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ORIGINAL RESEARCH

Review of the theory, principles, and design requirements of human-centric Internet of Things (IoT)

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Abstract

The rapid evolution of Internet of Things (IoT) technologies, with ever more profound implications for humans and societies, has triggered visions and initiatives to re-align the Next-Generation IoT with what works for humans and humanity first. However, despite the increased push towards "human-centric" IoT, it is still poorly understood what "human-centric" actually means in this context, how it is interpreted and embedded into the design, by whom, and for which purposes. To address these questions, we conducted a systematic literature review (N = 84) on the theory, principles, and design requirements of human-centric IoT. A key observation is that, despite the recent increase in research on humane perspectives for IoT, "human-centredness" often still seems to be used primarily as a label and overarching paradigm, not leading to a profound change in the underlying practices. We found no shared understanding of what "human-centric" implies in this context or common agreement on which principles human-centric IoT should be built upon. Furthermore, our analysis confirmed the predominance of technology-oriented fields, with a traditional approach towards user involvement and limited involvement of other disciplines. Overall, our findings point towards an apparent discrepancy between how contributions are positioned and framed ("human-centric"), the practices and assumptions they are based on, and their actual impact and ability to orient existing efforts towards genuine human-centric outcomes and key values. Based on the results, we formulate directions for future research aimed at building a more human-centric and empowering IoT.

Keywords Human-centric mechanisms · Internet of Things (IoT) · Empowerment · Agency · Socio-technical · Systematic review

1 Introduction

The Internet of Things (IoT) aims for the widespread diffusion of connected devices (sensors and actuators) that can interact with each other and cooperate to achieve a digital representation of the physical world with little human involvement (Atzori et al. 2010). IoT technologies are among the transformable technologies entering humans' physical world. They are becoming increasingly ubiquitous and intrusive, quickly penetrating every aspect of human lives: IoT sensors nestle themselves within us (i.e., body area networks and intrabody networks (Celik et al. 2021)), between us (i.e., social-internet-of-things (Atzori et al. 2012)), in our environment to realize smart environments (e.g., smart buildings and industrial IoT (Butun et al. 2020)). They also empower Intelligent Personal Assistants (IPAs) so that they may control and decide on human users' behalf, and continuously learn to act like us (i.e., supporting the realization of the human Digital Twins — DT). As a result, IoT technologies bring extraordinary promises and possibilities. However, they may also introduce significant risks and have considerable implications, both at the individual and societal level. Along with the increasing developments in this field, there is also a growing need to understand the nature, effect, and impact of IoT technologies. This should not just happen from a technological perspective but also concerning existing socio-technical systems and IoT technologies' capacity

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to support key human values, and collective ability to solve humanity's problems and thrive (Sawyer and Jarrahi 2014).

In this article, we understand human-centric IoT as an approach that can meet the needs of communities served by IoT technology and that helps to find out what technically works best for humans and society first and foremost. To date, IoT-related human-centered design has predominantly had a technical approach, concentrating for example on *adding computing to everyday objects*, *managing connectivity issues for things with dissimilar constraints*, technology that allows *things being able to communicate to each other*, and understanding how data can affect *people's sense-making of things* (Koreshoff et al. 2013a). Traditionally, IoT systems have lacked appropriate approaches for managing human-centric usability engineering, with many unresolved research questions touching upon multiple disciplines (Nunes et al. 2015). For instance, issues such as how people could interact with automated and Internet-connected technical systems, how they support empowerment, and how human agency is configured remain largely unaddressed (Wagner 2019).

While human aspects are to a certain extent taken into account, the technology's capabilities are limited in profoundly reflecting human values, needs and behaviors, ensuring that human judgment and discretion naturally flow into the system requirements (Wagner 2019). IoT implies a delegation of actions and decisions by human beings to objects, where the system does not ask but "adapts" to humans and the environment. Humans are therefore not represented as autonomous agents, with minds of their own, or as a particular kind of psychology with different susceptibilities (Pereira et al. 2013). Instead, current IoT network infrastructures consist of distributed devices communicating with each other, sometimes on behalf of humans, inside a connected physical environment. The pervasive network's logic aims to fit the human to the perceived or observed intelligent environment, not the other way around (Ystgaard and De Moor 2021).

To delineate the potential implications of these developments, one should also consider market and policy forces. Next-Generation networks have been developed to accelerate technology innovation and uptake, primarily to drive commercial and technological advantages for nations, corporations, and society (Huigen and Cave 2008). At the same time, however, the dominance and self-regulation of digital corporates have led to a context in which global actors are dictating the terms for the digital infrastructure, technology, and economy, towards a pervasive surveillance-society, propelled forward by platform and surveillance capitalism (Cammaerts and Mansell 2020). Other critical scholars have problematized that the logic that commands the technology development is based on economic and technology incentives to achieve an even more pervasive and intelligent IoT network (Zuboff 2019). IoT devices often dictate how users interact with their personal data. Once the IoT network is intelligent, it can learn, predict, and modify human behavior, using algorithms trained to manipulate for commercial gain. The danger presents itself as citizens' facing a complete loss of privacy and autonomy essential for participation in a democracy, along with unjust algorithmic discrimination exacerbating inequalities and operating for others' ends (Castells 2009).

In this regard, legal frameworks such as the General Data Regulation Protection (GDPR) (The European Parliament and the Council of the European Union 2016) and very recent initiatives towards a European Data Act (European Commission 2022) aim to ensure privacy protection, fairness, and compliance with ethical imperatives in the sharing and use of different types of data. However, they have important limitations, such as not being available worldwide. For instance, in the case of GDPR, it represents risks and tensions between conflicting interests (Padden and Ajehag Pettersson 2021), and such frameworks have also been criticized for unclear responsibilities in more complex scenarios (Wong 2021) and for offering limited protection in other cases (Royakkers et al. 2018).

At the same time, researchers in the fields of Human-Computer Interaction (HCI), privacy legislation, digital ethics, and humanized computing are calling for new technological infrastructures that support free and democratic societies and that have the technical ability to empower people (Hasselbalch 2021; Kazim and Koshiyama 2021). There is a need for insights and increased efforts to build a genuinely human-centric IoT, where restoring trust in the infrastructure is essential. Furthermore, underlying systemic issues in the existing infrastructure need to be solved, with various interventions targeted across all layers of the Internet technology stack (Bego and Brynskov 2020).

To effectively shape a human-centric IoT that establishes human potential in a societal and ethical way, we argue in this paper that the scientific community, engineers, and designers must first develop a shared understanding of what human-centredness conceptually translates to from a socio-technical perspective. Then, a shared framework is necessary to adjust the appropriate principles, requirements, and technical implementations in IoT. Scientifically, the understanding of the socio-technical embedding of IoT systems is still limited to date — for instance, the impacts they may have, and the effects society has on them, and their operation, among others. Yet, the importance of identifying and investigating socio-technical gaps ahead of the technology design is strongly emphasized in the literature (Mumford and Weir 1979). In addition, there is a need to re-discuss how IoT systems may help realize higher-level policy goals and challenges and avoid undesired consequences and implications.

We argue that a literature review is needed to understand the current scope of how human-centered design in IoT is addressed (conceptual definitions, methods, techniques, proposed solutions) and to create a roadmap for future research directions aligned with humanity-centered policy goals.

The following research questions guide our work:

- Which disciplines and types of expertise are involved in research on human-centric approaches in IoT?
- What are the principal underlying theories and conceptual definitions for human-centered design, and how are they interpreted in the context of the Internet of Things and sensor network technologies?
- In which ways and to which extent is human-centredness operationalized and embedded in the design, method, and implementation of Internet of Things technologies?
- What gaps should be addressed and prioritized in future research?

This research represents one of the first attempts to bring structure and clarity in the emerging work towards user/human-centredness in an IoT context. To this end, it adopts a socio-technical and critical perspective. There are to date no other systematic reviews that have investigated human-centric design theory, principles, and requirements of IoT. The most similar reviews have focused on specific user-centric issues in Internet of Things, such as privacy (Kounoudes and Kapitsaki 2020), human-in-the-loop (Nunes et al. 2015), and security requirements (Sicari et al. 2015; Rao and Deebak 2022), without widening the design perspective towards incorporating human and social values, human involvement, and impact on human and society (Atzori et al. 2010; Koreshoff et al. 2013b). In this work, we therefore undertook a systematic literature review of the human-centric Internet of Things to capture its breadth across multi-disciplinary databases and academic literature. Further, this review aims to bridge the divide between human-centric/humanity-centered theory and practice in the study of IoT networking.

The remainder of this paper is organized as follows: Sect. 2 introduces key elements of human and humanity-centred design and points to key socio-technical design aspects to be considered in the context of human-centric IoT. Section 3 presents the methodological approach that was adopted to conduct the systematic review, building upon the introduced elements from Sect. 2. Next, the main findings are presented in Sect. 4 and further discussed in Sect. 5. Finally, implications of this work for future research and overall conclusions are shared in Sect. 6.

2 Background

To achieve a model of Next-Generation Internet of Things that is truly human- and humanity-centered, one must consider a complex interplay between technology, humans, and the environmental context (Soegaard and Dam 2012). The assumed decline in trust towards digital technologies also in relation to Internet of Things technologies, due to algorithmic discrimination, inequality, and exploitative design practices represents an additional complexity in this respect. It has been argued that this decline continues to grow, despite initiatives worldwide in increased regulation on user and data privacy (Voas et al. 2018). The IoT paradigm can greatly benefit from boosting the involvement and diversity of human beings in the development of optimized services powered by technology, and hence minimize reluctance (Kim et al. 2017).

Therefore, design approaches that focus on the human and user concern primarily, such as humanity/human-centred approaches, are highly relevant and extremely important in the context of the forthcoming intelligent network environments (Stephanidis et al. 2019). To achieve this, this papers' research design focus was on the design structure, practice, and link to the technical contribution. Hence, this section briefly introduces key principles underlying human- and humanity-centered design. Further, it zooms in on a set of aspects to consider in the IoT context, which informed the framework underlying the conducted systematic literature review (see Sect. 3).

2.1 Human- and humanity-centred design

Traditional human-centered approaches in HCI and IoT focus on the system's usability, where the design problem is informed by the various participants' practices, as opposed to addressing a specific technical problem to an information-processing solution. The term "human-centered" rather than "user-centered" refers to the technology impact on a broader group of participants instead of those typically considered users, so that designers can develop a more humanized view of their responsibilities to the people they design for (International Standard 2010). The humanized approach applies a holistic framework that understands what is valued by a system's stakeholders and that is supporting them in delivering this value (Cockton 2004). The underlying principles for a *humanity-centered* experience can be summarized as (Wright and McCarthy 2010; Graeff 2018; International Standard 2010):

- Protection of human potential and humanity first, rather than exploiting vulnerabilities.
- Valuing the person behind "the user".
- Viewing the designer and human user as co-producers of experience (resulting in active human involvement).
- Viewing the human user as a part of a network of social (i.e., the self-interacting with connected environments) through which experience is co-constructed (resulting in

the appropriate allocation of function between between humans and the technological environment).
- Viewing the person as an acting, self-directed agent with the ability to imagine possibilities and make creative choices.

These principles align with the European declaration of digital rights, which put people and their rights at the center of digital transformation (The European Parliament 2022). The application of humanity-centered design principles tries to accommodate the needs of communities served by technology to find what technically works best for humans and society (Shneiderman 2020). It has important implications in terms of who should be involved in the design process, how, when, and on which grounds.

2.2 Human-centric approaches in IoT

Moving to a broader networking and IoT context, human-centered technology approaches are traditionally grounded in the interests and needs of the individual user, aiming to make products easy to use and understandable (Koreshoff et al. 2013a) and enabling smooth user experiences. This understanding is rooted in HCI developments in the area of IoT during the period 2012-2014, where users increasingly were included and considered (Chin et al. 2019). One of the related concepts originating from the Telecommunications domain that has been introduced in the literature in this respect is *Quality of Experience* (QoE) (Raake and Egger 2014). The existing network infrastructure aims for optimal technological performance and good *Quality of Service* (service perspective), as well as a high *Quality of Experience* (QoE) and perceived quality (user perspective). QoE metrics should ensure that the system meets users' expectations in any given context or situation (user perspective) and thus allows them to use services and applications easily and according to their needs and preferences (Suryanegara et al. 2019). However, the role of users in this view is still predominantly passive (for a detailed analysis, see (Wechsung and De Moor 2014)).

From the technical point of view, a human-centric IoT design is intended as the process that considers the requirements from the users' point of view in terms of needed functionalities, interaction modalities, and which sensors to adopt to monitor the user status (Koreshoff et al. 2013a). In this respect, the interaction between IoT technologies and humans is, at the bare minimum, designed to be trustworthy, secure, and deliver a consistent network performance (Kounelis et al. 2014). The introduction of the use of machine learning and big data analytics in IoT, during 2015-2017, spearheaded personalization as a way to adapt to specific and dynamic user needs, often referred to as a human-centric mechanism (Konstan and Riedl 2012; Chin et al. 2019). Personalized IoT services build the user's profile and monitor the varying context to adapt the system accordingly (Perera et al. 2013). In other cases, still from the machine learning and big data point-of-view, human-centric IoT refers to a connected network of sensors, objects, and machines with more "human-like" capacities and behaviors. This human-centric view is achieved by applying mathematical and algorithmic modeling to explain, replicate, or replace human action (Chin et al. 2019).

However, given the recent technological developments in the IoT domain and as illustrated in Sect. 1, one can argue that the original interpretations of human-centered design in an IoT context have important limitations and have become outdated. More worryingly, there are a range of human, societal and ethical implications that need to be systematically and profoundly considered due to the ubiquity and enhanced intelligent characteristics of the IoT domain (Bannon 2011). Based on similar developments, human-centered approaches in machine learning have begun to rethink how human-centric goals, context, and practises can make machine learning technologies work better for humans and society primarily (Ramos et al. 2010).

As such, future developments in HCI and intelligent environments identify the need to cater for meaningful human control, human safety, and ethics, in support of human health and well-being, learning and creativity, and social organization and democracy (Stephanidis et al. 2019). When approached from a socio-technical perspective, human-centered research in IoT should incorporate human involvement via methods used during the system technology design process (Breve et al. 2021; Ghiani et al. 2017). Individuals or a group of human stakeholders must have a voice through participation in order to balance requirements between various stakeholders' intention (situated rationality), the dynamic qualities of human activities, an understanding of the contextual environment, and the technical approach of rule-based, codified procedures managed by technical measures and performance indicators (Sawyer and Jarrahi 2014; Gasson 2003; Shin and Park 2017). Achieving this successfully is exemplified in the study presented by Karni et al. (2022), where they build a partnership with the human users and communities that are directly impacted by the technology. In this case, the design targets patient empowerment, based on the identification of clinically meaningful targets for modification instead of a pure technology-driven selection of measurement end points. Therefore, a key question — and part of our focus — is to what extent these aspects and considerations are already embedded in existing practices, and whether there are human-centric technical contributions in IoT that follow a common methodological framework.

2.3 Socio-technical design considerations in IoT

The complexity of building networked systems at the global scale that works and can deliver value to humans, an updated Internet, without amplifying inequities and jeopardizing human rights, introduces a range of design considerations (Giaccardi and Redström 2020). With the propagation of Cyber-Physical-Systems and IoT into every aspect of humans' everyday life and societal systems, the significance of socio-technical design dimensions in IoT increases (Streitz et al. 2019): design aspects, such as theoretical approaches, expertise, method for involvement, and technical translation, impact the development of a humanity-centered IoT. We argue in this work that they need to be acknowledged and better understood in order to identify blind spots and to reorient current practices and processes in such a way that key issues can be addressed. As a result, the above design aspects are relevant to consider in the analyses presented in this paper.

2.3.1 Design theories and approaches

Prior research on the role of human-centered approaches in IoT argued that there is a gap between human-centered design frameworks and technology design frameworks in IoT (Koreshoff et al. 2013a) and that a more profound focus on human-centered concerns is needed. To achieve this, the definition of the human role in IoT needs to be clear and incorporate human involvement in the design. To clarify the role humans play in IoT, a shared understanding of human-centredness can contribute to increased trust and collaboration between engineers, human users, communities, private industry, and governmental actors (Kounelis et al. 2014). However, to achieve a shared understanding, bridging the world of telecommunication, informatics, electronics, and social science requires additional effort (Atzori et al. 2010).

Previous attempts to establish a human-centered theoretical approach include Koreshoff et al. (2013a)'s design framework. Koreshoff et al. (2013a) presented a tool for an HCI audience to think through the design of IoT technologies that consider *things* as "the type of information it would produce" and how people would make sense of it. Koreshoff et al. (2013a)'s design tool considers co-design and "build with, not for" methodologies as a way to achieve human-centric technology solutions. However, this design framework is still predominately technical. It does not address deeper human-centered issues, such as social justice, human empowerment, and equality for all, where priorities and needs address the protection of user rights, also on a societal and community level (Koreshoff et al. 2013a). Accordingly, mapping the use of design frameworks and tools that account for socio-technical and human requirements in the research of human-centric IoT can help unravel more profound human-centered practices and challenges (Hochheiser and Lazar 2007).

As an illustration, human-centered, socio-technical design approaches in medical IoT is particularly important when developing Internet of Things (IoT) systems. Human-centric medical IoT offers opportunities to build safe environments for patients and caregivers to provide them with human autonomy and well-being (Tiersen et al. 2021). However, these systems also represent threats with a potentially significant impact on disadvantaged communities. For instance, ethical and social risks are substantial barriers to more widespread adoption of intelligent assistive technologies (IATs) serving people with dementia. Concerns about preserving autonomy are the greatest in the literature, along with issues surrounding beneficence, justice, independence, and privacy (Ienca et al. 2018).

2.3.2 Team composition, design mindset, and practices

The decisions that underpin IoT development have primarily been driven by experts with technical interest and competencies, also those relating to the human-centered perspective (Cherry et al. 2017; Sovacool and Del Rio 2020). When the expert-handled network technology and services no longer simply deliver connectivity to devices, but actively shape humans' daily experiences, also in their physical environments, a partnership with research communities that deal with human psychology, humanities, and social science is *crucial* (Calvo and Peters 2014). Furthermore, technology is never neutral, and the built-in intelligence is neither (Miller 2021). Therefore, the scientists, engineers, and designers' design mindset and associate practices are highly relevant when addressing the challenge of creating a human-centric IoT that responds to humans' fundamental needs with the aim for empowerment and inclusion.

The design mindset here refers to distinguishing between an expert mindset and a participatory mindset. When an expert mindset is applied, humans are referred to as *users*, *nodes*, or *subjects*, with no or little direct involvement in decision-making (Stead et al. 2019). Such a mindset is traditionally more associated with technology-oriented disciplines. However, with a participatory mindset, the designer and users operate as co-producers of the design, resulting in active human participation (Schneider et al. 2018).

Furthermore, interdisciplinary fields and research traditions, such as Human-Computer Interaction, science and technology studies, digital ethics, and digital humanities, have a long history of examining the development, use, and impact of technology on humans, society, and the environment, in their social, cultural, and historical context (Fuller 2009). Perspectives from various academic disciplines are better equipped to apply holistic theoretical frameworks, methodologies, factors, and techniques. As a result, diverse perspectives allow for creating a ubiquitously connected reality where human well-being, positive social impact, and sustainability thrive (Calvo and Peters 2014).

2.3.3 Policy goals and underlying value systems

What the envisioned Next-Generation IoT will look like will depend on various factors, e.g., what is promoted by policymakers and industry, as well as designers' value systems, aims, principles, and technical tools (Cockton 2004). In this respect, from a policy point of view, different countries and regions have suggested distinct and not necessarily compatible value systems and governance approaches (Lee 2021).

While the European Union has explicitly presented a vision, the Next-Generation-Internet initiative, where *"Human-centredness is key for a human and sustainable development of IoT"* (Brynskov et al. 2019), the United States of America (USA) have historically put forward policy rationales with an emphasis on minimal regulation in technological innovation and development. The recent US policy focus, however, introduces regulatory measures at the State level that protect consumers and citizens from harms associated with undermining public values (Jørgensen and Desai 2017). China has strategically adopted a top-down industry policy to IoT, with sustained financial investments, that influence the international technical standards of next-generation network technology (Lee 2021). For example, the Supreme Court of the People's Republic of China has become a relevant player in enforcing constraints and influencing the level of privacy in IoT, as in the example of new legislation restricting the use of face recognition technology (Qin 2021). Given the growing interest in strategically and politically exerting the national state's influence, one of the major challenges is to reach agreements on norms, governance, and operational goals, between the different state systems (Choucri 2012). As a result, the geographical dimension of human-centric approaches in IoT is also relevant to consider in this work.

2.3.4 Intended design outcomes

Naturally, policy perspectives strongly relate to the underlying intended outcomes and visions. Being human-centered also means being aware of the intended and the potentially unintended outcomes and the associated consequences of technology design. There is an increasing realization that design goals that are focused on profit, performance, and efficiency determine satisfactory results for engineers, designers, and employers. However, these goals can have harmful outcomes for human users, communities, or society as a whole (Cammaerts and Mansell 2020).

For a free, democratic society to function, the human user needs protection from harmful outcomes, which in the world of ubiquitous and intelligent sensor networks translates into an unwavering commitment to the privacy protection of human users (Zuboff 2019; Cheryl et al. 2021). Most often, this is technically translated into the protection of users' privacy and their data (Kounoudes and Kapitsaki 2020). However, the most effective safeguarding mechanism would be to integrate human-rights protection into the internet infrastructure, where user agency is achieved by technical design (Wagner 2019). More recently, however, the focus on human-centric IoT technology is increasingly geared towards and understood as maximizing human well-being and positive social impact (Calvo and Peters 2014). To account for both positive and negative outcomes, IoT technology should be designed to serve and protect public goals and values at a holistic level. To address the design logic holistically, there are trade-offs that need to be considered; a) between human control and automation and b) between privacy and intelligence (Streitz 2021). In this context, human-empowering IoT design outcomes are increasingly targeted and focus on non-instrumental goals such as protecting human privacy (Mähler 2019; Kounoudes and Kapitsaki 2020), agency (Wagner 2019; Cruickshank and Trivedi 2017a), empowerment (Royakkers et al. 2018; Streitz 2019), user control (Stephanidis et al. 2019; Nunes et al. 2015), but also trustworthiness (Hesselman et al. 2020; Kounelis et al. 2014) and civic aspirations (Graeff 2018; Winter 2015) related to the Next Generation IoT (Brynskov et al. 2019).

To achieve a genuinely human-centric IoT, the EU has prioritized three research and innovation areas: (1) privacy and safety (i.e., data protection), (2) humans and citizens, and (3) security (including cyber-security). In this respect, the policy challenges of ensuring privacy and security (including the protection of personal data); opposing disinformation online; guaranteeing access and freedom of choice for humans and citizens; respecting fundamental human rights and empowerment, personalized and enhanced support to increase well-being, and enforcing ethics and sustainability by design are explicitly highlighted by the EU's Next-Generation-Internet initiative (Brynskov et al. 2019).

2.3.5 Technical mechanisms for human-centric IoT

Combining the practical aspects of engineering with the human and social concerns to influence the design (e.g., intended outcomes as exemplified above) requires a translation and operationalization into technical requirements and mechanisms that work in practice and can be evaluated and validated. However, issues such as reliable IoT systems are not simply technical features that are objective or neutral. Instead, they are inherently socio-technical artifacts, produced in and through the actions of people and systems in the course of the working day (Oudshoorn and Pinch 2003; Shin and Park 2017) and implicitly or explicitly based on their assumptions and underlying value system. This raises the question of how exactly one can achieve human-centered IoT technically.

The technical translation of human-centered machine learning and artificial intelligence, include three solution areas: 1) Privacy and data ownership; 2) Transparency and accountability; 3) Fairness in AI-driven decision-making processes (Lepri et al. 2021). Similarly, human-centered technical solutions developed so far in the IoT domain are about making transparent, with or without automated decision support, the right next step for human users (Royakkers et al. 2018). However, the degree of involvement and control exercised by actual human users, who are involved and thereby represented in the design, may vary significantly. The goal of finding the correct technical translation combined with the suitable degree of human involvement, meets several challenges when entering a territory of system design according to human value frames, means, and ends (Bannon 2011). Mechanisms that allow for safeguarding humans' own individual objectives keep humans actively involved (Wagner 2019). The system includes human input in the process, method, technique, or solution (Adamo 2019). In this regard, interfaces that let humans observe and interact with the IoT system are used to provide transparency, understandability and accountability features to help humans interact with persuasive IoT technology (Turunen et al. 2015; Stephanidis et al. 2019). These include mechanisms that maintain "veillance" about the connected world, or "quantified selves", and that help mediate between humans and machines (Van Kranenburg and Bassi 2012). Recent examples, such as augmented reality applications in IoT have the potential to deliver richer, more immersive and timely interventions that lead to effective support for human users (Scargill et al. 2022). AR interfaces use AR visualization for instance to contextualize data disclosure and to improve users' perceptions of threats (Bermejo et al. 2021).

In this context, the term *human-in-the-loop* has gained momentum as a mechanism to determine the allocation given to machines and humans. Human-in-the-loop mechanisms provide persons, society, or other stakeholders with the opportunity to control both of one's actions and, through them, of events in the external world (Stephanidis et al. 2019). Here, human permission is required to have the system carry out an action (Wagner 2019; Adamo 2019). However, it can be argued that other (existing) mechanisms are not designed to enable human self-control or serve deeper human-centric purposes but instead aim to find technical solutions that target the underlying communication infrastructure (Hesselman et al. 2020). These solutions are designed to defer to humans passively, for safety, correction, adjustment, input, or simply be switched off. Well-known examples are the essential building blocks, such as blockchain technologies, along with other cryptography techniques, that put events into public view, boosting transparency, reducing red tape, and the likelihood for errors. Most importantly, such mechanisms provide accountability by ensuring that the responsibilities of actions are immutable and identifiable (Kounelis et al. 2014). Other examples, technically integrate uncertainty, as opposed to hard-coded measurements, to allow for multiple and debatable scenarios and outcomes (Russell 2019).

To summarize, the shift towards human-centric IoT comes with grand visions and opportunities, as well as a set of considerations and challenges to address. The work presented in this paper and underlying search explained in detail in Sect. 3, builds upon the above considerations and concepts to improve our understanding of how human-centredness is currently interpreted and embedded in IoT, and the intended outcomes it is targeting or associated with and what mechanisms are being proposed to do so.

3 Methodology

To answer the research questions introduced in Sect. 1, we carried out a systematic literature review to synthesize peer-reviewed conference and journal publications on user/human-centric Internet of Things (IoT). We chose this methodology to identify a complete census of relevant literature and investigate how various approaches tie the human element closer to the design and function of Next-Generation Internet of Things. To conduct the systematic literature review, we followed the methodological framework proposed by Levy and Ellis (2006), a mixed-method systematic framework that is commonly applied in the field of computer and information science. The Levy and Ellis (2006) framework consist of three stages:

- Stage 1: Planning the input; involved identifying the appropriate body of literature to analyze via a rigorous and iterative process of defining the key terms and search string.
- Stage 2: Processing the input; conducting the review, included screening, article selection, review of relevant studies, extraction, and analyses of data.
- Stage 3: Analyses, reporting and disseminating; involved reporting and disseminating the output, where this article's development took place. In this section, we describe each of these stages.

3.1 Stage 1: planning the input

To explore the various interpretations of human-centredness in Internet of Things, and building upon introduced concepts and considerations introduced in Sects. 1 and 2, the studies referred to in this review were found through combinations of the search terms; “Internet of Things”, “IoT”, “next-generation internet”, and “sensor technology” combined with expressions of “human-centric”. Other variations of “human-centric”, which can be intertwined in the same meaning, are often expressed as user-centric, people-centric, value-centric, humane, or human-aware/user-aware.

The keyword search for the human-centric Internet of Things was framed using four topics from the related literature. The four topics were chosen to capture the relevant methodological frameworks and technical contributions that targeted human-empowering design goals and mechanisms. The final keywords were defined and further delineated based on an iterative process. Applying the four-part division in the search string overcame focusing on keywords specific to niche technologies. It captured the breadth of how human-centric is defined, conceptualized, and operationalized in network technologies. At the same time, the iterative process ahead of defining the final keywords ensured that disciplinary differences in the use of terms and concepts was accounted for and that more niche or novel terms considered relevant for the search were included (i.e., “citizen-centric” and “civic”). The keyword selections are explained in Table 1. Keywords included in the search string are presented in Fig. 1 (see appendix for full search syntax in Table 9).

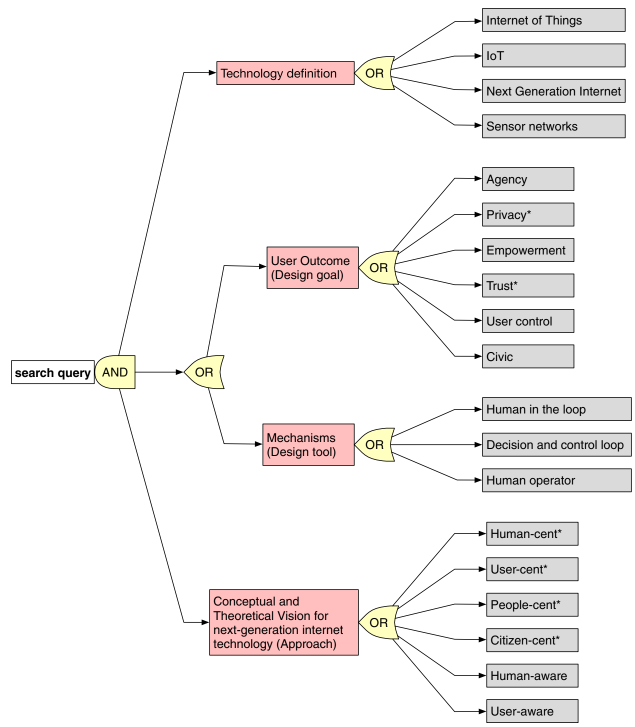


Fig. 1 Search query

3.2 Stage 2: processing the input

The scientific literature supporting this article was found in the digital libraries; Web of Science, Scopus, IEEE, and ACM Digital Library. The review expanded the search beyond the realm of information science to capture the large distribution of quality literature in a number of multi-disciplinary databases. To guarantee the quality of the inputs, we only considered peer-reviewed journal articles and conference proceedings published between 2010 and 2020. Furthermore, the search was originally limited to between 2010 to 2020 due to finding few articles focused on human-centered IoT earlier than 2010. Internet-of-things became more popular as a technology concept after 2010 (Kounoudes and Kapitsaki 2020). As part of the review process, the search was updated for the years 2021 and 2022, to include the most recent literature.

The different steps and phases in the selection process are visualized in Fig. 2. To ensure a complete census of relevant literature, we first conducted a keyword search, followed by backward searching, and finished with forward searching. The database searches were undertaken on September 9th and October 6th, 2020, while the backward/forward search was conducted on January 20th, 2021. The literature search measured the studies’ keywords, title, and the abstract categories. The total number of articles obtained following database searching and removing duplicates was 389. The screening was completed by reading the title, the abstract, and the keywords of each article. The article pool was reduced to 181 after a second duplicate removal (October 2020) and downloaded into Rayyan, a web-tool designed for the screening and selection processing of meta-analysis/

Table 1 Definitions of search terms

Search topic	Search terms	Description
Approach	User/human-centric	Approaches that bring the human element closer
Mechanism	Human in the loop	Mechanisms that involve humans in the operations
Outcome	User empowerment, trust, agency, privacy, civic, and control	Intended, actual and experienced user outcomes
Technology definition	Next-generation IoT	Wireless sensor network technology

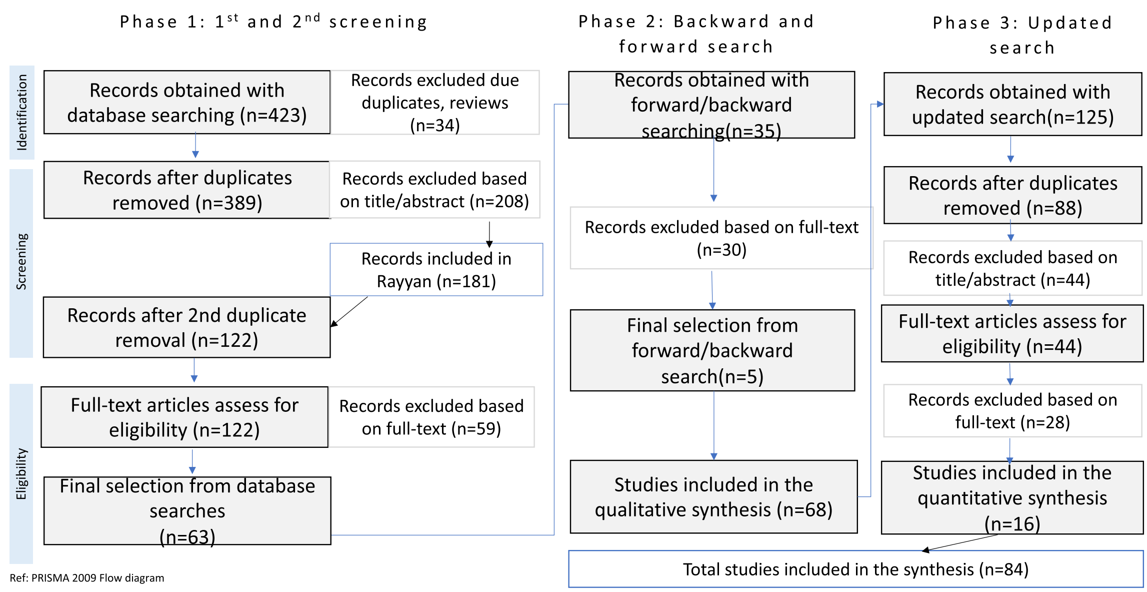


Fig. 2 Flow chart of the different steps in the selection process

review studies. Two reviewers screened the article pool for relevance based on the selection criteria. A third reviewer completed the screening for articles with selection disagreement. 122 articles were accepted for further screening of the full-text. One author applied the selection criteria to every paper, with another author verifying the decision of inclusion or exclusion.

After reading the full version of every article, a significant number of articles were excluded because they did not directly consider user/humans' role in-depth or were demo papers with incomplete contributions. Instead, these sources dealt mainly with improving efficiency or performance-related aspects of a specific technical solution without explicitly discussing a link to use/users/user outcomes or only mentioning "human-centredness" as a buzzword.

The final selection from database searches resulted in a list of 63 papers. In addition, a backward and forward search process complemented the article pool (January 2020), searching for articles that either used the selected articles as a reference or were referenced by them (Levy and Ellis 2006). From the backward and forward search, we obtained 35 additional articles, and these were screened with the selected criteria, ending up with an addition of 5 articles. A total of 68 studies were included in the qualitative synthesis.

An updated database search was completed on July 13th, 2022. Still, the search strategy and scope was considered relevant, and remained unchanged. After running the updated search for the years 2021 and 2022, a total number of 125 articles was obtained. When duplicates were removed, a total of 88 articles were selected for screening based on pre-existing selection guidelines (inclusion and exclusion criteria), where one author screened first title, keywords and abstract, then two authors screened full-text versions, resulting in an addition of 16 new articles. These articles were integrated into the quantitative analyses, ending up with a total of 84 articles in the updated dataset.

3.3 Stage 3: analyses, reporting and disseminating

This process aimed to gain an overview of the existing knowledge of human-centric approaches in the context of Internet of Things and sensor network technology. Each article was coded in Excel, using an analytical framework summarised in the themes: "general characteristics", "theory and definitions", "human involvement", "user outcomes and mechanisms", and "future research gaps". In addition, we used the statistical software program SPSS to investigate potential dependencies between key variables (e.g., discipline, approach, expertise).

4 Results

4.1 General characteristics

A summary of the reviewed approaches used in the current literature can be found in the Tables 10, 11, 12 and 13. These tables contain information about the origin of the study, the team discipline and perspective, level of involvement, the domain with examples of use, intended outcome, and a general description of the solution provided. As outlined in Table 2, we categorized the articles according to their general characteristics such as year, geographical origin, type of publication, academic discipline, and team expertise.

Figure 3 shows the frequency of articles per year and application domain. The majority of studies, 74.9 %, were published in the last 6 years (since 2017), which illustrates how research towards the human-centric side of IoT has increased in level of attention in recent years. Nearly a third, 28.6 %, of the included articles were coded as addressing a *generic IoT domain*, 27.4 % of the included articles were coded as addressing the application domain *Smart home*, closely followed by 26.2 % addressing the *Smart city* domain.

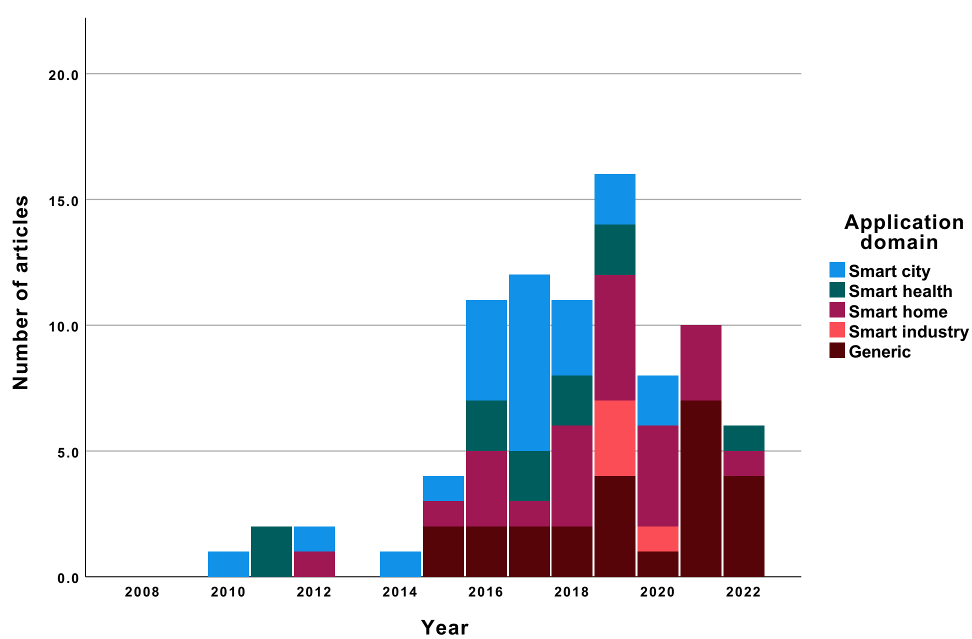
Geographical origin shows where the research team behind the article is located. 69.0 % of all included studies originated from Europe, while 31.0 % originated from the rest of the world. When only considering included papers from 2016 (i.e., the year that GDPR came into force) onwards, 70.3 % originated from Europe. Around 60 % of the publications were sourced from conference proceedings, where the most common venues were from *IEEE* and *ACM*. A smaller proportion originated from domain-specific venues such as *SECITC (Security for Information Technology and Communications*, *HAS (Human Aspects of Information Security, Privacy and Trust)* and *ICOST (Smart Homes and Health Telematics)*. Among the journals, most originated from technology-oriented publications; *Ambient Intelligence and Humanized Computing*, *IEEE Communications*, and *Pervasive and mobile computing*. Fewer originated from journals in other fields, some examples; *Digital policy, Regulation and Government*, and *The Design journal*.

The subject matter that the authors specialized in was coded as *Academic discipline*. The discipline was inferred based on the authors' affiliation. We looked at the academic teams' expertise in terms of being a research unit from one academic discipline or a research team with a variety of experts and thus a more multi-disciplinary composition. Of the studies reviewed, 64.3 % of the literature was produced by single-discipline teams. A statistical analysis using the Pearson Chi-square test showed that single-discipline teams in our sample are more likely to stem from technology-oriented fields ($\chi^2(1)= 17.850$, $p < .001$). More specifically,

Table 2 General characteristics

Characteristics	Category (percent)
Year	2016 – 2022 (88.1%), 2010 – 2015 (11.9%)
Geography	Europe (69.0 %), North-America (16.7 %), Asia and Middle East (11.9 %), Australia (2.4 %)
Publication type	Conference proceedings (60.7 %), Journals (39.3 %)
Discipline	Technology (81.0%), Social science (11.9 %), Humanities (7.1 %)
Expertise	Single (64.3 %), Multi-discipline (35.7 %)
Mindset	Expert (53.6 %), Participatory 47.3 %
Applic. Domain	Smart city (26.2 %), Smart home (27.4 %), Generic (28.6 %), Smart health (13.1 %), Smart industry (4.8 %)

Fig. 3 Overview of included articles by year and application domain



they primarily consist of researchers with an expertise in engineering, computer science, and informatics. Correspondingly, 35.7 % of the articles come from teams with academic multi-disciplinary knowledge. On the whole, three-quarters of the selected literature stemmed from technology fields, while 14.7 % originated from authors from social science and 8.8 % from humanities. The articles classified as social science included sociology, psychology, and media/communication, while those classified as humanities were from art, law, and philosophy. In terms of mindset (as defined in Sect. 2), a participatory mindset was — as expected — over-represented among contributions stemming from humanities and social science and less common in papers arising from technology-oriented fields, while the opposite holds for an expert mindset ($\chi^2(1)= 7.067$, $p < .05$).

4.2 Theoretical foundations and conceptual definitions

We extracted and analyzed the human-centric theoretical concepts and conceptual definitions from the included studies. The theoretical concepts were found by looking for an explicitly stated system of ideas that explained how the human-centered design worked and which theoretical assumptions it was based on. We also extracted the explicitly stated definition conceptualized for human-centric in an IoT context (see Table 3).

The theoretical concepts naturally fit into overarching perspectives; a *human-centric computing*, a *human-centred or user-centred design*, a *system thinking design*, and a *human–machine interaction* perspective. The human-centric computing perspective represents 51.2 % of the literature. This perspective treats the design primarily as an information and technical design problem, where computing resources are enhanced with technical capabilities extracted from human resources, represented as sensors, devices, data points, or algorithms (Conti and Passarella 2018; Nasir et al. 2012; Valenzuela-Valdes et al. 2017). Then, 35.7 % of the article pool comprises theoretical concepts from human or user-centered design traditions. Here, the design problem is primarily treated as a socio-technical, human, or user relation, ensuring that boundaries between the user, human and social requirements, and technical requirements are balanced. A smaller group of articles, 6.0 %, treat systemic or materialist theories as foundational design principles instead of human and social. Finally, 7.1 % of the articles are in the realm of the human–machine interaction technologies where humans are an integral part of the system/tool/technology that facilitate mediation for/with/or on behalf of humans, as a service, control, or feedback mechanism/tool (Kong et al. 2019; Dustdar and Scekic 2018; Sen et al. 2019; Adamo 2019).

Within the human-centric computing perspective, most of the conceptual definitions of human-centredness focus on describing components or technical resources of IoT using human, social or ethical labelling; examples include *Social-internet-of-things*, *Trusted IoT*, *Internet-of-people*, *user-aware IoT* or *social-aware IoT*. A large group of articles defined *user-centric* as enabling users with tools to protect their data and security. To illustrate, Nawaz et al. (2016) say; "*Incorporating user-centricity in ubiquitous IoT systems, is defined as security (integrity and confidentiality of the recorded image data), and privacy protection (altering the image to make it less recognizable)*".

The human/user-centered design perspective conceptually defines human-centredness in IoT as a *socio-technical or user-friendly system* (Chibaudel et al. 2018; Shin and Park 2017; Worthy et al. 2016; Feth et al. 2017; Kor et al. 2016). A set of articles included here defines human-centredness using more civic and holistic concepts; *Ethical and human-centred* (Winter 2015; Grundy 2020); *value-driven, human-centric collaborative system* (Dustdar and Scekic 2018). Here, human-centric IoT technologies support the cooperation between humans and smart devices for the public good. For example, Dustdar and Scekic (2018) state that the fundamental principle for human-centered design in IoT is an architecture of values that supports humans in performing their cognitive, creative, collective, and social activities.

4.3 Outcomes and mechanisms

Next, we captured the intended design outcomes as indicated in the included articles and mapped them to the related policy challenges explicitly specified by the EU, as addressed in Sect. 2.

In Table 4, the intended design outcomes were ranked according to the number of mentions and grouped according to related policy challenges. The first challenge is the most commonly addressed, with 36 % of the literature looking to guarantee security and privacy (i.e., data protection), describing the intended human-centric design outcomes in terms of security, privacy, and user control. The second group of authors, 20 % of the literature, addressed the challenge of developing personalized, mediated technology to enable ease of use and quality of life/experience. Third, 15 % of the literature addresses the challenge of "guaranteeing universal access", primarily for the intended design outcomes of transparency and cooperation. Finally, 14 % directed towards incorporating ethics and sustainability principles into the system, with outcomes such as civic participation and human agency, as well as 14 % respecting fundamental rights aiming to help achieve human empowerment.

Table 3 Human-centered perspectives in IoT: Theoretical and conceptual definitions

Perspective	Theoretical concepts	Conceptual definitions
Human-centred design (HCD)	HCD methodology (AMICAS)	Social-technical IoT systems (Chibaudel et al. 2018)
	Social-technical ensemble (Bijker 1993)	Social-technical factors (Shin and Park 2017)
		Concerns, values, contexts (Worthy et al. 2016)
	Democratic and civic participation	Ethical and human-centred internet systems (Winter 2015; Grundy 2020)
	Citizen participation/empowerment	Value-driven, human-centric, collaborative systems (Dustdar and Scekic 2018)
	Digital ethics	Ethical smart built environments (Gracanin et al. 2019)
User-centred design (UCD)	UCD methodology (Norman's principles)	Usable IoT systems (Kor et al. 2016; Feth et al. 2017; Karni et al. 2022)
	Participatory design	End-user development-enabled IoT (Ghiani et al. 2017; Breve et al. 2021)
		User inclusive IoT (Moreno-Cano et al. 2015)
		Human-centric software development (Sylla et al. 2019; Grundy 2020)
	Meaning through experience	'Domestic practises' of IoT (Kwon et al. 2018)
	Self-determination theory	Design-science based Cyber-Physical-System (Oppl and Stary 2022)
Systemic/ Ecological design	Object Oriented Ontology	Materialist design framing (Cruickshank and Trivedi 2017a, b; Lindley et al. 2018)
Phenomenology	Biomimicry	Symbiotic development strategies (Semeria 2016)
	Need-oriented design paradigm	User perceptions to balance agency (Jia et al. 2012)
User/human-centric embedded technology	Privacy-by-design (GDPR)	User-centred architecture (Beltran et al. 2017; Toumia et al. 2020)
		User-oriented data dissemination and distribution (Hashemi et al. 2016)
		People-centric IoT (Rivadeneira et al. 2021)
		Human-centric privacy engineering (Barhamgi et al. 2018; Aljeraisy et al. 2021)
		Human-centric mechatronics (Watt et al. 2016)
	Ubiquitous computing/Ami	Humane, sociable
		cooperative smart hybrid cities (Streitz 2017, 2021)
	Social network structure	Social Internet of things (sIoT) (Defiebre and Germanakos 2019)
		Inclusive Citizen-centric IoT (Moreno et al. 2014)
	Internet-of-people	Human-centric CPS (Garcia-Alonso et al. 2018)
	Universal design	Trusted IoT (Schulz 2014; Banerjee et al. 2019; Bati and Singh 2018)
	Human-centric sensing	People-centric IoT (Wearable IoT) (Valenzuela-Valdes et al. 2017)
	Participatory sensing	User-centric aware IoT (Moreno-Cano et al. 2015)
		Human-centric urban sensing system (Nasir et al. 2012)
	Cybermatics	Thinking-aware and social aware IoT (Dhelim et al. 2018)
	Security reference architecture (ARM)	User-centric IoT (Martinez et al. 2017)
		User-centric access control (Beltran et al. 2017)
	Open platform (SANE)	Citizen-centric smart city platform (Bornholdt et al. 2019)

Table 3 (continued)

Perspective	Theoretical concepts	Conceptual definitions
Human–machine interaction design	Human potential/Human-in-The-Loop	Industrial Wearable System (IWS) (Kong et al. 2019)
	Evolutionary algorithms/HiTL	User-centric IoT service-provisioning (Sen et al. 2019)
	Human emotion signal processing	Human-in-the-Loop Cyber-Physical System (Figueira et al. 2016)
	People-in-the-loop	Cyber-Physical-Human System (CPHS) (Dustdar and Scekic 2018)
		Cyber-Physical-Social Systems (CPSS)
	Social Contract Theory/HiTL	Society-in-the-loop (Adamo 2019)

All the papers analyzed, had addressed one or more of the outcomes outlined in Table 4.

Table 5 lists the key technical contributions of most of the proposed human-centered IoT solutions and the corresponding major intended outcomes. The table also highlights the approaches that are most often adopted. Very frequently, the focus is a new *Design framework* that is intended as a set of principles and procedures to be followed in the design phase. Very often, the human-in-the-loop approach is adopted which considers the human as an active player in the IoT framework. The social IoT model is also a major approach in this context, which gives the objects the capabilities to

Table 4 Mapping of policy goals to human-centric design outcomes

Policy goal	Intended outcome	Share (%)
Guarantee security and privacy	Security, Privacy, Control	36
Personalized, mediated technology	Ease of use, Quality of life, Trust	20
Guarantee universal access	Transparency, Cooperation	15
Ethics and sustainability by design	Civic, Agency (situated meaning)	14
Respect fundamental rights	Empowerment, Agency (decision power)	14

Table 5 Major technical contributions of technical proposals of human-centered solutions (note that some works have been associated to more than one contribution)

Technical contribution	Major outcomes	Share (%)	Adopted approaches
Design framework	Privacy, Security, Control, Empowerment,Trust, Cooperation	47	User/human-in-the-loop
			Social IoT
			Participatory model
			Game theoretic model
			Privacy laws
Architecture	Privacy, Security, Control, Trust	27	Privacy-by-design
			Blockchain and smart contracts
			Distributed architecture
			Human-object collaboration
			Digital twin
User interface	Privacy, Empowerment, Trust, Ease of use, Control	33	Game theoretic model
			Personal assistant
			Incentives for user collaboration
			Emotion modelling
			Transparency
User monitoring	Privacy, Security, Civic, Trust, Easy of use	9	User modelling
			Emotion estimation
			Perception layer

Table 6 Human-user involvement

Study Design	Category (percent)
Stage	Conceptual (34.5 %), Case study (8.3 %), Method (9.5 %) Empirical (27.4 %), Implementation (20.2 %)
Methodological approach	Holistic (41.7 %), Traditional (58.3 %)
Degree of user involvement	High (35.7 %), Medium (46.4 %), Low (19.4 %)

understand and exploit the humans' social interactions. Also, the participatory model is advocated as an effective methodology to encourage the users to actively participate in the generation and sharing of data in the relevant platforms. Some works are more concrete and propose novel *architectures* by adopting a human/citizen/user-centric perspective rather than the commonly used service-centric one.

Privacy, security, control of the shared data, and trust are often targeted in this context. The privacy by design approach is the one that is exploited very frequently, which results in adding security controls and relevant rules to almost any architectural layer. Several deployments of the proposed architectures are presented in the literature, especially with reference to the smart cities and smart housing scenarios. However, there are only a few times where there is a real assessment of whether the user-centric requirements have been attained; indeed, the performance analyses often focuses on technical indicators far from the user perceived experience, such as system memory occupancy and percentage of satisfied service requests.

The *user interface* is one of the platforms' components that is commonly the focus of technical contributions. Most of the time, the objective is to instill trust in the user and be empathetic to augment the relevant involvement in the deployed IoT applications. These design objectives may however contrast with each other, as analyzed in Gracanin et al. (2019), where empathy, privacy and ethics are considered all together in the design of the user-IoT-interaction modalities; for instance, what is a privacy-preserving action may not be appropriate from the emphatic point of view. The user interface should also stimulate the user towards collaborating with the other entities involved in the IoT applications; towards this objective appropriate incentives to the users are introduced, which need to be personalized to avoid poor behavior and preserve privacy (Dustdar and Scekic 2018). In the last few years, a complete personal assistant has been proposed as a crucial part of IoT platforms, which is intended to support the user to exploit the full potentials of the IoT platform and make interaction easier (see e.g., (Santos et al. 2018)).

The *user monitoring* is another important architectural component. The objective is to learn about user habits and create a user profile to personalize the system functionalities. To this end, different sources of information are used (video cameras, localization sensors, collection of data from the users personal devices, and others) and Machine Learning (ML)-based tools together with edge and cloud computing resources.

4.4 Human/user involvement

Finally, we have also considered the study design/contribution type and whether, how, and in what stages users were involved in research under a human-centric IoT umbrella. As observed from the literature and pointed out in Sect. 2, human-centric design can mean that humans or users are either actively or passively involved in the IoT technology design. The nature and degree of human involvement can vary significantly in this respect. A summary of the nature and degree of human involvement within the reviewed approaches can be seen in Table 6.

First of all, we considered the study stage, i.e., whether a paper presented a conceptual work, case study, method, empirical study, or if it had been implemented. We also considered the methodological approach towards involvement, referring to whether the design took a holistic or a more traditional approach, as introduced in Sect. 2. Here, we found that 34.5 % of human-centric approaches were in the conceptual stage of product/system design. 27.4 % were empirical

Table 7 ISO Human-centred design phase

A1 = Plan the human-centred design process
A2 = Understand and specify context of use
A3 = Specify the user requirements
A4 = Produce design solutions to meet user requirements
A5 = Evaluate the design against requirements
A6 = Design solution meets user requirements

The human-centred design phases are not strictly linear, but interdependent, where each phase uses output from the other phases

Table 8 Empirical studies: HCD phases and methods

Citation	Domain	Phase	Meth	User Req
Yao et al. (2019b)	SH	A1, A2, A3, A4	Ql	P
Zimmermann et al. (2019)	SH	A1, A2	Ql	P
Jia et al. (2012)	SH	A1, A2	Ql	P
Lundberg and Gustavsson (2011)	H-IoT	A2, A3, A4, A5	Ql	P, S
Schulz (2014)	SB	A5	Ql	P
Kwon et al. (2018)	SH	A2, A3	Ql	P, S
Marky et al. (2020b)	SH	A2	Ql	P, S
Marky et al. (2020c)	SH	A3	Ql	P
Yao et al. (2019a)	SH	A2, A3	Ql	P, S
Marky et al. (2020a)	SC	A2, A3	Ql	P
Memedi et al. (2018)	H-IoT	A4, A5	Ql	P
Schemmer et al. (2020)	SI	A2, A3, A4, A5	MM	P
Worthy et al. (2016)	SH	A1, A2	Ql	P
Shin and Park (2017)	SC	A2, A3, A4	MM	P, S
Bati and Singh (2018)	IoT	A4	Qt	P
Wang et al. (2019)	H-IoT	A1, A2, A4	MM	P
Wickramasinghe and Reinhardt (2019)	SH	A2, A3	Qt	P
Bermejo et al. (2021)	SH	A2, A3, A4, A5	MM	P
Breve et al. (2021)	IoT	A4, A5	MM	P
Oppl and Stary (2022)	IoT	A1, A2, A3	Ql	P
Mohanty et al. (2022)	IoT	A1, A2, A3, A4	Qt	P, S
Tiersen et al. (2021)	SH	A1, A2, A3	MM	P, S
Karni et al. (2022)	H-IoT	A1, A2, A3, A4, A5	MM	P, S
Kounoudes et al. (2021)	SH	A4, A5	Qt	P

SH smart home; *SD* smart devices; *SB* smart buildings; *SI* smart industry; *SC* smart city; *IoT* a generic IoT domain; *H-IoT* health-related IoT; *QI* qualitative; *Qt* quantitative; *MM* mixed methods; *P* primary user requirements; *S* secondary user requirements

studies, 9.5 % methods analyses, 8.3 % case studies, while 20.2 % were solutions that were being implemented (including prototypes that were tested or evaluated). 58.3 % of the studies reviewed had a traditional methodological approach towards user involvement, while 41.7 % had taken a more holistic approach. We coded *traditional* when the design focused mainly on a specific IoT technology/solution, such as in the case of Wickramasinghe and Reinhardt (2019) who investigate users' interacting with a particular privacy-preserving solution dedicated to smart home environments to tailor the experience to their needs, rather than any wider human-human or human-service interaction. The code *holistic* was assigned when the methodological approach considered the whole IoT technology system as interconnected and evolving with factors in broader human dimensions. Follow-up analyses indicated that holistic approaches are over-represented among contributions stemming from the social sciences and humanities, as opposed to those deriving from technology-oriented fields ($\chi^2(1)= 9.035$, $p < .01$). The latter is more likely to be based on a traditional approach.

Finally, Table 6 also refers to the degree of user involvement. *High* was assigned when a collaborative design approach brought additional stakeholders into the system development process - such as researchers, designers, users, or potential users working together. *Medium* involvement was assigned when end-users had a direct influence in terms of specific user input or feedback, but indirect methods were applied during most of the design process. *Low* was assigned when the design only indirectly involves users. For example, passive data collection or observation is used to infer user needs, behaviors, or preferences to adjust the IoT technology to the individual user.

As can be observed in Table 6, 35.7 % of the total article pool was classified as *high*, 46.4 % as *medium*, and 19.4 % as *low*. For example, Feth et al. (2017) involved users with high participatory involvement throughout the design process. Early involvement happened via a usability walk-through. They created personas for all user groups, including bystanders. Then, scenario use-cases were created to understand system context and goals for the users. They also brought in users to evaluate the performance of tasks. An example of medium involvement is given by Giannetsos et al. (2011) where quantitative models describe their users' individual and social behavior in the form of mathematical models or algorithmic descriptions. These behavioral models are used in devices to replicate the same behaviors of their users. Via their mobile device, humans/users provide input and data. The goal is to develop policies that complement technology designs and individual participant decisions. The users directly involved are the primary owners of IoT devices and solutions. Finally, in one example of low involvement, Dhelim et al. (2018), use sensors to map human emotions, behaviors, social context, physical context, personality, and thoughts passively to offer personalized service, without any direct involvement from users.

Further analyses confirmed (see Sect. 2) that the type of user involvement is also associated with the disciplinary background of the involved team: high user involvement is significantly over-represented and thus more common in the included articles stemming from the social sciences and humanities as opposed to those stemming from technology-oriented disciplines ($\chi^2(2)= 7.839$, $p < .05$).

The ISO 9241 requirements for human-centred design outlines five phases of design activities, as shown in Table 7 (International Standard 2010). The 24 articles that report on conducting empirical studies are mapped to these phases and the associated methods in Table 8. While most empirical studies described user involvement across the core design phases (A2-A5), only one of the papers provided an overview of an entire human-centered design process. Furthermore, the majority of studies applied qualitative methods, where the primary users were involved in understanding and specifying technology requirements. A few empirical studies considered secondary user requirements as well. The domain the empirical studies applied to was mostly in smart homes.

5 Discussion

5.1 Current status

In response to the policy focus and corresponding call for more democratic and humanity-centric (empowering) network technology design, the human-centric terminology and goals have found their way into scientific research development in the field of IoT.

5.1.1 Human-centric focus in IoT

Our study indicates that especially after 2015, the number of articles addressing human-centric IoT increased considerably (see Fig. 3). The majority of these originate from Europe-based research teams. Theoretical or conceptual foundations are explicitly stated by 82.1 % of the articles. Table 3 illustrates that the underlying theoretical perspectives remain somewhat fragmented and correspond to various understandings and human-centered perspectives. Furthermore, they are situated at different levels, while an overall and commonly referred to human-centric framework is lacking in the examined papers. As a result, existing research efforts under the heading of human-centric IoT appear to be fragmented rather than systematically addressing a shared vision. This lack of clear common goals and a consensual research agenda based on a shared understanding of what should be the underlying principles, may strongly reduce the potential impact of existing "human-centric" efforts.

5.1.2 Weak link between human-centred theory and practise

This recent rise of the notion of "human-centric" in the context of IoT technologies has informed approaches that conceptually define what human-centred means depending on who and what they are designing for: 1) the human or the social/ecological system, 2) the commercial, legal, and technological capabilities. Ideally, these two approaches should be intertwined, thus calling for inherently inter-and multidisciplinary approaches. However, the link between them (and the associated communities) appears to be at least partly missing or tends to be unclear when IoT solutions are implemented and evaluated in practice. Our analysis confirmed the predominance of technology-oriented fields in human-centric IoT research. While slightly more than 3 out of 10 of the analyzed articles stem from an interdisciplinary team, the majority is single discipline-based, with technology-oriented fields being over-represented in the latter category. The weak link between the above approaches and the lack of a common understanding can also be seen in the light of the under-representation of traditionally more human- and society-oriented fields (i.e., social science, humanities). In turn, this under-representation also has consequences for the adopted practices and the methodological approaches in human-centric IoT research that have been utilized.

5.1.3 Human concepts as technical formalisations

In this respect, the dominant notion of "human-centredness" primarily appears to have been developed from a "technology" approach, which aims to create emotional, social, or ethical network systems to act as decision advisors via a range of user-IoT-interaction modalities. The underlying assumption here is that it is possible to create a merged human user-IoT system with interfaces that fully act in the interests of the human and society. However, while these interests and intended outcomes are explicitly referred to in the majority of the analyzed papers, the question of how they are understood, transformed into technical requirements and mechanisms, and to which extent these mechanisms contribute to safeguarding these interests, seems to be less explicitly addressed. Furthermore, the primary involvement mechanism of the more "technology-driven approach" is either to more passively observe, collect, and analyze data to map human behavior, or to stimulate or coerce humans to participate by providing data, devices, or input (Table 5). In this regard, while slightly over half of the articles were coded as adopting an expert mindset, 58.3% were characterized as having a traditional approach towards user involvement. Within this group of articles, the involvement of different user groups and other stakeholders was less common. As a results, highlighted by Table 5, most of the technical contributions focused on novel frameworks or architecture, which, however, are not able to address some key outcomes such as agency and civic participation. Furthermore, as was shown in Tables 6 and 8, only slightly over one-third of the analyzed articles were based on high user involvement and only one of the empirical studies, being the study of Karni et al. (2022) reported on an entire human-centered design process. This points towards a discrepancy between how contributions are positioned and framed ("human-centric"), the practices and assumptions which they are based on, and their actual (potential) impact and ability to orient existing efforts towards genuine human-centric outcomes and key values.

5.1.4 A technical status hierarchy

The above mismatch may have important implications in terms of inherent power relations. It has been shown that when human-centred practises/processes are not adopted, and thus not impacting the decision-making of the technologists, the decisions that dictate codified procedures managed by technical measures and performance indicators are not factoring in who defines and enforces what the intended outcome is, and for whom, and from what position of power they are realized (Sloane 2019). In this respect, when technical experts and commercial actors mostly build the IoT/smart ecosystems, the primary measure of success will most likely be driven by the benefits of commercial development, legal requirements, cost-savings, and performance management/control over technical environments (Chin et al. 2019; Sovacool and Del Rio 2020). Commercial and business interests are likely to result in a (technology) push for "creating" needs instead of a pull for overcoming existing and future human and societal needs. An important assumption here is that the interests of those in control will also count for protecting the interests for all who are served by the technical system. Therefore, the matter of which stakeholders' needs are specified as part of the requirements, and when they are considered in the design process, determines the human-centric success measurements (Cockton 2004). Then, to be truly empowering, the selected success measurements should be evaluated against a shared beneficial outcome that improves based on the actual needs of humans and society, instead of metrics created by those in control of the IoT system (Graeff 2018).

5.1.5 Holistic design frameworks

In the analyzed article set, the requirements for safeguarding humans' interests are primarily translated as security, privacy, and control constructs, technically represented by protection from, e.g., unauthorized disclosure and mining of personal data or access to restricted resources. However, there is still room for improvement in terms of involving human users from their viewpoint in this translation process, actively and openly, allowing for choice and various interpretations and in line with the fundamental principles introduced in Sect. 2. The main mechanisms focused on universal access and protection of human rights are those that maintain knowledge and authority to the human users of the system. They can examine how to balance equal power between the constellation of actors (developers, users, government, technology), along with protection of the self-understanding as human agents (Feng et al. 2021). These are important advancements; however, they need to be integrated into a holistic framework that re-engineers design practices, based on principles that put people and their rights at the center of the development.

5.1.6 Participatory approaches where everyone is valuable

A humane and holistic design framework for IoT entails considerations that would work towards safeguarding user rights by regular consultations with diverse audiences in civil society, technical features to flag, prevent or mitigate misuse, and audits where the fault lines of existing power structures are addressed, to ensure equitable and empowering outcomes for all. In addition, assessments of the effect on humans' daily lives, incorporating socio-technical processes and measures to perform evaluations, can reduce certain forms of negative outcomes, such as bias, discrimination, and inequality (Hasselbalch 2021). The development of these assessments and guidance can be done via focused studies, monitoring, and analysis, which requires engagement with interdisciplinary groups, including computer scientists, social scientists, psychologists, economists, and lawyers (Stephanidis et al. 2019). While the literature search in our study yielded a number of recent examples of participatory approaches in this respect, e.g., the study by Tiersen et al. (2021) focusing on people with dementia and IoT smart home solutions or that by Karni et al. (2022) addressing the potential of IoT to empower people with Parkinson's disease, such examples are still scarce in the literature.

5.2 Towards a future research agenda

Based on the analyzed papers, the following aspects need to be explicitly considered in future efforts towards building a more human-centric and empowering IoT.

5.2.1 The role of non-human actors

In designing for new IoT technologies, the role of non-humans in new IoT/smart environments should be clear and well-understood, especially with regards to defining the relationship with humans. Furthermore, conceptual models of knowledge and action shared between humans and non-humans need to be developed (Cruickshank and Trivedi 2017b). To better understand the resulting tension between the two, a critical analysis of non-human versus human agency, by addressing their theoretical underpinnings (i.e., from the field of Science and Technology Studies / Actor-Network Theory), can help determine the appropriate design and deployment that will safeguard user-rights (Sloane 2019). From the human perspective, more research into how to provide agency to human users is needed, with the development of mechanisms that are at a standard whereby each human actor is able to understand the situation for themselves (Lindley et al. 2018). This calls for the design of novel frameworks and user interface components to provide humans with a more transparent and informed view of the role of the provided technologies and the impact at large of decisions taken (Benhamida et al. 2021). Additionally, transparency should also focus on the deployment and management phases, as the system configuration of even well-designed solutions may significantly impact the users' agency. From a technical perspective, there is ongoing research into the design for collaboration and information exchange between non-human actors based on human-like features and qualities (Defiebre and Germanakos 2019). The social IoT is tentatively able to smooth the interactions. However, the development of effective social behaviors still needs further development, especially in terms of the impact on the attitude of artificial social peers towards humans.

5.2.2 Diverse user involvement throughout the design process

To have a high level of trust, which is crucial for user adoption in IoT, humane, ethical, and legal considerations must be considered throughout the design process (Shin and Park 2017). Only a few of the analyzed contributions consider early user involvement. The literature to date identifies a need to facilitate the active involvement of various user groups with diverse needs, which requires a movement away from a single user perspective towards a community based or society level of involvement. Balancing multiple interests also requires systems design to address the tension between growing individual needs, private interest, and the collective social responsibility towards the common good (Semeria 2016). These processes should be humanity-based from the start, include regular consultations with multiple stakeholders and robust transparency reporting on activities that may have an adverse impact on human rights (Winter 2015). Finally, future IoT environments need to facilitate massive user involvement, in multiple environments, with new contexts (Gracanin et al. 2019). This may include recommendations for technical design frameworks where multiple stakeholder interests are balanced with system monitoring, and the design is governed throughout the development process.

5.2.3 New methodological approaches

Moreover, there is a mismatch and an overall lack of evaluation of the targeted outcomes to address and manage the effects that IoT systems may have on human users, communities, and society (Memedi et al. 2018; Shin and Park 2017). As such, the technical aspects should be more strongly linked with methods that are more suitable for evaluating the potential human and social impact in the context of IoT. Until now, the evaluation of the network systems' ability in meeting the user expectation has been quantified using QoE metrics. The scope for improvements into QoE provides an insight into future research to define meaningful human-centric metrics (Geerts et al. 2010). For most human-centric IoT contributions, real-world evaluations are scarce and limited, although future studies plan to conduct systematic assessments of the IoT technology's effectiveness, efficiency, comprehensiveness, and neutrality (Feng et al. 2021).

5.2.4 Discrete and unobstructed technology/merged machine-human interactions

In the subsequent development of human-centric IoT solutions, new research into tools that can equip users to obtain information, knowledge, and control of discreet IoT technology hidden in the background, often where the most intimate/private data is collected, is essential. In the past, where users only assisted the network in providing a better individual service, it should now evolve into future user equipment that is merged into the IoT architecture to form a deep-fused human–machine intelligent system (Adamo 2019). The gap between technology artifacts and the human experience, with thin and rigid distinctions separating humans and machines, and how these boundaries are established in the connected life compared to the non-connected life, are research topics that will help bring this vision to life. The research challenge of implementing trade-off procedures and conscious user choice remain, when guiding design principles are not adopted (Streitz 2019).

5.2.5 Multi-disciplinary expertise

Future research agendas would benefit from a significant effort to bring together expertise from different communities (e.g., computer science, physiology, cognitive science, communications, technology ethics, and user experience design) to jointly design IoT systems that are able to deliver empathetic communications and instill trust into users (Kaluarachchi et al. 2021). Even so, the challenges related to establishing a clear link between more human-centered aspects and the technology implementation relate to guidelines geared towards legal or design, not technical domains, developers passing the responsibility onto experts, and a lack of access to multi-disciplinary skills (Aljeraisy et al. 2021).

5.3 Limitations

We acknowledge that the methodology may have limitations due to keywords, selection, and eligibility criteria restrictions as described in section 3. However, we have addressed these by applying a rigorous search strategy upfront, grounded in the existing literature. Moreover, we have developed a standardised coding framework for the analyses supported by specific definitions that had to be explicit in the text. However, some articles did not explicitly address the variables of interest, and in such cases, we rigorously considered them to assign the most appropriate category correctly. For variables such as the geographical origins of the team, institutional information was used to assign the paper to the right category. However, due to this, the applied coding does not take into account that researchers are mobile and that for instance, teams located in Europe may have a more diverse composition. In other research papers, we were confronted by a need for shared terminology and definition of certain concepts/words. For example, when categorizing targeted user outcomes codes, such as privacy, agency, and empowerment, the grouping of the annotations and codes was first based on an explicit mention, then mapped to the most relevant goal that was expressed based on an interpretation. Despite this, we were able to define most other variables quantitatively with objective indicators. Based on these observations, we recommend that future research projects consider the discrepancy in understandings and explore the possibilities of clarifying and unifying the terminology used to achieve human-centric design outcomes and practices (Law and Van Schaik 2010), especially when aiming for a more inclusive, democratic, and empowering design.

6 Conclusion

This survey paper has covered the theoretical ground, conceptual definitions, methodologies, and the associated solutions to human-centric IoT technology. In particular, our aim has been to review the literature from a socio-technical lens to assess the re-alignment of IoT network technology towards human-centredness and sustainability. Furthermore, we have sought to address the divide between human-centered/humanity-centred theory and practices in IoT by detailing the existing scope for what human-centered translates into and how it can be practically implemented in the context of IoT.

A key observation is that, despite the recent increase in research on humane perspectives for IoT, "human-centredness" often still seems to be used primarily as a label and overarching paradigm, without leading to a profound and necessary change to underlying practices. This is also reflected in the under-representation of more human-oriented fields and disciplines and the associated approaches and practices, which still holds, also for the most recent years. When considering key principles of human- and humanity-centric design and their implications also reflected in the European declaration of digital rights, the human-centric label, therefore, seems to be misrepresented to a certain extent. This observed mismatch between higher-level intentions and reality calls for renewal and re-alignment at several levels.

We argue that increased multi-disciplinary research, such as the work presented in this paper, can help to shape how future human-centric IoT roadmaps may re-align towards one that benefits humans and humanity first, leading to a successful adoption on a societal scale. Future multi-disciplinary efforts need to be guided by a shared understanding of the fundamental underlying principles with the development of a common research agenda, and to have a shared vision of how the intended outcomes can be best addressed and evaluated.

We further call for more critical theory-based research on human-centric IoT. Research that challenges the "inevitability" of an IoT where the path represents a ubiquitous/pervasive presence of IoT devices in everyone's living environment is scarce. However, without exercising active human choice and direct participation in the development, the design equality of pervasive IoT environments needs to be challenged. This requires critical socio-technical values, factors, and principles to be considered more extensively and explicitly to actively enable human potential when everything is connected. Furthermore, the infusion of IoT with human users' everyday life and practices, requires that human users' are actively motivated to use it and for them to hold authority over the use of system (Kim and Gupta 2014). In order to be genuinely human-centered, IoT technologies require a clear-eyed model of user empowerment, inclusivity, human control, and involvement. Therefore, future work in this domain must ensure that human-centered IoT is at the core of societal, technological, economic, and political agendas.

Appendix

See Tables 9, 10, 11, 12, 13.

Table 9 Full search syntax

Database	Syntax	Filters
Web of Science	(TS=(("Human in the loop" OR "Decision and control loop" OR "Human operator" OR agency OR privacy* OR empowerment OR "user control" OR trust* OR civic) AND ("Human-cent*" OR "User cent*" OR "People-cent*" OR "Citizen-cent*" OR "human-aware" OR "user-aware") AND ("internet- of-things" OR "IoT" OR "next-generation internet" OR "sensor networks")))) AND LANGUAGE: (English)	Indexes=SCI-EXPANDED, SSCI, A &HCI, CPCI-S, CPCI-SSH, ESCI Timespan=2010-2020
Scopus	((TITLE-ABS-KEY ("Human in the loop" OR "Decision and control loop" OR "Human operator")) OR (TITLE-ABS-KEY (agency OR privacy* OR empowerment OR "user control" OR trust* OR civic))) AND (TITLE-ABS-KEY ("Human-cent*" OR "User cent*" OR "People-cent*" OR "Citizen-cent*" OR "human-aware" OR "user-aware")) AND (TITLE-ABS-KEY ("internet-of-things" OR "IoT" OR "next-generation internet" OR "sensor networks")) AND (LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011) OR LIMIT-TO (PUBYEAR, 2010)) AND (LIMIT-TO (LANGUAGE, "English"))	
IEEE	(("All Metadata": "Human in the loop" OR "Decision and control loop" OR "Human operator" OR agency OR privacy* OR empowerment OR "user control" OR trust* OR civic) AND ("All Metadata":"Human- cent*" OR "User cent*" OR "People-cent*" OR "Citizen-cent*" OR "human-aware" OR "user-aware") AND ("All Metadata": "internet-of-things" OR "IoT" OR "next-generation internet" OR "sensor networks"))	Conferences Early Access Articles Journals. 2010 - 2020
ACM	[[All: "human in the loop"] OR [All: "decision and control loop"] OR [All: "human operator"] OR [All: agency] OR [All: privacy*] OR [All: empowerment] OR [All: "user control"] OR [All: trust*] OR [All: civic]] AND [[All: "human-cent*"] OR [All: "user cent*"] OR [All: "people-cent*"] OR [All: "citizen- cent*"] OR [All: "human-aware"] OR [All: "user-aware"]] AND [[All: "internet-of-things"] OR [All: "iot"] OR [All: "next-generation internet"] OR [All: "sensor networks"]] AND [Publication Date: (01/01/2010 TO 12/31/2020)]	

Table 10 Part I: Summary of Human-centred solutions in IoT

Cit	Origin	Study type	Discipline	Involvement	Domain	User outcome	Solution
Krontiris and Freiling (2010)	Eur	Conceptual	Single	Medium	SC	Control	Participatory model for access control where the user opts to meet application requirements for data out of personal interest
Giannetsos et al. (2011)	Eur	Conceptual	Single	Medium	H-IoT	Control	A sensing environment where ordinary citizens are custodiants over managing data on devices
Lundberg and Gustavsson (2011)	Eur	Empirical	Single	High	H-IoT	Empowerment	Sensor systems tailored to the context of the individual user for support and empowerment
Jia et al. (2012)	Eur	Empirical	Diverse	High	SH	Agency	A design framework for balancing user and object agency
Nasir et al. (2012)	AME	Implementation	Single	Medium	ST	Control, Cooperation	Design of wireless sensor networks used to sense various objects and events and the effect on the environment
Moreno et al. (2014)	Eur	Conceptual	Single	Medium	SC	Control, Privacy, Trust	Privacy and security architectural framework with mechanisms for user control
Schulz (2014)	Eur	Empirical	Single	Medium	SB	Privacy, Security, Trust	A security assistant that can help users in presenting security and privacy information to create trust
Liu and Julien (2015)	NOAM	Implementation	Single	Low	IoT	Privacy, Trust	A context-sharing application, Magpie, for users to adjust their behaviour based on the sensed context while maintaining their privacy
Moreno-Cano et al. (2015)	Eur	Case study	Single	High	SC	Security, Control, Transparency	Architectural model designed for user control and transparency
Winter (2015)	NOAM	Conceptual	Single	Low	IoT	Civic	Inclusive standards, governance and design norms to guide development of technical systems
Figueira et al. (2016)	Eur	Implementation	Single	Medium	SS	Security	An implementation of a Human-in-the-Loop Cyber-Physical System (HiTLCPS) where the system can recognise and take into account the human interaction, making human emotion and actions an intrinsic party of the computational system
Garcia-Alonso et al. (2016)	Eur	Implementation	Single	Low	ST	Control, Agency	New model for cyber-physical systems that adapts to the humans situated context
Kor et al. (2016)	Eur	Implementation	Single	Medium	SH	Security, Control, Empowerment	An IoT integrated software architecture, SMART-ITEM, where users are extensively involved throughout the development lifecycle
Nawaz et al. (2016)	Eur	Case study	Single	Medium	H-IoT	Privacy, Security, Trust	An IoT vision system is presented that employs a network of fixed embedded cameras in a highly trusted manner, and discuss an Ambient Assisted Living (AAL) healthcare use case demanding privacy and security for outpatients
Nurse et al. (2016)	Eur	Method	Single	High	SH	Privacy, Security	A framework and support tool for users of IoT technology to intuitively model security and privacy risks
Semeria (2016)	Eur	Conceptual	Diverse	Low	IoT	Empowerment, QoL	Human-centred research approaches and symbiotic development strategies for IoT that thinks in systemic ways to achieve energy efficiency, empowerment for individuals and quality of life for everyone

Table 10 (continued)

Cit	Origin	Study type	Discipline	Involvement	Domain	User outcome	Solution
Shaikh et al. (2016)	AME	Conceptual	Single	High	SC	Control	Give user greater control over data from end-device sensors. User-centred control over devices and networks
Hashemi et al. (2016)	NOAM	Implementation	Single	Medium	H-IoT/SC	Privacy, Security, Control, Trust	Consensus mechanisms based on blockchain technology to provide users' access, control, security and privacy protection
Watt et al. (2016)	Eur	Conceptual	Diverse	Medium	IoT	Privacy	New design strategies for mechatronics systems where privacy legislation, regulations and standards, and the associated protocols move away from providing a hard, or impenetrable, security boundary, to more function based strategies to ensure privacy
Worthy et al. (2016)	OC	Empirical	Diverse	Medium	SH	Civic	Empirical research into human and socio-technical values and concerns that arise when living with IoT technologies
Zaric et al. (2016)	Eur	Implementation	Single	Medium	H-IoT	QoL	Ambient intelligence system for better quality of life and well-being for users
Azimi et al. (2017)	Eur	Conceptual	Single	Low	H-IoT	Ease of use, QoL	IoT systems for elderly monitoring to improve the quality of life for the user
Beltran et al. (2017)	Eur	Implementation	Single	Medium	SC	Privacy, Security	SMARTIE, a security-oriented IoT integration platform that provides authentication and access control for IoT services in smart cities that require efficient and user-centric security
Bernabe et al. (2017)	Eur	Implementation	Single	High	SC	Privacy, Trust	A reference architecture, the SocIoTal platform, with tools and mechanisms that simplify complexity and lower the barriers for citizen participation in the IoT
Conti et al. (2017)	Eur	Implementation	Diverse	Medium	IoT	Privacy, Security, Trust	Internet of people, a CPS paradigm, where humans and devices as active elements of applications, services and network service provisioning

Table 11 Part II: Summary of Human-centred solutions in IoT

Cit	Origin	Study type	Discipline	Involvement	Domain	User outcome	Solution
Cruickshank and Trivedi (2017a)	Eur	Conceptual	Single	Medium	ST	Agency	Design principles that facilitate technology design that are sustainable and ethical
Cruickshank and Trivedi (2017b)	Eur	Conceptual	Single	Medium	ST	Agency	Design theory based on OOO practise, Onto Cartography, which is the mapping of relations or interactions between machines, and how they influence each other or are modified
Feth et al. (2017)	Eur	Method	Diverse	High	SH	Security	Method for the design of usable security systems that closely involves the user— both at development and at run-time
Ghiani et al. (2017)	Eur	Method	Diverse	High	IoT	Ease of use	A developer environment that provides support for end users in composing triggers and actions for personalizing web applications
Martinez et al. (2017)	Eur	Implementation	Single	Medium	SC	Privacy, Security	A user-centric IoT platform, SMARTIE, which has been designed to efficiently disseminate data in smart city applications while ensuring citizens' security and privacy
Shin and Park (2017)	AME	Empirical	Diverse	High	SC	Civic	A socio-technical framework to design IoT ecosystem accounting for users, industry dynamics and contexts
Streitz (2017)	Eur	Conceptual	Diverse	High	SC	Control, Empowerment, Cooperation	A citizen-centered design approach for future self-aware cities (AmI) where 'cooperation' functions as an overarching goal for the design process
Valenzuela-Valdes et al. (2017)	Eur	Implementation	Single	Low	H-IoT	Security, Control	Human-in-the-loop implementation in Internet-of-things by means of automatic renewing of cryptographic keys, where humans have the capability to offer services to applications and devices, in turn serve humans
Barhamgi et al. (2018)	Eur	Case study	Single	Medium	SH	Privacy	A reference data architecture allows the user to balance the privacy risks with the potential benefits and make a practical decision determining the extent of the sharing
Bati and Singh (2018)	NOAM	Empirical	Diverse	Low	IoT	Trust	A quantitative model for trust propensity to mediate multiple socio-technical systems
Chibaudel et al. (2018)	Eur	Conceptual	Diverse	Medium	H-IoT	Ease of use	HCD methodology (AMICAS) applied to a specific IOT tool (UbiSmart) to make the system usable and useful by focusing on users, their needs and requirements, and applying human factors/ergonomics, usability knowledge and techniques

Table 11 (continued)

Cit	Origin	Study type	Discipline	Involvement	Domain	User outcome	Solution
Conti and Passarella (2018)	Eur	Conceptual	Single	Medium	IoT	Privacy, Trust	Internet of people, as data-management design, where user's personal devices become proxies of their human users in the cyber world, and plays an active role in data management, either through local decisions, or through collaborative decisions with other devices with which they interact
Dhelim et al. (2018)	AME	Case study	Single	Low	SH	Ease of use	User aware technology that acts on human's behalf to recommend and provide personalised services
Dustdar and Scekic (2018)	Eur	Conceptual	Diverse	High	SC	Empowerment	Smart city architecture of values with software mechanisms supporting ad-hoc, fully citizen-driven collaborations
Kwon et al. (2018)	Eur	Empirical	Diverse	Medium	SH	Privacy, Control	Help users understand intimate data to balance risks and benefits of data provisioning
Lindley et al. (2018)	Eur	Conceptual	Diverse	Medium	SH	Agency	New design research techniques incorporating concepts derived from contemporary philosophies of technology, such hCD and Privacy by Design. Introducing OOO as theoretical framing for design
Memedi et al. (2018)	Eur	Empirical	Single	H	H-IoT	QoL	IoT-based concept for addressing the needs for better management of PD by giving patients insights into symptom and medication information
Rantos et al. (2018)	Eur	Implementation	Single	Medium	SC	Privacy	Consent mechanisms designed to elevate privacy-protection for users
Adamo (2019)	Eur	Conceptual	Single	High	IoT	Agency	A "Society-in the-loop-system that extends decisional power to a larger group providing a more inclusive, democratic supervision
Banerjee et al. (2019)	NOAM	Method	Single	Low	IoT	Trust	Behavioural trait and trust awareness algorithmic models for network arrangements
Bornholdt et al. (2019)	Eur	Implementation	Single	Medium	SC	Privacy, Control	A smart city open platform (SANE) on which citizens can contribute data but also hardware, without any central authority or control
Chong et al. (2019)	NOAM	Conceptual	Diverse	High	SH	Privacy	Equipping users to protect their privacy with intelligent training systems, privacy coaches, that provide instructional requirements, activities, and assessments

Table 12 Part III: Summary of Human-centred solutions in IoT

Cit	Origin	Study type	Discipline	Involvement	Domain	User outcome	Solution
Defiebre and Germanakos (2019)	Eur	Method	Diverse	Low	IoT	Privacy, Security	A hierarchical model that maintains at its core human personality traits and drives the behavior and interactions of objects that travel autonomously in the open space
Gracanin et al. (2019)	NOAM	Implementation	Single	Medium	H-IoT	QoL	A design framework that incorporates a game theoretic model to address Empathy Privacy and Ethics interplay in SBEs (Smart Built Environments (SBE), as a subset of CPS)
Kong et al. (2019)	AME	Conceptual	Single	Medium	SI	Empowerment	Ergonomic design framework to integrate humans with manufacturing systems to achieve seamless collaboration and human empowerment
Lu and Tsai (2019)	AME	Case study	Single	High	SI	Privacy	A user-centered IoT service provisioning system that lets users manage their data, which is stored locally on their smartphones as much as possible and also lets the users manage their data according to their privacy concerns
Lu et al. (2019)	Eur	Conceptual	Diverse	High	IoT	Privacy	Data protection framework incorporating privacy and human-in-the-loop mechanisms balancing privacy trade-offs, human behavioural monitoring and automatic reasoning. Solution is service-independent, and completely under the user's control
Michael et al. (2019)	Eur	Implementation	Single	Medium	SI	Privacy, Control	A privacy-preserving system design for process mining that supports data owners to control privacy policies and monitor their compliance
Sen et al. (2019)	NOAM	Method	Single	Medium	IoT	Security, Personalised context of use	User-centric architect framework for secure and dynamic service provisioning in IoT environments
Streitz (2019)	Eur	Conceptual	Diverse	High	SC	Control, Empowerment, Cooperation	Human centred design approach of AmI with its attention to social interfaces that keep people in the loop and in control
Sylla et al. (2019)	Eur	Implementation	Single	Medium	SC	Ease of use, QoL	A context-aware security and privacy architecture for IoT
Wang et al. (2019)	NOAM	Empirical	Diverse	High	H-IoT	Agency	Empirical research to identify older adults' perspectives regarding AAL and AI technologies and gauge interest in participating in a co-design process
Wickramasinghe and Reinhardt (2019)	Eur	Empirical	Single	High	SH	Privacy	Participatory, user-centric design for privacy-preserving solutions dedicated to smart home environments
Yao et al. (2019a)	NOAM	Empirical	Diverse	High	SH	Privacy, Control	Consensus mechanisms that facilitate communication between stakeholders to mitigate privacy concerns and enable control

Table 12 (continued)

Cit	Origin	Study type	Discipline	Involvement	Domain	User outcome	Solution
Yao et al. (2019b)	NOAM	Empirical	Diverse	High	SH	Privacy, Control	Privacy by design mechanisms to simplify user effort
Zimmermann et al. (2019)	Eur	Empirical	Diverse	High	SH	Privacy, Transparency	Control mechanisms for transparency and oversight for users
Grundy (2020)	OC	Case study	Single	High	SC	Civic	Improved human centric requirements engineering, augmenting model-driven development with human-centric issues, and deployment and evaluation with edge-based systems for smart living domains
Marky et al. (2020c)	Eur	Empirical	Diverse	Medium	SH	Privacy, Transparency	Privacy decision support (multi-device interface) to guide users on which personal data to share
Marky et al. (2020b)	Eur	Empirical	Diverse	High	SH	Privacy, Transparency	Privacy aspects are negotiated with controls to adjust the output, especially concerning the status and existence of the device. Visitor mode of devices proposed as a mechanism
Marky et al. (2020a)	Eur	Empirical	Diverse	Medium	SH	Privacy, Transparency	Privacy by default mechanisms in smart homes
Mordacchini et al. (2020)	Eur	Method	Single	Low	IoT	Transparency, Ease of use	Personal devices act as proxies to allow users access to data via cognitive schemes that are embedded

Table 13 Part IV: Summary of Human-centred solutions in IoT

Cit	Origin	Study type	Discipline	Involvement	Domain	User outcome	Solution
Schemmer et al. (2020)	Eur	Empirical	Diverse	High	SI	Agency	User-centred process recommendation tool that supports human operators in decision-making situations
Toumia et al. (2020)	Eur	Conceptual	Diverse	High	SH	Privacy, Transparency	Privacy policies and data protection configuration designed for user participation
Aljeraisy et al. (2021)	Eur	Conceptual	Single	Low	IoT	Privacy	A systematic analysis of current privacy and data protection laws and introduction of a Combined Privacy Law Framework, further mapped with Privacy by Design schemes
Benhamida et al. (2021)	Eur	Conceptual	Single	Medium	IoT	Trust, Privacy	A fog-based and flexible architecture to enable Privacy by Design in IoT-based smart environments
Bermejo et al. (2021)	AME	Empirical	Single	Medium	SH	Privacy, Control	User study of a privacy-preserving assistant that uses Augmented Reality for enhancing user understanding and privacy control in smart home settings
Breve et al. (2021)	Eur	Empirical	Single	Medium	IoT	Control, Empowerment	Design, proposition and evaluation of a visual paradigm and smart solution that assists users to secure their smart environments and to understand and deal with security and privacy threats
Cheryl et al. (2021)	Eur	Case study	Diverse	Low	IoT	Privacy, Empowerment	Case study and model on the balance between technology exploitation and protection of user rights in the context of IoT development, using Malaysia as example as a case study
Feng et al. (2021)	NOAM	Conceptual	Single	Medium	IoT	Privacy, Control	A conceptual framework that considers privacy choice as a user-centered process and a set of guidelines for practitioners to enable meaningful privacy choices by design
Kounoudes et al. (2021)	Eur	Empirical	Single	High	SH	Privacy, User awareness	Machine learning-based approach to detect privacy interference in smart home use cases and application to inform users
Rivadeneira et al. (2021)	Eur	Conceptual	Single	Medium	IoT	Privacy	A privacy-preserving framework and architecture, which can be integrated into people-centric IoT systems

Table 13 (continued)

Cit	Origin	Study type	Discipline	Involvement	Domain	User outcome	Solution
Rohan et al. (2021)	AME	Conceptual	Single	Medium	IoT	Security, Privacy	A four-layered, human-centric, security and privacy preserving framework
Tiersen et al. (2021)	Eur	Empirical	Diverse	High	IoT	Agency, Dignity	A user-centered and mixed-method based analysis of challenges and opportunities for smart home sensing and monitoring to support individuals with dementia
Wickramasinghe and Reinhardt (2021)	Eur	Conceptual	Single	Medium	SH	Privacy, Control	A user-centric privacy-preserving approach, allowing users to have full control over data collection and disclosure in a smart home context
Karni et al. (2022)	Eur	Empirical	Diverse	High	IoT	Agency, Empowerment	User-centric design and evaluation of a home monitoring system supporting people with Parkinson disease
Mohanty et al. (2022)	Eur	Empirical	Single	Medium	IoT	Control, Flexibility	Survey-based empirical study (N=341) assessing factors that can help to mitigate privacy risks in IoT devices, self-assessment scorecard to evaluate privacy risks in IoT devices
Oppl and Stary (2022)	Eur	Empirical	Single	High	IoT	Privacy, Control, User motivation	A Design Science and Self-Determination Theory based framework for the development of CPS and user-centric privacy management
Rizvi et al. (2022)	NA	Conceptual	Single	Low	IoT	Privacy, Transparency	A model for analyzing the full impact of compromised data privacy in IoT networks, including Transparancy, Unlinkability and Intervenability (TUI)
Showail et al. (2022)	Eur	Conceptual	Single	Low	IoT	Privacy, Control	A user-centric cloud-based service architecture addressing security and privacy challenges for IoT devices at each level of the IoT ecosystem

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References

Adamo A (2019) Taming the techno leviathan: why we should adopt a society-in-the-loop model inside IoT utilities. AISEM annual conference on sensors and microsystems. Springer, Cham, pp 119–129

Aljeraisy A, Barati M, Rana O, Perera C (2021) Privacy laws and privacy by design schemes for the Internet of Things: a developer's perspective. ACM Comput Surv (Csur) 54(5):1–38

Atzori L, Iera A, Morabito G (2010) The Internet of Things: a survey. Comput Netw 54(15):2787–2805

Atzori L, Iera A, Morabito G, Nitti M (2012) The social Internet of Things (siot)-when social networks meet the Internet of Things: concept, architecture and network characterization. Comput Netw 56(16):3594–3608

Azimi I, Rahmani AM, Liljeberg P, Tenhunen H (2017) Internet of Things for remote elderly monitoring: a study from user-centered perspective. J Ambient Intell Humaniz Comput 8(2):273–289

Banerjee S, Hempel M, Ghasemzadeh P, Qian Y, Sharif H (2019) A novel approach to social-behavioral d2d trust associations using self-propelled voronoi. In: 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), IEEE, pp 1–5

Bannon L (2011) Reimagining HCI: toward a more human-centered perspective. Interactions 18(4):50–57

Barhamgi M, Perera C, Ghedira C, Benslimane D (2018) User-centric privacy engineering for the Internet of Things. IEEE Cloud Comput 5(5):47–57

Bati GF, Singh VK (2018) "Trust Us" mobile phone use patterns can predict individual trust propensity. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, pp 1–14

Bego K, Brynskov M (2020) A vision for the future internet. Working Paper. https://www.ngi.eu/wp-content/uploads/sites/48/2020/10/Vision-for-the-future-internet-long-version-final-1.pdf

Beltran V, Martinez JA, Skarmeta AF (2017) User-centric access control for efficient security in smart cities. In: 2017 Global Internet of Things Summit (GIoTS), IEEE, pp 1–6

Benhamida FZ, Navarro J, Gómez-Carmona O, Casado-Mansilla D, López-de Ipiña D, Zaballos A (2021) Pyff: a fog-based flexible architecture for enabling privacy-by-design IoT-based communal smart environments. Sensors 21(11):3640

Bermejo Fernandez C, Lee LH, Nurmi P, Hui P (2021) Para: privacy management and control in emerging iot ecosystems using augmented reality. In: Proceedings of the 2021 International Conference on Multimodal Interaction, pp 478–486

Bernabe JB, Elicegui I, Gandrille E, Gligoric N, Gluhak A, Hennebert C, Hernandez-Ramos JL, López C, Manchinu A, Möessner K, et al (2017) SocIoTal: the development and architecture of a social IoT framework. In: 2017 Global Internet of Things Summit (GIoTS), IEEE, pp 1–6

Bijker WE (1993) Do not despair: there is life after constructivism. Sci Technol Hum Values 18(1):113–138. https://doi.org/10.1177/016224399301800107

Bornholdt H, Jost D, Kisters P, Rottleuthner M, Bade D, Lamersdorf W, Schmidt TC, Fischer M (2019) SANE: Smart networks for urban citizen participation. In: 2019 26th International Conference on Telecommunications (ICT), IEEE, pp 496–500

Breve B, Desolda G, Deufemia V, Greco F, Matera M (2021) An end-user development approach to secure smart environments. International symposium on end user development. Springer, Cham, pp 36–52

Brynskov M, Michele Facca F, Hrasko G (2019) Building a roadmap for the Next Generation Internet of Things. Research, Innovation and Implementation 2021–2027. Scoping Paper. https://www.ngiot.eu/wp-content/uploads/sites/26/2019/09/NGIoT_scoping-paper.pdf

Butun I, Almgren M, Gulisano V, Papatriantafilou M (2020) Industrial IoT. Springer, Cham

Calvo RA, Peters D (2014) Positive computing: technology for wellbeing and human potential. MIT Press, London

Cammaerts B, Mansell R (2020) Digital platform policy and regulation: toward a radical democratic turn. Int J Commun 14:20

Castells M (2009) The rise of the network society, volume 1, with a new preface.

Celik A, Salama KN, Eltawil AM (2021) The internet of bodies: a systematic survey on propagation characterization and channel modeling. IEEE Internet Things J 9(1):321–345

Cherry C, Hopfe C, MacGillivray B, Pidgeon N (2017) Homes as machines: exploring expert and public imaginaries of low carbon housing futures in the United Kingdom. Energy Res Soc Sci 23:36–45

Cheryl BK, Ng BK, Wong CY (2021) Governing the progress of internet-of-things: ambivalence in the quest of technology exploitation and user rights protection. Technol Soc 64:101463

Chibaudel Q, Joaquim B, Véronique LN, Mounir M (2018) Human centered design conception applied to the Internet of Things: contribution and interest. Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics), volume 10898 LNCS. Springer, Cham

Chin J, Callaghan V, Allouch SB (2019) The internet-of-things: reflections on the past, present and future from a user-centered and smart environment perspective. J Ambient Intell Smart Environ 11(1):45–69

Chong I, Xiong A, Proctor RW (2019) Human factors in the privacy and security of the Internet of Things. Ergon Des 27(3):5–10

Choucri N (2012) Cyberpolitics in international relations. MIT Press, London

Cockton G (2004) Value-centred HCI. In: Proceedings of the Third Nordic Conference on Human-Computer Interaction, pp 149–160

Conti M, Passarella A (2018) The internet of people: a human and data-centric paradigm for the next generation internet. Comput Commun 131:51–65

Conti M, Passarella A, Das SK (2017) The Internet of People (IoP): a new wave in pervasive mobile computing. Pervasive Mob Comput 41:1–27

Cruickshank L, Trivedi N (2017a) Beyond human-centred design: supporting a new materiality in the Internet of Things, or how to design when a toaster is one of your users. Des J 20(5):561–576

Cruickshank L, Trivedi N (2017b) When your toaster is a client, how do you design? Going beyond human centred design. Des J 20(sup1):S4158–S4170

Defiebre D, Germanakos P (2019) Towards a Human-Centered Model in SIoT-enhancing the interaction behaviour of things with personality traits. In: 2019 IEEE SmartWorld, Ubiquitous Intelligence and Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Cloud and Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI), IEEE, pp 1760–1767

Dhelim S, Ning H, Bouras MA, Ma J (2018) Cyber-enabled human-centric smart home architecture. In: 2018 IEEE SmartWorld, Ubiquitous Intelligence and Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Cloud and Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI), IEEE, pp 1880–1886

Dustdar S, Scekic O (2018) On managing the social components in a smart city. In: 2018 IEEE 38th International Conference on Distributed Computing Systems (ICDCS), IEEE, pp 1159–1163

European Commission (2022) Proposal for a regulation of the european parliament and of the council on harmonised rules on fair access to and use of data (data act). https://digital-strategy.ec.europa.eu/en/library/data-act-proposal-regulation-harmonised-rules-fair-access-and-use-data. Accessed 25 Feb 2022

Feng Y, Yao Y, Sadeh N (2021) A design space for privacy choices: Towards meaningful privacy control in the Internet of Things. In: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp 1–16

Feth D, Maier A, Polst S (2017) A user-centered model for usable security and privacy. International conference on human aspects of information security, privacy, and trust. Springer, Cham, pp 74–89

Figueira A, Nunes D, Barbosa R, Reis A, Aguiar H, Sinche S, Rodrigues A, Pereira V, Dias H, Herrera C, et al (2016) WeDoCare: a humanitarian people-centric cyber-physical system for the benefit of refugees. In: 2016 IEEE Global Humanitarian Technology Conference (GHTC), IEEE, pp 213–219

Fuller S (2009) The handbook of science and technology studies.

Garcia-Alonso J, Berrocal J, Canal C, Murillo JM (2016) Towards distributed and context-aware human-centric cyber-physical systems. European conference on service-oriented and cloud computing. Springer, Cham, pp 59–73

Garcia-Alonso J, Berrocal J, Canal C, Murillo JM (2018) Towards distributed and context-aware human-centric cyber-physical systems. In: Advances in Service-Oriented and Cloud Computing: Workshops of ESOCC 2016, Vienna, Austria, September 5--7, 2016, Revised Selected Papers 5, pp 59–73. Springer

Gasson S (2003) Human-centered vs. user-centered approaches to information system design. J Inf Technol Theory Appl (JITTA) 5(2):5

Geerts D, De Moor K, Ketyko I, Jacobs A, Van den Bergh J, Joseph W, Martens L, De Marez L (2010) Linking an integrated framework with appropriate methods for measuring GOE. In: 2010 Second international workshop on quality of multimedia experience (QoMEX), IEEE, pp 158–163

Ghiani G, Manca M, Patern (2017) Personalization of context-dependent applications through trigger-action rules. ACM Trans Comput Hum Interact 24(2):1–33

Giaccardi E, Redström J (2020) Technology and more-than-human design. Des Issues 36(4):33–44

Giannetsos T, Dimitriou T, Prasad NR (2011) People-centric sensing in assistive healthcare: privacy challenges and directions. Secur Commun Netw 4(11):1295–1307

Gracanin D, Lasisi RO, Azab M, Eltoweissy M (2019) Next generation smart built environments: the fusion of empathy, privacy and ethics. In: 2019 First IEEE International Conference on Trust, Privacy and Security in Intelligent Systems and Applications (TPS-ISA), IEEE, pp 260–267

Graeff EEC (2018) Evaluating civic technology design for citizen empowerment. Ph. D. thesis, Massachusetts Institute of Technology

Grundy J (2020) Human-centric Software Engineering for Next Generation Cloud-and Edge-based Smart Living Applications. In: Proceedings 20th IEEE/ACM International Symposium on Cluster, Cloud and Internet Computing, CCGRID 2020, pp 1–10

Hashemi SH, Faghri F, Rausch P, Campbell RH (2016) World of empowered IoT users. In: 2016 IEEE First International Conference on Internet-of-Things Design and Implementation (IoTDI), IEEE, pp 13–24

Hasselbalch G (2021) Data ethics of power: a human approach in the big data and AI era. Edward Elgar Publishing, Cheltenham

Hesselman C, Grosso P, Holz R, Kuipers F, Xue JH, Jonker M, de Ruiter J, Sperotto A, van Rijswijk-Deij R, Moura GC et al (2020) A responsible internet to increase trust in the digital world. J Netw Syst Manag 28(4):882–922

Hochheiser H, Lazar J (2007) Hci and societal issues: a framework for engagement. Int J Hum Comput Interact 23(3):339–374

Huigen J, Cave M (2008) Regulation and the promotion of investment in next generation networks: a European dilemma. Telecommun Policy 32(11):713–721

Ienca M, Wangmo T, Jotterand F, Kressig RW, Elger B (2018) Ethical design of intelligent assistive technologies for dementia: a descriptive review. Sci Eng Ethics 24(4):1035–1055

International Standard (2010) ISO9241-210: ergonomics of human-system interaction. Human-centred design for interactive systems. The International Organisation for Standardisation, Geneva

Jia H, Wu M, Jung E, Shapiro A, Sundar SS (2012) Balancing human agency and object agency: an end-user interview study of the Internet of Things. In: Proceedings of the 2012 ACM Conference on Ubiquitous Computing, pp 1185–1188

Jørgensen RF, Desai T (2017) Right to privacy meets online platforms: Exploring privacy complaints against facebook and google. Nordic J Hum Rights 35(2):106–126

Kaluarachchi T, Reis A, Nanayakkara S (2021) A review of recent deep learning approaches in human-centered machine learning. Sensors 21(7):2514

Karni L, Jusufi I, Nyholm D, Klein GO, Memedi M et al (2022) Toward improved treatment and empowerment of individuals with Parkinson disease: design and evaluation of an Internet of Things system. JMIR Formative Res 6(6):e31485

Kazim E, Koshiyama AS (2021) A high-level overview of AI ethics. Patterns 2(9):100314

Kim HW, Gupta S (2014) A user empowerment approach to information systems infusion. IEEE Trans Eng Manag 61(4):656–668

Kim Y, Park Y, Choi J (2017) A study on the adoption of IoT smart home service: using value-based adoption model. Total Qual Manag Bus Excell 28(9–10):1149–1165

Kong XTR, Luo H, Huang GQ, Yang X (2019) Industrial wearable system: the human-centric empowering technology in Industry 4.0. J Intell Manuf 30(8):2853–2869

Konstan JA, Riedl J (2012) Recommender systems: from algorithms to user experience. User Model User-Adap Inter 22(1):101–123

Kor AL, Yanovsky M, Pattinson C, Kharchenko V (2016) SMART-ITEM: IoT-enabled smart living. In: 2016 Future Technologies Conference (FTC), IEEE, pp 739–749

Koreshoff TL, Leong TW, Robertson T (2013a) Approaching a human-centered Internet of Things. In: Proceedings of the 25th Australian Computer-Human Interaction Conference: Augmentation, Application, Innovation, Collaboration, pp 363–366

Koreshoff TL, Robertson T, Leong TW (2013b) Internet of Things: a review of literature and products. In: Proceedings of the 25th Australian Computer-Human Interaction Conference: Augmentation, Application, Innovation, Collaboration, pp 335–344

Kounelis I, Baldini G, Neisse R, Steri G, Tallacchini M, Pereira AG (2014) Building trust in the human? Internet of Things relationship. IEEE Technol Soc Mag 33(4):73–80

Kounoudes AD, Kapitsaki GM (2020) 9. Mapping of IoT user-centric privacy preserving approaches to the GDPR. Internet of Things 11:100179. https://doi.org/10.1016/j.iot.2020.100179

Kounoudes AD, Kapitsaki GM, Katakis I, Milis M (2021) User-centred privacy inference detection for smart home devices. In: 2021 IEEE Smart World, Ubiquitous Intelligence and Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/IOP/SCI), IEEE, pp 210–218

Krontiris I, Freiling FC (2010) Integrating people-centric sensing with social networks: a privacy research agenda. In: 2010 8th IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops), IEEE, pp 620–623

Kwon H, Fischer JE, Flintham M, Colley J (2018) The connected shower: studying intimate data in everyday life. Proc ACM Interact Mobile Wearable Ubiquitous Technol 2(4):1–22
Law ELC, Van Schaik P (2010) Modelling user experience-an agenda for research and practice. Interact Comput 22(5):313–322
Lee J (2021) The connection of everything: China and the Internet of Things. MERICS, China Monitor. https://merics.org/sites/default/files/2021-06/MericsChinaMonitor70InternetOfThings2.pdf
Lepri B, Oliver N, Pentland A (2021) Ethical machines: the human-centric use of artificial intelligence. IScience 24(3):102249
Levy Y, Ellis TJ (2006) A systems approach to conduct an effective literature review in support of information systems research. Inf Sci 9:181–212
Lindley J, Coulton P, Cooper R (2018) The IoT and unpacking the Heffalump's Trunk. Proceedings of the future technologies conference. Springer, Cham, pp 134–151
Liu C, Julien C (2015) Pervasive context sharing in magpie: adaptive trust-based privacy protection. International conference on mobile computing, applications, and services. Springer, Cham, pp 122–139
Lu C, Tsai C (2019) IoT-enabled cross-field and reconfigurable service provisioning with user-centered design. IEEE Syst J 13(4):4072–4080. https://doi.org/10.1109/JSYST.2019.2901595
Lu Y, Li S, Ioannou A, Tussyadiah I (2019) From data disclosure to privacy nudges: a privacy-aware and user-centric personal data management framework. International conference on dependability in sensor, cloud, and big data systems and applications. Springer, Cham, pp 262–276
Lundberg J, Gustavsson R (2011) Challenges and opportunities of sensor based user empowerment. In: 2011 International Conference on Networking, Sensing and Control. IEEE, pp 463–468
Mähler V (2019) The thing about the Internet of Things: scoping the social science discourse in IoT research. IFIP international Internet of Things conference. Springer, Cham, pp 235–251
Marky K, Prange S, Krell F, Mühlhäuser M, Alt F (2020a) "You just can't know about everything": privacy Perceptions of Smart Home Visitors. In: 19th International Conference on Mobile and Ubiquitous Multimedia, pp 83–95
Marky K, Voit A, Stöver A, Kunze K, Schröder S, Mühlhäuser M (2020b) "I don't know how to protect myself": Understanding Privacy Perceptions Resulting from the Presence of Bystanders in Smart Environments. In: Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society, pp 1–11
Marky K, Zimmermann V, Stöver A, Hoffmann P, Kunze K, Mühlhäuser M (2020c) All in one! user perceptions on centralized iot privacy settings. In: Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems, pp 1–8
Martinez JA, Hernez Ramos JL, Beltran V, Skarmeta A, Ruiz PM (2017) A user-centric Internet of Things platform to empower users for managing security and privacy concerns in the Internet of Energy. Int J Distrib Sens Netw 13(8):16
Memedi M, Tshering G, Fogelberg M, Jusufi I, Kolkowska E, Klein G (2018) An interface for IoT: feeding back health-related data to Parkinson's disease patients. J Sens Actuator Netw 7(1):14
Michael J, Koschmider A, Mannhardt F, Baracaldo N, Rumpe B, Cappiello C, Ruiz M (2019) User-centered and privacy-driven process mining system design for IoT. International conference on advanced information systems engineering, vol 350. Springer, Berlin, pp 194–206
Miller B (2021) Is technology value-neutral? Sci Technol Hum Values 46(1):53–80
Mohanty S, Cormican K, Dhanapathi C (2022) Analysis of critical success factors to mitigate privacy risks in IoT devices. Proced Comput Sci 196:191–198
Mordacchini M, Conti M, Passarella A, Bruno R (2020) Human-centric data dissemination in the IoP: large-scale modeling and evaluation. ACM Trans Auton Adapt Syst (TAAS) 14(3):1–25
Moreno MV, Hernández JL, Skarmeta AF, Nati M, Palaghias N, Gluhak A, Van Kranenburg R (2014) A framework for citizen participation in the Internet of Things. In: 2014 28th International Conference on Advanced Information Networking and Applications Workshops, IEEE, pp 815–820
Moreno-Cano MV, Santa J, Zamora-Izquierdo MA, Skarmeta AF (2015) Future human-centric smart environments, modeling and processing for next-generation big-data technologies. Springer, Berlin, pp 341–365
Mumford E, Weir M (1979) Computer systems in work design-the ETHICS method: effective technical and human implementation of computer systems: a work design exercise book for individuals and groups. Wiley, New York
Nasir A, Lim HB, Soong BH (2012) An integrated vehicular and urban sensing system: Framework and modeling. In: The International Conference on Information Network 2012, IEEE, pp 159–164
Nawaz T, Rinner B, Ferryman J (2016) User-centric, embedded vision-based human monitoring: a concept and a healthcare use case. In: Proceedings of the 10th International Conference on Distributed Smart Camera, pp 25–30
Nunes DS, Zhang P, Silva JS (2015) A survey on human-in-the-loop applications towards an internet of all. IEEE Commun Surv Tutor 17(2):944–965. https://doi.org/10.1109/COMST.2015.2398816
Nurse JRC, Atamli A, Martin A (2016) Towards a usable framework for modelling security and privacy risks in the smart home. In: Human aspects of information security, privacy, and trust: 4th International Conference, HAS 2016, held as Part of HCI International 2016, Toronto, ON, Canada, July 17-22, 2016, Proceedings 4, pp 255–267. Springer
Oppl S, Stary C (2022) Motivating users to manage privacy concerns in cyber-physical settings–a design science approach considering self-determination theory. Sustainability 14(2):900
Oudshoorn N, Pinch T (2003) How users matter: the co-construction of users and technology (inside technology). The MIT Press, London
Padden M, Ajehag Pettersson A (2021) Protected how? Problem representations of risk in the general data protection regulation (GDPR). Crit Policy Stud 15(4):486–503. https://doi.org/10.1080/19460171.2021.1927776
Pereira ÂG, Benessia A, Curvelo P (2013) Agency in the Internet of Things. Publications Office of the European Union. Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC87270
Perera C, Zaslavsky A, Christen P, Georgakopoulos D (2013) Context aware computing for the Internet of Things: a survey. IEEE Commun Surv Tutor 16(1):414–454
Qin P (2021) Based on the full-scene smart community model: analysis on the development and challenges of the home-use of Internet of Things in china. In: 2021 International Conference on Computer, Internet of Things and Control Engineering (CITCE), IEEE, pp 92–95
Raake A, Egger S (2014) Quality and quality of experience. Springer International Publishing, Cham, pp 11–33
Ramos G, Suh J, Ghorashi S, Meek C, Banks R, Amershi S, Fiebrink R, Smith-Renner A, Bansal G (2019) Emerging perspectives in human-centered machine learning. In: Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems, pp 1–8
Rantos K, Drosatos G, Demertzis K, Ilioudis C, Papanikolaou A, Kritsas A (2018) ADvoCATE: a consent management platform for personal data processing in the IoT using blockchain technology. International conference on security for information technology and communications. Springer, Cham, pp 300–313

Rao PM, Deebak B (2022) Security and privacy issues in smart cities/industries: technologies, applications, and challenges. J Ambient Intell Humaniz Comput 13:1–37

Rivadeneira JE, Silva JS, Colomo-Palacios R, Rodrigues A, Fernandes JM, Boavida F (2021) A privacy-aware framework integration into a human-in-the-loop IoT system. In: IEEE INFOCOM 2021-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), IEEE, pp 1–6

Rizvi S, Williams I, Campbell S (2022) Tui model for data privacy assessment in IoT networks. Internet of Things 17:100465

Rohan R, Funilkul S, Pal D, Thapliyal H (2021) Humans in the loop: cybersecurity aspects in the consumer IoT context. IEEE Consum Electr Mag 11(4):78–84

Royakkers L, Timmer J, Kool L, van Est R (2018) Societal and ethical issues of digitization. Ethics Inf Technol 20(2):127–142

Russell S (2019) Human compatible: artificial intelligence and the problem of control. Penguin, London

Santos J, Rodrigues JJPC, Casal J, Saleem K, Denisov V (2018) Intelligent personal assistants based on Internet of Things approaches. IEEE Syst J 12(2):1793–1802. https://doi.org/10.1109/JSYST.2016.2555292

Sawyer S, Jarrahi MH (2014) Sociotechnical approaches to the study of information systems, computing handbook, third edition: information systems and information technology. CRC Press, London, pp 1–5

Scargill T, Chen Y, Eom S, Dunn J, Gorlatova M (2022) Environmental, user, and social context-aware augmented reality for supporting personal development and change. In: 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), IEEE, pp 155–162

Schemmer T, Brauner P, Schaar AK, Ziefle M, Brillowski F (2020) User-centred design of a process-recommender system for fibre-reinforced polymer production. International conference on human-computer interaction. Springer, Cham, pp 111–127

Schneider H, Eiband M, Ullrich D, Butz A, (2018) Empowerment in HCI-A survey and framework. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, pp 1–14

Schulz T (2014) Creating universal designed and trustworthy objects for the Internet of Things. In: Zaphiris P, Ioannou A (eds) Learning and collaboration technologies. Technology-rich environments for learning and collaboration. Springer International Publishing, Cham, pp 206–214

Semeria MN (2016) Symbiotic low-power, smart and secure technologies in the age of hyper connectivity. In: 2016 IEEE International Electron Devices Meeting (IEDM), IEEE, pp 1–3

Sen A, Fletcher K, Madria S (2019) A Secure User-Centric Framework for Dynamic Service Provisioning in IoT Environments. In: 2019 18th IEEE International Conference on Trust, Security and Privacy in Computing and Communications/13th IEEE International Conference on Big Data Science And Engineering (TrustCom/BigDataSE), pp 334–341

Shaikh T, Ismail S, Stevens JD (2016) Aura Minora: a user centric IOT architecture for Smart City. In: Proceedings of the International Conference on Big Data and Advanced Wireless Technologies, pp 1–5

Shin DH, Park YJ (2017) Understanding the Internet of Things ecosystem: multi-level analysis of users, society, and ecology. Digit Policy Regul Gov 19(1):77–100

Shneiderman B (2020) Human-centered artificial intelligence: reliable, safe and trustworthy. Int J Hum-Comput Interact 36(6):495–504

Showail A, Tahir R, Zaffar MF, Noor MH, Al-Khatib M (2022) An internet of secure and private things: a service-oriented architecture. Comput Secur 120:102776

Sicari S, Rizzardi A, Grieco LA, Coen-Porisini A (2015) Security, privacy and trust in Internet of Things: the road ahead. Comput Netw 76:146–164

Sloane M (2019) Inequality is the name of the game: thoughts on the emerging field of technology, ethics and social justice. In: Weizenbaum Conference, DEU, p 9

Soegaard M, Dam RF (2012) The encyclopedia of human-computer interaction. The Interaction Design Foundation, Aalborg, Denmark

Sovacool BK, Del Rio DDF (2020) Smart home technologies in Europe: a critical review of concepts, benefits, risks and policies. Renew Sustain Energy Rev 120:109663

Stead MR, Coulton P, Lindley JG, Coulton C (2019) The little book of sustainability for the Internet of Things. Imagination Lancaster, Lancaster, UK

Stephanidis C, Salvendy G, Antona M, Chen JY, Dong J, Duffy VG, Fang X, Fidopiastis C, Fragomeni G, Fu LP et al (2019) Seven HCI grand challenges. Int J Hum-Comput Interact 35(14):1229–1269

Streitz N (2017) Reconciling humans and technology: the role of ambient intelligence. European conference on ambient intelligence. Springer, Cham, pp 1–16

Streitz N (2019) 2. Beyond smart-only cities: redefining the smart-everything paradigm. J Ambient Intell Humaniz Comput 10(2):791–812. https://doi.org/10.1007/s12652-018-0824-1

Streitz NA (2021) From smart-only cities towards humane and cooperative hybrid cities. Technoll Architect+ Des 5(2):127–133

Streitz N, Charitos D, Kaptein M, Böhlen M (2019) Grand challenges for ambient intelligence and implications for design contexts and smart societies. J Ambient Intell Smart Environ 11(1):87–107

Suryanegara M, Prasetyo DA, Andriyanto F, Hayati N (2019) A 5-step framework for measuring the quality of experience (GOE) of Internet of Things (IoT) services. IEEE Access 7:175779–175792

Sylla T, Chalouf MA, Krief F, Samaké K (2019) Towards a context-aware security and privacy as a service in the Internet of Things. IFIP international conference on information security theory and practice. Springer, Cham, pp 240–252

The European Parliament and the Council of the European Union (2016) Regulation (eu) 2016/679 of the european parliament and of the council of 27 april 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing directive 95/46/ec (general data protection regulation). Official Journal of the European Union L 119/1

The European Parliament (2022) European declaration on digital rights and principles for the next decade. The European Parliament, Brussels

Tiersen F, Batey P, Harrison MJ, Naar L, Serban AI, Daniels SJ, Calvo RA et al (2021) Smart home sensing and monitoring in households with dementia: user-centered design approach. JMIR Aging 4(3):e27047

Toumia A, Szoniecky S, Saleh I (2020) ColPri: towards a collaborative privacy knowledge management ontology for the Internet of Things. In: 2020 Fifth International Conference on Fog and Mobile Edge Computing (FMEC), pp 150–157

Turunen M, Sonntag D, Engelbrecht KP, Olsson T, Schnelle-Walka D, Lucero A (2015) Interaction and humans in Internet of Things. IFIP conference on human-computer interaction. Springer, Cham, pp 633–636

Valenzuela-Valdes JF, Lopez MA, Padilla P, Padilla JL, Minguillon J (2017) Human neuro-activity for securing body area networks: application of brain-computer interfaces to people-centric Internet of Things. IEEE Commun Mag 55(2):62–67. https://doi.org/10.1109/MCOM.2017.1600633CM

Van Kranenburg R, Bassi A (2012) Iot challenges. Communications in mobile. Computing 1(1):1–5

Voas J, Kuhn R, Laplante P, Applebaum S (2018) Internet of Things (IoT) trust concerns. NIST Tech Rep 1:1–50

Wagner B (2019) Liable, but not in control? Ensuring meaningful human agency in automated decision-making systems. Policy Internet 11(1):104–122. https://doi.org/10.1002/poi3.198
Wang S, Bolling K, Mao W, Reichstadt J, Jeste D, Kim HC, Nebeker C (2019) Technology to support aging in place: older adults perspectives. Healthcare, vol 7. Multidisciplinary Digital Publishing Institute, London, p 60
Watt S, Milne C, Bradley D, Russell D, Hehenberger P, Azorin-Lopez J (2016) Privacy matters-issues within mechatronics. IFAC-Papers OnLine 49(21):423–430
Wechsung I, De Moor K (2014) Quality of experience versus user experience. Springer International Publishing, Cham, pp 35–54
Wickramasinghe CI, Reinhardt D (2019) A survey-based exploration of users' awareness and their willingness to protect their data with smart objects. In: Privacy and Identity Management, pp 427–446
Wickramasinghe CI, Reinhardt D (2021) A user-centric privacy-preserving approach to control data collection, storage, and disclosure in own smart home environments. International conference on mobile and ubiquitous systems: computing, networking, and services. Springer, Cham, pp 190–206
Winter J (2015) Algorithmic discrimination: Big data analytics and the future of the Internet, The future internet. Springer, Cham, pp 125–140
Wong B (2021) Problems with controller-based responsibility in EU data protection law. Int Data Privacy Law 11(4):375–387
Worthy P, Matthews B, Viller S (2016) Trust me: doubts and concerns living with the Internet of Things. In: Proceedings of the 2016 ACM Conference on Designing Interactive Systems, pp 427–434
Wright P, McCarthy J (2010) Experience-centered design: designers, users, and communities in dialogue. Synth Lect Hum Cent Inf 3(1):1–123
Yao Y, Basdeo JR, Mcdonough OR, Wang Y (2019a) Privacy perceptions and designs of bystanders in smart homes. Proc ACM Hum-Comput Interact 3(CSCW):1–24
Yao Y, Basdeo JR, Kaushik S, Wang Y (2019b) Defending my castle: A co-design study of privacy mechanisms for smart homes. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, pp 1–12
Ystgaard KF, De Moor K (2021) Bring the human to the network: 5G and beyond. In: 2021 28th International Conference on Telecommunications (ICT), IEEE, pp 1–7
Zaric N, Djurisic MP, Mihovska A (2016) Ambient assisted living systems in the context of human-centric sensing and IoT concept: eWall case study. 2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications Workshop, pp 1–7
Zimmermann V, Gerber P, Marky K, Böck L, Kirchbuchner F (2019) Assessing users privacy and security concerns of smart home technologies. i-com 18(3):197–216
Zuboff S (2019) The age of surveillance capitalism: the fight for a human future at the new frontier of power: Barack Obama's books of 2019. Profile Books Ltd