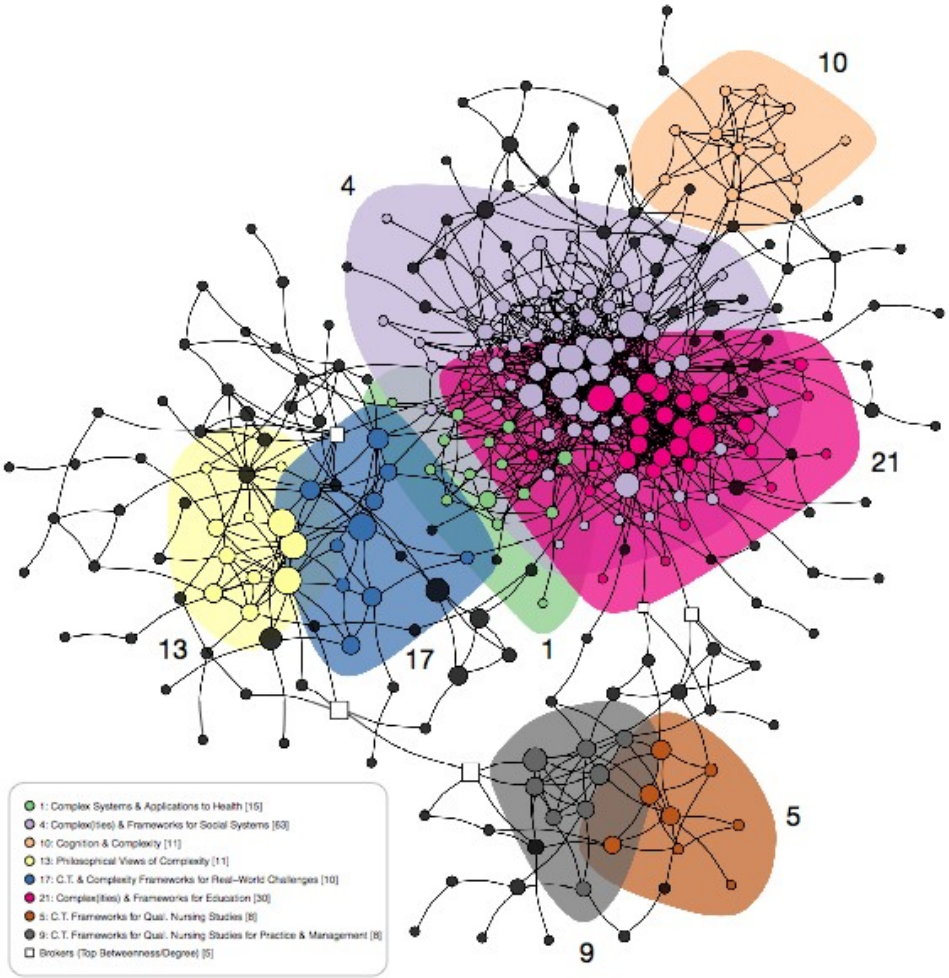

Figure 1 Schematic representation of the (main component) of the document coupling network containing 292 nodes and 1032 edges. Nodes represent documents and are connected by an edge if the corresponding documents have a citation in common (the number of citations in common is not taken into account - i.e. the edges are not weighted). Nodes are scaled in size by their degree (i.e. how many edges they have). Communities within the network were distinguished using the Walktrap algorithm. The nodes in each community are distinguished by different colors; the names of the communities result from a detailed qualitative analysis of a sample of papers from each community.

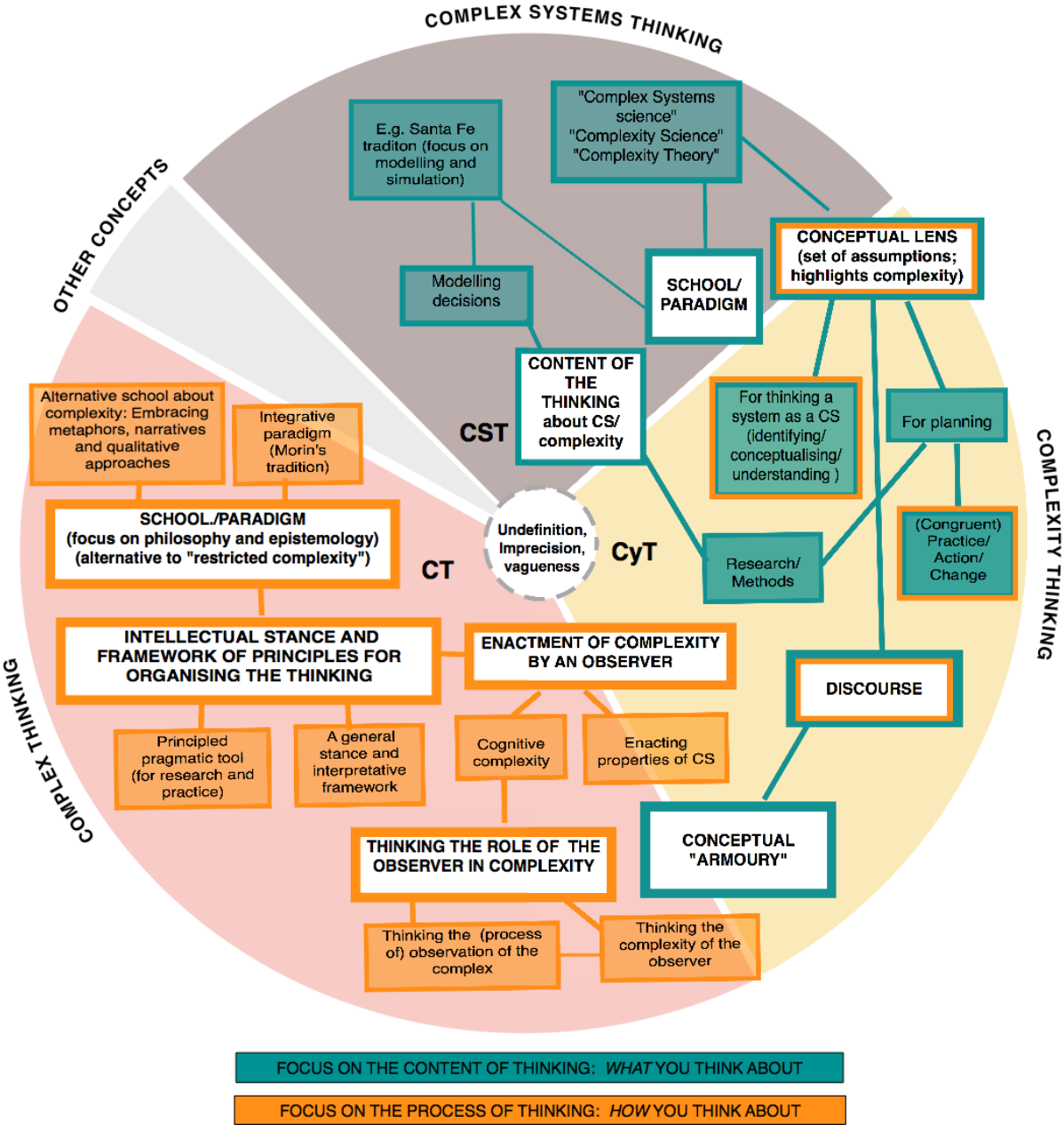

Figure 2. Schematic map of the usages of concepts related to thinking (in) complexity.

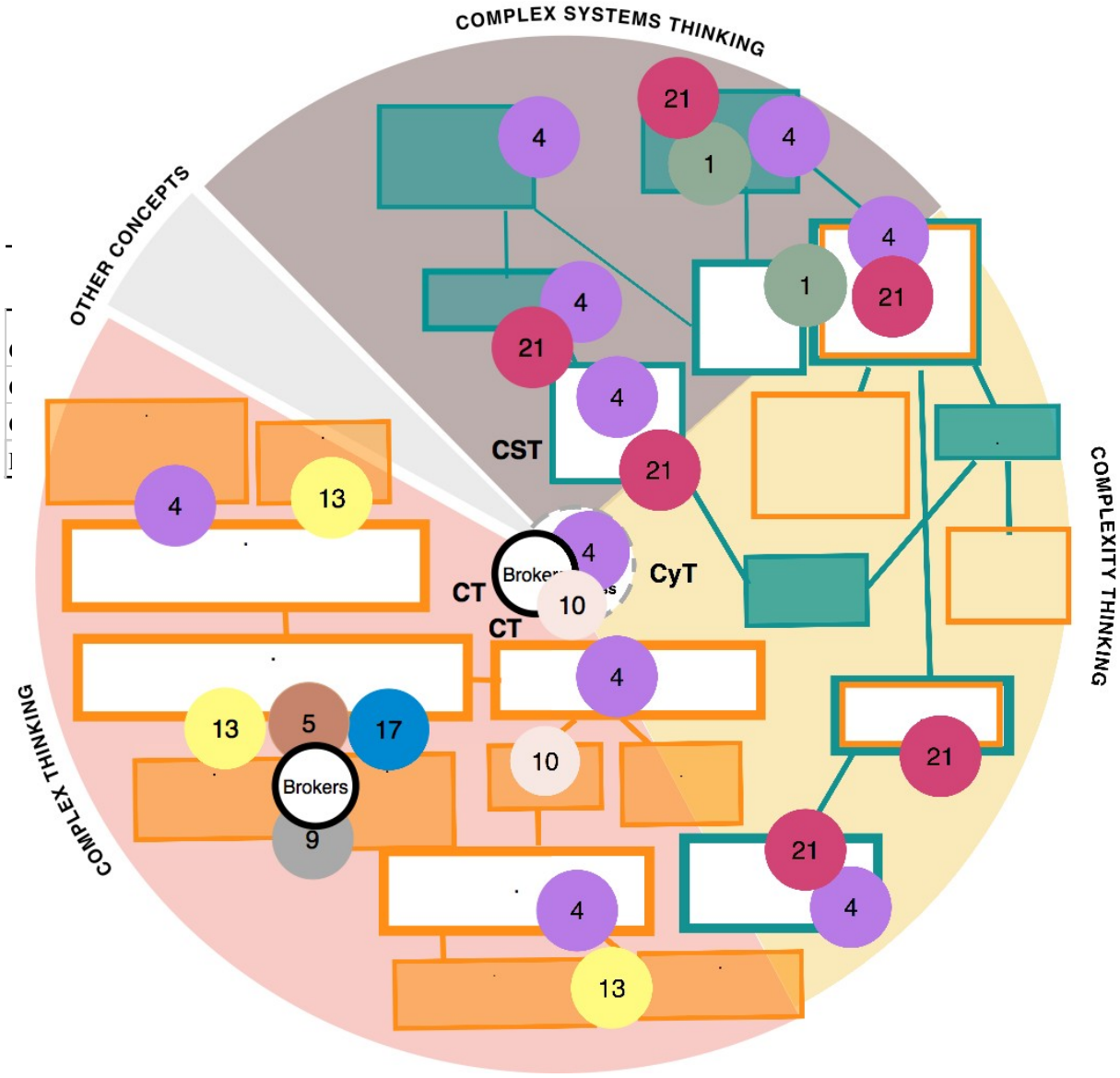

Figure 3 Indicative projection of the different intellectual communities (see Table 3 and Figure 1) onto the schematic map of the usage of the concepts related to thinking (in) complexities (Figure 2). Circled numbers represent the different communities (n.b. the same community can appear in multiple positions on the map).

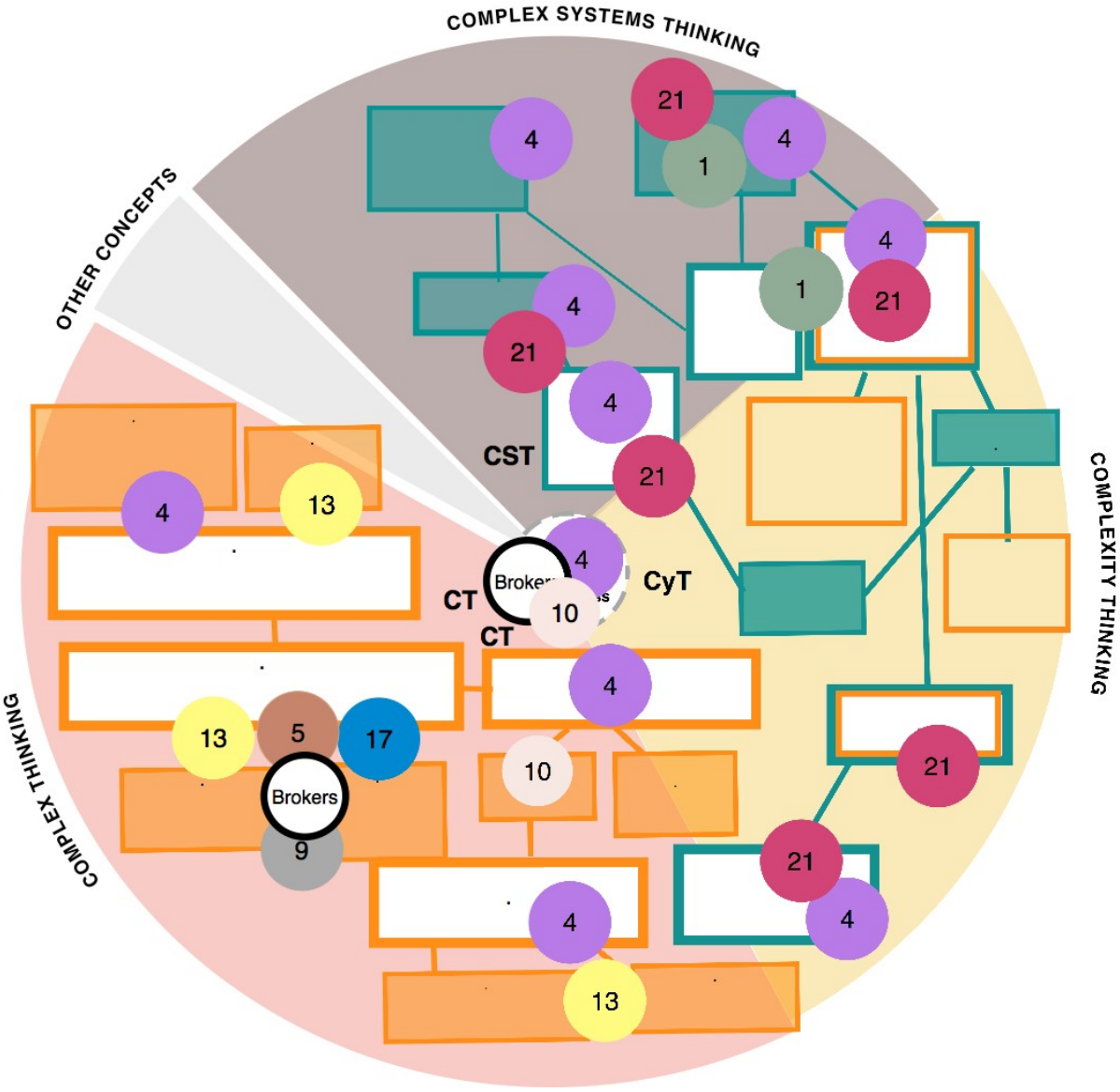
COMPLEX SYSTEMS THINKING
OTHER CONCEPTS
COMPLEXITY THINKING
COMPLEX THINKING
CST
CT
CT
CyT
Brokers
Brokers
21
4
1
4
4
1
21
4
21
4
21
4
13
4
10
4
13
5
17
10
21
Brokers
9
21
4
4
13

Table 1. Full text analysis: Proportions of the full text documents (n= 358) with at least one occurrence of the target concepts

Target Concept (Search Term)	**Code**	**Proportion (%) and number of documents**
Complex thinking	CT	59.6 % (214)
Complexity thinking	CyT	27.0 % (97)
Complex systems thinking	CST	12.0% (43)
Pensée complexe	PC	2.5% (9)

Table 2. General Properties of the Core Component of the Coupling Network

Property	**Value**
Number of nodes	292
Number of edges	1032
Edge Density	2.43%
Transitivity	41.90%
Diameter	13
Average Path Length	4.56

Table 3. Summary of the targeted communities, with identification of themes and classifications of concept usage

Com [1]	N all docs	n sample docs	Extracted Theme (All abstracts & Keywords)	Summary of Theme	Usage of terms (in sample docs)[2]
1	15	4	Complex Systems & Applications to Health	Complex systems approaches and lenses are applied to health systems for the development of frameworks for conceptualising, understanding and planning interventions to support change in such systems.	CST(I) = 2 CST(U) = 1 CyT(I) = 1
4	63	16	Complex(ities) & Frameworks for Social Systems	Different notions of complexity, complexity related concepts and thinking are used to develop frameworks aimed at conceptualising, understanding and planning interventions in different types of social systems	CT(E) = 2 CT(U) = 1 CST(E) = 2 CST (I) = 2 CyT (E) = 5 CyT (I) = 4
10	11	3	Cognition & Complexity	Complexity is considered and investigated as a property of cognition operationalised as cognitive complexity	CT(E) = 1 CT(I) = 2
13	11	3	Philosophical Views of Complexity	Complexity and complex thinking are approached from a philosophical perspective (e.g. addressing issues of ontology and epistemology) and as guiding concepts from which to extract principles for thinking different human systems and different dimensions of the human condition	CT(E) = 3
17	10	2	Complex Thinking & Complexity Frameworks for Real-World Challenges	Notions of complex thinking and complexity are integrated in the development of frameworks directed at understanding and addressing real-world challenges	CT(I) = 1 CT(U) = 1
21	30	7	Complexit(ies) & Frameworks for Education	Different notions of complexity and complexity related concepts and thinking are used in frameworks aimed to different topics in the field of education	CST(E) = 1 CyT(E) = 5 CyT(I) = 1
5	8	2	Complex thinking (CT) Frameworks for Qualitative Nursing Studies	CT is applied as a lens/framework for the planning and interpretation of qualitative nursing studies	CT(E) = 2
9	8	2	Complex thinking (CT) Frameworks for Qualitative Nursing Studies for Practice & Management	CT is applied as a lens/framework for the planning and interpretation of qualitative studies focused in the practice and management of care in nursing	CT(I) =1 CT(U) = 1
Broker	-	5	Brokers	Documents that are important in connecting the different regions of the network (high betweenness/degree)	CT(I) = 4 CT(U) = 1
Total	156	44			

Key: 1: Community; 2: The number of documents in the respective sample containing Explicit, Implicit definitions or Undefined concepts pertaining to the three target terms CT (complex thinking); CST (complex systems thinking) and CyT (complexity thinking). E.g. CT(I) = 2 means that for Complex Thinking, 2 examples of implicit definitions were found.

Table 4. Distribution of the classification of concepts regarding the type of definitions.

	Explicit	Implicit	Undefined	Totals
CT	40% (8)	40% (8)	20%(4)	45.4% (20)
CST	37.5% (3)	50% (4)	12.5% (1)	18.2% (8)
CyT	62.5% (10)	37.5% (6)	0% (0)	36.4% (16)
Total	47.7% (21)	41% (18)	11.3 % (5)	100% (44)

Table 5. Main categories of themes associated with the definitions/meanings underlying the usage of the concepts

Main categories	**Short definition of the usage of the target concepts**
The content of the thinking	Refers to the contents of the thinking that focuses on complex systems or complexity
A school/paradigm	Refers to a certain tradition of thinking associated with a particularly School or Paradigm for thinking about complexity.
A conceptual lens	Refers to the application of a set of key concepts and assumptions about the operations and properties of complex systems highlighting particular features (contents and processes) associated with and/or underlying the organisation and change of a given system of interest. It may support the articulation of concepts for building theoretical frameworks.
A discourse	Refers to a discourse or a type of narrative that reflects a way of thinking organised around a set of assumptions about the complexity of the world (worldview). It may support the articulation of concepts for building theoretical frameworks.
A conceptual armoury	Refers to a vocabulary that includes a set of concepts pertaining to properties or features of complex systems.
An intellectual stance and framework of principles for organising the thinking	Refers to general intellectual stance that, to a large extent, is influenced by the contributions of Edgar Morin and that is sensitive to the organisational aspects of complexity and to its ontological and epistemological implications. This stance is associated with a framework of principles for organising the process of thinking that is associated with properties of complexity (e.g. relation parts/wholes; recursiveness; conjunction principle; complementarities) and is targeted to grasp them. This stance informs the development of pragmatic tools for research and strategies for interventions in the real world that are congruent with its principles. It also embraces more narrative and qualitative ways of exploring complexity and attempts to integrate knowledge and different ways of knowing.
An Enactment of Complexity	Refers to the thinking that acknowledges the role of the observer in complexity and the complexity of the observer, not only in relation to how complex the cognitive operations of the observer are, according to certain criteria, but also in relation to how the observer conducts the process of thinking about the complex and how they integrate themselves in that process