Making sense of the Internet of Things: A critical review of Internet of Things definitions between 2005 and 2019.

Structured Abstract

Purpose: This paper aims to study the evolution of IoT definitions through time, critically assess the knowledge these definitions contain, and facilitate sensemaking by providing those unfamiliar with IoT with a theoretical definition and an extended framework.

Design/methodology: Using snowball sampling, we collected 164 articles between 2005 and 2019 identified 100 unique definitions. The definitions are examined using content analysis based on a five-dimensional theoretical framework.

Findings: In declarative/relational dimensions of knowledge, increasing levels of agreement are observed in the sample. Sources of tautological reasoning are identified. In conditional and causal dimensions, definitions of IoT remain underdeveloped. In the former, potential limitations of IoT related to resource scarcity, privacy and security are overlooked. In the latter, three main loci of agreement are identified.

Research limitations/implications: This study does not cover all published definitions of IoT. Some narratives may be omitted by our selection criteria and process.

Practical implications: This study supports sensemaking of IoT. Main loci of agreement in definitions of IoT are identified. Avenues for further clarification and consensus are explored. A new framework that can facilitate further investigation and agreement is introduced.

Originality/value: This is, to our knowledge, the first study that examines the historical evolution of definitions of the IoT vis-à-vis its technological features.

This study introduces an updated framework to critically assess and compare definitions, identify ambiguities, and resolve conflicts among different interpretations. The framework can be used to compare past and future definitions and help actors unfamiliar with IoT to make sense of it in a way to reduce adoption costs. It can also support researchers in studying early discussions of IoT.

Keywords: Internet of Things; definition; sensemaking; literature review; content analysis;

1. Introduction

Sensemaking of the Internet of Things (IoT) faces a great challenge. Not only, there is a plethora of terms that are synonymous or have similar meanings such as *Ubiquitous Computing, Machine 2 Machine,* or the *Internet of Everything,* but also the meanings of these terms are negotiated with a broad range of interpretations, varying from pragmatic ones such as "network of devices" to very abstract ones such as "vision of a naked world" (Ahmad *et al.*, 2018). This diversity in meanings is not without reasons. In semiotics, the relationship between a signifier (the symbol, the word, the arguments) and the signified (the meaning, the concept, the context) is regarded as complex and dynamic. When the signified takes diverse forms or the signifier is associated with multiple other signifiers, resulting redundancies have negative implications for sensemaking (Chandler, 2002). Furthermore, although it is very difficult to disconnect a word from its meanings at a particular point in time, they depend on each other in elusive ways (Davis and Hunt, 2017) and this relationship changes over time (Keane, 2003).

Sensemaking is "[…] the ongoing retrospective development of plausible images and rationalise what people are doing" (Weick *et al.*, 2005: pp. 409). Hence, sensemaking builds an action space for individuals (Sewell, 2005) and it is a path-dependent process in which new and improved signifiers rely on previous ones. Sensemaking of novel technologies, or in our case novel technological ecosystems, involves additional challenges. As technologies advance with time, so do their corresponding features. While this change may bring new and different interpretations (Griffith, 1999; Dilaver, 2013; Olson *et al.*, 2015), individuals and organisations need to follow, and at times, predict corresponding signifiers quickly and with adequate accuracy (Yates and Rosenberg, 1996). Furthermore, interpretations of the technological features do not only vary in time due to technological progress, but also among actors who are influential in making sense of, and contextualising them (Nelson and Metaxatos, 2016; Weick *et al.*, 2005). The broader the scope of corresponding technologies, the more heterogeneous the stakeholders are. As sensemaking of technology is deeply embedded in the existing and newly emerging social contexts (Dilaver, 2013) heterogeneity among stakeholders brings different interpretations of the signifier and reduces the level of agreement around the signified. For organisations, lack of agreement on the signified hinders the emergence of a common vision and increases the costs of adoption of the technology (Swanson and Ramiller, 1997; Weick *et al.*, 2005; Griffith, 1999; Park *et al.*, 2018; de Boer *et al.*, 2019)

The IoT presents a particularly challenging and interesting instance for sensemaking theory because the advent of the IoT initiated an important change for how we understand internet. Humans were, and still are, at the epicentre of the internet, which acts as a means to support communication and information sharing in various forms and formats (Santucci, 2009). In the context of IoT, however, objects equipped with devices that can collect, process, and transmit data can become active participants of the internet. Thus, IoT transcends previous boundaries of information technology (IT) sector, initiating an ever-growing discourse among various stakeholders struggling to make sense of the phenomenon and its exponentially increasing value (Fleisch, 2010; CISCO, 2019; Manyika *et al.*, 2013; Nelson and Metaxatos, 2016; Menard, 2017).

In addition, in the case of IoT, the high number of the underpinning technologies creates a grid of interrelated elements, which facilitates a wide spectrum of corresponding configurations, and designs and architectures (Pan *et al.*, 2011). Furthermore, as Park *et al.* (2018) argue for the case of smart speakers, users of technologies value the platforms of technologies differently compared to the features of the hosted technologies, adding another layer of complexity on individual and collective sensemaking. Similarly, Kim and Shin (2016), who studied the factors that affect innovation in open source IoT platforms, highlight the influence of the social context over shaping the technological platforms of IoT. Overall, the sensemaking of IoT involves two levels of complexity: the technical characteristics of the technologies (Akgun *et al.*, 2014) which contain a wide spectrum of interrelated and rapidly updated elements, and perceptions of their use-value (Griffith, 1999; Dilaver, 2013; Shin, 2014) which vary across heterogeneous user groups.

Hence, in the case of IoT, the link between the signifier and signified remains fluid and contingent upon the level of agreement among users within society (Eco, 1979). As different stakeholders interpret uses and value of IoT in different ways, multiple definitions emerge. Definitions, from a constructivist point of view, are hierarchical cognitive schemata (Derry, 1996; Ba et al., 2015) and the result of a sensemaking process on various levels including individual, community and organisational (Fiske and Linville, 1980; Bingham and Kahl, 2013). Star and Ruhleder (1996) argue that as users interact with technologies, they use individual or collective narratives for sensemaking. Definitions are such narratives that can affect the evolutionary trajectory of the technological features. As products of collective sensemaking, definitions continuously evolve (Taylor and Crocker, 1981). They change through a process called 'learning tuning' (Segalowitz, 2001), through which, new experiences are used to elaborate on and refine concepts.

In academic research, definitions often emerge in research fields in a stipulative form, assigning meaning to a term for the first time, either by coining a new term or giving new meanings to old ones (Hurley, 2000). The use and meaning of terms, then, evolve in time as new concepts emerge and empirical observations accumulate. Caws (1959) refers to a *historical order* of meanings - how a new concept relate to what is already known in a field - and argues that, from the sensemaking point of view, it is likely to structure knowledge in a random sequence. Thus, as a research field matures and reaches a certain level of complexity, it goes through a refinement process that arrange concepts in a *logical order*. Caws points out that while the historical order of ideas and concepts are fixed by temporal succession of their discovery, logical order may vary in a way to suit different researchers' convenience. Nonetheless, the refinement process can facilitate formation of *theoretical definitions* that aim *"to formulate a theoretically adequate or scientifically useful description of the objects to which the term applies*" (Copi and Cohen, 1990) or *formal definitions* that clarify the necessary and sufficient elements of identification (Sell, 2018).

We will demonstrate in the following sections that in the case of IoT, three common characteristics of definitions add to the abovementioned challenges of sensemaking. First, definitions of IoT are often too abstract, focusing on technological imaginaries instead of existing implementations of IoT. Second, many definitions involve tautologies, explaining IoT through “things” and “internet”. Third, as sensemaking constructs, definitions are products of their time. As IoT technologies rapidly advance, inconsistencies between various discourses hinder the perceived value of IoT (Whitmore *et al.*, 2015; Luo *et al.*, 2016).

This paper aims to identify the evolution of the IoT signifier through time, critically assess both framing and content of definitions of IoT and facilitate sensemaking. To achieve this, we attempt a longitudinal review of the literature of the IoT as it has been historically encapsulated by the corresponding definitions. We perform an analytical decomposition of the IoT definitions to i) assess the evolutionary trajectory of the IoT discourse, ii) identify the main dimensions the discourse and iii) explore which of the dimensions have been under emphasised. Furthermore, as new definitions emerge because of the evolutionary process of sensemaking, we provide to those unfamiliar with IoT, a useful framework to critically assess and compare the different dimensions of the definitions providing a platform for ongoing sensemaking. Finally, we present a theoretical definition of IoT based on our extended framework.

The paper is structured as follows: in Section 2, we discuss the theoretical background of the framework we use to analyse the IoT definitions. We also explain the sampling methodology and strategy. In section 3, we present our findings in both longitudinal (Subsection 3.1) and cross-sectional (Subsection 3.2) analysis. Finally, in Section 4, we summarise our findings and attempt to increase the level of agreement in IoT signifier through a new and comprehensive definition.

2. Methodology

2.1. Analytical Framework

In this paper, we approach definitions as both essential elements of academic research and as schemata that impacts upon social structures of knowledge (Crocker *et al.*, 1984). In terms of social organisation of knowledge, definitions constitute structure around what Zack (1999b, 2002) calls *dimensions of knowledge*. Three original dimensions of knowledge were: know-what, know-how and know-why (Miranda *et al.*, 2015), also known as *declarative* knowledge, *procedural* knowledge, and *causal* knowledge respectively (Zack, 1999b, 2002). Declarative knowledge, or factual knowledge, describes the information a person possess about a particular topic and can be explicated (Bruning *et al.*, 1999). Procedural knowledge refers to the capacity of a person to act and the process of acting. Causal knowledge refers to the rationale and motivation behind acting according to one's declarative and procedural knowledge (Rehder and Hastie, 2001). Causal knowledge is also called emotional memory (Akgun *et al.*, 2014) and is important for theorising (Bacharach, 1989) as it assigns meaning and value to the external world (Sewell, 2005).

In our paper we build upon Zack (1999b, 2002) framework and expand it by two additional dimensions of knowledge: *conditional* and *relational* (Halford *et al.*, 2010; Miranda et al. 2015) knowledge. Conditional knowledge further explicates the procedural dimensions by referring to the spatiotemporal conditions for the capacity to act and relational knowledge further explicates the declarative dimension through the constituent elements of the schema.

Zack's (1999b) framework has been influential within the knowledge management literature by emphasizing on the social issues when designing knowledge management systems and encouraging empirical research (Kankanhalli *et al.*, 2005). In this paper, we follow Taylor and Crocker's (1981) hierarchy which classifies dimensions of knowledge according to the level of abstractness (see Figure 1) and adopt this extended framework to perform directed content analysis (Potter and Levine-Donnerstein, 1999). We aim to deductively categorise the salient features of the definitions based on the five knowledge dimensions (Zack, 1999, 2002; Alavi and Leidner, 2001). We also study the change in definitions of IoT over time and propose a theoretical definition.

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2.2 Sampling

We produced a set of 100 definitions IoT (Table A.II) using *snowball sampling* method (Biernacki and Waldorf, 1981; Chromy, 2008). The seed sample of 21 definitions was built in 2019 based on Web of Science Service for UK Education, the Social Science Research Network (SSRN). We used search terms "Internet of things" and "IoT". We did not use relevant terms such "Industry 4.0", "ubiquitous computing" and "machine 2 machine" for both keeping the task manageable and avoiding ambiguities related to different signifiers. We worked backwards from 2019 following a mixed strategy of snowballing sampling (Faugier and Sargeant, 1997) depending on the following three events: i) if the source provided an original definition, snowballing process ended, ii) if the source cited another definition, for example, from previous years we followed up these cited sources until an original definition was found, iii) if the source provided a synthesis of definitions based on multiple other sources, we applied an exponential snowballing strategy.

Acknowledging the limitation of our initial seed sample, which emphasises academic discourse on IoT, we included additional definitions from documentary data and reports using a second seed sample generated through Postscapes (2015). Postscapes (2015) is an online network for promotion and support for early adopters of the IoT, and provides a comprehensive list of IoT definitions from non-academic sources such as a) governmental organisations and b) standardisation institutes (Srivastava and Kelly, 2005; Santucci, 2009; IERC, 2014: Table A.I). The cross referencing within this seed sample was limited and as a result, linear snowballing sampling was employed.

The initial sample, without taking into consideration cross referencing, generated a total of 164 papers that contained explicit or implicit definitions of the IoT. However, not all the proposed definitions were unique. After controlling for cross-referencing, we successfully identified 100 unique definitions. We acknowledge our sample of 100 definitions does not contain all published definitions of the IoT. We addressed this limitation by including an additional seed sample that covers non-academic definitions and comparing our sample with other definition repositories such as Postscapes (2015).

The resulting sample consisted of two types of definitions: synthetic (using definitions from more than one sources) and primary definitions that are suggested by the author(s). A comprehensive list of definitions is included in Table A.II. Furthermore, Table I contains a brief description of our sample distribution according to the type of the source of the definition.

2.3 Data Analysis

We applied directed content analysis that consists of two stages: In the first stage, the complete definition is considered as the *locus of meaning*. We use *exact word frequency* analysis to explore the collective latent pattern of the sample of the definitions, as well as for each year between 2005 and 2019 (Potter and Levine-Donnerstein, 1999). This approach also allows us to examine the level of agreement in definitions more systematically. To control for bias, the term “IoT” was excluded from the word frequency analysis when it was used to signify the focus of the definition. The words “Internet” and “things” were included in the analysis if and only if they signified any of the knowledge dimensions of the corresponding definition. Exact word frequency analysis was used to avoid overrepresentation of certain words with similar root, but different meaning, for example, “object” and “objective”. To validate the results of our analysis, we performed word frequency analysis using different levels of similarity without significant impact on the results of the analysis.

In the second stage of our analysis, we explored how the five dimensions of knowledge manifest in definitions by shifting the locus of meaning to words or very short sentences. For each code (excluding the causal dimension), we performed exact word frequency analysis using different levels of word matching freedom to validate our results. Regarding the causal dimension, we opted for greater freedom regarding word similarity while performing the word frequency analysis because the inherent complexity of the latent content. For data storage, management, coding, and analysis the tenth version of NVivo software was used. An example of how the framework was used as an analytical tool is presented in Table A.I at the appendix.

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3. Findings and discussions

A collective analysis of the definitions, without controlling for the year of publication, allowed us to identify four major sources of ambiguity related to the definition of the IoT (Figure 2). The first one relates to the relationship between IoT and the internet. More specifically, that the word "internet" is used both as a signifier and the signified in definitions of IoT is an important source of ambiguity. For example, in the declarative dimension of knowledge, IoT is conceptualised as "… *an extension of the Internet* …" (Luo *et al.*, 2016: p. 436), as "… *part of the Internet* … " (Bandyopadhyay and Sen, 2011: p. 49), " … *the future Internet for the new generation*…" (Li *et al.*, 2014) and *part of the future Internet* (Tan and Neng, 2010; Kopetz, 2011; Khan *et al.*, 2012; Perera, Zaslavsky, Liu, *et al.*, 2014). Furthermore, from a procedural point of view, the word "internet" is also used to describe how the "things" are connected. For example, "… *items, are connected to the Internet via wireless and wired Internet connections*" (Lopez, 2013), or "… *communicate via the Internet*" (Zheng *et al.*, 2014), or the "… *the physical objects are connected to the Internet*" (Kopetz, 2011).

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Relatedly, the second source of ambiguity is about sensemaking in relation to the shift from human-centric to machine-centric conceptualisations of internet. Currently, the internet is human-centric and a means of communication among its users. The IoT, on the other hand, introduces devices as "users" which interact, intentionally or not, with human actors. This shift creates an additional ambiguity for the declarative use of the word "internet". While definitions include declarative use of "internet" to explain a relatively new term through well-known terms, in this case it is the nature of the latter that is changing. Hence, this novel interaction requires a new sensemaking process, particularly for assessing privacy, security and ethical issues (Li *et al.*, 2016). This tension is not captured by a significant number of definitions. To overcome this limitation, Xiao *et al.* (2014) and Borgia (2014) further explain that connectivity takes place "through Internet protocols" (TCP/IP), acknowledging the heterogeneity of the information technologies used to allow devices to share data, and the value of the corresponding standards.

The third source of ambiguity is in the relational dimension. After "internet" the second most frequently used word in the definitions of IoT is 'object', used in many cases as an alternative to 'things'. A significant number of definitions (2.63% in total word count: Figure 2) use the word "objects" or "things" to add to the relational dimension of IoT-related knowledge. The circular reference in this conceptualisation falls short of clarifying the meaning of IoT in a way to facilitate sensemaking process. Several sources (Lopez, 2013; Ofcom, 2015; Luo *et al.*, 2016; Ornes, 2016) circumvent the cyclicality by expanding the relational and procedural dimensions of the IoT, arguing that it is not the objects, or things that can communicate, but rather the devices (such as sensors) attached to these objects. For example, Xiao *et al.*, (2014) explicitly refer to devices being capable of being discovered and used as service providers for industrial and business purposes. Others attach adjectives such as 'physical' (Kopetz, 2011; Selby, 2012; Lopez, 2013; Luo *et al.*, 2016), 'virtual' (Smith, 2007; Jiang *et al.*, 2014), or 'digital' (Benghozi *et al.*, 2012) to 'things' and 'objects'. In addition to disambiguation of the relational dimension, these adjectives are also used with the declarative purpose of describing IoT as a (digital world, physical world etc.) 'world' (Bandyopadhyay and Sen, 2011; Lopez, 2013; Ornes, 2016).

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The fourth source of ambiguity relates to the level of abstraction. We observe through collective analysis of the 100 definitions of the IoT that as the discourse moves to more abstract levels of knowledge (conditional dimension of example) the consensus gets weaker (Figure 2, Table II). Conditional dimension captures the spatiotemporal requirements under which the devices are "awakened", to transmit the data or synchronise, and then to go back to "sleep". A number of authors, such as Smith (2007), Xu *et al*, (2014) and Botta *et al.* (2016), argue that given the resources necessary to facilitate the deployment of an infrastructure of a global scale, as well as the heterogeneity of the actors, it is important to shed more light upon the conditions under which the connectivity takes place. These conditions are important because minimising energy consumption is at the core of value generation and competition for the IoT technologies and platforms.

3.1. Longitudinal analysis: The evolution of the definition

As highlighted in previous sections, definitions continuously evolve in a way to capture interpretations of different actors as well as changes in the use and meaning of the signified. We studied definitions of IoT with a longitudinal analysis to identify changes that have occurred in the signifier through time. This long-term perspective also allowed us to study overlapping meanings. To these aims, we employed word frequency analysis for each year between 2005 to 2019 and identified the consensus if it is reached and how it evolved for each dimension of knowledge. Our findings are summarised in Table II.

Although a consensus begun to formulate as of 2017 from a declarative point of view, the differentiating point between the internet and the IoT was not clear in corresponding definitions. The modularity and scalability of the IoT, which draws from the internet, is emphasised as early as 2009 as "… a network of networks …" (Santucci, 2009; Barbry, 2012: citing Massit-Follea *et al.*, 2009), "… a global network infrastructure" (Smith, 2007; Borgia, 2014: citing Jain *et al.*, (2009), part of an "information network" (Ashton, 2009). However, the relational dimension (IoT's building blocks) remains underdeveloped, often described with the overarching terms 'objects' or 'things'. There was an early demystification attempt by Smith (2007), followed by Giusto *et al.* (2010), who distinguish between physical and virtual objects which can be uniquely identified, and that would be capable of sensing and establishing connections.

References to the relational and procedural dimensions of the IoT does not emerge before 2010 in our data. During this year, we can observe a more in-depth discussion regarding the building blocks of IoT and how they are connected. For example, Chui, *et al*., (2010) attempt to improve the clarity and consistency of the relational dimension of the IoT by arguing that the devices attached to objects, and not the objects themselves are the ones with the capabilities of data collection, transmission and actuation. The authors further distinguish between sensors and actuators on these devices. Moreover, Iera and Floerkemeier (2010) include identifiers in the form or 'wireless tags' (such as Radio Frequency Identification (RFID)). The capability of the devices to alter their behaviour according to the analysis of the data they generate is captured in the definition by linking the IoT directly to the term 'ubiquitous computing' (Tan and Neng, 2010) or allowing the objects to be 'intelligent' (Tan and Neng, 2010; Nolin and Olson, 2016: citing Sundmaeker *et al.*, 2010). Still, a significant number of authors continue using the term object (Ganji *et al*, 2010; Miesenberger, 2010).

Moving upwards in the knowledge hierarchy in terms of abstractness, in the causal dimension of the IoT (see Figure 1), a few definitions identify businesses as the main beneficiary and foci of value creation and capturing. For example, Cai *et al.*, (2014), argues that the "*IoT technology connects physical things or objects around us with the Internet so as to communicate with each other for business [...] goals*". At this point it is not clear whether the source of value creation is within the supply or demand side of business. Uckelmann *et al*., (2011) acknowledge both dimensions of value creation potential of, and through, the IoT. They argued towards improving the efficiency and efficacy of the supply side, and attracting interest in a more convenient way of life at the demand side (see also Nolin and Olson, 2016). A number of authors identify the source of value creation to the services provided by the objects through the devices attached to them. Xiao *et al.* (2014), for example, argues that objects are discoverable through the attached devices and the "…services provided by those devices can be used for industrial and commercial purposes". This is feasible, by design, through the Service Oriented Architecture (SOA) of the IoT (Guo *et al*., 2016), where the attached devices can provide services to other devices in the ecosystem through data transmission, storage and analysis (Whitmore *et al*., 2015), paving the way to a fully deployed digital economy.

From the perspective of organisations, loci of agreement in relation to value creation can shape new organising visions of the IoT, and so facilitate sensemaking and successful commercialisation (Haller *et al*., 2009), information gathering and decision making (Abarúa, *et al*.,, 2019; Burgess, 2018). Our findings indicate the emergence of agreement between authors on sectors that will be able to benefit the most in terms of potential future growth. In this respect, fields that are at the core of value creation include software engineering such as big data analysis, cloud computing and artificial intelligence (Kortuem *et al*., 2009; Xu *et al*., 2014). In addition, one of the main sources of value revolves around addressing limitations related to resource scarcity, privacy and security (Kopetz, 2011). However, as we highlight in the following section, consensus is far from being formed when it comes to the value of IoT in general.

3.2. Cross-sectional analysis: The five knowledge dimensions

Among the five dimensions of knowledge in our analytical framework, the highest level of agreement between definitions of IoT emerges in the declarative dimension. Figure 3 shows the results of the exact word frequency analysis. Our findings indicate that a solid consensus among authors is being formed since 2012 over the declarative dimension of the IoT (14% of word frequency), regarding IoT as a network (Table II). For example, Smith (2007), Srivastava and Kelly, (2005) and Sundmaeker *et al.*, (2010) regard the IoT as "a network infrastructure". Benghozi *et al.*, (2012) uses a combination of relational and declarative keywords to describe the IoT as "… a dynamic, global network infrastructure" which was corroborated in 2019 by Maryska *et al.* (2019)

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Other definitions of IoT cover broader themes in declarative dimension of knowledge. The potential socioeconomic impact of the IoT is emphasised over and above its technical features in these definitions. Kevin Ashton, who coined the term "the IoT" in 1999, for example, envisioned a world with ubiquitous sensors connected to the internet. Similarly, a more contemporary definition by the International Telecommunications Union defines the IoT as "[…] *virtually every physical thing can also become a computer that is connected to the internet*" (Srivastava and Kelly, 2005). Likewise, Ornes (2016) compares the IoT with the vision of pervasive computing and describes it as the realisation of the vision of a "… *world in which computing isn't limited to tablets, smartphones, and laptops*". In a similar vein, Haller *et al*., (2009) draw from pervasive computing and define the IoT as "… *a world where physical objects are seamlessly integrated in to the information network*…" and Srivastava and Kelly, (2005) regard the IoT as "*a new dimension added to the world of information and communication*". The theme of world-wide impact is emphasised in these definitions. Others regard IoT as a vision of the future Internet (Bandyopadhyay and Sen, 2011), of a *world* (Ornes, 2016), or a *vision of the extension of the Internet* (Floerkemeier, 2008).

Hence, apart from those that regard IoT as a network, existing definitions of IoT use technological imaginaries as opposed to clear organising visions to explain declarative dimension of IoT. While the potential of IoT is yet to be realised in terms of space, scope, and number of tangible applications, in our view, there are numerous empirical instances of IoT-based applications in various fields (Miorandi *et al.*, 2012; Al-Fuqaha *et al.*, 2015) and these can form a more concrete basis for its definitions.

With respect to the relational dimension of knowledge, definitions of IoT cover the building blocks of IoT (see Figure 4). The generic terms 'objects' (Xia *et al.*, 2012) or 'things', and objectives 'physical' and 'virtual' (Smith, 2007) are commonly used by authors. These terms are very general and have certain limitations in defining IoT. They obscure divergences in the way the building blocks of IoT (Ganji *et al.*, 2010) are thought of. "Objects" can be "electronic, electrical, or non-electrical" (Lee *et al.*, 2010), devices (Xiao *et al.*, 2014), such as sensors or actuators (Bandyopadhyay and Sen, 2011; Luo *et al.*, 2016), people through devices such as mobile phones (Manzalini *et al.*, 2012; Luo *et al.*, 2016), or personal terminals (Manzalini, *et al.*, 2012). It is evident, however, that the referred subjects and objects often lack the capacity to collect, store and transmit data. Instead, devices attached to these objects, have the networking capability, either within local area networks (Zorzi *et al.*, 2010; Burgess, 2018; Campeanu, 2018; Airehrour *et al.*,, 2019) or within the worldwide web (Benghozi *et al.*, 2012).

Moreover, these devices' various technical characteristics (see Figure A.I for a comprehensive taxonomy of IoT related technologies) and their functionalities co-evolve with corresponding technologies (Al-Fuqaha *et al.*, 2015). For instance, RFID tags provide object or subject identification, iPv6 and uCode allow a unique identification, Gyroscopes and GPS permit localised operability, and Zigbee, Z-Wave, Wi-Fi, Bluetooth allow local connectivity. Finally, Lora, Sigfox, Ingenu, EC-GSM and LTE-M permit a geographically broader deployment of the IoT. It can be argued that the heterogeneity of technologies and their features is the source of ambiguity which hinders adoption of the IoT and becomes evident in the definitions of it. Figure A.I presents a comprehensive map of the technologies based on their functionality within the IoT paradigm. Based on the above, we identified four main functionalities of IoT devices: i) data collection, ii) data storage, iii) data analysis and iv) data transmission.

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Regarding the procedural dimension of knowledge, definitions of IoT highlight that the internet acts as the backbone of the IoT supporting and enabling its basic functionalities (Smith, 2007; Bandyopadhyay and Sen, 2011; Lopez, 2013). There is a growing discussion among engineers and computer scientists over the architecture of the IoT and how it influences the corresponding functionality of the IoT devices (Singh *et al.*, 2014). A typical high-level architecture of the IoT consists of four main layers: the object layer (physical layer), the devices (identifiers, sensors, actuators) that are attached to the objects/subjects, the connectivity infrastructure layer that provides the connectivity corridors between devices, and, finally, the processing, decision making layer (Khan *et al.*, 2012).

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Relatedly, connectivity is an emerging theme in procedural dimension. Figure 5 shows the most frequently used term to describe the interaction among devices is by connecting through data exchange. However, the data exchange has broader implications than just connecting devices. Data exchange varies in terms of volume, variety, venue, and veracity of the data generated and exchanged (Akhtar *et al.*, 2018). Following Bello and Zeadally (2015), we argue that the term 'communication' can better describe this dynamic process which encapsulates the entire spectrum of the functionality of IoT devices. Communication among devices also entails the optimal allocation of resources which becomes more prominent as the scale of IoT deployment increases. As opposed to 'connectivity', which refers to the inherent, hardware-related capabilities of the device to exchange data (Al-Fuqaha *et al.*, 2015), communication refers to the optimal allocation of resource (energy, storage space, analytic power: Kortuem *et al.*, 2009) specifying the conditions necessary for their communication to take place (Figure 6).

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With respect to the conditional dimension of knowledge, the first theme that emerges from our analysis is the lack of recognition of the conditions in which IoT can create value. Several authors argue that the objects or subjects of are connected 'anytime' (Lee *et al.*, 2010; Manzalini *et al*., 2012; Perera *et al.*, 2013) in 'anyplace' or 'anywhere' (Lee *et al.*, 2010; Manzalini, *et al*., 2012; Olson *et al*., 2015; Bilal, 2017; Alshehri *et al*., 2018). While this may be a technological possibility, this emphasis on ubiquity obscures one of the biggest challenges of IoT: resource scarcity. Energy is both a resource that IoT requires and a source of value from IoT applications (A. Zanella *et al.*, 2014; Pan *et al.*, 2015). Studies that aim to circumvent the resource scarcity challenge use data analysis and artificial intelligence (Bello and Zeadally, 2015) to allow devices and ecosystems to adjust their behaviour, or optimise resource allocation in an ad hoc manner based on the context of a given problem or scenario (Perera *et al.*, 2014). In both cases, the connection is unlikely to take place *anywhere* or *anytime*. Instead, it would take place according to predefined conditions of value generation.

The causal dimension of knowledge in definitions of IoT covers the ways individuals and organisations can create value through IoT. Our analysis indicates the emergence of an agreement among authors (see Figure 7) is formed on the potential value of the data that that IoT generates (Luo *et al.*, 2016; Yu *et al.*, 2016) in supporting knowledge creation and decision making in organizational level. Miesenberger (2010) argues that the analysis of the data provides valuable "information, features, and functionality". Similarly, Kopetz, (2011) argues that combining the information generated by the IoT and the actuators attached to object allows "remote … control of the physical world", or "high-resolution management" (Haller *et al*.,2009). Uckelmann *et al*., (2011) argue that "… management can start to move freely from macro to micro levels and will be able to measure, plan and act accordingly". According to the authors, the IoT can create cost reductions at organizational and societal levels by allowing efficient and effective management of business processes. Overall, the value derived from the application of the IoT is generated by the timely, accessible, and relevant information that substantially improve the efficiency and granularity of management.

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Value creation at the level of individuals is also covered in IoT definitions. Haller *et al*., (2009) position the devices of IoT within 'social processes' creating value for both users and platforms. This approach requires devices to have some level of autonomy as implied in the adjective 'smart' that is commonly used to describe these devices (Xia *et al.*, 2012). Uckelmann *et al* (2011) refer to "a more convenient way of life". SOAs which allow groups of devices to compete with each other in order to access particular services (Guo *et al.*, 2016) are proposed. The corresponding services depend on the context of application. Currently researchers identified several fields of application of the IoT such as wearables

(Thierer, 2015), houses (Pan *et al.*, (2015), citing Zanella *et al.*, (2014)), and healthcare (Miorandi *et al.*, 2012; Agrawal and Vieira, 2013; Shah and Yaqoob, 2016).

From a more critical perspective, Nolin and Olson (2016), summarise the individual value of IoT with gossiping technology, personalisation and disempowerment of smartphone user. All three aspects entail significant implications for privacy and security, indicating a tension between potential value of data granularity and its cost to individuals (Zhao and Ge, 2013). This tension stems from the IoT's volume and relevance of data which leads to privacy issues, and the accessibility to the data, which raises issues regarding security. Weber (2015) points out that it is important to provide users with tools, information, and background to enable them to control what data are they willing to share. This approach would have a significant impact on the procedural and conditional dimensions of the IoT. Sicari *et al.* (2015), for example, suggest that middleware should be independent from the platforms serving those applications. However, the literature on the socioeconomic impact of the IoT remains limited. More intensive theoretical and empirical work is required to inform the design of the IoT in a way to address socioeconomic issues such as privacy and security.

4. Synthesis and concluding remarks

The IoT is an ecosystem of technological innovations that changes the way we engage with devices and the internet. Its adoption and successful implementation poses a series of significant challenges for individuals and organisations (Miorandi *et al.*, 2012; Singh et al., 2014; Cunningham and Whalley, 2020). Multiple and, at times, conflicting interpretations of the IoT are among these challenges. Overlapping signifiers lead to redundancies (Chandler, 2002) which prevents the formulation of a working consensus among stakeholders and efficient mobilisation of resources (Berente *et al.*, 2011). For this reason, providing clarity in definitions of IoT and establishing a high level of agreement on its meaning is crucial for the diffusion of the IoT-related technologies. Clearer definitions also allow policy makers to develop and implement policies without hindering the diffusion process (Swanson and Ramiller, 1997).

In this paper, we visit the discourse on what IoT is focusing on 100 definitions that have been developed by various stakeholders between 2005 and 2019. We critically examine what IoT is and how discourse on IoT evolved over time. We adopt a metacognitive point of view and analyse definitions according to five dimensions (Alavi and Leidner, 2001; Zack, 2002; Ba *et al.*, 2015) - declarative (know-what), relational (know-with), procedural (know-how), conditional (know-when), and causal (know-why) – with the aim of building a consensus within each dimension. The framework can be used in the future to analyse and compare new definitions of the IoT, as the technology evolves through time, and allow personal and collective sensemaking of the IoT, particularly from users unfamiliar with the technology.

We argue that the IoT discourse is hindered of circular references and tautological reasoning stemming from extensive meaning overlapping and ambiguation. A notable example is how the terms 'internet' and 'things' are used to signify different and in cases conflicting points of view. Second, we argue that the IoT technologies evolved significantly and the definitions do not capture the heterogeneity and complexity of the emerging ecosystem.

Moreover, we argue that the conditional and causal dimensions of the IoT is underdeveloped and underrepresented in definitions of IoT and ruled out most notably in expressions such as "anywhere" and "anytime". Underrepresentation of the conditional dimension of IoT leads to underestimation of the challenges related to: a) resource allocation, operability and governance of the IoT ecosystem, and b) security and privacy over the governance of the generated data (Li *et al.*, 2016). To address these limitations, new definitions of IoT can incorporate the allocation of resources such as energy, and future research can be directed towards developing novel architectures, AI, cloud or a combination of those (Gubbi *et al.*, 2013; Xu and Helal, 2016).

Our analysis also highlights the value of IoT generated data (casual dimension) from both the supply and demand side (Yu *et al.*, 2016). At the supply side, the value creation processes involve improved efficiency and effectiveness. At the demand side, the use value of IoT is perceived in the form of convenience and this use-value can initiate diffusion of the IoT (Yu *et al.*, 2016).

Finally, we propose a new, theoretical definition of the IoT as a means of consensus building and sensemaking. This definition is a product of our analysis, and it should not be regarded as definitive or exhaustive. Instead, it encapsulates the main findings of our systematic analysis of IoT definitions. To facilitate and encourage comparison with past definitions we will present the definition in a structured way according to the five dimensions of knowledge (see Table III):

--- Insert Table III about here ---

According to Karl Weick, who coined the term “sensemaking”, people make sense of environmental stimuli by placing them into a framework that allows them not only to cope with the complexity of a given situation but also enact upon it (Ancona, 2011). Definitions of IoT, as cognitive schema, are important tools for sensemaking. The more complex and fast changing the environment, the more necessary sensemaking is (Weick, 1995). This is the case with technological paradigms like IoT, which evolve rapidly following and being followed by collective sensemaking.

In this paper, we argue that the discourse on IoT emphasises the procedural dimension and, consequently, the technological aspects of IoT. This constrains the collective sensemaking of IoT with the level of expertise of stakeholders. As we demonstrated in the paper, to promote sensemaking of IoT the discourse needs to be expanded significantly regarding the causal dimensions. We suggest, therefore, that an avenue for future research is investigating the causal dimension of knowledge. Future research can tackle this avenue with interdisciplinary approaches incorporating insights from sociology, cognitive psychology, organisational science, and management. Expanding the discourse on what IoT is in a way to cover causal dimensions would be beneficial for helping people in “framing the unknown” (Ancona, 2011), making the discourse more inclusive and encouraging collective sensemaking. Since sensemaking allows people to act upon their understanding, it would also facilitate adoption of the IoT technologies.

Appendix A

Table A.I: An example of using the knowledge-based framework to analyse definitions of IoT

Knowledge Dimension	**Definition**	
	*Vashi et al. (2017)**	*Kumar et al. (2018)***
Declarative	[…] an emerging technology	[…] a technology […]information technology and communication networks embedded with a hardware unit
Procedural	[…] connect […] through internet connectivity	[Using] wireless technology to connect to the Internet
Relational	sensors, vehicles, hospitals, industries, and consumers	[…] various objects
Conditional	[..] the world	N/A
Causal	[…] Smart Cities, Smart home, Smart agriculture, and Smart World	[…] specific works [by] enabling data transfer, analytics, [and] decision making [there by] increasing the productivity and efficiency […] information technology and communication networks embedded with a hardware unit […]
*The Internet of Things is an emerging technology across the world, which helps to connect sensors, vehicles, hospitals, industries, and consumers through internet connectivity. This type of architecture leads to Smart Cities, Smart home, Smart agriculture and Smart World.		
** The Internet of Thing (IoT) is a technology which links various objects that are made to operate for performing specific works by enabling data transfer, analytics, and decision making there by increasing the productivity and efficiency. IoT, in simple can be framed as combination of both the information technology and communication networks embedded with a hardware unit. The need for maximizing the efficiencies, productivity, quickness, simple operation and effective control and monitoring gave scope for IoT in all fields of science and engineering		

Table A.I: the table provides two examples of how the knowledge-based framework is used to analysis the IoT definitions between 2005 and 2019. […] indicates omitted text. The examples of definitions were also provided for reference.

Table A.II: The list of the 100 IoT definitions.

No	Author	Source Type	Sub-type
1	Abarúa *et al.* (2019): p. 1	Working Paper	Tech
2	Adat and Gupta (2018): 423	Journal	Tech
3	Airehrour *et al.* (2019): pp. 860-861	Journal	Tech
4	Alam *et al.* (2017): p. 192	Proceedings	Tech
5	Alansari *et al.* (2019): p. 339	Book	Tech
6	Alshehri *et al.* (2018): p. 419	Journal	Tech
7	Anithaa *et al.* (2016): p. 150	Journal	Tech

8	Attaran (2017): p. 10	Journal	Management
9	Atzori *et al.* (2017): p. 123	Journal	Tech
10	Bandyopadhyay and Sen (2011): p. 49	Journal	Tech
11	Barbry (2012) citing Massit-Follea *et al.* (2009): p. 86	Book	General
12	Barbry (2012) citing Srivastava and Kelly. (2005): p. 86	Policy	Law / Tech
13	Behera *et al.* (2019): p. 195	Journal	Tech
14	Benghozi *et al.* (2012): p. 14	Journal	Tech
15	Bilal (2017): p. 3	Journal	N/A
16	Borgia (2014): p. 3	Journal	Tech
17	Botta *et al.* (2016): p. 685	Journal	Tech
18	Burgess (2018): p. 1	Policy	N/A
19	Cai *et al.* (2014): p. 1558	Journal	Tech
20	Campeanu (2018): p. 1	Proceedings	Tech
21	Chui *et al.* (2010): p. 1	Policy	N/A
22	Čolaković and Hadžialić (2018): p. 17	Journal	Tech
23	Cui *et al.* (2018): p. 1399	Journal	Tech
24	Desai and Phadke, (2017): p. 1	Proceedings	Tech
25	El-Haddadeh *et al.* (2019): p. 310	Journal	Government
26	EPoSS (2008): p. 6	Policy	N/A
27	Farhan *et al.* (2018): p. 195	Journal	Social
28	Fleisch (2010)	Working Paper	Management
29	Floerkemeier (2008): p. 1	Proceedings	Tech
30	Ganji *et al.* (2010): p. 1	Proceedings	Tech
31	Gelenbe *et al.* (2018): p. 90	Proceedings	Tech
32	Georgakopoulos and Jayaraman (2016): p. 1041	Journal	Tech
33	Gil *et al.* (2016): p. 1069	Journal	Tech
34	Giusto *et al.* (2010)	Book	Tech
35	Haller *et al.* (2009): p. 14	Proceedings	General
36	Hamidi (2019): p. 434	Journal	Tech
37	IERC (2014)	Policy	N/A
38	Jat *et al.* (2019): p. 94	Book	Tech
39	Jiang *et al.* (2014): p. 1443	Journal	Tech
40	Jorda *et al.* (2019): p. 68	Working Paper	Tech
41	Khan *et al.* (2012): p. 257	Proceedings	Tech
42	Kopetz (2011)	Book	General
43	Kortuem *et al.* (2009): p. 44	Journal	Tech
44	Kumar *et al.* (2018): p. 1	Proceedings	Tech

45	Lee *et al.* (2010): p. 5	Policy	N/A
46	Li *et al.* (2014) citing Iera and Floerkemeier (2010): p. 1461	Journal	Tech
47	Li *et al.* (2016): p. 338	Journal	Tech
48	Li *et al.* (2015) citing Pretz (2013)	Policy	N/A
49	Lin *et al.* (2017): p. 1125	Journal	Tech
50	Liu and Wang (2017): p. 1	Proceedings	Tech
51	Lopez Research (2013): p. 3	Policy	N/A
52	Lu *et al.* (2018): p. 285	Journal	Management
53	Luo *et al.* (2016): p. 436	Journal	Tech
54	Maryska *et al.* (2019): p. 585	Journal	Tech
55	Matta *et al.,* (2017): p. 1306	Proceedings	Tech
56	Mattern and Floerkemeier (2010): p. 1	Lecture notes	Tech
57	Mehmood *et al.* (2017): p. 16	Journal	Tech
58	Miesenberger (2010)	Policy	N/A
59	Miorandi *et al.* (2012): p. 1497	Journal	Tech
60	Murar and Brad (2015)	Book	Tech
61	Negash *et al.* (2019): p. 96	Journal	Tech
62	Nolin and Olson (2016): p. 360	Journal	Social
63	Ofcom (2015): p. 2	Policy	N/A
64	Olson *et al.* (2015): p. 885	Journal	General
65	Ornes (2016): p. 11059	Proceedings	General
66	Oxford English Dictionary (2013)	Policy	N/A
67	Papert and Pflaum (2017): p. 175	Journal	Economic
68	Soldatos and Yuming (2014): p. 8	Policy	N/A
69	Perera *et al.* (2013): p. 316	Proceedings	Tech
70	Perera *et al.* (2014): p. 406	Proceedings	Tech
71	Perwej *et al.* (2019): p. 2394	Journal	Tech
72	Privat (2012): pp. 101 / 109	Journal	Tech/Management
73	Priya *et al.* (2016): p. 144	Journal	Tech
74	Rajkumar *et al.* (2017): p. 21410	Journal	Tech
75	Regalado (2014)	Policy	N/A
76	Sadiku *et al.* (2016): p. 40	Journal	Tech
77	Sadique *et al.* (2018): p. 199	Proceedings	Tech
78	Said and Masud (2013): p. 1	Journal	Tech
79	Santucci (2009): p. 3	Policy	N/A
80	Sehnaz *et al.* (2016): p. 168	Journal	Tech
81	Selby (2012): p. 22	Journal	Economic

82	Smith (2007) p. 10	Policy	N/A
83	Srivastava and Kelly (2005): p. 11	Policy	Tech
84	Sujithra and Padmavathi (2016): p. 227	Journal	Tech
85	Suma (2019): p. 27	Journal	Tech
86	Tan and Neng (2010): pp. V5-376	Proceedings	Tech
87	Uckelmann *et al.* (2011): p. 2	Book	Tech
88	Vashi *et al.* (2017): p. 492	Proceedings	Tech
89	Vermesan and Friess (2011)	Book	Business
90	Webb (2012): p. 57	Journal	Tech/Management
91	Weber and Weber (2010)	Journal	General
92	Whitmore *et al.* (2015): p. 261	Journal	Tech/ Management
93	Xia *et al.* (2012): p. 1101	Journal	Tech
94	Xiao *et al.* (2014): p. 1486	Journal	Tech
95	Xu *et al.* (2014) citing Van Kranenburg (2007): p. 2233	Policy	Tech
96	Yassein and Aljawarneh (2017): p. 38	Journal	Tech
97	Zanella *et al.* (2014): p. 22	Journal	Tech
98	Zeng *et al.* (2011): p. 424	Journal	Tech
99	Zhang *et al.* (2019): p. 12686	Journal	Tech
100	Zheng *et al.* (2014): p. 1506	Journal	Tech

Table A.I: Sources (and typology) of the 100 definitions between 2006 and 2019 used for the analysis.

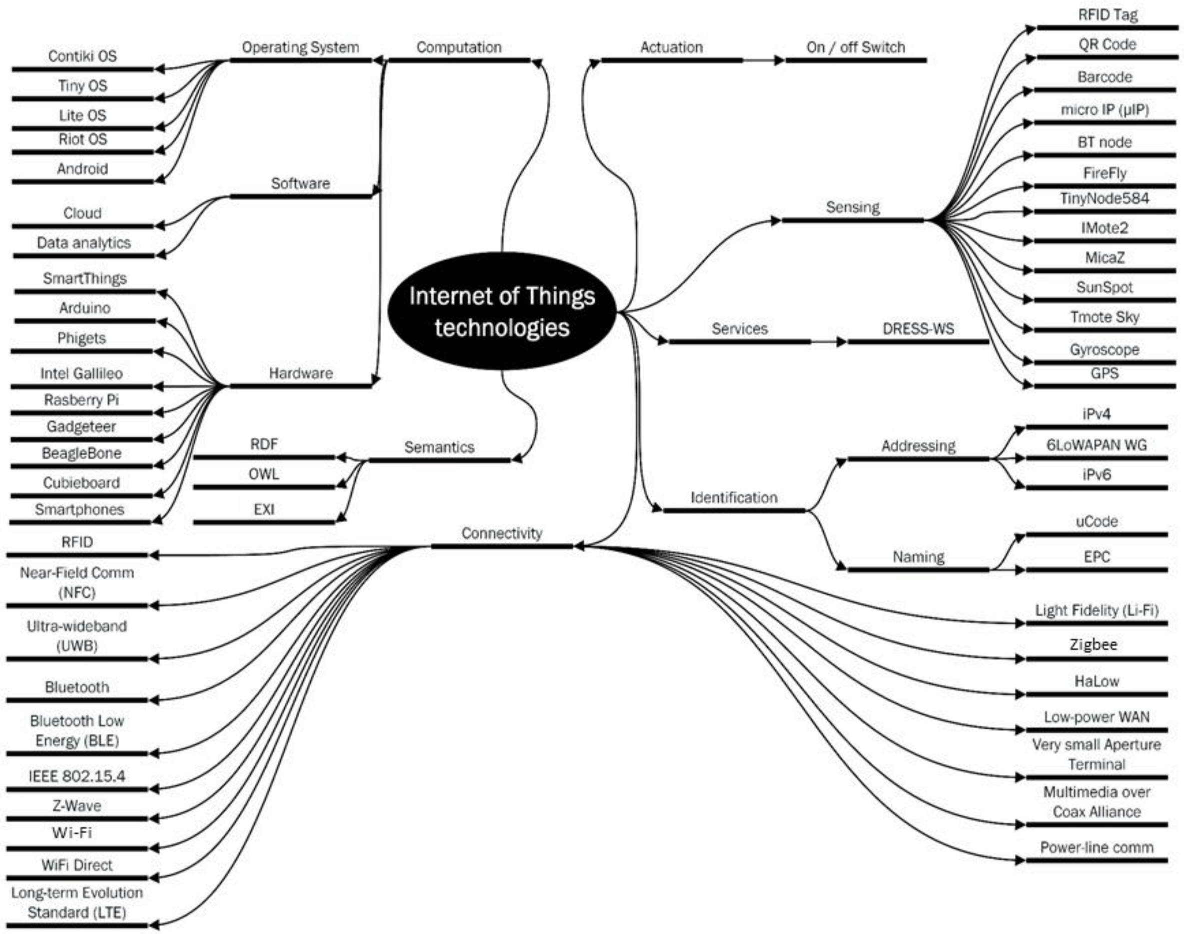

Figure A1: Map of the IoT technologies according to their functionality

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Academic	Journals	54
	Proceedings	17
	Books	8
	Working Papers	3
	Lecture Notes	1
Policy		17
Total		*100*

Table I: The distribution of the 100 definitions of the IoT based on the source type.

Year	Declarative	Relational	Procedural	Conditional	Causal
2005	World (5%)	Anything (2.38%)	Connectivity (5%)	Anywhere / Anytime (2.4%)	N/A
2006	N/A	N/A	N/A	N/A	N/A
2007	Network (7.14%)	Things (3.57%)	Communication (3.57%)	N/A	N/A
2008	Network (6.25%)	Objects (6.25 %)	Internet (6.25%)	Anyplace / Anytime (1.25%)	Business (1.25%)
2009	Network (3.66%)	Objects (2.44%)	Communication (1.63%)	Global (1.22%)	Information / Services (2.44%)
2010	Internet (2.82%)	Objects (4.08%)	Internet (2.82%)	Global (1.25%)	Services (0.63%)
2011	World (2.21%)	Things (3.68%)	Internet (3.68%)	Global (0.37%)	Information (4.41%)
2012	Network (1.41%)	Objects (2.12%)	Internet (1.94%)	Global (0.71%)	Information (2.47%)
2013	Network (0.95%)	Things (4.03%)	Internet (3.08%)	Space (0.95%)	Information (0.95%)
2014	Network (0.81%)	Objects (2.85%)	Internet (3.05%)	Anywhere / Anytime (0.20%)	Information (1.22%)
2015	Network (3.33%)	Objects (2.67%)	Internet (6%)	Dynamic (1.33%)	Information (4.67%)
2016	Network (3.81%)	Objects (2.86%)	Internet (2.14%)	Anywhere (0.24%)	Information (0.95%)
2017	Network (5.34%)	Objects (5.84%)	Internet (3.26%)	World (4.56%)	Information (4.33%)
2018	Network (7.14%)	Objects (7.18%)	Internet (3.34%)	World (4.37%)	Information (3.30%)
2019	Network (5.39%)	Object (6.01%)	Internet (3.70%)	World (3.61%)	Information (2.39%)

Table II: The word (most frequently used in parenthesis) for each dimension of the IoT as they progress through time. The word frequency (%) can be interpreted only within a given year and is not suitable for comparative insights through time because of it is calculated in relation to the total words used in the definitions within a given year. Years with more definitions will tend to reduce the word frequency.

Dimension	Definition
Declarative	*The IoT is an ecosystem…*
Relational	*… of networked devices attached to objects or subjects.*
Procedural	*These devices can collect data regarding internal and external variables of the objects or subjects, analyse them, transmit them, and act based on the analysis of the data in accordance with certain goals and limitations.*
Conditional	*The devices can transmit and analyse data either locally, or remotely, and based on predetermined conditions that actors are required to take into consideration such as limited resource availability, privacy, and security issues.*
Causal	*The generated information allows physical, and digital entities to interact in novel ways allowing value to be created in terms of cost efficiencies and/or perceived utility, and captured through the emergence of new isolation effects, on an individual, organizational and society level.*

Table III: A theoretical definition of IoT

List of Figures

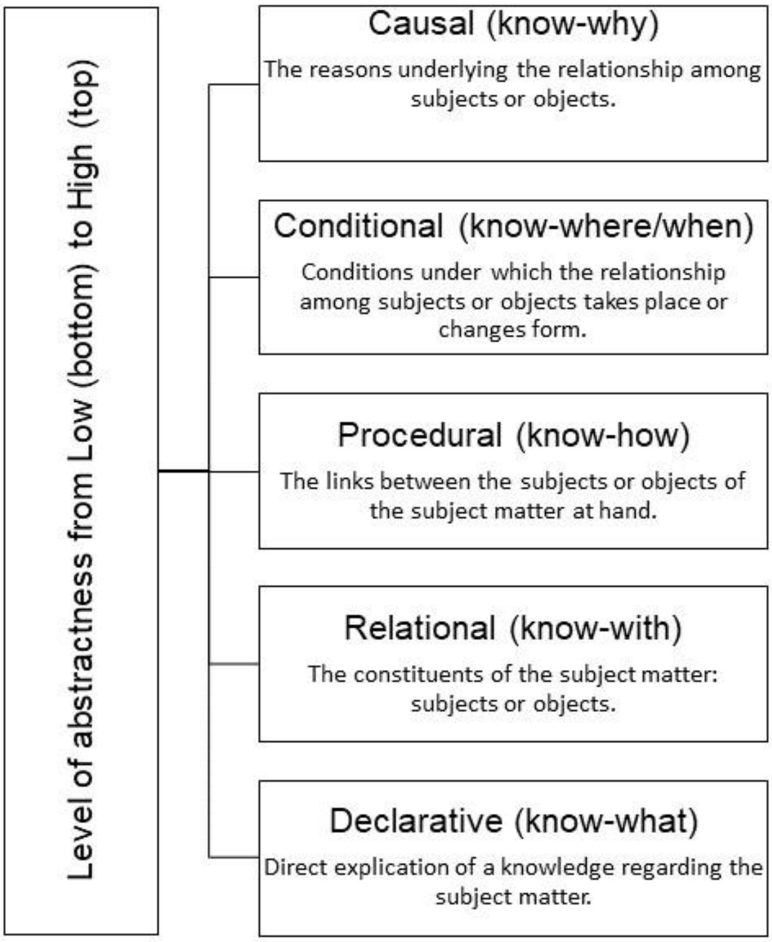

Figure 1: The hierarchical structure of the dimensions of cognitive schemata.

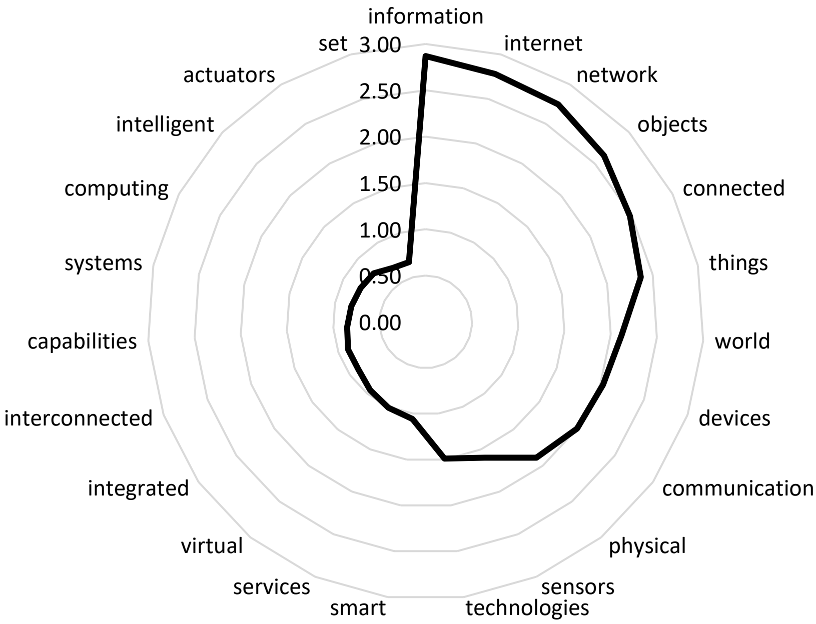

Figure 2: Word frequency (% of a word compared to total) analysis of the sample of 100 definitions of the IoT between 2005 and 2019. The 23 most frequently used words are depicted.

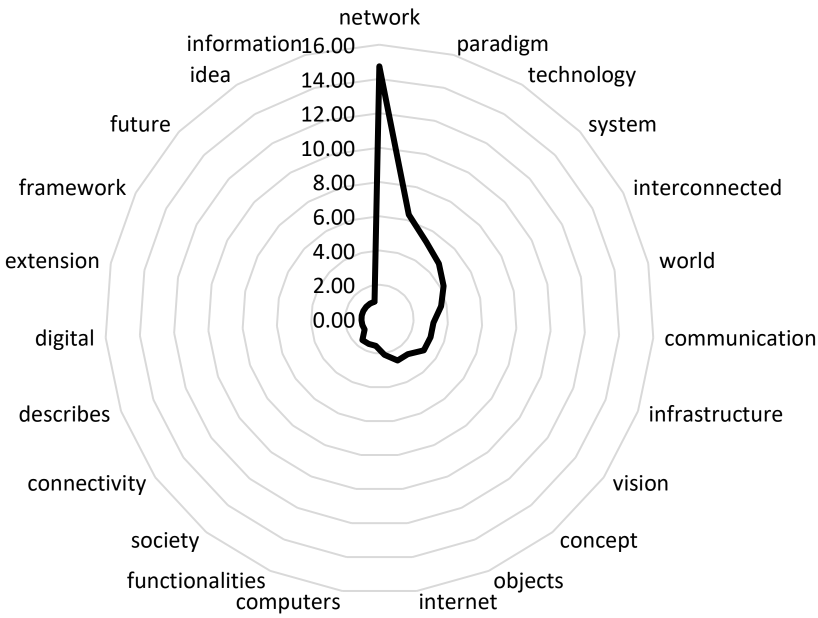

Figure 3: **Declarative** dimension of the IoT (know-what) based on exact word frequency analysis of 100 definitions between 2005 and 2019. The graph presents the 23 more frequently used words contained in the definitions as % over the total words.

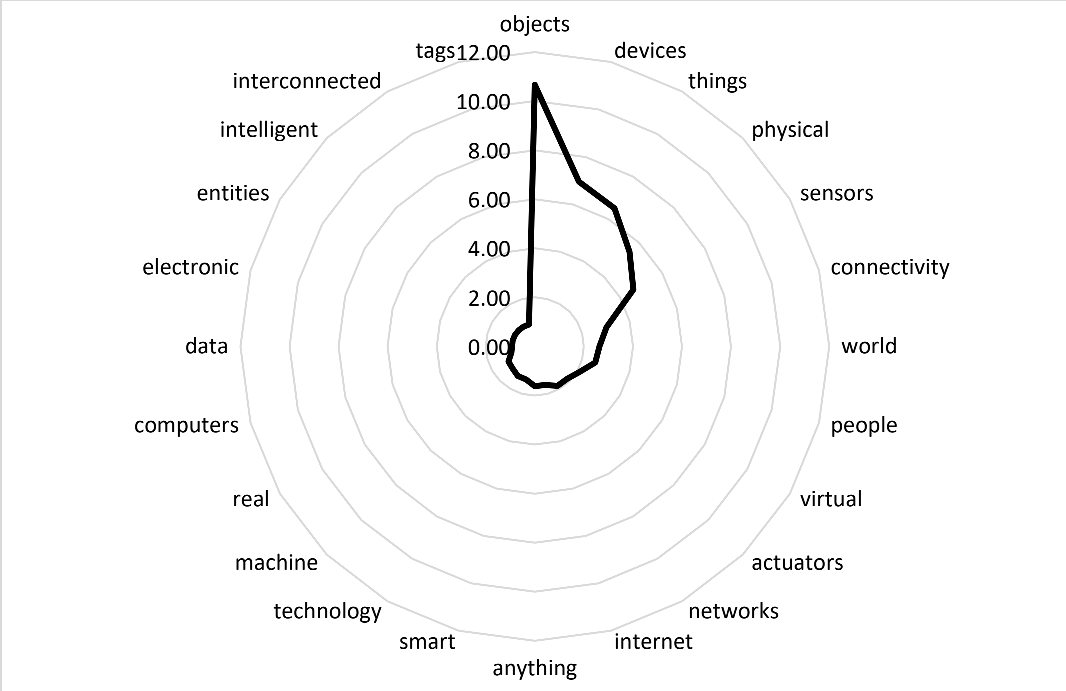

Figure 4: **Relational** dimension of the IoT (know-with) based on exact word frequency analysis of 100 definitions between 2005 and 2019. The graph presents the 24 more frequently used words contained in the definitions as % over the total words.

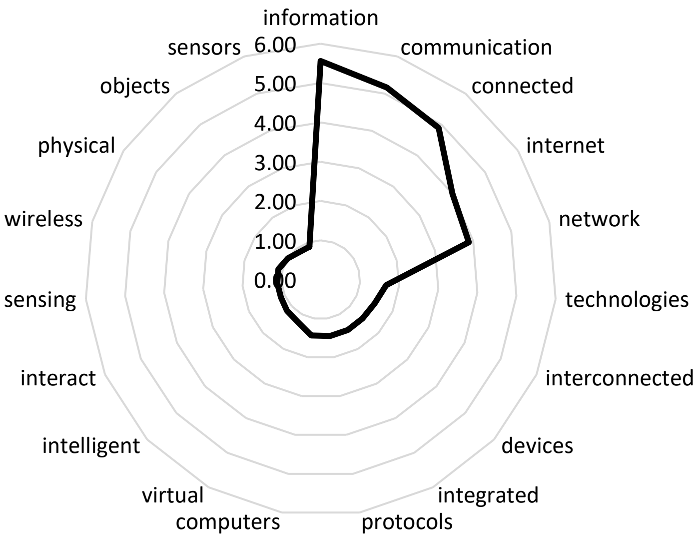

Figure 5: **Procedural** dimension of the IoT (know-how) based on exact word frequency analysis of 100 definitions between 2005 and 2019. The graph presents the 19 more frequently used words contained in the definitions as % over the total words.

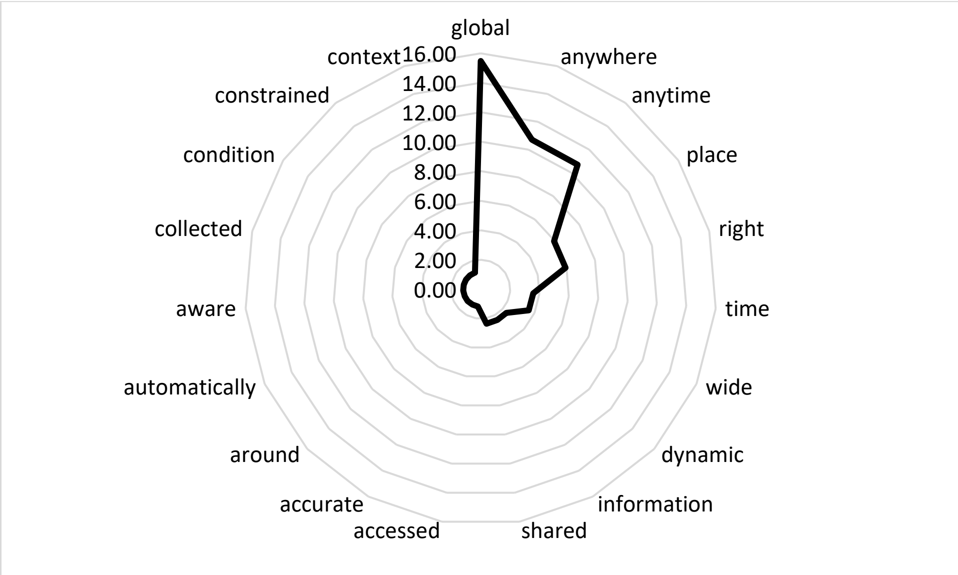

Figure 6: **Conditional** dimension of the IoT (know-when) based on exact word frequency analysis of 100 definitions between 2005 and 2019. The graph presents the 19 more frequently used words contained in the definitions as % over the total words.

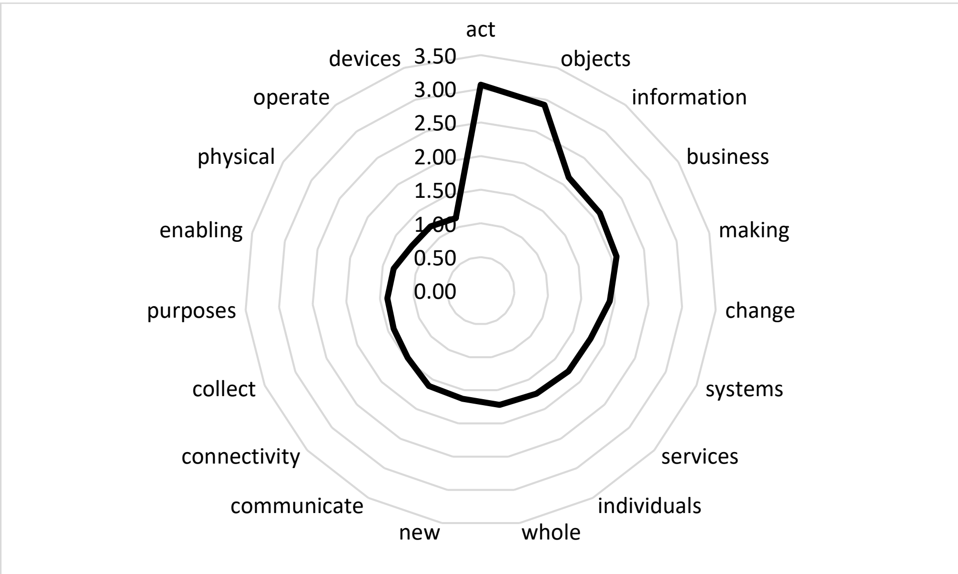

Figure 7: **Causal** dimension of the IoT (know-why) based on approximate word frequency analysis of 100 definitions between 2005 and 2019. Similar words are presented in Table I. The graph presents the 19 more frequently used words contained in the definitions as % over the total words.