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Revisiting IoT definitions: A framework towards comprehensive use

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ABSTRACT

New technologies constantly change the paradigm of how businesses will be run in the future. The Internet of Things (IoT) enables new business opportunities for data-driven transformation in organisations. The emergence of the IoT concept has resulted in numerous definitions, with earlier references primarily focussed on the technological aspects. This has hindered the broader diffusion of the term IoT as, arguably, the definitions do not integrate other non-technological elements of IoT and focus more on business and service provisions. To resolve this, our research identifies the most significant building blocks required in designing an IoT system. This is accomplished through a methodological review of 122 definitions and their consolidation into a novel definitional framework. The definitional framework unifies the traditional technology focus of the earlier definitions and integrates additional elements that are likely to increase the adoption of a comprehensive definition to support the development of future business applications. Furthermore, the framework serves as a reference set for scholarly societies and standards organisations who, in the future, can be tasked with formulating a definition of IoT, as has been the case with the NIST definition of Cloud Computing, which was preceded by several academic studies on defining the term.

1. Introduction

The Internet of Things (IoT) as a concept has been around for about two decades (Ashton, 2009; Brock, 2001). It is expected to radically influence our lives, the way we do business and even the global economy (Carayannis et al., 2018; Lu et al., 2018). As early as 2005, the International Telecommunications Union (ITU) published a widely read report on the IoT. The report declared that people would be in the minority in creating and receiving data once digital devices became ubiquitously connected to the Internet. The same report introduced a vision of a ubiquitous network – "anytime, anywhere, by anyone and anything" (ITU, 2005, p. 3). Since then, many scholars have created descriptions that elaborate on what this vision means in practice. According to Westerlund et al. (2014), the IoT will not only have effects on information processes but also business and even social processes, and by doing so, will provide numerous opportunities – even unexpected ones. It will change the way individuals interact with machines when machines become smart through self-aware 'things' (Vermesan et al., 2009). For example, the IoT will improve the efficiency of supply chains by enabling orders to guide themselves autonomously through the whole supply chain (Kiel et al., 2017), reduce energy consumption in properties (Vermesan et al., 2009), improve asset tracking (Dorsemaine et al., 2016), reduce healthcare costs by monitoring our health (Dijkman et al., 2015) and increase efficiency in education by introducing 'interactive high-definition lectures' (Byun et al., 2016). All of the above will be enabled by collecting data from processes with sensors and actuators and then using the analysed results for process control and development.

However, contrary to the IoT revolution that was expected in areas such as marketing (Bang and Simkin, 2017) and primary industries such as oil and gas (Geng, 2017), it can be argued that recent studies indicate that IoT is being adopted at a slower pace than earlier estimations. According to a Gartner study released in September 2018 (Pettey, 2018), the number of IoT sensors is estimated to exceed 10 billion units, and the annual growth rate is expected to be around 30%. Another study by IoT Analytics estimated the number of sensors to be only seven billion and the annual growth rate to be 18–20% (Lueth, 2018). Nevertheless, these studies confirm that the estimate by the *World Economic Forum (WEF) Global Agenda Council (GAC)* on the future of software and society made in 2015 was too optimistic when approximating the number of connected things at over 50 billion by 2020 (Global Agenda Council on the Future, of Software & Society, 2015). There are several reasons for this deceleration, for example, implementation challenges and issues with

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the IoT standardisation of platforms, connectivity, business models and killer applications (Banafa, 2016). Another reason for the slower uptake has been that research has primarily focussed on the technological aspects of IoT and has ignored research into business models and value creation. For example, the *National Institute of Standards and Technology (NIST)*, though being a part of the U.S. Department of Commerce, considers IoT to include five building blocks (i.e., primitives): sensor, aggregator, communication channel, external utility (eUtility) and decision trigger (Voas, 2016). While eUtility is stated to be “a software or hardware product or service”, their main purpose is described to be feeding data. It neglects to describe why the data needs to be fed, i.e., what kind of (business) value the data enables. Similarly, nearly 40 ISO standards related to IoT exist that all focus solely on technological aspects (e.g. (International Organization for Standardization, 2019, 2020a, 2020b, 2021). These standards address issues such as requirements for data exchange, interoperability, reference architecture, and technical management process. While these are important to the technical implementation, they do not help in defining why an IoT system should be built. The vagueness of the definitions of what constitutes the IoT is also a contributory factor. This lack of clarity and consensus in definitions has thus hindered the level of understanding of IoT concepts, tools and technologies.

In this paper, we methodologically review existing definitions of IoT and, through a detailed analysis of the literature, identify the essential elements present within the current descriptions of IoT. Using these elements, we develop a comprehensive and overarching definition that includes the key IoT characteristics outlined in the existing definitions. We propose a definitional framework for IoT system design. Based on the findings of the analysis, this study aims to contribute to the cumulative and iterative building of a descriptive theory of IoT, as well as supporting practitioners in developing new, commercially successful IoT systems. Our work is the first step towards the development of a consensus definition for IoT. Similar to the development of the NIST definition of Cloud Computing (Mell and Grance, 2011), and which was preceded by several other examples of scholarly work all intending to define Cloud Computing (e.g., Vaquero et al., 2009; Wang et al., 2016; Madhavaiah et al., 2012), we hope that our work will help inform scholarly societies and standards organisations such as NIST and IEEE when developing a formal definition of IoT.

Following the introduction section, in Section 2 we argue the need for a synthesis of existing definitions of IoT. There have been several studies on investigating a common definition for emerging technologies like Big Data (De Mauro et al., 2016) and Business Intelligence (Ponelis and Britz, 2012); however, there are no existing studies that have focussed on a methodological approach towards the formulation of a standard definition for IoT. The methodological approach adopted for the review is described in Section 3, followed by Section 4, which outlines the different phases for the development of the framework. Section 5 is our discussion section. The paper concludes with Section 6 which highlights the key contributions of the work, articulates its limitations and draws pointers for future work.

2. Need for a common definition of IoT

Since being introduced, the IoT has attracted increasing interest amongst both academics and practitioners. Nonetheless, thus far, there is no universal consensus on the definition of IoT in academic or technical literature. Due to this imprecision and inadequacy in the clarity of the concept, it can be conceived as more complex than it might be (Gharajedaghi, 2011). Although a concept may not have an exact meaning, understanding its features helps to generate knowledge (Berenskoetter, 2016). Concerning the Internet of ‘Things’, Vermesan et al. (2009) point out that “things have identities”. Atzori et al. (2010) complement this view by stating that things should operate through unique addressing protocols. Fleisch (2010) combines both perspectives in his white paper “What is the Internet of Things? An Economic Perspective”, where he also states that IoT is an application of the Internet. On the other hand, Ju et al. (2016) see the IoT as a network infrastructure globally used by the information society, which is a combination of the Internet, near-field communications and networked sensors. Smedlund et al. (2018) emphasise the role of physical objects and the distributed nature of the network where devices exchange information. These examples describe the two approaches to IoT. Some consider it to be the sum of its parts, whereas others emphasise that it is an entity per se.

While most of the definitions focus on physical objects and virtual things – i.e., “non-living” sources, some consider that even individuals need to be seamlessly integrated into the IoT (Zhang and Wen, 2017). Keskin et al. (2016) take the idea a step further. In their view, the IoT will include “equipping all objects and people in the world with some form of identifying devices” (Keskin et al., 2016). Arguably, the two elements of the definition that most academics agree on are that the IoT includes “things” – either virtual, physical or both – and that there is some sort of interconnection or interaction between those things. This rather confusing assortment of definitions emphasises the need for clarification and especially a fundamental discussion amongst academics to create a shared understanding. Next, we present three reasons that articulate the need for a common definition of IoT.

Reason 1 for the need for a common definition of IoT: It can be assumed that growth in both the volume of literature and diversification of the subject areas has led to vagueness and more variety as to what constitutes the IoT. Having a common definition will help us weave together the core concepts and technologies that should be seen as fundamental to the IoT.

The volume of literature on the IoT has increased exponentially over the years (Fig. 1). For example, a Scopus search (conducted in August 2021) using the keyword “Internet-of-Things” in article titles, abstracts or keywords identified over 107,000 articles published in the period from 2003 to 2021 (note that we have excluded around 25 papers from this count that are pre-assigned to volume/issues that will appear in 2022): of these approx. 58% were conference papers, 34% were journal papers, and 2.3% were classified as review articles. The remaining 5,7% included books and book chapters, editorials, letters and short surveys. The earliest IoT publications date from 2003 (2 papers). The number of articles increased to double digits (15) in 2006 and to over 100 papers in 2010 (392). As illustrated in Fig. 1, there was a remarkable growth in the volume of publications between 2009 and 2019. In 2019, over 23,000 articles listed in Scopus included the keyword “Internet-of-Things”, and by mid-August 2021, the number stood at approx. 13,400. The growth trend observed until 2019 seemed to have plateaued; however, this may be due to a possible delay in indexing articles in Scopus.

It is also interesting to note the breadth of publications concerning the different subject areas associated with the articles. While interpreting this data, the readers should bear in mind that an article can be categorised under multiple subjects in cases of inter-disciplinary and multi-disciplinary work for example, and thus the total count is over 107,000 articles. As can be seen in Fig. 2, Computer Science accounts for ~37% of papers (approx. 81,500 articles), followed by Engineering (~24%), Mathematics (~7%), Physics and Astronomy (~6%), Decision Sciences (~5.5%) and Social Sciences (~3.5%). Environmental Science with approx. 2600 papers were the last subject category that meets the Fig. 2 display threshold of 2500 or more articles.

Reason 2 for the need for a common definition of IoT: Several synonyms or terms describing a similar concept have emerged during the past years. Without a commonly agreed definition, it is challenging to position emerging research and application areas such as Cyber-Physical-Systems (CPS), Industrial Internet of Things (IIoT), Industry 4.0 or the Internet of Things and Services related to the IoT (IoT&S).

Concepts are linguistic tools for defining and understanding the world around us. Without a commonly agreed definition, it is challenging to delineate supporting, associated or contrasting concepts (Berenskoetter, 2016). Concepts should be defined parsimoniously but include all necessary and sufficient attributes (Brennan, 2017;

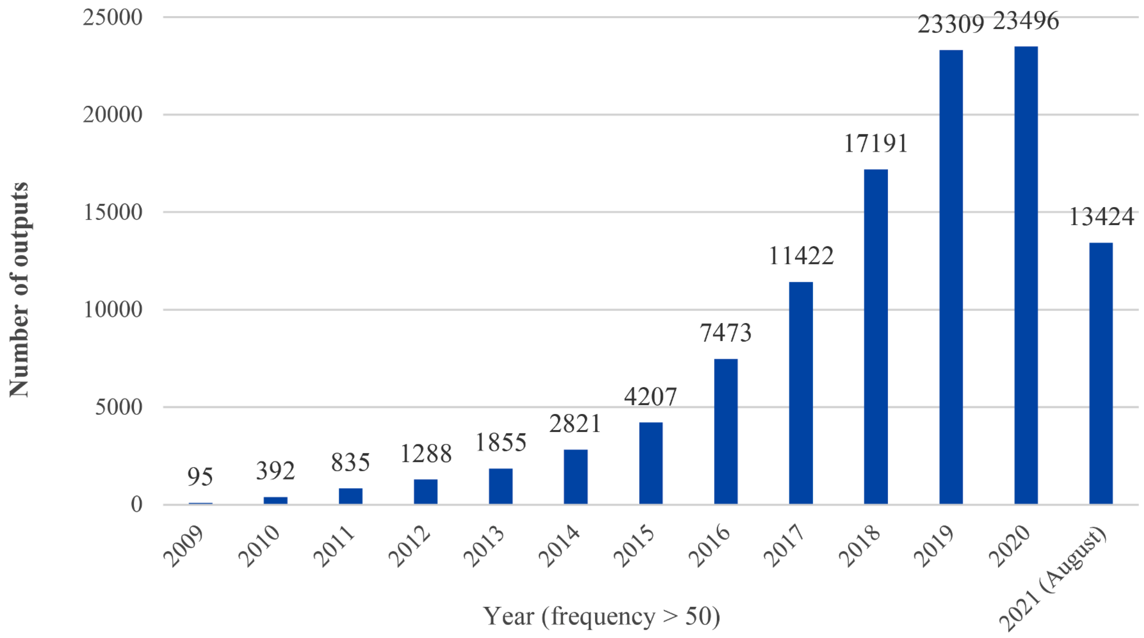

Fig. 1. The number of publications that include the keyword "Internet-of-Things" has increased rapidly between 2009 and 2021 (Scopus search - August 2021).

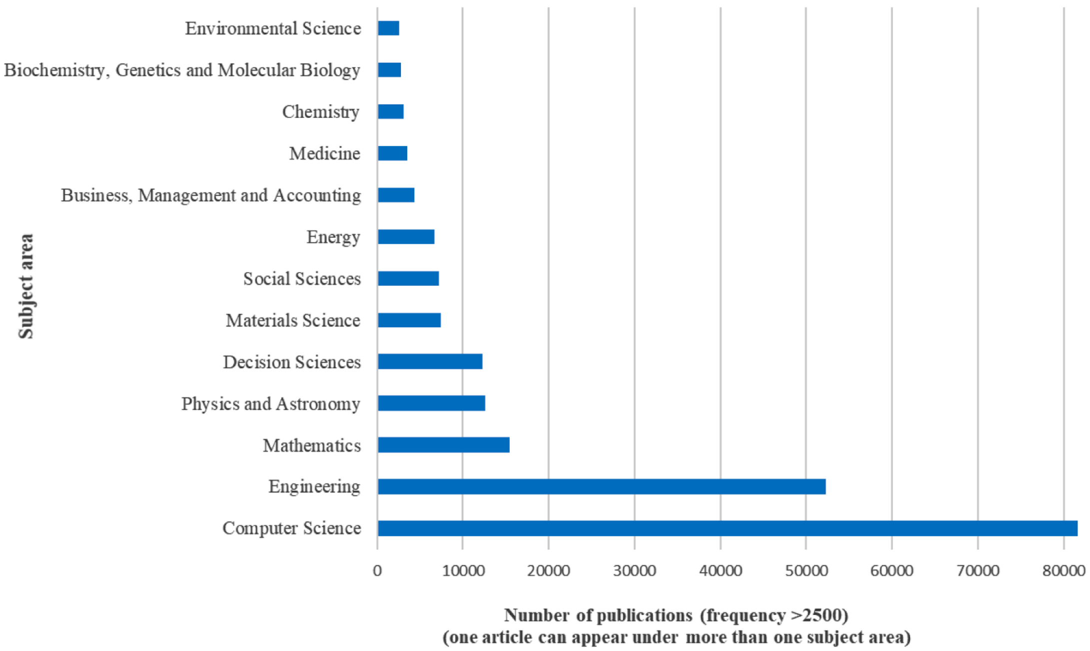

Fig. 2. IoT papers published in different subject areas (Scopus search - August 2021).

Podsakoff et al., 2016). Otherwise, confusion over definitions may limit the generalisability and comparability of research. For example, is the Internet of Things and Services (IOT&S) a superset of IoT or is it an extension of IoT with a business dimension? From the literature, the IOT&S can be understood either "to consist of business models, infrastructure for services, the services themselves and participants'' (Wang et al., 2016) or as a "seamless integration of physical objects such as sensors or home appliances (i.e., things) and services, which can be loosely defined as a network interface that exposes a piece of functionality" (De Leusse et al., 2009). Whilst the former definition prominently features business models, the latter's focus is restricted to technical artefacts (network interface). Thus, without an agreed definition of IOT&S, the term may be used as a synonym for IoT. Similarly, we consider a commonly accepted definition crucial for the future development of IoT. Hence, in this paper, we strive to bring clarity to the concept of IoT.

Reason 3 for the need for a common definition of IoT: IoT utilisation seems to be expanding at a slower pace than earlier estimations, for example, by the World Economic Forum (WEF) Global Agenda Council (GAC) on the Future of Software and Society (Lueth, 2018).

The utilisation of IoT seems to be expanding at a slower pace than earlier estimations have predicted. This is also contrary to the growth of academic literature related to IoT (Figs. 1 and 2). In 2015, the WEF Global Agenda Council (GAC) estimated the number of connected devices to be over 50 billion by 2020 (GAC, 2015). In contrast, three years later (in 2018), the prediction was reduced to just below 10 billion. As illustrated in Table 1 below, the number of active connections globally was expected to be 21.5 billion in 2025. This would correspond to the

Table 1
Number of active connections globally (in billions), actual and predictions (in grey).

Report	Report's year	2014		2015		2016		2017		2018		2019		2020		2021		2022		2023		2024		2025	
Cisco IBSG	2011		14		25										50										
IoT Market, Forecast at a glance*	2014	11	14											32	50										
World Economic Forum	2015														50										100
Statista	2016				15.4		17.7		20.4		23.1		26.7		30.7		35.8		42.6		51.1		62.1		75.4
State of the IoT 2018*	2018			3.8	13.9	4.7	15	5.9	16.4	7	17.8	8.3	19.4	9.9	21.2	11.6	23.2	13.5	25.4	15.8	27.9	18.5	30.9	21.5	34.2
State of the IoT 2020*	2020	2.8	12.5	3.6	13.3	4.6	14.4	6.1	16	8	17.9	10	20	11.7	21.7	13.8	23.9	16.4	26.5	19.8	29.9	24.4	34.6	30.9	41.2
State of IoT 2021*	2021			3.6		4.6		6.1		8		10		11.3		12.3		14.5		17.3		21.8		27.1	

*IoT Analytics' report

**right-hand figure in per each year includes phones and tablets

*** grey figures are estimates in reporting year

total market being $1567 billion in 2025 (Lueth, 2018). Only one year after that report, Forbes Business Insights reduced their estimation of market size to $1102 billion (reduction of nearly 30%). The latest estimation (Lueth, 2018) is slightly more optimistic but still far less than the early projections. We can assume from Table 1 below and the market size figures that the speed of IoT diffusion is decelerating. According to Rogers (2003), diffusion depends on complexity, trialability, observability, compatibility and relative advantage. IoT systems are complex, and the required investment reduces the trialability of IoT. While IoT development has focussed on technology, it makes it complicated for potential adopters to understand the potential benefits of IoT systems, to perceive its consistency with their past experiences and the relative advantage that IoT may create. Consequently, the definition should emphasise the enhanced diffusion created by the value of IoT.

Arguably, the variety of definitions has led to multiple development projects that are in practice competing for the same resources, which may have delayed the implementation of IoT systems. The motivation for identifying a consensus definition also exists across other research fields. We carried out a benchmark study to select an appropriate method for formulating a common definition. The benchmarked existing work is presented in Table 2, which shows that the most typical types of the literature review were employed; however purposive sampling was also used in some cases. The typical number of papers considered in the reviews varied between 15 and 66. The analyses were typically made through content analysis, and a selection of the most representative definitions was also used.

3. Methodology for review

For this study, we were motivated by the literature review approach presented in “A break in the clouds: towards a cloud definition” by Vaquero et al. (2009). In this highly cited paper (as of March 2022, Google Scholar reports nearly 4700 citations), the authors described their literature selection process and then extracted the minimum definition of Cloud Computing from 22 previous definitions. The high citation count demonstrates the acceptance in the academic community of a literature review as an underlying approach for structuring technical definitions, which are expected to include constituent elements of numerous other definitions. Therefore, we decided to adopt a similar approach for this study. Furthermore, a temporal analysis of the development of the definition (Manikas and Hansen, 2013) is included to enhance understanding of the history of IoT.

Thematic analysis (Boyatzis, 1998) was chosen as the research method. The thematic analysis offers a flexible but systematic approach to analysing qualitative data (Saunders et al., 2019). This study applied a similar process to that of Estelles-Arolas et al. (2012) when they examined the definition of crowdsourcing. Thus, the study included four phases (Fig. 3). In the first phase, the existing definitions were identified through a literature review and analysed to identify common IoT descriptive thematic categories. The second phase analysed the text with the *Voyant* tool to identify the relevant descriptive words and phrases. In the third phase, a list of descriptive words was stemmed using the Porter Stemming Algorithm (Porter, 1980) and the destemmed descriptive words were assigned to descriptive thematic categories. Finally, the framework was refined in the fourth phase by selecting the most significant descriptive categories and delineating them with explanations and examples.

Table 2
Existing work on formulating a common definition.

Application Domain	Description of the definition process	Reference
Cloud Computing	Gathered 22 definitions, summarised features to create an encompassing definition	Vaquero et al. (2009)
Big Data	Identified 15 definitions, classified into 4 groups, conjoint analysis to identify "the nucleus of the concept"	De Mauro et al. (2016)
Cyber Security	Systematic literature review, 29 definitions, exploratory text analysis with text mining, lexical overlap analysis, a correlation matrix for a sparse document-term matrix. The definition is based on the five most "representative" definitions	Schatz et al. (2017)
Business performance measurement system	Multi-database systematic literature review, 17 definitions, main features and content analysis of roles and processes, two teams, mutual agreement	Franco-Santos et al. (2007)
Crowdsourcing	Systematic multi-database literature review, 32 definitions, Tatarkiewicz’s approach (to unite sentences referring to the intention of the term), integrated "differentia specifica" elements to the definition	Estellés-Arolas and González-Ladrón-de-Guevara (2012)
Innovation	Thorough literature review, 66 definitions, content analysis conducted by counting word frequencies	Baregheh et al. (2009)
Business intelligence	Purposive sampling, 27 definitions, content analysis to consider connotations, a priori coding	Ponelis and Britz (2012)

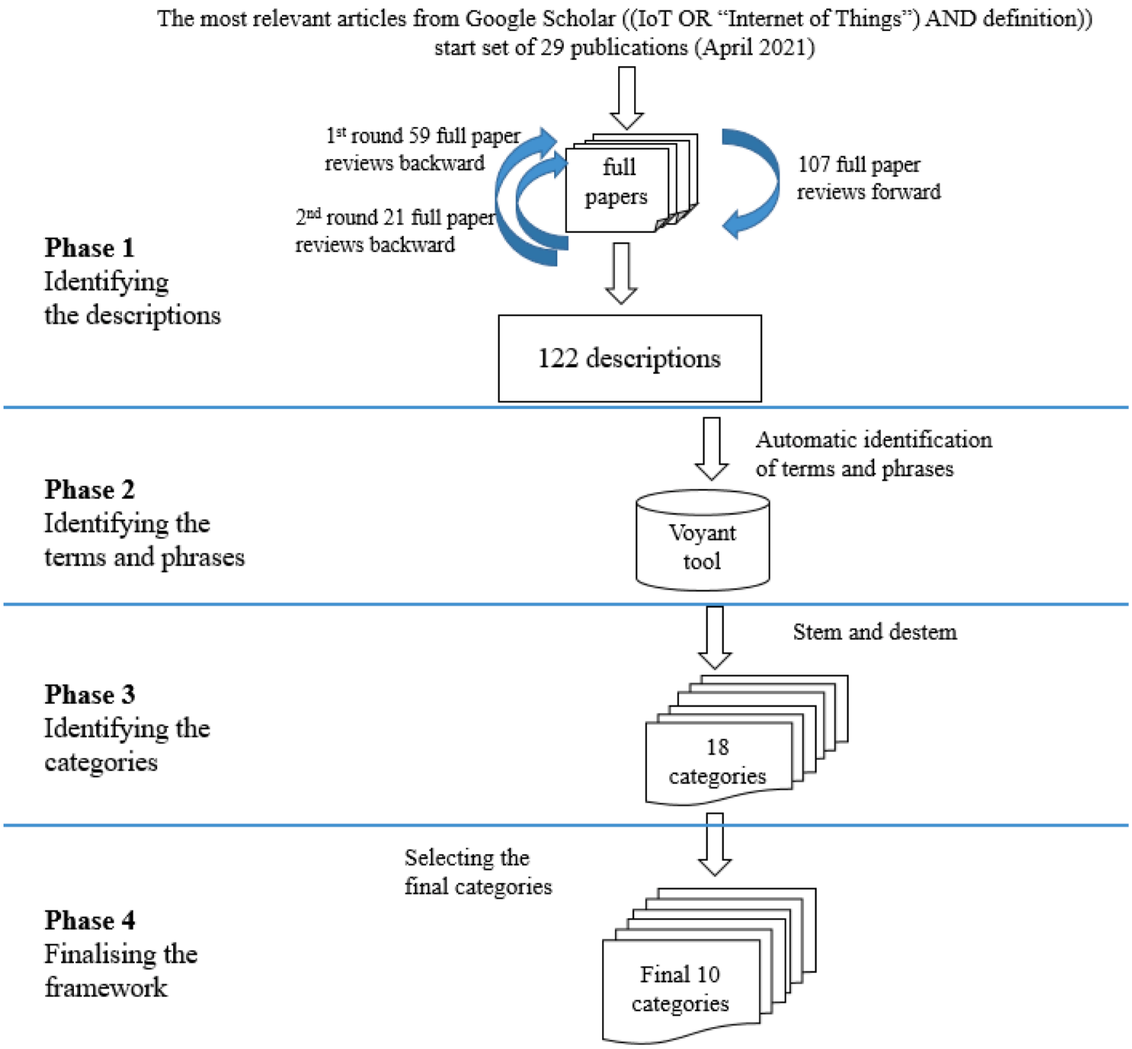

Fig. 3. Process of creating the framework. The names of the phases are shown in Fig. 3 (identifying the descriptions, terms and phrases, categories, framework finalisation). The following section on framework development uses the phase names and provides further details on the four phases.

4. The four phases of framework development

4.1. Phase 1 – identifying common descriptions

To identify relevant papers, in addition to our Scopus-based search with key terms, backward and forward snowballing were applied (Fig. 3). Especially in cases like an under-defined concept such as IoT, snowballing may reduce the noise caused by non-applicable manuscripts (Wohlin, 2014). Badampudi et al. (2015) have demonstrated that snowballing is as accurate as database searches when the start set is defined appropriately. The snowballing is done from the start set both forward (i.e., identifying publications that have used the start set articles as reference) and backward (exploring the reference lists of the start set publications) (Jalali and Wohlin, 2012). Since the aim was to have a non-biased start set, not limited to a single publisher, research methodology or geographical area, Google Scholar (GS) was selected as the search engine. As the focus was on scientific research results, citations and patents were excluded from the search. In ranking the publications, Google Scholar's search function uses full texts weighted by writer, publisher and recent citations in academic literature, emphasising the citation count (Beel and Gipp, 2009). Google Scholar was also selected as the search engine because it provides multi-disciplinary, publisher-independent access to a wide range of academic publications (Harzing and Alakangas, 2016; Hilbert et al., 2015).

When undertaking a literature review, the researchers need to make a judgment call related to identifying the initial set of papers for the review (hereafter, the start set). Identification of the start set requires balancing between comprehensiveness and "an overwhelming number of false positives" requiring manual exclusion and time (Wohlin et al., 2012, p.47). Our start set was created in April 2021 by conducting a search: (IoT OR "Internet of Things") AND (definition). The search results identified 29 most relevant papers (see Appendix 1). The papers were published between 2009 and 2019 and consists of 16 articles published in conference proceedings, ten journal papers, two book sections and one white paper. While most of the articles were from information technology and information system publications, there were also articles from the production management and management innovation domains. The affiliations of papers' lead authors were in four continents (Asia, Europe, Africa and North America), altogether 16 countries.

To understand the variety and complexity of descriptions, backwards and forward snowballing approaches were adopted to extend our start set, as suggested by Wohlin et al. (2012). The review was conducted by the whole research team (the three co-authors), and after each review phase, the selected descriptions were discussed to resolve the identified discrepancies. Backwards snowballing, also referred to as reference chasing, involved the full-text reading of the articles and identifying IoT definitions cited in the papers in our start set. A total of 59 definitions

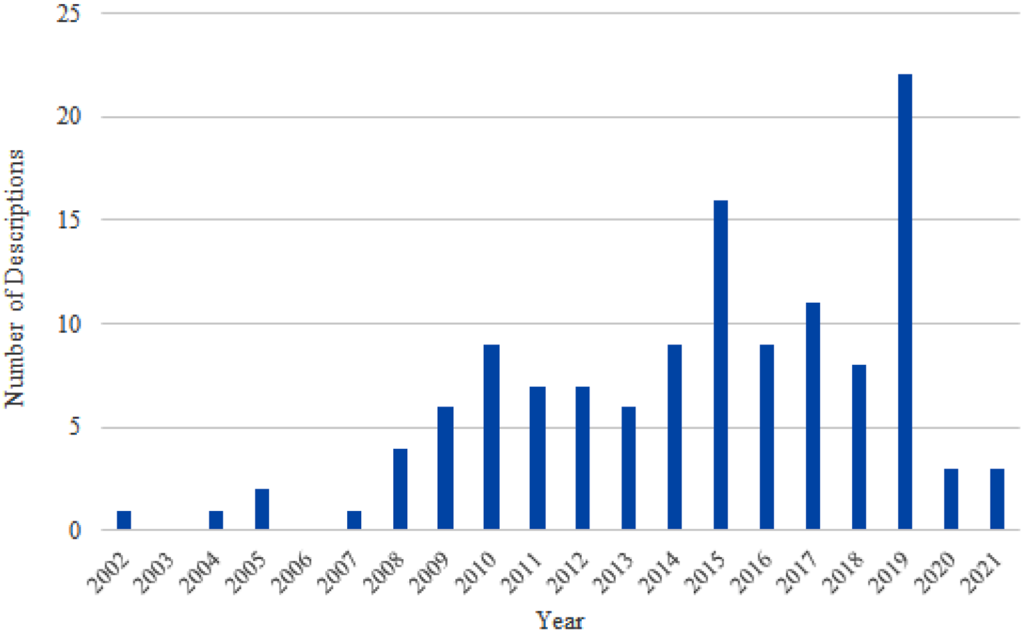

Fig. 4. The number of descriptions per year.

were retrieved through this process. Next, forward snowballing to identify relevant literature that cites the articles of the start set and complementing papers from the backwards snowballing. Google Scholar was employed for undertaking a structured approach also to forward snowballing. A Google Scholar search using the article title (verbatim) retrieves the link for full-text access and the list of citing articles. From the list of citing papers, we selected papers that included terms such as literature review, taxonomy, classification, frameworks, mapping study, survey, and definition. A total of 75 definitions were identified through the forward snowballing approach. The review was finalised by conducting a second backward snowballing, including the articles, where new definitions were identified. This resulted in additional eight definitions. As mentioned earlier, each author was responsible for a subset of cited articles resulting from the respective allocation from the start set. A master list of definitions enabled identification of the duplicate definitions. After reviewing 216 full papers identified by the backward and forward snowballing methods, 122 different descriptions of IoT were identified (the supplementary material can be downloaded from the publisher site). The number of descriptions is the highest in the year 2019 (Fig. 4) Some of the IoT sources, e.g., Atzori et al. (2010), were referred to more often than others. For this study, all descriptions were considered equally relevant.

After collecting the data, the descriptions were carefully read to identify initial themes for thematic analysis. These initial themes included network, physical object, virtual thing, data, protocols, and services. The themes were revisited in Phase 3.

4.2. Phase 2 – identifying the terms and phrases

The analysis began by inputting the descriptions into the Voyant tool, which is a web-based reading and analytics environment for digital texts. It is an effective way to identify the most important terms as an initial phase of the analysis as it calculates the frequency of each word and allows sorting those by frequency. When the volume of text is large, compared to manual analysis and frequency count, a Voyant-based analysis reduces the chance of missing meaningful words. The Voyant tool identified 1022 different words. Naturally, IoT was used very frequently in the descriptions, but, as the subject requiring definition, it was excluded. By analysing the most frequently used words, it became evident that many descriptive words had a similar meaning. However, Voyant considers the singular and plural forms of a word as two different words. In more technical terms, the words retrieved from the Voyant analysis contained inflexional endings (extra letters added to words in their different grammatical forms) and needed to be removed. Consequently, a second round of analysis was required.

We used the Porter Stemming Algorithm (PSA) for this analysis (Porter, 1980). More specifically, we used the Visual Basic implementation of PSA (Mustafee, 2003) to normalise the words through the process of stemming. In information retrieval, stemming refers to the removal of the inflexional endings to their morphological base term. We also refer to the base term as the PSA meta-data. The subsequent destemming process allows for the grouping of words that have the same PSA meta-data. Taking an example from our Voyant analysis, the words “network” (104), “networks” (20), “networking” (12) and “networked” (7) are four distinct words (frequencies reported by Voyant included in parenthesis). However, the PSA algorithm normalises these words to only one PSA meta-data called "network". Another example is "communication" (58), "communications" (10), "communicate" (26), "communicating" (5) being normalised to the PSA meta-data called "commun". In addition to automation (which included both stemming and destemming operations), this phase involved manual analysis of the results of the stemming algorithm and organising the words into groups. This enabled us to calculate the total occurrences of the words with inflexional endings, and which were assigned to a unique PSA meta-data. Furthermore, the manual analysis enabled us to assign the most relevant word to represent the group of words that were stemmed (for example, the PSA meta-data "commun" was re-labelled "communication"). For further information on the specifics of our implementation of the stemming and destemming process, please refer to Mustafee and Katsaliaki (2020).

4.3. Phase 3 – identifying the categories

The stemming led to 731 stems describing IoT. Each destemmed word is linked with a stem. Of these, stems used more than 20 times account for 50% of the total word count and 6.3% of the stems. This was sufficient to identify the most important descriptor categories. The destemmed words from the most frequent stems were grouped to themes by meaning. The descriptive words used in the descriptions were reviewed before being assigned to a group. This process led to 18 different categories . The ten most frequently mentioned categories are also the descriptive ones (see Table 3). The last eight include more general verbs or adjectives like based (used in 'based on'), which as such are not descriptive. Hence the top ten categories were chosen as the "obligatory building blocks of IoT".

4.4. Phase 4 – finalising the framework

In the final step of the study, a framework for creating an IoT system was developed. The diversity within each category was analysed, followed by explicating the meaning and content of each descriptive category. Finally, some examples were included in the framework for further elucidation.

Table 3
Descriptive categories identified through destemming.

Stems	Examples of destemmed words	Descriptor (group)	Frequency
network	networking, networked	Interaction	507
commun	communication, communicating, communities		
internet	internet		
connect	connected, connectivity, connections		
interact	interaction, interactive, interacting		
interconnect	interconnecting, interconnections, interconnectivity		
integr	integrant, integrated, integration		
thing	thing, things, thing's	Virtual Thing	361
devic	device, devices		
virtual	virtual, virtually		
sens	sensing, sense, sensed		
sensor	sensor, sensors		
actuat	actuator, actuators, actuating		
digit	digital		
servic	service, services	Services	241
applic	application, applications		
comput	computing, computation		
process	processing, processes		
capabl	capabilities, capability, capable		
object	object, objects	Physical object	229
physical	physical, physically		
product	product, products		
technolog	technologies, technology, technological	Standardised Technologies	179
protocol	protocol, protocols		
standard	standard, standardisation, standardised, standardisation, standardised		
infrastructur	infrastructure, infrastructural		
interfac	interface, interfacing		
software	software, softwares		
Inform	information	Information	166
smart	smart, smartness		
intellig	intelligence, intelligently		
data	data	Data	82
world	worldwide	Ubiquitous	67
ubiquit	ubiquitous, ubiquitously		
pervas	pervasive		
ubiqu	ubiquity		
worldwid	worldwide		
human	human, humans	User	66
user	user, users		
peopl	people		
owner	owners		
custom	customers		
uniqu	uniquely, unique	Unique	65
identifi	identifiable, identifier, identify		
identifi	identification		
ident	identity, identities		
us	use, using, used, useful		48
entiti	entity, entities		41
environ	environment, environments		37
base	based		33
enabl	enable, enables, enabling, enabled		31
provid	provide, provided, provider		31
includ	including, includes, include		22
manag	management, manager, managing		21

Although 122 different descriptions of IoT were identified in our study, notably, many scientific publications did not present any IoT description at all. The term is used fluently but in a rather inconsistent manner between publications. A similar inconsistency can be observed between the descriptions used. Two descriptions mention only one of the descriptive categories, while another two use all ten of them (see Fig. 5). Typically, a description employs four to five different categories.

After identifying the descriptive categories, the research team focused on the complete descriptions to comprehensively understand what should be included in each category.

The first group, *interaction*, includes terms like communication, interoperability, seamless integration and exchange of information. Although many terms are used, they are almost synonyms. The parts of IoT must communicate with each other to enable data utilisation.

The second group, *virtual thing,* was also described in different ways. It is referred to as a smart object, actuator, active participant, embedded electronics, microcomputer, sensing object, etc. It is inarguably an important term in the descriptions, although it is also the one that is most heterogeneously portrayed.

The third group, *services*, includes terms such as innovative applications, digital enhancement and decision making, amongst others. The value of this contribution comes from articulating the importance of acknowledging the IoT services as value-creating business enablers. Well-designed services can have pronounced implications for individuals and on a societal level. For example, utilising IoT in e-governance can promote government transparency and alleviate tax evasion (Brous 2015; Uyar et al., 2021). For example, The IoT also enables contactless services in healthcare diagnostics, treatment and even disease prevention, the importance of which has increased during the Covid-19 pandemic (Lee and Lee, 2021). Moreover, IoT services in the energy sector can have significant social, economic and environmental implications (Hiteva and Foxon, 2021). While the concept of the services group is likely to be important, it seems that the content is imprecise and lacks clarity. Considering the imbalance between the presumed importance and the vagueness, this group requires more attention.

Most of the descriptions emphasise the difference between a *physical object and a virtual thing* that makes the fourth group (*physical*). An object refers to the product to which things are attached or embedded. For example, a fridge may have a temperature sensor: the former being the object and the latter the thing. There seems to be a mutual understanding of differentiating these two items. Both are needed. The virtual thing enables a complimentary service for the user of the physical thing.

The fifth group is *standardised technologies*. The addressing scheme, agreed protocol, architecture, intelligent interfaces and enabling ICT are all related to standardised technologies. Standardisation is essential so that all things can connect to each other. Machines are not creative like humans; thus, the former know how to connect only when clear standardised instructions (like a TCP/IP protocol) have been given. Without a doubt, creating ubiquitous structure connectivity is necessary.

The sixth group is *information*, including terms like cloud computing, knowledge mining and data analytics. This group is closely related to the seventh group of terms, which is *data.*

The seventh group is data – whether it be big data, raw data, semantic level data or middleware level data. This is a significant group to include in this study. Data and information enable smart products, which are intended to add value significantly to IoT users and thus offer business opportunities. The difference between data and information is that data has not yet been processed or analysed. Both data and information can be considered to be new types of assets. They may be less observable and more malleable than a traditional physical asset, but have value, as they are not diminished when shared or used. One could even say the value of data and information increases when shared.

The eighth group is *ubiquitous*. It is described with terms such as information network, network infrastructure, real-time, pervasive and

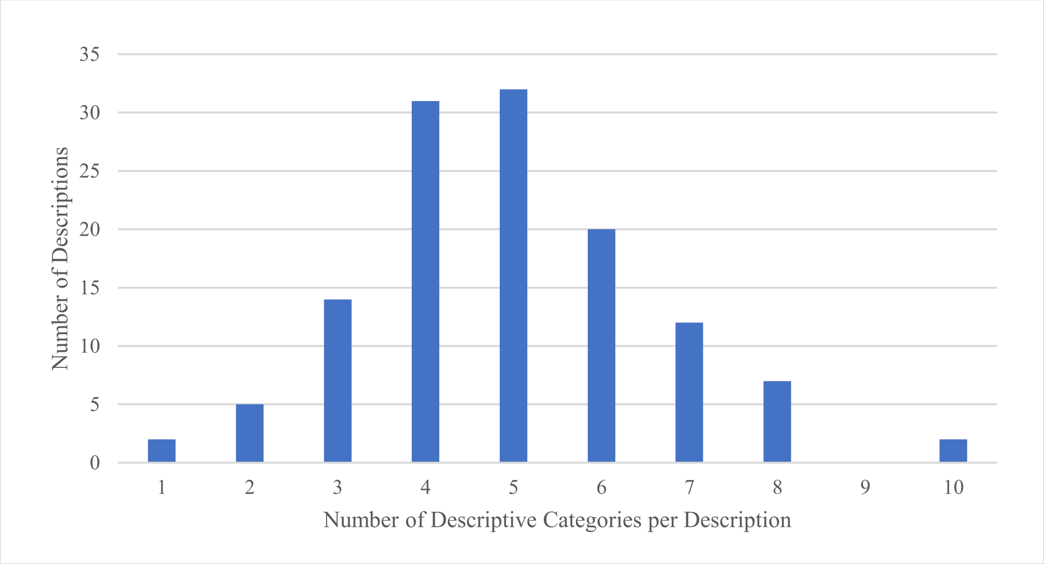

Fig. 5. The number of descriptive categories used in the descriptions.

ubiquity. All these indicate the same sentiment – anyone, anything, anywhere and anytime. While ubiquitous refers to availability anywhere, it is good to remember it does not mean that things and data must be available everywhere. The same applies to anytime in connectivity. Anytime is different from all the time. It is enough to have the ability to connect to the network; it is not necessary to be online all the time. In many cases, a continuous connection would be a waste of energy and money.

The ninth group is *user*. This group is important as it is the user who pays the bill and whose expectations should be met – or even exceeded. The user was also referred to as an owner or a human in the search. The user is closely linked to services. Consequently, the value offered to the users through services is the backbone of successful IoT system provenance, the importance of security issues can be expected to increase in the future.

The last group is *uniqueness*. Each physical or virtual thing in the IoT needs to be uniquely addressable (Glova et al., 2014). Other terms in the same group are also automatic identification, clearly identifiable and intelligent identifying.

While IoT technologies have developed substantially during the past decades, the system-level theories seem to have progressed less. This may be an indication that the concept is still unclear, and consequently, the academic community has not been able to build a commonly agreed descriptive – let alone normative – definition.

5. Discussion

Data, information and services constitute the core of transforming existing technology into business. These are the fundamental parts of creating value through the IoT. As Gupta (2016) stated: “Data is the new dollar”. Through the IoT, a vast amount of data is created and shared effortlessly. This creates a new way for companies, networks or ecosystems to (co-)create and capture value, which can be turned into an asset with which business value can be created (Tiwana, 2014). This value can be either monetary or non-monetary – sometimes both. The key is that someone finds it valuable and thus is willing to trade the value.

Some of the descriptions include business aspects or business models for the basic structure of IoT (such as Leminen et al., 2012; Turber et al., 2014; Fleisch et al., 2015; Keskin and Kennedy, 2015; Serrano et al., 2015). Khan et al. (2012) even include business aspects in their model of an IoT stack. Moreover, the business can be considered to be built on the IoT: the Industrial Internet of Things, IIoT (Burmeister et al., 2016; Gierej, 2017; Iivari et al., 2016), which utilises data for developing new types of value for customers; or the Internet of Things and Services, IoT&S (De Leusse et al., 2009), where the IoT stack is combined with new valuable services for the customer. Although Xueqin et al. (2011) has a strong technology orientation in his description, he still recognises that IoT will not be able to become a part of our everyday life unless it has appropriate business models to utilise.

Examples of IoT devices include cameras (e.g., Nest Dropcam, Samsung SmartCam and Ring doorbell), switches and triggers (iHome, Belkin Wemo Switch), hubs (e.g., Amazon Echo), air quality sensors (e.g., Awair air quality monitor), electronics (e.g., Google Chromecast), healthcare devices (e.g., Withings Aura smart sleep sensor and Blipcare blood pressure meter) and light bulbs (e.g., Philips Hue and LiFX Smart Bulb) (Sivanathan et al., 2018). For this work, we have chosen Amazon Echo as an example, subsequently referred to as “Echo”. Echo is an intelligent home assistant or “smart home” IoT hub, which takes voice commands from the users to control itself and other connected IoT devices/sensors, e.g., smart lights, smart kettles, smart locks, smart thermostats and smart doors (Li et al., 2019). The voice commands are interpreted and carried out by Amazon’s cloud-based intelligent personal assistant service "Alexa", through which Echo carries out voice interaction, music playback, provides information like weather and traffic, and also controls other IoT devices (Jackson and Camp, 2018).

We have created a definitional framework to clarify the structure of IoT, especially for practitioners designing IoT systems. This framework describes each of the key categories identified in this study by presenting a short explanation and concrete examples (see Table 4).

Some of the descriptions emphasise ecosystemic thinking (Keskin and Kennedy, 2015; Leminen et al., 2015; Shin and Jin Park, 2017) when designing and implementing IoT. According to Westerlund et al. (2014), IoT systems and applications support businesses built on IoT only if value creation and capture are constructed with an ecosystem focus. Considering value co-creation at the ecosystem level, Mejtoft (2011) reminds us that, in addition to technological changes, society also needs to become more accepting of the newly advanced ecosystems, including ‘things’, which may be largely self-controlled by machines. For example, as Tiwana (2014) and Xuequin (2011) have demonstrated, applications are more likely to create business value than the technology itself. Metallo et al. (2018) have found that value proposition and key activities play a crucial role in IoT-enhanced business. The IoT offers significant business opportunities. One should remember, however, that

Table 4
Explanation of categories with examples in order of frequency in descriptions. The last column describes the categories with reference to Amazon Echo.

Descriptor	Explanation	Examples	Amazon Echo
Interaction	Virtual things are connected to each other and can interact.	Wireless or wired connection. Able to request, send and receive data.	Echo is often connected to other IoT devices and sensors, e.g., smart lights, smart kettles, smart locks, smart thermostats and smart doors (Li et al., 2019). Multiple Echo devices can also be connected to each other, for example, to make a stereo pair (Andersen, 2018).
Virtual Thing	The active participant that collects and possibly stores the data from the functioning of the physical object	Sensor, actuator, embedded electronics in general	Echo stores the interaction of the virtual agent Alexa in SQLite database and Web cache files (Li et al., 2019).
Services	The functionalities the system has to improve the process	Innovative applications, visualisation (like heat maps), decision making, optimisation, i. e. the value for the customer	Echo provides services such as music playback services, information services like weather and traffic reporting, and control services for other connected IoT devices like smart lights and smart thermostats (Jackson and Camp, 2018).
Physical Object	An object where the virtual thing will be embedded. Can also be an object whose performance needs to be controlled.	Fridge, car, welding machine	Echo is embedded with a conversational agent (Alexa) that can take voice commands from users and perform several tasks (Gao et al., 2018).
Standardised Technologies	The means enabling data collection	A protocol like TCP/IP, a programming language like HTML, addressing schemes, architecture	Echo uses HTTP (port number 80), HTTPS (port number 443) and ICMP (port number 0) and accesses a number of domain names including *softwareupdates.amazon.com, devicemetrics-su.amazon.com, pindorama. amazon.com* and *pool.ntp.org* (Sivanathan et al., 2018).
Information	Information processing	Cloud computing, knowledge mining or data analytics	Echo receives voice commands ('ubiquitous listening') that are interpreted and carried out by Amazon's cloud-based intelligent personal assistant service "Alexa", and through which Echo carries out voice interaction, music playback, provider of information like weather and traffic, and also controls other IoT devices (Jackson and Camp, 2018).
Data	Actual bits and bytes. Raw data, big data	Temperature, friction, current, location, vibration	Some of the data stored in Alexa includes the user's history data, data on interactions with Alexa (e.g. user behaviour, user activity), account information, customer setting, Alexa-associated devices (Li et al., 2019).
Ubiquitous	The data needs to be available anywhere, but not necessarily everywhere.	Geographically, preferably real-time and openly	Echo has a complex cloud ecosystem that allows ubiquitous use of Alexa (Chung et al., 2017). It constantly scans for user voice commands to perform tasks. This is also referred to as 'ubiquitous listening' (Hui and Leong, 2017).
User	The human-to-machine interaction	The person(s) using Alexa's assistance	The user finds Alexa's assistance valuable, and thus is willing to buy one, create data by using it and trusts the system does not
Unique	All objects and things must be uniquely identified for data collection and analysis purposes.	An IP address	Amazon Echo has a unique IP address.

the value companies and consumers see may be either monetary or non-monetary – in some cases, even both. Thus, when designing the IoT, different ways to create and capture value should be evaluated – not only from the designer point of view but considering the needs of all the different potential stakeholders.

All the identified categories should be included when designing IoT systems. However, as there are already many different technologies available, IoT developers should change their focus from technology to value offering. Thus, we propose a design process that is depicted in Fig. 6 and elaborated below.

While IoT is known to have implications for the individual and right up to the societal level, IoT system design should first start by defining the kind of value that is exchanged by describing the services offered. The second step is to analyse what kind of information is needed to create value and which physical object(s) can obtain it. This leads to the requirements for data. Third step focuses on the nature of the data: to define the risks related to that specific type of data and to plan data security accordingly. In the fourth and final step the technical

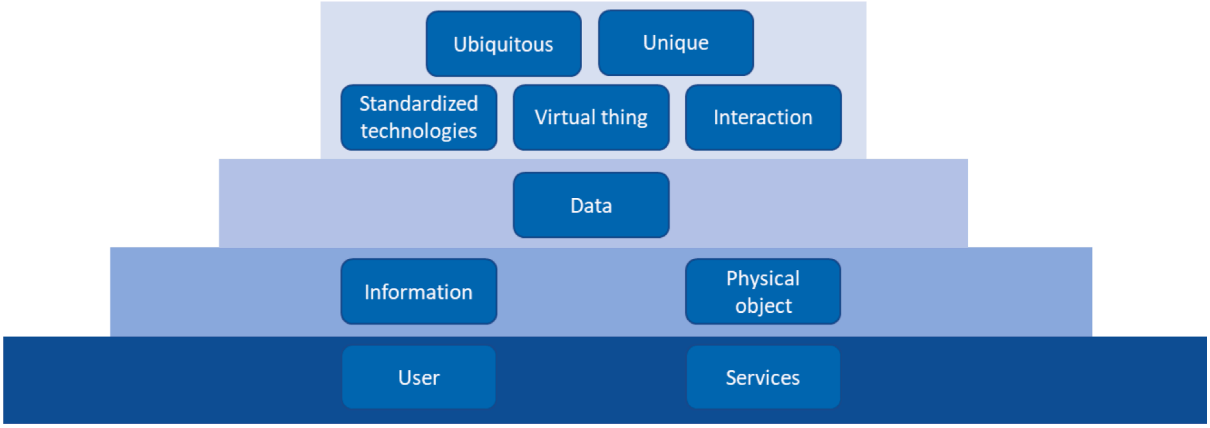

Fig. 6. Design flow for a value-based IoT system.

implementation is planned: which types of actuators, which protocols, etc.

Sometimes it is more intriguing to discover what is not included in descriptions. Relatively few of the publications emphasise the importance of safety and security. This refers to data security, privacy, and safety and control.

(1) Security: In these days of mis- and disinformation and other questions regarding data sovereignty and provenance, the importance of security issues can be expected to increase in the future. While the data in this study did not identify the importance of security and privacy, these aspects should be properly evaluated when designing the IoT. The magnitude of cyber risks is difficult to define, but nonetheless, without proper risk analysis, companies may face lethal attacks. Luckily, some risk assessment frameworks have already been developed, but impact evaluation models are still needed (Radanliev et al., 2018). Perhaps the first security risks that come to mind are cybersecurity attacks. A cyber-attack can affect operational continuity, control integrity, intellectual property, strategic information, identifiable business information, personally identifiable information or payments. According to Jacobs et al. (2016), income, assets, equity, growth, market share and liquidity are all jeopardised if a cyber attacker penetrates an IoT system.

(2) Privacy: Oriwoh et al. (2013) points out that there are four different privacy concerns: socio-ethnic, legislation/regulation, economic and technological – all of which need to be resolved. Hence, many parties (technology vendors, governments and the public) should be interested in resolving these challenges. Glova et al. (2014) draws attention to intellectual property rights and defining data ownership. They also raise concerns regarding data management, especially data privacy. While some data can – or even should – be open, some data (like health data) should be shared on a need-to-know basis. Data usage policies are needed to ensure data sovereignty and provenance, especially when data is stored and processed in clouds (Baracaldo et al., 2017; Biswas and Mukhopadhyay, 2018), as is often the case in IoT systems. Data provenance, integrity, correctness and privacy enforcement are important from the legal perspective and from an ethical perspective (Baldini et al., 2018).

(3) Safety (e.g., as in traffic safety): Now that autonomous vehicles are closer than ever, it is of utmost importance to ensure that the vehicles make correct decisions and are not attacked by cybercriminals, causing traffic accidents. Machines operated by the IoT or artificial intelligence need to be safe for use by the public (Chan, 2015).

While Haller et al. (2009) mention security and privacy issues in their description of the IoT, they fail to explain what they mean in detail. Vermesan et al. (2009), however, give a detailed description. They divide security, privacy and safety into four types: economic and market, social and ethical, technical, and legal and regulatory types. The economic and market issues include codes of conduct, privacy certifications and standards. Social and ethical issues cover consumer rights, public awareness and anonymity mechanisms. Legal and regulatory issues ensure safety and security by consent, use and collection limitations, openness, accountability and agreed data ownership principles. The largest group of security, safety and privacy issues are included in the technical section. These include technological safeguards, encryption, accessibility, data integrity and ID management. This presents the diversity in the meaning of security well, but it still omits the physical safety aspects in an environment where autonomous cars and robots are present.

6. Conclusions and future work

Jacobides et al. (2018) describe ecosystems as an economic community where interacting, interdependent participants commercialise innovation. While most of the definitions do not include business as a part of the IoT, we consider the IoT to be an entity and that it can be an ecosystem and thus a business enabler. Interaction, data and services are the means for achieving new types of shared and exchanged value. We also claim that the IoT is a system. It collects input (data with sensors), processes it (interaction, information) and delivers output (services) to "serve a common purpose", thus fulfilling the traditional definition of a system (Merriam-Webster, 2019)

Based on our study, we propose that all ten of the categories be included in the IoT framework. Consequently, the two most comprehensive existing descriptions (the CERP-IoT report by Vermesan et al. (2009) and a definition written by Minerva et al. (2015), which are shared by the IEEE IoT initiative) are both valid. Hence, as a conclusion, our framework in the form of a list of ten categories with explanations and examples is proposed for the development and implementation of new IoT systems. Everything starts from the value it adds and ends with the details of technical implementation.

There are some limitations to this study. First, the research design relies heavily on selected databases. Hence, to improve the credibility through data collection triangulation, this research employed several different data sources. An important design issue was the selection of Google Scholar as the first source of literature, "the seed" input. It is difficult to estimate how much the results might have changed if the seed source had been different. Second, the literature was collected by snowballing, where credibility relies strongly on the credibility of the start set. To minimise this potential risk to credibility, the source set for snowballing was taken twice, 30 months apart and then combined. The source set was deliberately relatively large and heterogeneous to increase the credibility. However, due to the enormous number of citations in some of the source articles, the research team may have missed some descriptions. Nonetheless, 122 descriptions are likely to give a reasonably valid result. Third, the credibility was also improved through scrutinizing the preliminary findings against the raw data. Furthermore, a conceptual study also relies a lot on the meaning of the concept, and the IoT is a typical "suitcase word" that carries many meanings. The thematic analysis mostly focussed on the descriptions. On the one hand, this ensured that the core of the sources' message was emphasised, but it also may have neglected the rest of the texts. This may have caused bias to the emphasis of the categories. To reduce the risk to credibility caused by this, the literature review was conducted by all three authors and the analysis phase by two researchers.

To increase the confirmability, the research process and used methods have been described in detail to enable repeatability of the research method. This will also improve the transferability of the research process to other underdefined concepts. Due to the rapid development of the IoT and IoT-related matters, the timing of the study may cause some unavoidable source of maturation bias. Thus, replicating studies to this review would be welcomed.

From the dependability point of view, there is a clear conflict in the sample used in this study on what to include in the IoT. Some scholars include a business model (e.g., Meyer et al., 2013), whereas others leave it out (e.g. Khan et al., 2012). Based on this study, many scholars consider business to be outside the IoT concept, hence the business is built *on* the IoT, not *in* the IoT. However, the value offering should be identified to understand what kinds of services are needed to enable business.

IoT applications already exist for environmental monitoring systems, smart energy grids and multiple industrial automation systems (Tarkoma and Katasonov, 2011). As we are on the verge of having autonomous cars and even autonomous ships, various safety and security issues also need to be considered (Gubbi et al., 2013; Stankovic, 2014). It is assumed that their importance will only increase. Therefore, the focus on designing the IoT should also be converted from "bits and pieces" towards system-level service and security issues.

The ITU vision of "anytime, anywhere, by anyone and anything" remains valid. To achieve this, an IoT business should be sustainable. Services, data and security are cornerstones in accelerating the expansion of IoT utilisation. Consequently, IoT development must be value-based. In the future, we propose more research be conducted on how IoT systems are currently created and what kinds of benefits if any, are offered by a value-based development process.

Our research has shown that there is considerable ambiguity in the definition of IoT. In this paper, we have reviewed existing definitions and have developed a unifying framework to support the development of a comprehensive definition. One direction for future research is the development of a classification scheme for IoT with a controlled indexing language. The IoT classification scheme could consist of an index of terms for the identification of the different categories defined in our framework (and indeed extending it to new categories and subcategories). Such a scheme will limit the chances of ambiguity and help towards the development of a common language for IoT. This would be like other domain-specific classification schemes, for example, the 2012 *Association for Computer Machinery (ACM) Classification Scheme* (ACM, 2020). Other widely used and accepted, domain-specific classification schemes are the *American Institute of Physics' (AIP) Physics and Astronomy Classification Scheme* (AIP, 2020) and the *American Mathematical Society's 2000 Mathematics Subject Classification* (AMS, 2020). Barki et al. (1988, 1993) developed a classification scheme for Information Systems. Mustafee and Katsaliaki (2020) have also developed a classification scheme for Operations Research/Management Science (OR/MS), with the aim of recognising the considerable overlap of OR/MS tools and techniques with those used in disciplines like Industrial Engineering, Operations Management, Computer Science and Statistics.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.techfore.2022.121623.

APPENDIX 1

List of articles included in the start set.

Author	Title	Year
Alam et al.	IoT virtualisation: a survey of software definition & function virtualisation techniques for Internet of Things	2019
Asemani et al.	Understanding IoT platforms: towards a comprehensive definition and main characteristic description	2019
Atzori et al.	Siot: Giving a social structure to the Internet of Things	2011
Atzori et al.	Understanding the Internet of Things: definition, potentials, and societal role of a fast-evolving paradigm	2017
Ben-Daya et al.	Internet of things and supply chain management: a literature review	2019
Boyes et al.	The industrial Internet of Things (IIoT): An analysis framework	2018
De Leusse	Self-Managed Security Cell, a Security Model for the Internet of Things and Services	2009
Dorsemaine et al.	Internet of Things: a definition & taxonomy	2015
Duan et al.	A QoS architecture for IOT	2011
Fleisch	What is the Internet of Things? An Economic Perspective	2010
Floris & Atzori	Quality of Experience in the Multimedia Internet of Things: Definition and practical use-cases	2015
Jia et al.	IoT business models and extended technical requirements	2011
Ju et al.	Prototyping Business Models for IoT Service	2016
Kebane, Ray	A generic digital forensic investigation framework for Internet of Things (iot)	2016
Khan et al.	Future internet: The Internet of Things architecture, possible applications and key challenges	2012
Krco et al.	Designing IoT architecture(s): A European perspective	2014
Li & Xu	Research on business model of Internet of Things based on MOP	2013
Meddeb	Internet of Things standards: who stands out from the crowd?	2016
Mejtoft	Internet of Things and co-creation of value	2011
Meyer et al.	Internet of Things-aware process modelling: integrating IoT devices as business process resources	2013
Patel &Patel	Internet of Things-IOT: definition, characteristics, architecture, enabling technologies, application & future challenges	2016
Radanliev et al.	Definition of Internet of Things (IoT) Cyber Risk–Discussion on a Transformation Roadmap for Standardisation of Regulations, Risk Maturity, Strategy Design and Impact Assessment	2019
Rayes & Salam	Internet of Things (IoT) overview	2019
Stancovic	Research directions for the Internet of Things	2014
Thoma et al.	On iot-services: Survey, classification and enterprise integration	2012
Uckelman et al.	An architectural approach towards the future Internet of Things	2011
Weber & Boban	Security challenges of the Internet of Things	2016
Xu et al.	Ubiquitous data accessing method in IoT-based information system for emergency medical services	2014
Zhang et al.	IoT security: ongoing challenges and research opportunities	2014

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