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User experience key performance indicators for industrial IoT systems: A multivocal literature review

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ABSTRACT

In software systems, user experience (UX) is a quality that provides value to its intended users. Therefore, we consider it critical to manage UX and its link to business value quantitatively. Key performance indicators (KPIs) have been widely adopted for objectively measuring factors that influence business success, including measuring UX characteristics and their business contribution in the context of software systems in general. Yet, measuring UX in the context of complex Internet of Things (IoT) systems, especially Industrial IoT (IIoT) systems, remains a challenge.

This paper presents a multivocal literature review (MLR) of the UX-KPIs proposed in the context of (I)IoT systems, along with factors influencing UX and challenges of quantifying UX. We investigate the status quo and derive recommendations for measuring the UX of (I)IoT systems.

Our analysis of 64 publications shows that UX has so far received relatively little attention in the context of (I)IoT. Although we identified 605 KPIs, 78 influencing factors, and 119 challenges, most of the UX features discussed were defined in a broader context of software systems, i.e., they were less specific to IoT, but rather focused on universal system quality characteristics such as functional suitability, performance efficiency, usability, and reliability.

Finally, no generally accepted approach for measuring UX in (I)IoT systems and how these contribute to the overall business value has been proposed yet. We also found little evidence that improving UX or achieving a good UX currently plays an explicit role in the design and development of IoT systems.

1. Introduction

Organizations traditionally follow financial metrics to evaluate and assess their *business success*. No generally accepted model for measuring business success has yet been established, but approaches such as the Balanced Scorecard (Kaplan & Norton, 1996) show that measuring a firm's long-term success requires various success dimensions to be measured and monitored (Meskendahl, 2010). Transparent metrics, including appropriate key performance indicators (KPIs), support managing success by helping to evaluate the business performance against the key business objectives (Helmold, 2019). A growing number of companies are deploying Internet of Things (IoT) systems to improve their business performance and support operational processes within and outside of the company. The user experience (UX) is a high-level

quality that adds value for a software system's intended users and should be considered during development.

In the context of socio-technical systems, such as digital ecosystems (Nass-Bauer & Trapp, 2019), product service systems (PSS; Morelli, 2006), digital twins (Negri, Fumagalli, & Macchi, 2017), or IoT (Asghari, Rahmani, & Javadi, 2018; Shin, 2014), measuring business success depends not only on technical aspects – such as interconnectivity or interoperability among different systems – but also, among other things, on the performance of the system for the end customer (e.g., product quality), the UX (particularly the interaction of system users), and the related business success (e.g., cost savings). The engineering of such complex systems requires the involvement of various disciplines (Mo & Beckett, 2020) and harnessing the potential value of such systems implies managing and controlling their inherent complexity (Lammabhi-

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Lagarigue et al., 2017).

Usability and customer satisfaction are difficult to measure (Jain, Aagja, & Bagdare, 2017; Hornbæk, 2006). According to Weader and Schmidt-Subramanian (2022), about 54% of Customer Experience (CX) teams struggle to demonstrate their positive impact on a firm's Return on Investment (ROI). Here, KPIs can be used to measure the impact and degree of UX-related success and can be translated into numerical metrics. UX-KPIs can be defined using behavioral metrics to measure users' actions (e.g., a website's abandonment rate) and attitudinal metrics to measure UX efficiency (e.g., a customer survey on brand awareness), but optimally, they should both be used (Zhao, 2022). UX-KPIs indicate the success of a software system in terms of its UX (meeting user needs) and should be aligned with business goals to establish relationships between UX-driven value (e.g., better usability leads to time savings) and associated business value (e.g., time savings lead to 12% cost reduction). A KPI should typically be quantified (made measurable) using one or more metrics to capture corresponding data (measurements) and associated business goals.

With increasing system complexity, the appropriate UX is becoming more difficult to define, measure, and evaluate. Indeed, UX is no longer limited to the way a person interacts with a single device, but extends to the interaction with a fully interconnected environment; essentially an *ecosystem of experiences* (Bergman, Olsson, Johansson, & Rassmus-Gröhn, 2018). Therefore, it is necessary to think of UX from a system perspective that includes multiple devices, physical hardware, the properties of networks, the business context, and underlying technology aspects (Rowland & Charlier, 2015).

In just over a decade, the IoT has established itself firmly in people's personal and professional lives. With these systems still evolving, verification and validation activities are primarily concerned with ensuring that the IoT system delivers on its functional promises and, from a quality standpoint, that its complexity induces minimal delay or interruption. Yet, UX has generally not been considered explicitly, although a demonstrable impact of UX can be directly related to benefits. These include increased attractiveness of an IoT system to the organization managing it, increased satisfaction and efficiency of the people interacting with the IoT system (i.e., end-users), and increased strategic advantages for the organization developing these systems (Rowland, Goodman, Charalier, Lui, & Light, 2015).

For example, Lin, Sommer, and Ahmed-Kristensen (2021) studied whether non-IoT watches and IoT watches differ in terms of their UX. They found that both types of watches provide the same level of pleasurable to users. The authors concluded that it is essential for UX designers to understand how IoT watches interact with other devices in a network when designing their usability and functionality to improve the UX. We argue that UX should not be overlooked in the context of IoT systems and requires further research (Bergman et al., 2018; Rodrigues, Genesio, Paiva, & Fortes, 2020). To close this gap and set a baseline for further research on measuring and controlling user experience, specifically its contribution to the business success of IoT systems, we performed a systematic multivocal literature review (MLR; Garousi, Felderer, & Mäntylä, 2019) to answer the following research questions:

- **RQ1:** What are the key performance indicators of the user experience of IoT systems, in particular Industrial IoT systems?
- **RQ2:** What context factors influence the user experience of IoT systems, in particular Industrial IoT systems?
- **RQ3:** What challenges are unique to the design and evaluation of user experience of IoT systems, in particular Industrial IoT systems?

Research question RQ1 asks about relevant indicators of the UX of IoT systems that are aligned with the systems' business value. Research question RQ2 probes the context-specific factors that may influence these UX-KPIs and thus should be considered in order to properly interpret and to control them. Finally, research question RQ3 explores the challenges associated with evaluating the UX of IoT systems,

including challenges related to defining, measuring, and interpreting UX-KPIs and their influencing factors.

This article makes two contributions:

1. We present an MLR of key performance indicators related to user experience in the context of Industrial IoT systems.
2. We identify the remaining research gap, suggesting future research directions towards better understanding the relationship between IoT systems and user experience.

The remainder of the article is structured as follows. Section 2 presents the theoretical background of IoT, KPIs, and UX. The study design is presented in Section 3. The results of the conducted literature review are presented in Section 4, and the theoretical and managerial implications are discussed in Section 5. The limitations of this study are discussed in Section 6, and the final section provides a summary of the results and opportunities for future studies.

2. Background

This paper explores key performance indicators (KPI) of user experience (UX) in the context of the Industrial Internet of Things (IIoT). This section provides definitions of the associated core concepts. In Section 2.1, we first introduce IoT concepts and definitions. In Section 2.2, we then describe what KPIs and variation factors are, and outline their strategic importance for achieving business goals. In Section 2.3, we define UX and associated metrics. Section 2.4 ties all three concepts together.

2.1. Internet of things (IoT) and industrial IoT (IIoT)

The Internet of Things (IoT) represents a network that connects physical objects ("things"), such as sensors, machines, or cars, through wireless protocols within an overall interconnected system (Asghari et al., 2018; Jeschke, Brecher, Meisen, Özdemir, & Eschert, 2016; Li, Xu, & Zhao, 2015). The IoT can be realized as a result of the convergence of three visions: Internet-oriented vision (middleware), things-oriented vision (sensors), and semantic-oriented vision (knowledge). The IoT is not a domain-specific concept, and applications can be found in a wide variety of domains, including industry, healthcare, agriculture, mobility, energy, and smart cities (Atzori, Iera, & Morabito, 2010; Gubbi, Buyya, Marusic, & Palaniswami, 2013). Within this domain, the Industrial IoT (IIoT) forms a subdomain (cf. Atzori et al., 2010). Therefore, whenever we refer to IoT systems in this paper, it implies that the IoT comprises the IIoT as well (i.e., it may be read as "(I)IoT"). We will only use the term "IIoT" whenever we specifically mean the subdomain of Industrial IoT. Atzori et al. (2010) found that IIoT applications comprise around 10% of all considered IoT systems. Jeschke et al. (2016) consider IIoT a technological movement that is largely synonymous with Industry 4.0 except that it is less concerned with its expected economic impact. In line with Boyes, Hallaq, Cunningham, and Watson (2018), we define IIoT as "a complex system consisting of cyber-physical assets and associated information technologies in an industrial context that creates value by improving the maintenance, productivity, and efficiency of industrial value creation processes."

2.2. Key performance indicators and variation factors

KPIs generally refer to quantifiable indicators of progress towards an intended result. A high-level KPI could, for example, indicate the overall performance of a business, while a low-level KPI may focus on processes, products, employees, or departments (Helmold, 2019). In practice, the terms KPI and metric are often used interchangeably. However, this can lead to potential confusion over monitoring and controlling the achievement of KPIs because "you cannot control what you cannot measure" (Demarco, 1986). Yet, when KPIs are defined as well-

established measurable parameters in business management, they help achieve organizational goals and enable controllers to capture, monitor, and evaluate the performance of a business and its processes (Roubtsova & Michell, 2013). The success of KPIs depends on their appropriateness for the management objectives at hand, their mutual alignment, and the suitability of the metrics for quantifying them.

In addition to KPIs, the area of goal-oriented measurement introduces the concept of the *variation factor* (Basili et al., 2014). A variation factor refers to a context characteristic that may influence a quality characteristic of interest, e.g., a product's usability, and thus the associated KPI. Variation factors do not directly indicate a specific quality characteristic, but their impact on specific quality characteristics must be understood in order to be able to properly interpret a KPI in a given context. For example, the usability of a product could be influenced by the user's familiarity with the product (variation factor), on which their assessment of the product's usefulness depends (KPI). In this case, usability and UX directly influence the actual utility the product creates.

2.3. User experience (UX)

A leading standard on UX is ISO 9241-210 (ISO, 2019), which defines UX as "a person's perceptions and responses that result from the use and/or anticipated use of a product, system or service." The term includes the expectations before and during the use of a product or service, but also a user's potential emotions after finishing their task with the product. Fulfilling all the needs of the user is the most important requirement for achieving an outstanding UX (Norman & Nielsen, 2022), and can be further augmented by hedonic qualities, which help achieve simple and elegant products that are a joy to use (Hassenzahl, 2010). However, UX extends well beyond a software product. Companies must assure that they create a seamless combination of their services – including software engineering, industrial and interface design, and even marketing – into a holistic overall concept that the user also perceives as such. In turn, the quality of the UX directly affect the perception of the system.

Due to the changes in what users have come to expect from technology, UX has to adapt continuously. Specific UX measurements are often too complex or specific for managerial decision-making when evaluating whether the UX has improved over time or not. Providing good UX for IoT, in particular, poses a great challenge, with more stakeholder groups and a greater variety of hardware and software interfaces to consider (Elizalde, 2017). For example, throughout the development and operation of the IoT system, relevant stakeholder groups include workers operating the machine, management teams measuring and evaluating production, developers building and technicians maintaining the IoT system, and customers purchasing the system.

2.4. Interplay of concepts

The intersections among the three domains discussed in this paper – IoT, KPIs and UX – can be typified as follows:

IoT-KPIs help assure the success of an IoT system by making sure it follows a value-driven engineering approach. This is done by establishing causal relationships between goals – measured through appropriate KPIs – and organizational strategies to deliver the IoT offering as value propositions to stakeholders. Establishing an appropriate set of KPIs for an IoT business should be based on four key aspects: whether (1) products can be connected, (2) customers will adopt the digital service, (3) an ecosystem can be offered to develop an IoT business, and (4) profits can be made (Lamprecht, Gebauer, Fleisch, & Wortmann, 2022).

UX-KPIs are measured from a customer viewpoint, which distinguishes them from technical KPIs (such as IoT-KPIs) and business KPIs. Appropriate UX-KPIs can be developed using UX questionnaires (Hinderks, Schrepp, Domínguez Mayo, Escalona, & Thomaschewski, 2019). Measuring these KPIs help assure that customer satisfaction is achieved. On the one hand, this relates to improved experience with a system in terms of usability, performance, and reliability, among other things. On

Table 1
Types of information sources and search tools.

	White literature	Gray literature
Electronic database	Scopus database https://www.scopus.com/	Google Search https://www.google.com/
Information sources	Peer-reviewed publications: <ul style="list-style-type: none"> ■ Journals ■ Conference proceedings ■ Workshop proceedings 	Non-peer-reviewed publications: <ul style="list-style-type: none"> ■ Books and book chapters ■ Article preprints, e.g., arXiv^a ■ Whitepapers and technical reports ■ Blog posts and press releases ■ Theses (Master and PhD) ■ Seminars, lectures, slide decks

^a <https://arxiv.org/>.

the other hand, this is driven by how well customers' expectations and values are met, such as perceived safety and security, value for money, and quality of the rollout process.

Measuring **UX aspects of an IoT system** helps to make sure that it addresses the stakeholder needs, enhancing its business success. During design and implementation, ensuring that the correct UX aspects are addressed helps to take a stronger customer-centric business model perspective. If UX aspects of an IoT system are measured using KPIs, we can speak of **IoT UX-KPIs**. Beyond typical UX-KPIs, these take the complexity of IoT systems into account, and beyond typical IoT-KPIs, they add customer satisfaction to the technical and business focus.

3. Study design

In this section, we describe the design of our literature review, summarizing the overall review approach, the search strategy, the information sources used, the inclusion and exclusion criteria, and the methodology used to obtain the results.

3.1. Study approach

We performed a multivocal literature review (MLR; Garousi et al., 2019), a form of systematic literature review that includes *gray literature* (GLR; i.e., non-peer reviewed publications, such as technical reports, whitepapers, seminars, blog posts, or press releases) in addition to *white literature* (WLR; i.e., peer-reviewed publications such as conference and journal articles).

We followed the method proposed by Garousi et al. (Garousi et al., 2019), which builds upon Kitchenham's guidelines for systematic literature reviews (Kitchenham & Charters, 2007). Wherever possible, we consistently applied our review design to both the white literature review (WLR) and the gray literature review (GLR) to enable joint analysis and interpretation of the outcomes.

3.2. Information sources

We considered various white and gray literature sources in our MLR. Table 1 summarizes the types of information sources and the electronic databases we used for the review. The focus of the white literature was on peer-reviewed publications of primary studies. For the gray literature review, we initially intended to employ multiple search tools to avoid any outcome bias associated with the search algorithms of a specific search engine. Google Search is an established search engine for gray

literature searches (Adams et al., 2016; McGrath, Sumnall, Edmonds, McVeigh, & Bellis, 2006). However, with the exception of Google Search, none of the other search tools tested (DuckDuckGo,¹ Bing,² Yahoo Search,³ Ask,⁴ and Ecosia⁵) supports advanced search operators such as *AND*, *OR*, and *AROUND* for constructing search queries, and the use of simplified search strings yielded poor results (e.g., advertisements instead of useful publications). As a result, Google Search was the only search engine that fulfilled the requirements for our gray literature search.

3.3. Inclusion and exclusion criteria

To identify publications eligible for the review, we defined a set of inclusion and exclusion criteria. To avoid potential deviations in the classification of the publications by the researchers involved in the study, the criteria were discussed among the researchers to ensure a consistent understanding. Table 2 presents the final set of inclusion and exclusion criteria. **Since IoT and IIoT represent a relatively new topic, we did not include any constraint on the publication date and thus did not define any corresponding inclusion/exclusion criteria – neither for the gray literature nor for the white literature search.** The search results confirmed this assumption as it did not result in excessive numbers of publications encompassing a large time range (the reviewed publications cover the years 2015–2021). To ensure comparability of the white and gray literature reviews, we used a consistent set of criteria for both types of literature. The only exception was that we allowed German-language publications to be included for the gray literature. In this way, we hoped to find a larger number of relevant publications, such as whitepapers, reports, and academic theses, which, in contrast to the scientific white literature, are often published in a local language. Differences in the formulation of the gray literature criteria in Table 2 are marked in bold.

3.4. Search terms and queries

Based on the research questions (see Section 1) and the main aspects they address, we derived the associated search terms, which are presented in Table 3.

After testing several alternative search queries, we decided to build search queries upon two main study topics: user experience (UX) and Internet of Things (IoT). Because the test search on white literature resulted in relatively few hits, we decided to use a more generic search query and invest more effort to review the search outcomes. We first searched through publications' titles using the following query:

```
("user experience" OR "ux" OR "usability" OR "ease of
use" OR "customer satisfaction" OR "user satisfac-
tion" OR "qoe" OR "quality of experience") AND
("internet of things" OR "iot" OR "industrial
internet")
```

For the purpose of the gray literature review, this search query turned out to be mostly too inclusive, producing too many hits, and a review of the first 50 hits revealed that it often contained irrelevant results, including product offers and websites of IoT system developers. Some words, such as “measure”, introduced further irrelevant results. Moreover, search strings typically match text-based content in a document, regardless of its exact location in text. In consequence, it is possible that a search query will match a long document that discusses

Table 2

Inclusion and exclusion criteria used in the white (WRL) and gray (GLR) literature reviews.

	ID	Review	Criterion
Inclusion	IC1	Both	The work focuses on user experience key performance indicators of IoT or IIoT systems or context factors influencing user experience.
	IC2	Both	The work focuses on challenges in designing and evaluating the user experience of IoT systems, in particular that of industrial IoT.
Exclusion	EC1	Both	The work does not fulfill IC1.
	EC2	Both	The work is not accessible even after contacting the authors.
	EC3	WLR	The work is not primarily written in English.
		GLR	The work is not primarily written in English or German .
	EC4	Both	The work is an exact duplicate of another study. This includes, for instance, multiple versions or extensions of the same publication, which in principle present the same content.
EC5	WLR	The work is a white literature publication, that is, a peer-reviewed article published in a journal or conference proceedings and represents a primary study.	
	GLR	The work is not a white literature publication, that is, a peer-reviewed article published in a journal or conference proceedings and does not represent a primary study.	
EC6	Both	The work is not a full (proper) publication in the sense of EC5; for example, it is a secondary or tertiary study, a short research article (3 pages or less), a review or recension of another publication, a foreword, a few-lines description of a project, or a job offer.	

Table 3

Search terms.

Aspect (Keyword)	Synonyms and abbreviations
User experience	UX, usability, ease of use, customer/user satisfaction, Quality of Experience, QoE
Key performance indicators	KPI, measurement, quantification, measure, metrics, evaluation, testing, validation
Internet of Things Challenges	IoT, IIoT, industrial internet of things problems, threats, issues

IoT in one chapter and UX in an entirely unrelated chapter. To counteract this phenomenon, we replaced the *AND* operator with *AROUND* (), which forces Google Search to match results in which the keywords are at best only a specified number of words apart. Therefore, we excluded a few keywords that we had found to lead to irrelevant results, and set the proximity threshold to 100 words. Our final search consisted of executing three search strings (Table 4), which could not be combined into a single search string due to specific parameters.

3.5. Review process

The process of the white and gray literature review mostly followed the same steps and, to facilitate synthesis at a later stage, used the same templates for publication selection and for data extraction. The only difference was the snowballing phase, which was performed only in the white literature review. The review involved a total of six researchers. Depending on the amount of effort required, at least two researchers performed the same review task to avoid individual bias. First, the researchers simultaneously performed the same review task independent of one another, and then discussed their individual outcomes to reach a final decision. To reduce the amount of individual work, during the abstract and full review, the publications returned by the search query were divided into two parts, each of which was then reviewed by a different pair of researchers. The search and review results were

¹ <https://duckduckgo.com/>

² <https://www.bing.com/>

³ <https://search.yahoo.com/>

⁴ <https://www.ask.com/>

⁵ <https://www.ecosia.org/>

Table 4
Search strings used for gray literature search.

No.	Search String
1	("user experience" OR "ux" OR "ease of use") AND ("iot" OR "internet of things") AND ("kpi" OR "validate" OR "measure")
2	("user experience" OR "ux" OR "usability" OR "ease of use" OR "design" OR "user satisfaction") AROUND(10) ("internet of things" OR "iot" OR "industrial internet") AROUND(10) ("key performance indicator" OR "perform*" OR "kpi" OR "metrics" OR "validation")
3	("user experience" OR "ux" OR "usability" OR "ease of use" OR "customer satisfaction" OR "user satisfaction") AROUND(100) ("internet of things" OR "iot" OR "industrial internet") AROUND(100) ("key performance indicator" OR "kpi")

systematically logged to make the process transparent and replicable. Fig. 1 provides a graphic overview of the review process. Rows represent review tasks and columns represent the task flows of the white and gray literature review ("WLR" and "GLR", respectively), including the number of experts performing the same task (numbers in parentheses) and the number of publications accepted for the next phase.

The process started with one researcher executing the predefined search query in the selected electronic databases (Scopus, Google). We performed the search in September 2021. Next, the publications were screened with respect to the inclusion and exclusion criteria. White literature publications were screened based first on the title and subsequently on the abstract, whereas gray literature publications were screened based on a description, summary, or the first 500 words of the document (if a summary or abstract was not explicitly distinguishable). Each expert performed this review individually for all publications, followed by discussions and reconciliation of disagreements among the experts. The white literature review was extended with one iteration of snowballing (cf. Wohlin, 2014), through which additional publications cited in the identified articles (forward snowballing) or that cited the identified articles (backward snowballing) could be included. The articles identified in the snowballing phases were screened according to the inclusion and exclusion criteria based on their titles and abstracts. Finally, the included white and gray literature publications were read and the relevant information was extracted and documented in the data extraction form (see Appendix 9.3 for an overview of the form).

Information extraction for KPIs, variation factors, and challenges was performed separately for the white and gray literature, with frequent alignments between these reviews to ensure compatibility between the classifications used. The classification was carried out by one researcher and critically reviewed by another, following which questions and disagreements were reconciled. The classification considered all available texts related to a KPI, variation factor, or challenge to prevent misattributions. For example, in one publication, a KPI entitled "performance" was meant by the authors to refer to the quality of *reliability* rather than *performance efficiency*. The outcomes were then merged, with a variable indicating the source in order to differentiate between findings from the white and gray literature.

The merged results could then be further reviewed to identify duplicates. Because these KPIs were obtained from different sources and domains, this had to be done carefully to prevent judgment errors. For example, sometimes different terminologies were used that meant the same thing, while similar-sounding entries might take different perspectives or address a different part of an IoT platform's operation. The results were structured in order to provide a title for each entry, a description based on the source(s), a reference to its source(s), classification of the entry, and, in the case of KPIs, also a metric definition if one was provided in the source publication.

4. Results

In Section 4.1, we first summarize the included publications with

respect to their basic demographic characteristics. In Section 4.2, we introduce the classification scheme according to which we organized the products of our literature review. The subsequent sections present a detailed analysis and discussion of the review outcomes. Each section addresses one of our research questions separately. UX-KPIs are discussed in Section 4.3, variation factors in Section 4.4, and challenges in Section 4.5. Lastly, in Section 5, we discuss how the outcomes contribute to answering our research questions.

4.1. Overview of studies

4.1.1. Demographic characteristics

The literature review yielded a total of 64 publications included in our full review: 38 from the white literature and 26 from the gray literature. Fig. 2 summarizes the distribution of the papers across publication years; note that one gray literature paper is not shown because it had no publication date. The publication years ranged from 2015 [W06; W31; W32; G14; G16; G17; G20; G23]⁶ to 2021 [W05; W14; W18; W35; W36; G06],⁷ which suggests that the topic of measuring UX-KPIs of IoT systems was not discussed in the literature before 2015. We also observed a peak of white literature publications in 2019, while the gray literature showed no clear trend.

Fig. 3 summarizes the type of the papers. The white literature consisted of journal and conference papers, with the former being the predominant publication type. The gray literature predominantly consisted of blog posts and non-peer-reviewed magazine articles. Please refer to the Appendix, Section 9.5, for the classification of the publications and the detailed demographic data. We provide the complete list of primary studies with corresponding categories in Appendices 9.7 and 9.8.

Only a small subset of 12 publications (19.0%) [W04; W12; W24; W31; G01; G05; G09; G10; G13; G17; G19; G21] explicitly addressed the subdomain of Industrial IoT (see Fig. 4). Publications that did include Industrial IoT placed these systems into the general context of IoT systems, while a majority of publications focused on non-industrial IoT systems.

In most cases, the publications either considered multiple domains ('cross-domain') or did not specify any domain (see Fig. 5). Still, a large share of about 38% of the publications focused on a specific IoT domain or addressed particular systems such as smart devices (e.g., in the context of entertainment systems, smart home, wearables), or services within a single domain, such as smart home [W01; W02; W23; W35], smart wearables [W05], or smart public communication systems [W15; W18; W27]. All publications that specifically addressed Industrial IoT systems were cross-domain, except [W12], which did not specify one.

4.1.2. Information content

The number of relevant information points from the perspective of research questions (i.e., KPIs, variation factors, and challenges) varied between publications, both for the white and the gray literature. Fig. 6 and Fig. 7 visualize the distribution of the counts across the reviewed publications. These were sorted by the number of KPIs identified in the publications to reveal any possible association between the number of KPIs, the variation factors, and the challenges found in each publication. However, neither in the white nor in the gray literature does such an association become evident.

Regarding existing key performance indicators of user experience (RQ1), we identified a total of 730 KPIs – 352 KPIs in the white literature and 677 in the gray literature publications. Both Fig. 6 and Fig. 7 suggest that there are "outlier" publications that provided significantly more KPIs than any of the remaining publications: one in the white literature

⁶ The list of primary studies from the white literature is provided in the Appendix, Section 9.7.

⁷ The list of primary studies from the gray literature is provided in the Appendix, Section 9.8.

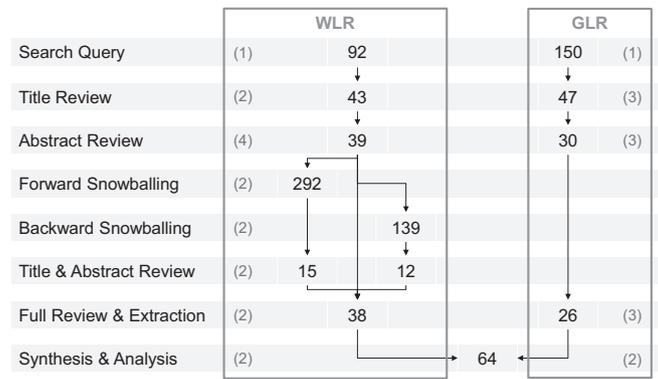


Fig. 1. Review process, including the number of researchers involved (in parentheses) and the number of publications considered.

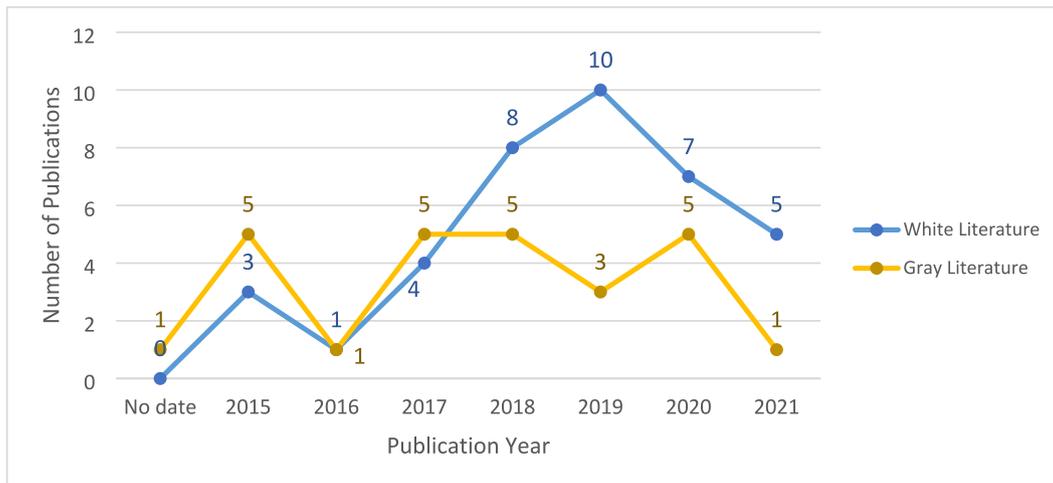


Fig. 2. Time distribution of reviewed publications (for one gray literature publication, the date was not available).

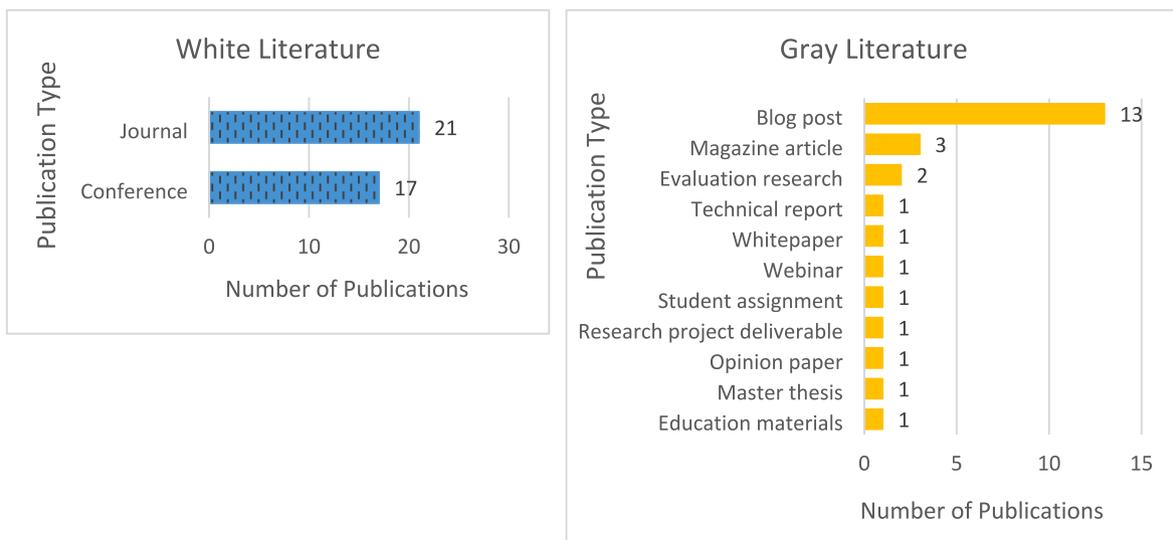


Fig. 3. Type of reviewed publications for white literature (left) and gray literature (right).

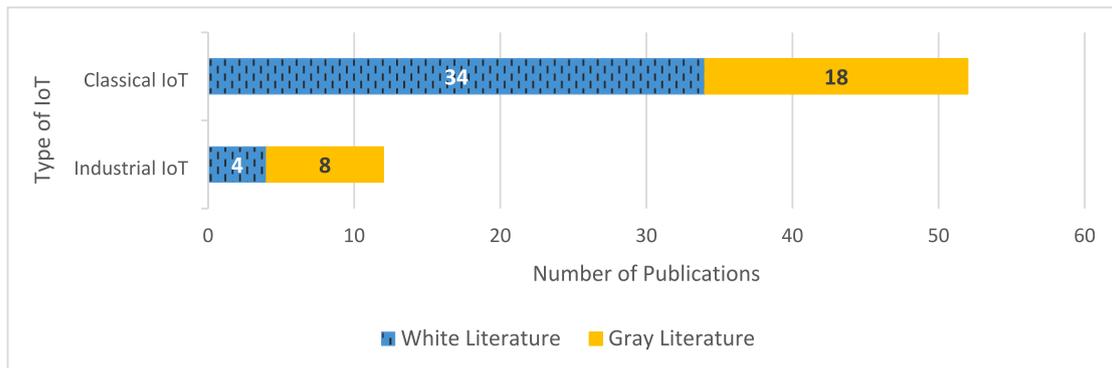


Fig. 4. Explicit consideration of Industrial IoT in reviewed publications.

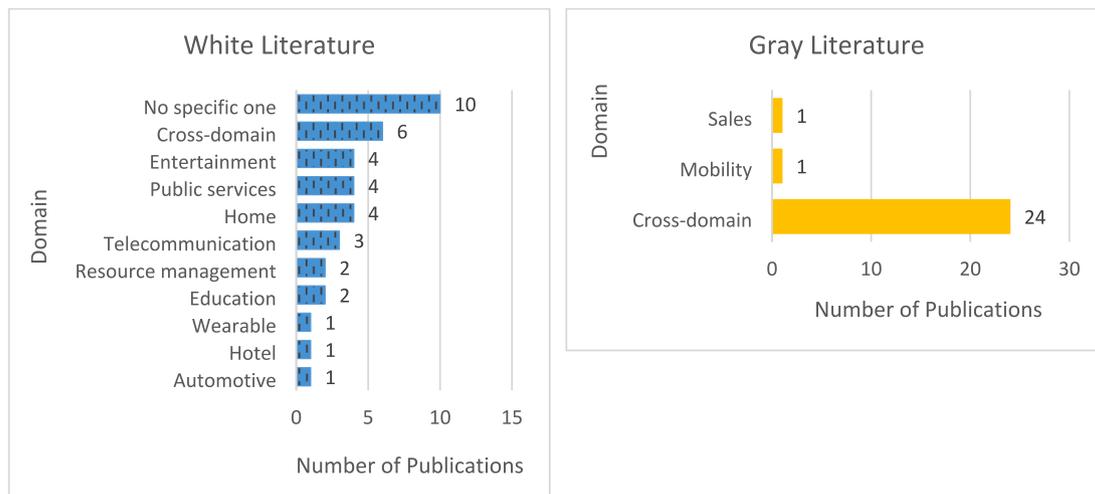


Fig. 5. Domains considered in the reviewed publications: white literature (left) and gray literature (right).

[W18], and two in the gray literature [G04; G07]. In the white literature, [W18] proposed a holistic approach for evaluating the performance of IoT applications and services, with the authors proposing a number of specific KPIs. In the gray literature, [G04; G07] are deliverables from the large European research project CREATE-IoT⁸ that document the outcomes of two work packages. Despite originating from the same project context, the two deliverables took different perspectives on the lists of key performance indicators they compiled, due to the variance of partners from research and industry involved in them. Consequently, these two sets of KPIs are quite different and have very little overlap between them. Of the 311 KPIs extracted from the two publications, only 12 overlap, three of which are also found in other publications. Table 5 in Section 4.3 summarizes our classification of the KPIs in both publications, which demonstrates the different foci of these deliverables.

While selecting the publications for extraction, we ensured that neither the white literature nor the gray literature considered in our study was explicitly based on non-primary studies. However, for the gray literature publications, it was not always possible to definitely rule out that the results presented were not based in part on other literature sources; especially for [G04] and [G07]. To reduce potential bias and avoid associated validity threats, we analyzed the outcomes of the white and gray literature reviews separately and only aggregated them to answer the research questions.

Regarding variation factors, that is, factors influencing UX-KPIs (RQ2), we identified 77 such factors – 37 factors in 5 white literature

publications and 40 factors in 8 gray literature publications. Regarding the challenges of defining and evaluating UX-KPIs (RQ3), we identified 113 challenges – 73 challenges in 24 white literature publications and 40 challenges in 13 gray literature publications. The two gray literature publications G07 and G04, which stand out regarding the number of KPIs, discussed neither any variation factors nor any challenges.

In the end, only seven white literature publications and two gray literature publications included in the data extraction did not provide any data associated with our research questions, that is, neither KPIs nor variation factors or challenges.

4.2. Classification scheme for UX-KPIs

The analysis of the works included in our review resulted in 605 KPIs, 78 variation factors, and 119 challenges, which were too many to compare directly without employing an additional abstraction level. For this reason, a classification structure was sought to systematically group them into logical categories in order to facilitate omitting duplicates and analyze them according to their relation to the domains of UX and IoT. Beginning with an open classification of the KPIs into logical categories, we found that in most cases, they addressed a quality aspect of an IoT system. As the ISO/IEC 25010 standard (ISO, 2011) is the de-facto standard for structuring a software system's quality requirements, we chose it as our initial reference model. We classified the KPIs along the characteristics and subcharacteristics of the two dimensions on quality defined in the standard:

⁸ <https://european-iot-pilots.eu/create-iot/>

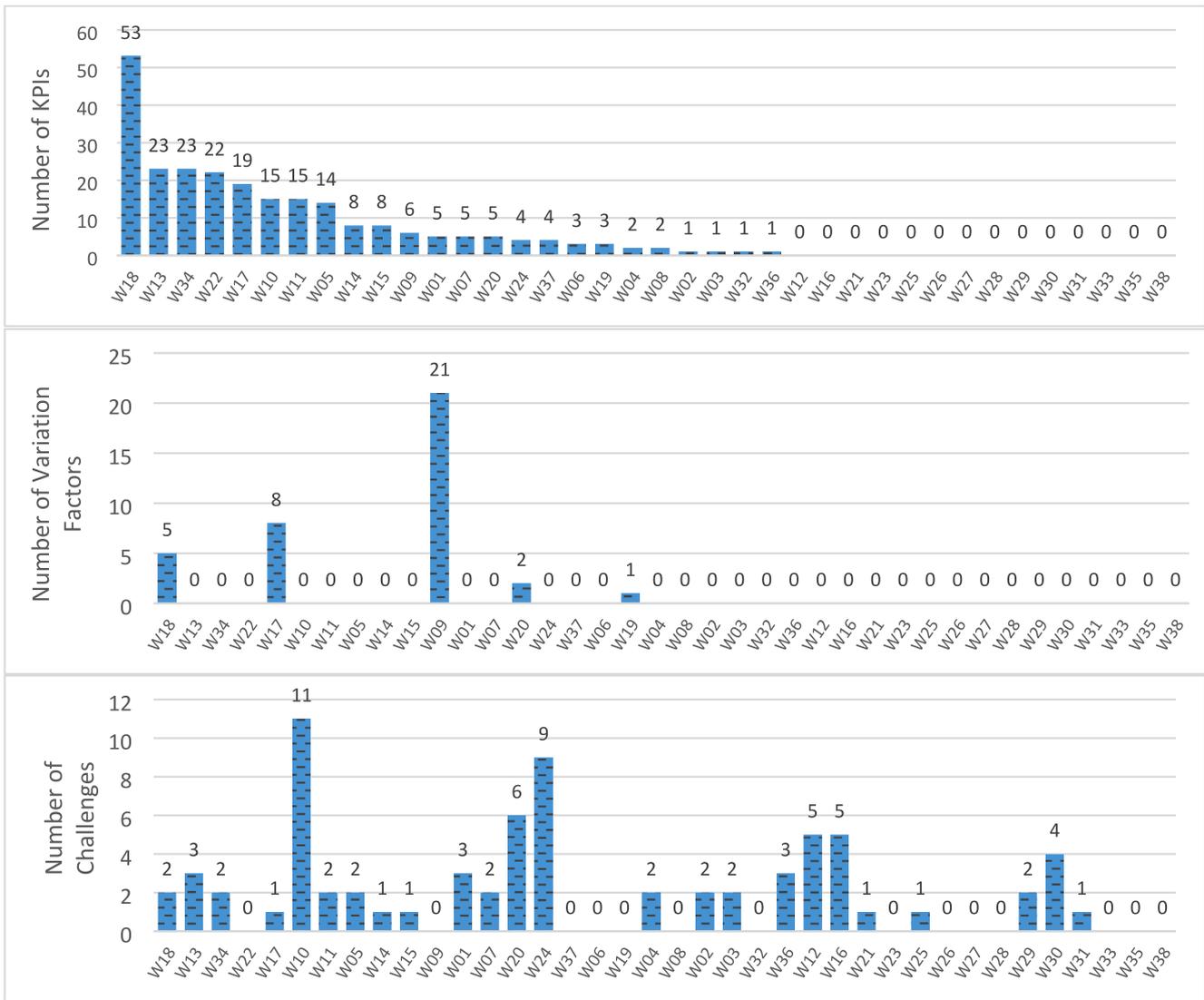


Fig. 6. Number of data entries extracted from the white literature publications.

- **Software/system quality in use** perspective, which is related most closely to UX because it is determined not only by the quality of the software and hardware components of a system, but also by “the characteristics of the users, tasks and social environment” (ISO, 2011). Quality in use includes such aspects as user satisfaction, pleasure, and comfort, which are hard to measure objectively, but predominantly reflect a user’s subjective perception of a product. In the context of IoT systems, this primarily concerns the interactions that end-users have with the edge devices of the IoT system.
- **Software/system product quality** perspective, which refers to product-intrinsic characteristics that are less subjective than quality in use and are easier to measure objectively. In IoT systems, the usability and functional suitability qualities of a system are measured at the interface, while the other quality characteristics must be considered end-to-end for the IoT system as a whole because problems of one component in a chain are detrimental to the IoT system as a whole.

The majority of KPIs could be classified according to the characteristics and subcharacteristics provided by ISO 25010. Moreover, these KPIs covered nearly all of the standard’s subcharacteristics. We also found that many results classified as *functional suitability* were concerned with assuring particular ISO 25012 data quality characteristics in the

sense that improved data quality improves *functional suitability*, and vice versa. Further classification of the variation factors and challenges could also be performed successfully according to this standard’s dimensions, making the classifications of the results (i.e., KPIs, variation factors, and challenges) mutually compatible.

To prevent contrived classifications, it was possible to assign the subcharacteristic *general* if a result was related to the main characteristic instead of a particular subcharacteristic, and any result not fitting the ISO 25010 characteristics were classified as **other quality**. Upon further analysis of these items, we found that they do not represent quality aspects pertaining to the IoT system itself, but rather its **usage context quality**. After refining the classification of these items into a custom set of characteristics, we found eight classification categories in three dimensions: IoT strategy, stakeholder focus, and system constraints. See the Appendix, Section 9.6 for definitions of the eight usage context quality characteristics. In the taxonomy by Glinz (2007), non-functional requirements of a system can be distinguished into quality requirements (i.e., system quality and quality in use) and constraints. Thus, by including constraints, we account for all non-functional aspects of IoT systems.

The usage context quality characteristics specifically address aspects related to the company developing the IoT system: its *IoT strategy* to assure the effectiveness and profitability of their IoT system; the

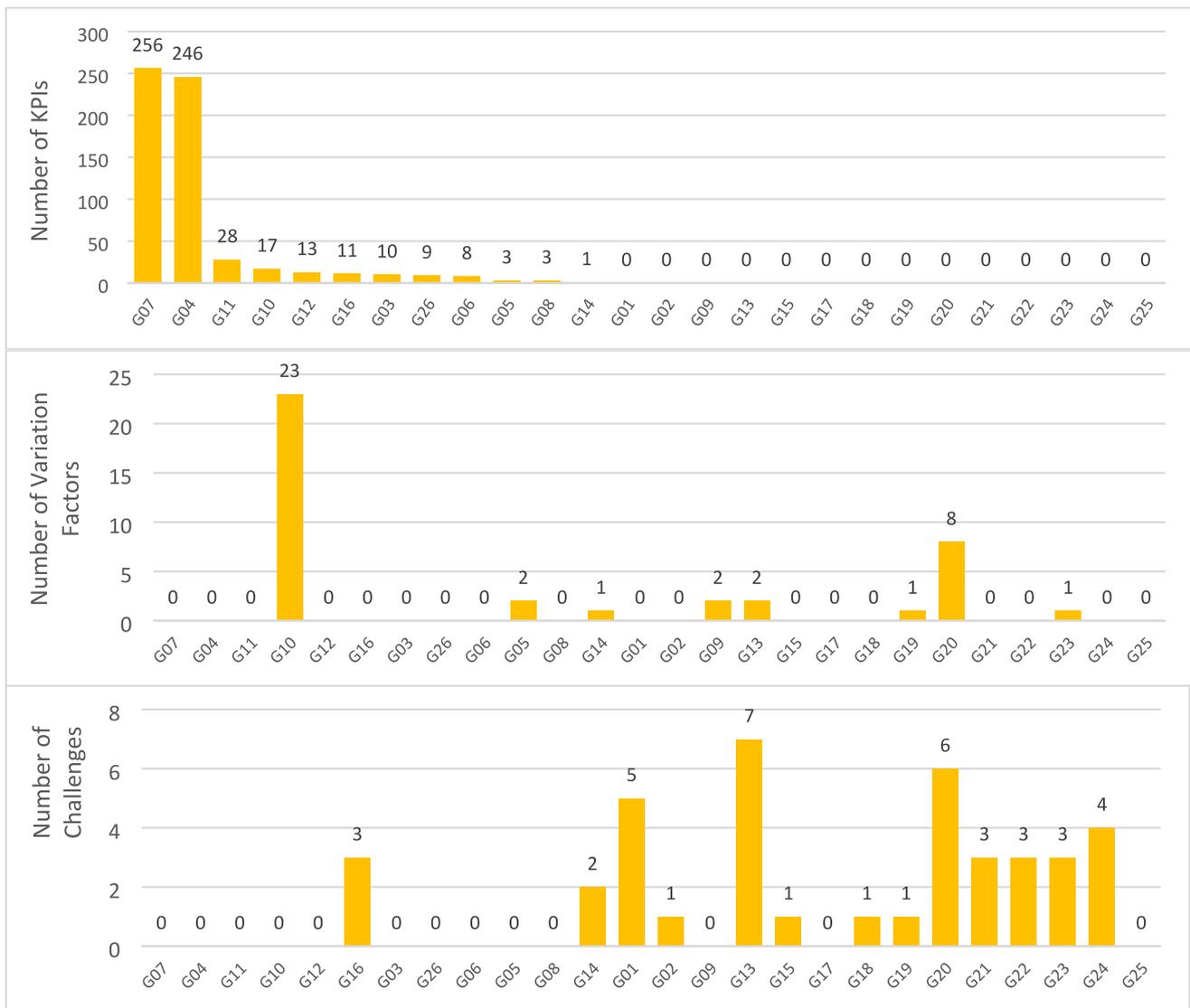


Fig. 7. Number of data entries extracted from the gray literature publications.

Table 5
Comparison of KPI classification between publications [G04] and [G07].

Classification	G04	G07	Sum
System Quality	91	32	123
Quality in Use	57	107	164
Usage Context Quality	91	100	191
Total	239	239	478
No IoT	11	6	17
No KPI nor UX	4	11	15
Total	254	256	510

constraints imposed on the IoT system, and their assurance of stakeholder focus (compare the customer focus of ISO 9001; ISO, 2015). These dimensions are so diverse that no known standard addresses all three, but we did find that they are compatible with the aspects related to business, finance, and customers in the Balanced Scorecard (Kaplan & Norton, 1996), the business model canvas (Osterwalder & Pigneur, 2010), the product canvas (Pichler, 2012), the PEST analysis approach (political, economic, socio-cultural, and technological factors; Aguilar, 1967), and later expansions (e.g., legal and environmental factors; Yüksel, 2012).

Consequently, our multilevel classification consists of three main dimensions – quality in use and software/system product quality as defined

by the ISO 25010 standard, and usage context quality, as well as associated subcharacteristics. Our final classification scheme is visualized in Fig. 8. It suggests that for an IoT system to be successful, its quality focus should not only target the technical soundness of the IoT system, but also its business and environmental context, such as the relationship between the developing company and relevant stakeholders.

4.3. What are the key performance indicators of the user experience of IoT systems, in particular industrial IoT systems?

We identified 488 key performance indicators for user experience and IoT systems, out of which 280 (57.4%) concerned the user experience (UX) of IoT systems and a further 22 (4.5%) may additionally be related to UX in certain contexts. A list of the identified KPIs can be found in the supplementary materials for this paper.

The reviewed publications typically define UX-related KPIs in combination with other KPIs that measure business and technical aspects. The gray literature provided the most KPIs per publication, while the white literature particularly provided KPIs for measuring system quality. Taken together, UX-related KPIs cover a broad spectrum of perspectives in which all aspects of our classification scheme are covered, but they most often measure what impact system quality has on the way end-users perceive an IoT system. We found no KPIs that pertain exclusively to Industrial IoT systems. They can all be

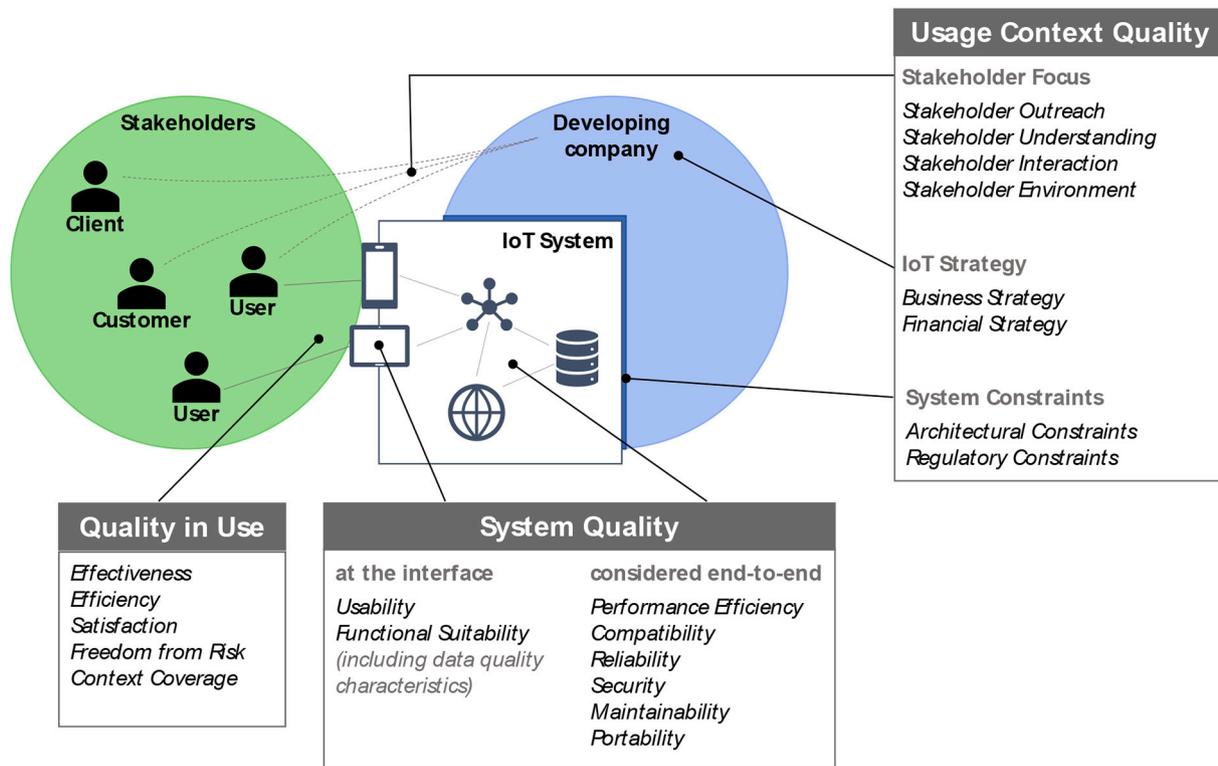


Fig. 8. Quality framework for IoT systems.

generalized to IoT systems; at best, some KPIs might be somewhat context- or domain-specific.

In the following, we will present the results by alternating between the findings from the white literature review, the gray literature review, and combined results. An overview of all KPIs tabulated according to both the quality and the IoT/UX classifications is included in the Appendix in Section 9.4.

From the **white literature**, we collected 243 potential KPIs from 22 publications. Each publication provided between 1 KPI [W32; W36] and 53 KPIs [W18] (average 11.2; median 6.5). Fig. 9 shows the distribution of the number of KPIs per publication and suggests that, in most cases, the white literature provided fewer than ten KPIs. Two KPIs were found

to consist of more than one KPI. An entry in [W17] on “Usability, Usefulness, Personalization” was considered to address both *functional appropriateness* and *satisfaction – pleasure*, and an entry in [W24] named “Application and service specific KPIs” was composed of aspects pertaining to *operability, functional appropriateness, and satisfaction – usefulness*. After splitting the composite KPIs, the white literature provided 246 KPIs in total.

From 12 **gray literature** publications, we collected 605 potential KPIs. Each publication provided between 1 KPI [G14] and 256 KPIs [G07] (average 51.8; median 10.5). Fig. 9 shows the distribution of the number of KPIs per publication, which suggests that most gray literature publications provided ten or more KPIs. Nine KPIs were found to consist

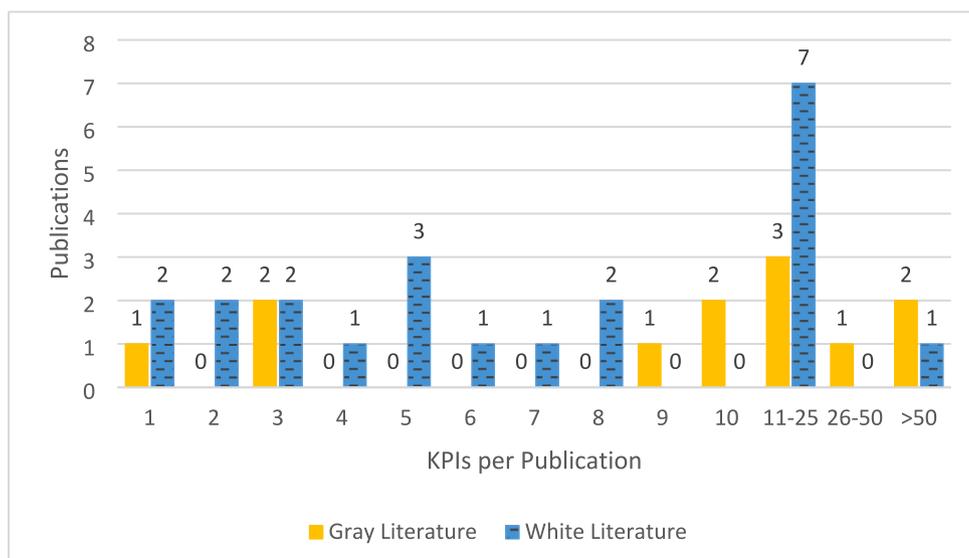


Fig. 9. Number of KPIs extracted per publication from the white and gray literature.

of more than one KPI. For example, the KPI “Customer experience” from [G12] was split into three because it considered this experience in general (*satisfaction – usefulness*), dependent on the platform's performance (*time behavior*), and dependent on the platform's flexibility (*context coverage – flexibility*). After splitting the composite KPIs, the gray literature provided 621 KPIs in total.

Combined, these results show that although we found fewer gray literature publications with KPIs, they typically provided far more KPIs per publication than the white literature, resulting in most KPIs stemming from the gray literature.

The largest numbers of KPIs were derived from two gray literature publications, which were both deliverables from the same research project in the IoT domain [G04; G07]. These were found to address distinct perspectives on IoT systems from different consortium partners. [Table 5](#) compares their focus with regard to our classification of the KPIs.

[Fig. 10](#) shows that of the three dimensions considered, the **white literature** provided predominantly KPIs relating to *system quality* (59.7%). Some entries were not considered KPIs because they were either too unclear without further context information (e.g., “Multi-media system” [W09]) or did not imply any measurement (e.g., “Provision of requested information” [W11]). Furthermore, one KPI from [W06] (“Appreciation of the cultural exhibition visited”) neither addressed IoT nor UX, and was therefore irrelevant to this study. This excluded 4.1% of the KPIs from further analysis.

The **gray literature** provided about equal numbers of KPIs across the three quality dimensions considered, with a slight emphasis on *usage context quality*. Several entries could not be considered KPIs because they were either too unclear without further context information (e.g., “Improved traceability” [G07]), did not imply any measurement (e.g., “Privacy policy: protection of the data generated by the user” [G11]), or in the case of [G10] were judgment criteria for IoT platform providers and consequently were variation factors instead. Several other KPIs from [G04] and [G07] (see [Table 5](#)) neither addressed IoT nor UX (e.g., “New interdisciplinary collaborations” [G04]). This excluded 9.3% of the KPIs from further analysis.

Combined, the results show that the focus of the types of literature differed, with the white literature mainly providing KPIs related to *system quality*, while the perspective of the gray literature publications was broader. The share of KPIs that were excluded was higher for the gray literature.

After merging duplicate KPIs, 151 unique KPIs from the **white literature** remained. The most prevalent quality category in the classification was *system quality* (80 KPIs; 53.0%), followed by *quality in use* (54 KPIs; 35.8%) and *usage context quality* (17 KPIs; 11.3%), which are analyzed in more depth below. [Fig. 11](#): Overlap of KPIs between distinct publications shows that there was little overlap between specific KPIs from different publications, with 70.9% of the KPIs mentioned in a single publication, 19.9% mentioned in two publications, and 7.9%

mentioned in three publications:

- **Interoperability**: Overall assurance that the system design promotes interoperability with internal components and external touchpoints (e.g., edge devices), especially when deployed in an existing context with preexisting devices [W10; W13; W17; W34].
- **Data accuracy**: Degree of accuracy of information for the decision maker [$0 < A < 1$] according to the degree to which the IoT system's data is exactly what is necessary, correct, reliable, and certified to be free of error [W11; W13; W18; W34].

For the **gray literature**, 369 unique KPIs remained after merging. The most prevalent quality category in the classification was *usage context quality* (139 KPIs; 37.7%), followed by *system quality* (135 KPIs; 36.6%) and *quality in use* (95 KPIs; 25.7%), which are analyzed in more depth below. There was very little overlap between specific KPIs from different publications, with 93.8% of the KPIs mentioned in a single publication, 5.4% mentioned in two publications, and the remaining 0.8% mentioned in three or four publications. The only KPI that was provided in four publications was: “User satisfaction: Overall acceptance of an application or service that is perceived subjectively by users and can be influenced by expectations, user context, opinion on look and feel, usability of different functionalities used, and improvements made to the system” [G07; G11; G12; G26].

Combined, the results show that only a small share of KPIs were similar enough to be merged for a total set of 488 KPIs, with the variation of KPIs from the gray literature being greater than that of those from the white literature. There was also little overlap between the two types of literature; only 31 KPIs were found in both white and gray literature publications. We performed an analysis to determine whether publications tended to focus on particular dimensions of our classification scheme, but the results were inconclusive; publications did not appear to focus specifically on one type of quality. Indeed, as observed before, the white literature does cover *system quality* more strongly, but not exclusively, in publications that provided at least five KPIs. The KPI found in the largest number of publications was *user satisfaction* in seven unique publications. The overlap between the white literature (WLR) and the gray literature (GLR) was also very low; 33 KPIs (6.7%) were found both in the WLR and the GLR, while 122 KPIs were exclusive to the WLR (45 of which originated from multiple publications), and 336 KPIs were exclusive to the GLR (23 of which originated from multiple publications). The aforementioned KPI on “User satisfaction” was provided in the largest number of publications from the white and gray literature combined [W17; W18; W24; G07; G11; G12; G26]. Merging KPIs had a negligible effect on the distribution of the categories in which the KPIs were classified.

[Table 6](#) shows how many of the KPIs in our final set were labeled as relating to IoT systems and measuring UX. It shows that 57.4% of these KPIs measure the UX of IoT systems. IoT-KPIs not measuring UX aspects

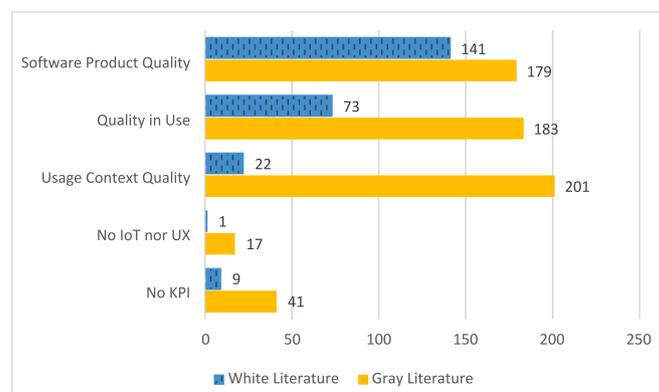


Fig. 10. Distribution of KPIs found per category.

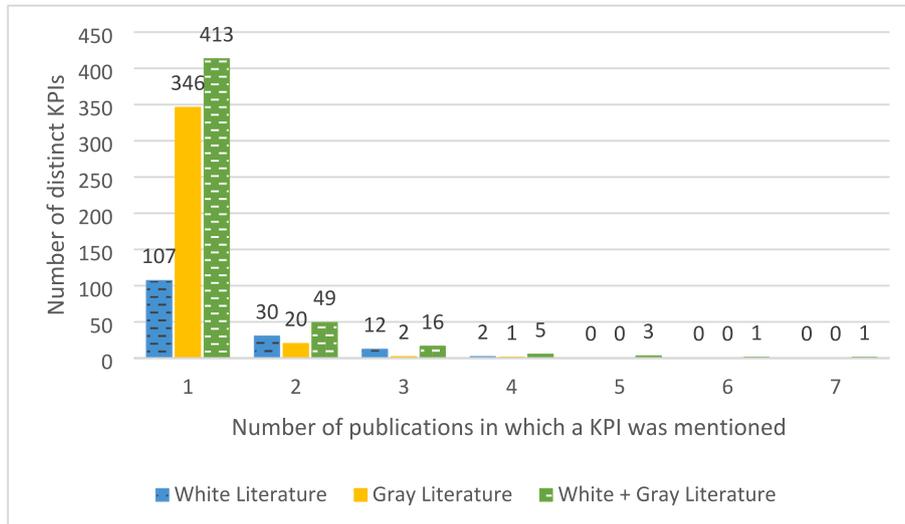


Fig. 11. Overlap of KPIs between distinct publications.

but rather organizational and purely technical aspects accounted for 34.2% of the KPIs. The context-dependent KPIs might, under some circumstances, be considered to address both IoT systems and UX. For example, “Network availability” [W10; W18; W24; G04; G16] is an IoT-KPI that might sometimes affect UX, and “Relatedness” [W05] is a UX-KPI that might apply to certain IoT systems. The context-dependent KPIs combined with the KPIs that always relate to both IoT and UX together account for 61.9% of our set.

Fig. 12 shows the distribution of classifications across the **system quality** characteristics. The **white literature** provided predominantly KPIs pertaining to *performance efficiency* and *functional suitability*, and the fewest KPIs on *security* or *portability*.

The KPIs from the **gray literature** were more distributed across the classifications, providing more KPIs per category except for *performance efficiency*. Like the white literature, the largest number of KPIs from the gray literature addressed *functional suitability* and *performance efficiency*, but additionally also provided relatively many KPIs on *reliability*. The fewest KPIs were provided for *portability* and *maintainability*.

We can establish that the results of the KPIs of the white and gray literature **combined** could be classified into each of the *system quality* characteristics. Moreover, they were classified into all but three sub-characteristics (*coexistence*, *authenticity*, and *accountability*). This suggests that KPIs cover a wide range of quality aspects pertaining to IoT systems. The characteristic of *functional suitability* has the most entries as it was prevalent in both types of publications. We found that these were often related to *data quality*, and accordingly further classified them according to the ISO/IEC 25012 data quality model (ISO, 2008). Because these dimensions include their *currentness*, *credibility*, and *correctness*, problems with data quality may negatively impact UX. Similar effects can be observed for *performance efficiency* if the system's *time behavior* is subpar, for *reliability* if the system or network stability is impaired, and for *compatibility* if the communication between IoT system components

is impaired.

Fig. 13 shows the distribution of classifications across the **quality in use** characteristics. The **white literature** provided predominantly KPIs pertaining to *satisfaction – pleasure* and *satisfaction – usefulness*, i.e., user *satisfaction* dimensions that make the interaction pleasurable for users, provide physical comfort, and possess perceived usefulness for their purposes. The publications contained no KPIs on *freedom from risk* (neither *environmental* nor *economic risk mitigation*).

The distribution of KPIs from the **gray literature** over the *quality in use* characteristics was less even than over those of *system quality*. They predominantly related to *efficiency*, which describes the resources a user needs to spend to fulfill their tasks, and secondarily to *satisfaction – comfort*. The fewest KPIs pertained to *freedom from risk – economic risk mitigation* and *context coverage – flexibility*.

For the two types of literature **combined**, we identified KPIs for each characteristic and subcharacteristic, but large differences were found between the two types of literature. For eight of eleven characteristics, the gray literature provided the most KPIs.

Fig. 14 shows the distribution of classifications across the **usage context quality** characteristics. The **white literature** publications provided very few KPIs in this dimension for all characteristics, although the subcharacteristics related to *IoT strategy* were slightly more prevalent, accounting for 52.9% of the KPIs in this category. The *business strategy* (55 KPIs) involves decisions on how the business model around the IoT system is shaped along with the organizational orientation and support structures, e.g., “Business model flexibility”. The financial strategy (28 KPIs) is aimed at making the IoT system profitable, e.g., “Cost fairness”. These KPIs relate to strategic aspects on which KPIs typically focus, making these qualities the largest non-runtime characteristics.

The **gray literature** publications provided more KPIs in this dimension, especially regarding *IoT strategy*, accounting for 54.0% of the KPIs. The KPIs belonging to *IoT strategy*, however, are mostly concerned with organizational aspects of the IoT system (e.g., “Net revenue”) and only a few KPIs take the user experience into account (e.g., “Cost fairness” in *financial strategy*, and “Trust in provider” in *business strategy*). The third-largest characteristic, *stakeholder understanding*, is related to measuring user experience in IoT systems more strongly. This characteristic pertains to the actual usage of a system, which is unrelated to the inherent *system quality of capacity* limits, and consequently does not express the system's quality but gauges only the current demand, for example: “Active devices”. Only few KPIs were found for *stakeholder outreach*, while the literature provided no KPIs for measuring *stakeholder environment*, which can be explained by this being an aspect on which a

Table 6

Confusion matrix of KPIs classified as relating to IoT systems and measuring user experience aspects (note that 18 KPIs labeled “no / no” were omitted earlier as “no IoT nor UX”).

KPI Type		IoT			Total
		Yes	Context	No	
UX	Yes	280	7	19	306
	Context	15	0	0	15
	No	167	0	0	167
	Total	462	7	19	488

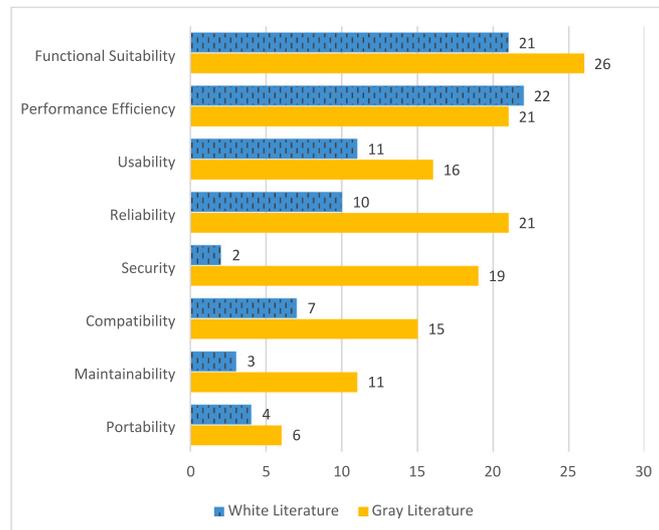


Fig. 12. Number of KPIs classified into a system quality characteristic.

company has limited to no influence.

For both types of literature **combined**, we observed that the gray literature publications seem to consider KPIs both in relationship to an IoT system's organizational and user contexts, and regarding more technical aspects of IoT systems, such as *system quality*. The white literature, on the other hand, was found to focus on more technical measurements of IoT systems while providing only few KPIs related to the organizational context – a typical purpose of KPIs.

To summarize, the publications we found overall provided fairly few KPIs each, with the exception of two outliers, which accounted for 84% of all KPIs from the gray literature. The gray literature covered a broad variety of qualities, while the white literature predominantly provided KPIs regarding system quality. In this category, both types of publications emphasized KPIs measuring functional suitability and performance efficiency. The gray literature moreover provided relatively many KPIs on the quality in use characteristic of efficiency and the usage context quality of business strategy.

4.4. What context factors influence the user experience of IoT systems?

We identified 77 context factors that influence the user experience of IoT systems. The UX of IoT systems is mainly influenced by the characteristics of a system's stakeholders and their interaction with IoT system providers. User skills, familiarity with the system, and mood are important aspects influencing the users' perceived UX of an IoT system. The quality of services associated with the IoT products and communication with users are the most relevant factors on the IoT system providers' side. A list of the identified variation factors can be found in the supplementary materials for this paper.

As introduced in the Background section (Section 2.2), variation factors differ from key performance indicators, yet they are necessary to properly interpret the outcomes of the evaluation and to effectively control specific key performance indicators. In the context of user experience evaluation, variation factors describe the context characteristics that may influence UX, and thus UX-KPIs. Although variation factors alone do not indicate UX characteristics directly, it is important to identify relevant variation factors and understand their impact on UX in order to be able to properly interpret UX-KPIs in a given context. For example, when the complexity of a system's interface is measured through a UX-KPI that counts the number of interface elements, the interpretation of this KPI – i.e., whether its value means good or bad UX – depends on the system's criticality and the user's perception. A more critical application domain might demand a simpler interface for acceptable UX in situations with high cognitive load, while advanced users in a less critical context might prefer seeing more information at a given time, resulting in a more complex interface getting favored.

Hence, a variation factor might not only have a positive or negative effect on UX, but may also be context-dependent.

In total, 77 variation factors were found: 37 from the white literature (WLR) and 40 from the gray literature (GLR). These are associated with 10 subcharacteristics of our classification scheme (see Section 4.1), as shown in Table 7.

Five publications from the WLR [W09, W17, W18, W19, W20] and eight from the GLR [G05, G09, G10, G13, G14, G19, G20, G23] mentioned aspects that, according to our definition, fall under variation factors. Fig. 15 and, in more detail, Table 7 show the classification of the variation factors of the WLR and GLR. It is clear at first sight that the category *stakeholder focus* is dominant in both the white and gray literature and represents around two thirds of all variation factors (66.2%). However, the foci in the subcharacteristics are different.

In the **white literature**, the subcharacteristic *stakeholder understanding*, in particular, is dominant [W09; W18; W20]. Variation factors in this category are related to socioeconomic factors of the target group (e.g., age, education, gender) and further stakeholder characteristics (e.g., usage frequency, emotions/mood). For example, the familiarity and expertise of different user groups with a specific IoT system may influence how these groups evaluate the system's UX. Especially in publication W09, variation factors were found in this subcharacteristic (10 out of 13). The second-largest subcharacteristic in WLR is *stakeholder environment* [W09; W18], which comprises the operating conditions of IoT sensors and edge devices that may perform poorly in operating conditions they are not designed for. For example, high humidity, rain, or sunlight might influence the accuracy of IoT sensors or the visibility and readability of user interfaces. *Stakeholder interaction* [W17; W18] is the third-largest category in the WLR and refers to service qualities and psychological aspects of the users. In the white literature, 56.8% of all variation factors were found in publication W09.

In the **gray literature**, the distribution of the identified variation factors was different. Here, three subcharacteristics were dominant: *stakeholder interaction* [G10; G20], *business strategy* [G05; G09; G10], and *stakeholder outreach* [G10; G20; G23]. *Stakeholder interaction* describes in what ways, how well, and how often the organization developing the IoT system interacts with stakeholders, such as customers. This includes quality and efficiency estimates of the services provided, the organization's consulting and implementation skills depending on domain knowledge and know-how, and the availability of instructional guides. For example, for a given IoT system, the better the associated services provided to the customers and users, the higher they will evaluate the perceived UX of the IoT system. Compared to the white literature, where only service quality and psychological effects were mentioned, more

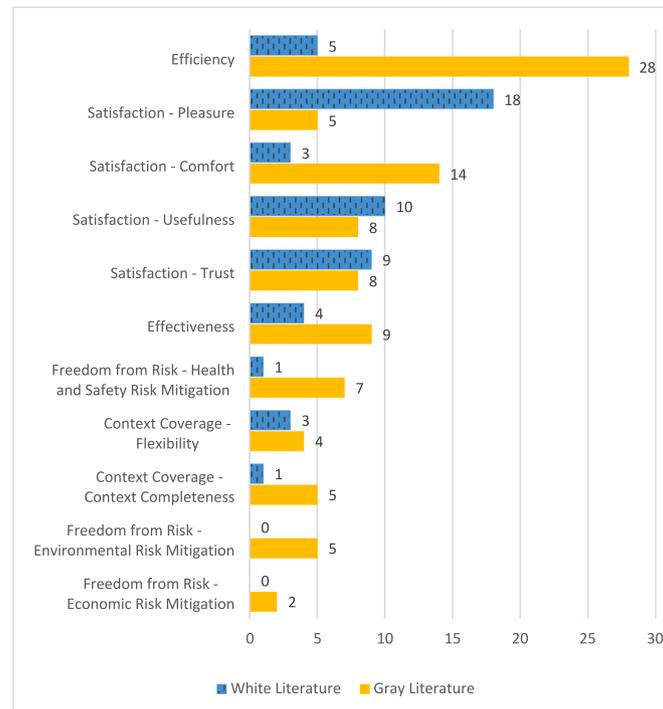


Fig. 13. Number of KPIs classified into a quality in use (sub)characteristic.

examples were identified in the gray literature. The second-largest category of variation factors in the gray literature was *business strategy*. Variation factors in this category pertain to characteristics and priorities of the organization, which understandably shape the context of the IoT system and thus also its KPIs. For example, the role of UX is strongly influenced by the type of IoT service offered and the service model adopted. The discrepancy between the white and gray literature becomes very clear here, as only two variation factors were found in the white literature. The third-largest group in the gray literature is *stakeholder outreach*, and is related to marketing and the perceived reputation of the organization or brand, which highlights the importance of assuring the appeal of an IoT system to potential customers. Before a potential customer can order an IoT system from a particular vendor, they must first be aware of this vendor. Moreover, because of the investment costs, they must gain confidence that this vendor is capable of supplying them with an IoT system that meets their requirements (e.g., by consulting testimonials or benchmarking reports). In the gray literature, a total of 76.7% of the variation factors were identified in G10.

Combined, we found that the GLR publications [G10; G13; G14] provided far fewer examples of variation factors on *stakeholder understanding* than the WLR publications [W09; W18; W20]. A similar distinction can be seen in the subcharacteristic *stakeholder environment*, regarding which more examples are provided in the WLR [W09; W18] than in the GLR [G19; G20]. A difference can also be seen in the subcharacteristic *stakeholder outreach*, which is mostly mentioned in the gray literature [W09; W19; G10; G20; G23]. The *IoT strategy* category comprises *business strategy* and *financial strategy*. Variation factors regarding *business strategy* were particularly found in the GLR [W17; G05; G09; G10], whereas *financial strategy* (e.g., satisfaction with the pricing model) was not so strongly represented across both publication types [W09; G10].

It is worth noting that in both the WLR and the GLR, the category *system quality* is not strongly represented [W09; W17; G09; G10]. *System quality* variation factors pertain to *interoperability* [W17; G09; G10] (e.g., the degree to which services can be integrated and work cultures are compatible), increasing the level of *security* through technical measures [W17; G09], and *performance efficiency* [W09] (*resource utilization*

relates to image and voice quality). In the next main category, *quality in use*, we identified only one characteristic, namely *satisfaction*, specified in the subcharacteristic *pleasure* [W09; G05; G13]. The identified variation factors included interpersonal relationships and image quality in terms of color and texture.

To summarize, the variation factors we found in the white and gray literature focus primarily on the organizational and stakeholder aspects and less on technical aspects of IoT. Regarding the latter, especially the interoperability of new functions or newly integrated sensors is a key factor.

4.5. What challenges are unique to the design and evaluation of the user experience of IoT systems, in particular industrial IoT systems?

We identified a total of 113 challenges, with about twice as many challenges identified in the white literature as in the gray literature. The challenges especially concern system quality and related challenges due to the inherent complexity of IoT systems. For example, it is challenging to evaluate the UX of an IoT with different user interfaces. Furthermore, challenges in the area of quality in use and usage context quality were defined for the WLR, which primarily considers the new subcharacteristic stakeholder acceptance (e.g., different adoption behavior in different domains [W36]). A list of the identified challenges can be found in the supplementary materials for this paper.

The review identified a total of 113 challenges; 73 challenges from the white literature from 24 publications, and 40 challenges from the gray literature from 13 publications. We grouped the identified challenges according to our classification scheme (see Section 4.1), adding the possibility of including other challenges not covered already by the dimensions found for KPIs. To prevent information loss, similar challenges were not merged. Table 8 presents an overview of the challenges.

We found that challenges are typically considered in terms of **system quality** and especially the inherent complexity of (I)IoT systems. *Interoperability* becomes more important when systems need to be linked across vendors, locations, and companies [W10; W11; W30; G13; G23; G24], which poses further challenges as the number of parties involved grows. These challenges were found to be distributed across all three categories of our classification scheme for KPIs (see Section 4.1): *system quality* (46 challenges; 40.7% – including *complexity* 84 challenges,

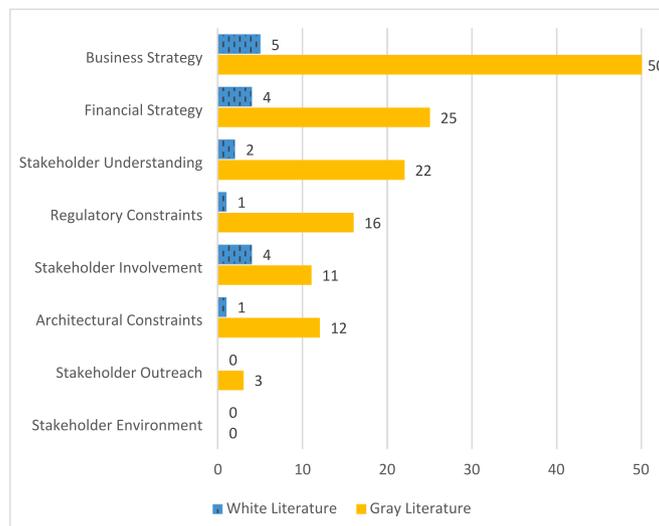


Fig. 14. Number of KPIs classified into usage context quality.

Table 7
Frequency of variation factor classifications.

	Characteristic	Subcharacteristic	WLR	GLR	Total
System Quality	Compatibility	Interoperability	3	2	5
	Security	General	1	1	2
	Performance	Resource Utilization	1	0	1
Quality in Use	Efficiency				
	Satisfaction	Pleasure	2	2	4
Usage Context Quality	Stakeholder Focus	Stakeholder Outreach	2	8	10
	Stakeholder Focus	Stakeholder Understanding	13	3	17
Usage Context Quality	Stakeholder Focus	Stakeholder Interaction	5	11	16
	Stakeholder Focus	Stakeholder Environment	7	2	9
	IoT Strategy	Business Strategy	2	9	11
IoT Strategy	Financial Strategy	1	2	3	
		Total	37	40	77

74.3%), *quality in use* (20; 17.7%), and *other challenges* (9; 8.0%).

The single most frequently named challenge regarding **system quality** is *complexity*. Proportionally, this characteristic was mentioned most often in both the WLR [W01; W02; W04; W07; W11; W12; W14; W16; W17; W18; W20; W24; W29; W30; W31; W36] and the GLR [G13; G14; G16; G18; G20; G21; G23; G24]. Although *complexity* represents a specific system property rather than an abstract quality aspect in terms of our classification scheme, we decided not to map it to any quality aspect and rather list it separately in Table 8 under *system quality*. One reason is that the publications we analyzed discussed *complexity* directly. They defined *complexity* in such terms as the number of different technologies used by an IoT system [G13; G14], the number of interfaces and data points defined [W30; G13], the interactions of the target customer with different devices and platforms [W10; W16; G13; G21], and linking the digital and the real world [G13; G20; G24; W16; W18; W24]. The assessment and evaluation of IoT systems also belongs to *complexity*, as this is very challenging. This aspect was only identified in the white literature [W01; W07; W10; W11; W12; W14; W17; W18; W24; W29; W31; W36]. Another reason for treating *complexity* separately was that it may influence various quality aspects of a software system, such as *reliability* and *maintainability*; mapping complexity to multiple quality aspects would have resulted in redundant counts in our analysis. In total, *complexity* accounts for 33.6% of all challenges found.

Further common *system quality* challenges are associated with an IoT system's *security* [W03; W10; W12; W13; W16; W20; W34; G01; G15;

G21; G22], *compatibility* [W10; W11; W20; W24; W30; G13; G21; G23; G24], and *usability* [G01; G13; G14; G19; G22; G23; G24; W12; W30] characteristics. Several publications name *security* together with *privacy*⁹ [G21; W10; W12; W16]. These describe the difficulty of implementing appropriate protection mechanisms in the context of highly complex, interconnected, and heterogeneous IoT systems. *Compatibility* challenges refer to the *interoperability* [W10; W11; W30; G13; G23; G24] and *coexistence* [W10; W20; W24; G21] of different devices within an IoT system, in particular issues related to data exchange and increased risk of failures. *Usability* challenges include *operability* challenges such as poor connectivity of devices in specific locations [W30; G13; G19; G23; G24], *learnability* challenges in terms of understanding a system's setup [G14; G22], or difficulties with *appropriateness recognizability* if there is a mismatch between the response from an IoT product's operations and the expectation of the user [G01; G24].

Less frequent *system quality* challenges are *reliability* [W16; W24; G13; G20] and *portability* [W10; G01; G22]. *Reliability* challenges include the *availability* of IoT devices in areas with poor reception. An example of a *portability* challenge is the ease of installing or integrating new devices within an IoT system. For two characteristics, we found only one challenge in the GLR: *performance efficiency – time behavior*, which addresses system response times and lags in the transmission of time-critical information [G01], and *maintainability – testability*, which is related to the impaired ability to test all relevant aspects and layers of an IoT system [G02].

The second-largest category of challenges is the **quality in use** of an IoT system, with 20 challenges [W02; W05; W07; W10; W12; W13; W20; W25; W30; G01; G13; G16; G20]. Most of these address dimensions of *user satisfaction* in terms of *trust* in the system with predictability and consistency of interactions [W10; W13; W20; W30; G13], perceived *usefulness* with a consistent look and feel [W02; W25; G01; G16; G20], and achieving proper *context completeness*, among other things by providing a seamless experience and involving the right stakeholders in

⁹ The ISO/IEC 25010 standard does not specifically address (data) privacy as a quality characteristic. We acknowledge that it is possible to consider *privacy* as a separate quality characteristic; for example, Schmitt and Groen (2021) proposed considering *privacy* as a standalone software/system quality characteristic, with subcharacteristics taken from the Standard Data Protection Model (Data Protection Conference, 2020). However, because *privacy* is strongly interwoven with *security*, we believe that for the purpose of this paper, *privacy* aspects of IoT systems can be considered to be predominantly achieved through *security* measures.

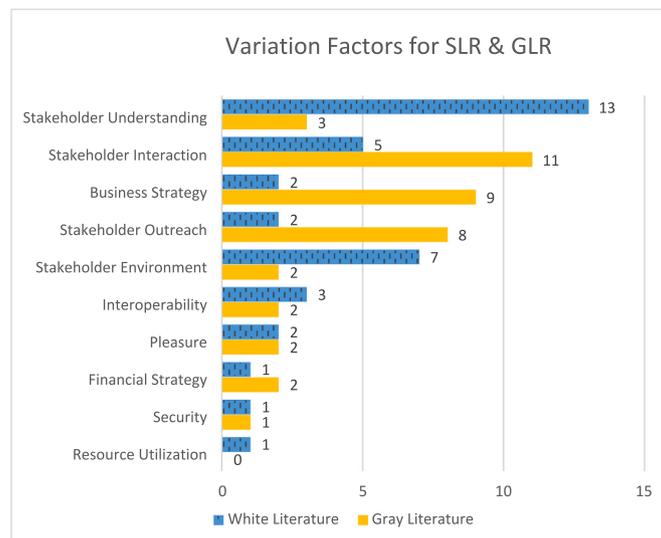


Fig. 15. Distribution of variation factors found in the white and gray literature across classes.

Table 8 Classification frequency of challenges.

	Characteristic	Subcharacteristic	WLR	GLR	Total
System	Compatibility	Coexistence	3	1	4
		Interoperability	5	3	8
	Maintainability	Testability	0	1	1
	Performance	Time Behavior	0	1	1
	Efficiency				
	Portability	Installability / Replaceability	1	2	3
	Reliability	Availability	2	2	4
	Security		11	4	15
	Usability	Accessibility	1	0	1
	Usability	Appropriateness	0	2	2
		Recognizability			
	Usability	Learnability	0	2	2
	Usability	Operability	1	4	5
Complexity	Complexity (Usage)	26	12	38	
Total		50	34	84	
Quality in Use	Context	Context	2	2	4
	Coverage	Completeness			
	Satisfaction	Pleasure	1	0	1
	Satisfaction	Trust	7	1	10
	Satisfaction	Usefulness	2	3	5
	General		2	0	2
Total		14	6	20	
Usage	Stakeholder	Stakeholder	6	0	6
	Context	Acceptance			
	Quality	IoT Strategy	2	0	2
		System	1	0	1
	Constraints	Constraints			
Total		9	0	9	
Total		73	40	113	

co-creation sessions [W12; G13; G20]. Additionally, pleasure of use was named once [G05].

The least-represented category of challenges, **usage context quality**, was exclusively found in the white literature [W01; W04; W15; W16; W20; W21; W29; W36]. This involves six challenges in a new category coined *stakeholder acceptance*, which particularly affects the stakeholders' attitude towards the IoT system (i.e., technology acceptance), technology adoption behavior, and openness to innovation among users/consumers [W15; W16; W20; W21; W29; W36]. Two further challenges that belong to *financial strategy* highlight investment costs [W01; W36], and one challenge regarding *architectural constraints* discusses the need to shift from integrated designs towards modularized designs [W04].

To summarize, most of the challenges we found were related to technical

issues. Challenges related to quality in use and context usage quality were mostly mentioned in the white literature.

5. Discussion

This review is, to our knowledge, the first systematic study of solutions and challenges with respect to evaluating the user experience of IoT systems, specifically Industrial IoT. In our study, we focused on three aspects: indicators of user experience (UX key performance indicators), context factors influencing user experience (UX variation factors), and challenges of evaluating the UX of IoT systems.

Despite the importance of the user experience of software systems in general, and of IoT systems in particular, our study indicated that evaluating UX through KPIs is still rather a budding field in the IoT domain, specifically for the Industrial IoT. The amount of literature on the UX of IoT systems is still relatively small. Yet, the peer-reviewed and other literature sources we found provided a number of KPIs, variation factors, and challenges that enable us to draw initial conclusions about the current state of evaluating the user experience of IoT systems.

5.1. Key performance indicators of IoT Systems' user experience (RQ1)

Our literature review yielded several hundred KPIs. It should, however, be noted that more than half of them were collected in the context of a large European research project, which encompassed a wide range of domains. The remaining publications each typically provided a relatively small number of KPIs. Surprisingly, we also found very little overlap between the considered studies with respect to the KPIs they discussed, including those from the large European project. This suggests that user experience indicators are very diverse and that so far, no standardized structure for organizing them logically exists. If additional publications provide UX-KPIs, the probability that these will not overlap with those we already found is quite high. However, future publications on UX-KPIs should also be encouraged to disclose a greater collection of KPIs rather than provide just a handful of examples. This will facilitate the mutual exchange of UX-KPIs and can inspire others to build on it.

Thus, our study showed that **there exists a potentially far larger number of UX-KPIs than those we identified, which represents a significant challenge for practitioners who wish to select effective KPIs to quantitatively manage UX in their specific context.** Therefore, the identification of relevant KPIs should be accompanied by the development of a systematic taxonomy and the determination of how valuable each KPI is, which would help practitioners identify potentially

useful KPIs. We made a first attempt towards providing such a taxonomy and systematized the outcomes of our review using the ISO 25010 software quality model. However, we could not classify all KPIs according to the dimensions of this standard, as various factors play a role in the usage context in which the IoT system is deployed. These concern aspects related to the organization developing the IoT system and the IoT system's stakeholders.

The white literature focuses mainly on system quality characteristics, which might suggest that these works take a stronger engineering view on (IoT) systems development. The gray literature, on the other hand, emphasizes the importance of quality in use and usage context quality, which suggests that these publications approached IoT systems from multiple, perhaps less formalized, perspectives and considered more subjective aspects, too. A potential reason for this discrepancy between the white and gray literature might be that it is generally more challenging to specify, quantify, and empirically validate a system's runtime and usage context characteristics than the properties of the system itself. Practitioners searching the white literature for useful UX-KPIs should be aware of this bias; researchers, on the other hand, should pay more attention to investigating the usage and context aspects of the user experience of IoT systems.

We found that studies consider UX-KPIs in combination with other KPIs. Although one explanation might be that UX-KPIs are still a relatively novel phenomenon in the context of IoT and have not established themselves as an independent field, we find it more plausible that UX is just one of several aspects when considering an IoT system holistically. Moreover, they may be mutually beneficial: Technical aspects such as proper modularization may lead to a better overall UX because of greater reliability. Similarly, an IoT system with high user satisfaction because of a good UX may result in higher demand and greater profit by positive word-of-mouth. Furthermore, UX-KPIs were found for all system quality characteristics and nearly all their subcharacteristics, which can often be measured with mostly objective measures, making UX more tangible than if it is only based on subjective metrics like perception and opinion. Practitioners should identify and harness possible dependencies between non-UX system and context qualities and UX aspects to boost their IoT system's success, while researchers should investigate the relationships between UX-KPIs and other KPIs.

The utility and efficiency of the IoT system are of primary concern in measuring its success, which is directly associated with the added value of introducing IoT technology to improve business/production processes. Specifically, this concerns the resources a user needs to spend to fulfill their tasks. Among other things, it involves expected time savings. In this context, UX helps to assure that the IoT system facilitates efficient interaction, both through a responsive IoT system and by optimally supporting the users in performing their tasks and achieving their goals. This includes the system fulfilling its responsibility of providing the right information at the right time. In addition to utility and efficiency, the way the IoT system affects the user is another important concern. The user satisfaction dimensions of pleasurable interaction, physical comfort, trust in the system, and perceived usefulness for their purposes are important drivers for a user's productivity while interacting with the IoT system. For practitioners, this calls for considering metrics in their business that determine the IoT system's ability to provide good UX, and in turn the effect of good UX on workers' attitude, efficiency, and effectiveness while using the IoT system in their workflow. Researchers should seek to extend the research on context awareness in IoT systems (Gil, Ferrández, Mora-Mora, & Peral, 2016) with analyses on how to satisfy the stakeholders' UX needs and usage context quality aspects.

The user experience of an IoT system is largely determined by the quality of its underlying data. On the one hand, the quality of the information presented to users directly influences their perceived usability of the system. On the other hand, the functional suitability of the system is influenced by the data it uses; this is especially critical for systems that learn their functionality from examples represented by data

(i.e., systems involving machine learning and artificial intelligence components). Since the UX of IoT systems increasingly depends on the data such systems are built upon, system engineering processes should be integrated with data engineering and processing processes. Concepts of development and operation (DevOps) for data-driven software systems, such as DataOps (Munappy, Mattos, Bosch, Olsson, & Dakkak, 2020), should be applied in the context of IoT systems development.

Finally, although it was not in the focus of our study, we did observe that key performance indicators and variation factors are generally discussed without formally specified quantitative evaluation criteria, that is, objectively measurable metrics and the associated interpretation (preference) rules. In consequence, although the UX-KPIs we identified provide practitioners with guidelines on what aspects to focus on when developing IoT systems, they do not provide proper support for evaluating whether these aspects were actually attained. This calls for research on decision support models for interpreting data on multiple KPIs with the explicit consideration of relevant variation factors. For example, the Quamoco method (Haindl, Plösch, & Körner, 2019; Wagner et al., 2015) for software quality evaluation could be adapted for this purpose.

5.2. Factors influencing the user experience of IoT systems (RQ2)

Our review resulted in 77 variation factors that influence the user experience of IoT systems and must therefore be considered in order to properly interpret UX-KPI data and correctly evaluate the UX of IoT systems.

We found that the characteristics of the IoT system's stakeholders, especially its users, primarily govern its user experience. This includes, in particular, individual characteristics of the IoT system's users, both intrinsic ones such as gender, background, and capabilities, and contextual ones such as education or mood. Understanding these characteristics is a critical aspect in designing and evaluating the UX of an IoT system. The paramount role of user characteristics also influences potential strategies that providers of IoT systems can implement to improve the UX of their products. One strategy involves communication with the intended users, in terms of gathering their feedback and providing associated services, such as deployment and usage guidance. Another strategy might be to reduce the cognitive complexity of products, or more precisely, adjusting the cognitive complexity to the capabilities and expectations of the target users. In this area, there is also still a need for research to take greater account of the different end-user groups and their UX needs accordingly.

Variation factors related to the technical context of the operation of IoT systems were given very little attention in the reviewed literature. The few variation factors found referred to interoperability and security aspects of target ecosystems operated by an IoT system. Characteristics of the environment in which an IoT system operates, such as temperature or light conditions and their interactions with the system's and the users' capabilities, were sporadically mentioned in the literature as well. This means that providers of IoT systems currently find little support from the literature regarding the aspects of the target environment that impact the UX of a system. It is currently up to them to investigate these aspects, particularly in the interaction with relevant stakeholders (especially the system's deployers, maintainers, and users within the target context). On the other hand, researchers investigating UX key performance indicators are missing the information on potent confounding factors they should consider explicitly to ensure validity of their results. In consequence, they have to extend their research to identify potentially relevant confounding factors as well.

5.3. Challenges of defining and quantifying the UX of IoT systems (RQ3)

In the reviewed literature, we found 113 challenges of defining and evaluating the user experience of IoT systems. These challenges referred to both UX indicators (KPIs) and context characteristics (variation

factors). **The most prominent challenge of IoT systems is their inherent complexity, which is related to the number of involved technologies, interfaces, data points, and interactions with various devices and platforms – not to mention interactions with various stakeholders.** This challenge is reflected in the variation factors. For example, it is challenging to implement the appropriate UX for individual systems in IoT systems, considering specific stakeholder groups and their needs. Depending on the size of the IoT system, the relevant user groups must be identified in advance and UX requirements must be addressed accordingly. This implicitly contains another important challenge, namely the evaluation and assessment of IoT systems. Metrics need to be defined to perform an assessment or evaluation of an IoT system, but this is challenging and depends on its complexity.

Another major challenge is the security of IoT systems. This challenge is closely related to the complexity of IoT systems, which is the result of large amounts of data being exchanged and processed simultaneously among highly connected and heterogeneous systems. Security, in turn, has an impact on the next major challenge, which is the stakeholders' attitude towards the IoT, specifically their trust. Major components of trust mentioned in the literature include transparency and understandability of how an IoT system works, especially how it processes user data and computes its results (i.e., explainability of the system).

6. Limitations and threats to validity

In this section, we discuss a selection of the most relevant validity threats and the actions we took to avoid them. We grouped the threats based on [Ampatzoglou, Bibi, Avgeriou, and Chatzigeorgiou \(2020\)](#).

Research design validity refers to issues regarding the overall design of a study and the conformance between the defined and the performed review process. To avoid threats in this category, we designed our study using best-practice guidelines defined in related literature, particularly [Garousi et al. \(2019\)](#) for the overall design of the multivocal literature review (MLR), and [Kitchenham and Charters \(2007\)](#) and [Adams, Smart, and Huff \(2017\)](#), respectively, for the white literature and gray literature review parts of the MLR.

Publication selection validity refers to issues that may threaten the validity of searching and including all relevant publications in the review. To ensure the inclusion of relevant publications, we combined white and gray literature reviews. Search terms were defined collectively by all researchers involved and were tested in a series of pilot search queries before being applied in the final search. Pilot searches improved the search query in that specific terms and synonyms for the study topic were identified. Inclusion and exclusion criteria were based on best-practice guidelines. Moreover, to counteract any subjectivity bias of individual researchers, at least two researchers screened the identified publications and decided jointly on their potential inclusion or exclusion. Finally, as recommended by [Wohlin \(2014\)](#), we applied forward and backward snowballing on the initially selected publications to include relevant publications we might have missed in the automated search. We searched for white literature using the Scopus database, which maintains a comprehensive set of potential publication sources. One remaining issue is selection bias associated with the use of a single search engine (Google) for the gray literature search because none of the alternative search engines provided the required search functionalities. Another potential issue might be inclusion of German-language publications, yet its impact is minimal as the final selection included only one such publication (from the gray literature).

Data validity refers to issues that may threaten the validity of the data extracted from the selected publications. To assure valid data, all researchers jointly derived the information items to be extracted. We also ensured that all involved researchers were knowledgeable about the study topics and thus able to properly extract the required information from the publications. Finally, to avoid bias associated with differing quality between publications, we performed a basic quality assessment

of the reviewed publications using a few predefined criteria, which included “explicit definition of study objectives”, “extent of systematic analysis”, and “discussion of threats to validity”. In our work, we could not account for the quality of completeness, for example if a publication provided only some examples instead of disclosing all KPIs, variation factors, or challenges known to its authors.

Data synthesis and conclusions validity refers to issues that may threaten the validity of the conclusions drawn from the review. To ensure wide applicability of the study outcomes, we used widely acknowledged definitions of the key concepts of KPI, UX, and IoT, and adapted the ISO/IEC 25010 standard to classify the KPIs identified in the study. The use of this standard as a basis for the classification scheme may have induced a bias towards a particular view on quality that might have been different if another perspective had been taken (e.g., according to the ISO 9241 family of standards). However, we deem the chosen structure to be appropriate and observed that several sources implicitly used this structure, too. Further validity issues might be caused by gray literature typically having lower credibility than white literature. Our independent analyses of the white and gray literature data were intended to mitigate the associated validity threat. After the separate analyses, we used consistent synthesis methods to discuss differences and synergies to answer the research questions. Although we ensured that the review did not include explicitly non-primary studies, we could not definitely rule out that results presented in gray literature publications – especially the two outliers [G04; G07] – were not based in part on other literature sources.

7. Conclusions and further research

Our multivocal literature review identified 242 studies from searches of the literature, of which 64 were found to be research studies of acceptable rigor, credibility, and relevance. Of these, 38 studies represented white literature and 26 gray literature publications. The review resulted in a comprehensive list of KPIs related to UX and IoT systems that is based on a wide range of white and gray literature sources. The list is accompanied by a collection of factors influencing UX (variation factors) and challenges discussed in the studied literature.

We found a total of **848 key performance indicators for user experience**, 243 in the white literature and 605 in the gray literature. The gray literature KPIs were dominated by two reports from a large research project where 256 and 246 UX-KPIs were identified, respectively. **The final set contained 488 KPIs, out of which 280 (57.4%) were dedicated to the user experience (UX) of IoT systems** and a further 22 (4.5%) may additionally be suitable in certain contexts. Most of the work reviewed addresses the UX aspects known from non-IoT software systems and a small portion the UX of non-industrial IoT systems. **We found no KPIs that pertain exclusively to Industrial IoT systems**; they can all be generalized to IoT systems. At best, some KPIs might be somewhat context- or domain-specific. **The research dedicated to IoT systems has primarily a functional focus, concentrating on IoT systems providing basic functionality to assist the end-user.** The most common KPIs found are related to a system's *functional suitability* and are often related to *data quality* aspects such as *currentness*, *credibility*, and *correctness*, which may negatively impact UX. The other most common quality aspect of UX addressed in the literature is *performance efficiency*, in particular the system's *time behavior*; delays in system response are often considered to have a large impact on the users' perception of UX.

The reviewed literature also acknowledges the fact that a system's UX is not only determined by the properties of the system itself, but is also shaped by the context within which it is used. The characteristics of the usage context that influence user experience and which must necessarily be considered to properly interpret UX-KPIs are referred to as variation factors. The review identified **78 variation factors, 38 in the white literature and 40 in the gray literature.** **The most common variation factors include the capabilities of the system's users and the**

interaction of IoT solution providers with users. Example factors include *users' familiarity with the system and the technologies it uses* and *provision of additional services associated with IoT products*.

Finally, a number of challenges regarding the evaluation of user experience, in particular the definition of appropriate KPIs, were discussed in the reviewed literature. The review identified a total of **119 challenges, 79 in the white literature and 40 in the gray literature**. The challenges typically referred to product quality aspects of an IoT system such as its complexity, memory utilization, or response time. In fact, **complexity is the most commonly highlighted challenge**. It includes both the inherent complexity of a product itself, e.g., in terms of the number of different technologies used, and the complexity of its usage context, e.g., different interfaces and data points or the interaction with different devices and platforms.

An additional observation from the study is the large heterogeneity of indicators of and factors influencing the UX of IoT and IIoT systems. Despite a relatively large number of KPIs identified, only few of them recurred in more than one publication, which makes the lists of UX-KPIs and variation factors that we compiled from the literature rather unlikely to be anywhere near saturation. Although specific application contexts would require the consideration of further aspects of user experience, the classification proposed in this article shows that understanding the UX of IIoT systems requires a holistic view of different quality dimensions, including *product quality* and *quality in use* or intrinsic (context-independent) and contextual quality.

We conclude our study with the hypothesis that despite the large number of KPIs found, the **evaluation of UX using well-defined key performance indicators and influencing factors in the context of IoT systems in general, and Industrial IoT systems in particular, is still an emerging topic**. In addition to valuable findings, our study also revealed a few research gaps, which imply the need for further research. **Further research directions** should include:

- **Definition and measurement of user experience key performance indicators.** The relative novelty and high complexity of IoT systems, which distinguish them from other types of information systems, pose the greatest challenge when managing such systems, including the definition of appropriate KPIs. Furthermore, the UX of an IoT system has a potentially different meaning for each of its stakeholders (e.g., developers, customers, end-users) and thus requires considering different KPIs and their mutual interactions. This specifically adds a layer of complexity for IoT designers in terms of how to consider UX in their development process (e.g., business, data, technological, legal layers). Further research is thus needed to provide an approach for goal-oriented measurement of the user experience of IoT systems, accompanied by a catalog of specific measures that can be reused in various contexts. Methods that have been successfully applied in the context of classical software systems should be empirically evaluated and adapted for IoT systems. Examples of such approaches include Balanced Scorecard (Kaplan & Norton, 1996) or GQM⁺ Strategies (Basili et al., 2014), with the latter dedicated to the software systems engineering context. In the course of this work, detailed research is needed to identify specific characteristics of IoT systems that determine their user experience, particularly unique ways of user interaction with these systems. For example, a categorization of the types of interaction between IoT systems and users as well as an overview of the different modes of

interaction for IoT systems will help to deal with their complexity and to define appropriate indicators and metrics.

- **Identification and consideration of variation factors.** In general, the context in which an IoT system is developed and operates may influence its quality. Regarding user experience, the development context has an indirect impact in that it influences other quality characteristics of a software system, which then may contribute to the user experience. The operation context, on the other hand, rather has a direct impact on user experience because it defines the conditions in which users interact with the system. Future research should investigate context characteristics that are relevant from the perspective of evaluating and controlling the UX of IoT systems, and how to measure them. Furthermore, empirical studies should investigate the direction and magnitude of the impact the variation factors have on UX and on the associated UX-KPIs.
- **Understanding the value of UX in the context of IoT systems and its contribution to business success.** Insights have to be gained through systematic methods for aligning UX-KPIs to business objectives with the explicit consideration of context-specific constraints, both known and assumed. Example methods that can be adapted for this purpose are GQM⁺ Strategies (Basili et al., 2014) or Strategy Maps (Kaplan & Norton, 2004); they both combine strategic alignment and measurement of key performance indicators.
- **Providing a taxonomy and guidelines for practitioners:** There exist a huge number of potential UX-KPIs and variation factors; this review has already identified a few hundreds. To be useful in practice, they must be systematized and accompanied by guidelines so that practitioners can quickly identify and adapt the indicators that are most relevant in their specific context. UX-KPIs may, for instance, be classified according to the type of IoT system or business objectives. In this review, we have proposed a classification scheme based on a software quality standard to systematize the KPIs we found in the literature. Further research is needed to validate this scheme and propose alternative schemes that address its weaknesses.
- **Managing the complexity of IoT systems.** Complexity is becoming increasingly important in the domain of IoT, especially as Industrial IoT systems continue to grow in size and number. Our study shows complexity to be the predominant challenge of IoT systems influencing their UX. Reliable indicators and associated effective measures are thus required to manage the complexity of IoT systems quantitatively in order to increase their acceptance among customers and users.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Appendix

A.1. Recommendations for successfully implementing UX-KPIs for IoT systems

In our study, we uncovered several key challenges regarding the measurement of UX-KPIs in the context of IoT that practitioners must address

before they can quantitatively manage the UX of IoT systems and ensure its contribution to business success. Although we already found several hundred UX-KPIs that the literature proposes for IoT systems, only very few specifically address Industrial IoT systems. Moreover, for many KPIs, the appropriate measurement process and alignment to business objectives are not defined; consequently, it is not clear how to collect, analyze, and interpret the corresponding data. Yet, it is crucial for business success to identify relevant indicators of an IoT system's UX as well as factors that influence it (i.e., variation factors). To address these challenges, we derived the following basic recommendations for practitioners based on the experience and insights gained through our research:

- We propose defining relevant stakeholders of a particular IoT system; specifically those who contribute to the UX (e.g., product developers, designers, service providers) and those who profit from its UX. In particular, a distinction should be made between customers and users.
- We recommend explicitly considering the usage context of an IoT system, in particular those factors that influence UX and those that are required to properly interpret data on UX indicators. The GQM⁺Strategies approach (Basili et al., 2014) can be adapted to support a step-wise process for deriving specific UX goals and strategies, and for making them measurable (and thus quantitatively manageable). As we observed in our literature study, UX-KPIs are often missing specific metrics and measurement processes; GQM⁺Strategies supports systematic, goal-oriented measurement.
- We propose explicitly aligning the business success criteria of an IoT system influenced by its UX through mutually associated and measurable indicators (KPIs) and taking into consideration the usage context. For example, KPIs derived from the usage context quality characteristics (see Section 4.2) can be aligned with the perspectives of the Balanced Scorecard (Kaplan & Norton, 1996) for the purpose of strategic planning:
 - The financial perspective is reflected by the IoT strategy.
 - The customer perspective is reflected by the stakeholder focus, which can be extended to the process and capability perspectives when considering employees as stakeholders.
 - The product perspective is reflected by *system quality*, *quality in use*, and *system constraints*.
- It can be helpful to reuse existing KPIs and metrics as a reference basis, and adapt them for an IoT system's specific context and stakeholder needs.

The aspects listed represent observations of the authors and can be understood as lessons learned. We make no claim to completeness.

A.2. Domains covered by the literature review

Domain	Description and examples
Automotive	Smart car: vehicle automation and autonomous driving
Education	Student activity tracking, success prediction, smart campus environment
Entertainment	Smart cultural spaces, multiplatform television, multimedia audio/video services
Home	Smart home, incl. Smart TV, home control or smart laundry
Hotel	Hotel and accommodation services
Mobility	Public transportation and information systems, e.g., smart parking and bus information systems
Public services	Government services to the public and smart city, e.g., city hall smart service center, fire and rescue management, or public bus transportation
Resource management	Smart management of resources such as energy and water
Sales	Sales and e-business
Telecommunications	Telecommunications network simulation, adaptive bandwidth allocation, path selection
Wearables	Smart watch and smart clothes
Cross-domain	General aspects such as IoT/IIoT business models or multiple domains, e.g., healthcare, well-being, logistics, industrial production and robotics, energy, wearables, home automation, smart irrigation

A.3. Data extraction form

Category	Aspect	
General information	Author(s), title, publication year, publication source, etc.	
Content demographics	Domain	Domain considered, e.g., automotive, medical, energy
	Industrial IoT	Whether Industrial IoT, in particular, is considered
	IoT system	Specific type of IoT system considered, e.g., smart house, smart gym machine
	Motivation	The reason for the publication
	Research questions	Specific research questions listed
Study quality	Research category	Type of research presented, e.g., validation, evaluation research, solution proposal, philosophical papers, opinion papers, experience papers (Wieringa, Maiden, Mead, & Rolland, 2006)
	Study objectives	The extent to which the objectives of the publication or study presented there are defined explicitly
	Results analyzed	The extent to which the outcomes of a study presented in the publication are systematically analyzed and presented
Challenges	Threats to validity	The extent to which threats to the validity of the study and the results presented in the publication are discussed systematically
	Challenge	Threat, issue, problem, or difficulty related to <ul style="list-style-type: none"> (1) defining KPIs in the context of IoT; (2) defining UX-KPIs in the context of IoT; (3) business alignment or value of UX in the context of IoT.
Key performance indicators	Solution	Solution to specific UX challenges
	Key performance indicator	Any KPI considered at any abstraction level (e.g., organization, IoT system, user). For each KPI, its name, a brief definition, and the associated measurement method (if documented) were extracted.
Variation factors	Variation factor	Additional characteristics associated with the context in which UX-KPIs are considered and that may influence them or their use. For example, the UX of a specific software system is influenced by the individual skills of the user or the time pressure when using the system. A variation factor should be known and considered to properly interpret UX-KPI data; for instance, the UX of different users should not be compared without knowing their skills if a skills factor is known to influence individual UX.

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Category	Impact	Aspect
Guidelines	Guideline	How the variation factor influences UX. Potential values: positively, negatively, context (if the factor is a context factor) Practical advice (at best based on experience from practice) for (1) defining KPIs in the context of IoT; (2) defining UX-KPIs in the context of IoT; (3) business alignment or value of UX in the context of IoT.

A.4. Key performance indicators

	Characteristic	Subcharacteristic	UX-IoT-KPI	IoT-KPI	UX-KPI	Context	Total	
System Quality	Functional Suitability	Functional Completeness	11	5	1		17	
		Functional Correctness	6	2		1	9	
		Functional Appropriateness	12	4		2	18	
	Performance Efficiency	Time Behavior	11	3			14	
		Resource Utilization	2	6			8	
		Capacity	9	4			13	
		<i>General</i>		2			2	
	Compatibility	Coexistence					0	
		Interoperability	11	8			19	
	Usability	Appropriateness Recognizability	4				4	
		Learnability	4				4	
		Operability	10				10	
	Reliability	User Error Protection	2				2	
		User Interface Aesthetics	1				1	
		Accessibility	6				6	
		Maturity	2				2	
		Availability	7			2	9	
		Fault Tolerance	8	1			9	
		Recoverability	6			1	7	
	Security	Confidentiality	7	2			9	
		Integrity	3	5			8	
		Non-Repudiation		1			1	
		Authenticity					0	
		Accountability					0	
		<i>General</i>	1	1			2	
	Maintainability	Modularity	1				1	
		Reusability		5			5	
		Analyzability		1			1	
		Modifiability	1				1	
		Testability	1	4			5	
		<i>General</i>		1			1	
		Portability	Adaptability	3	1			4
	Installability	3				3		
	Replaceability	1				1		
	<i>General</i>	1				1		
Quality in Use	Effectiveness		10		1	1	12	
	Efficiency		31		1		32	
	Satisfaction	Usefulness	12	1	2		15	
		Trust	13		1	1	15	
		Pleasure	14		2	4	20	
		Comfort	14		1	1	16	
	Freedom from Risk	Economic Risk Mitigation	1	1			2	
		Health and Safety Risk Mitigation	8				8	
		Environmental Risk Mitigation		5			5	
	Context Coverage	Context Completeness	6				6	
		Flexibility	5	2			7	
	Usage Context Quality	IoT Strategy	Business Strategy	3	47	2	3	55
			Financial Strategy	4	23		1	28
Stakeholder Focus		Stakeholder Outreach			3		3	
		Stakeholder Understanding	14	4	1	4	23	
		Stakeholder Involvement	10		4	1	15	
System Constraints		Stakeholder Environment					0	
		Architectural Constraints			13		13	
		Regulatory Constraints	1		15		16	
Total				280	167	19	22	488

A.5. Classification and descriptive data of publications

	ID	Year	Type	Domain	Industrial IoT?
White Literature	W01	2018	Journal	Home	No
	W02	2016	Conference	Home	No
	W03	2020	Journal	No specific one	No
	W04	2020	Journal	Cross-domain	Yes
	W05	2021	Conference	Wearable	No
	W06	2015	Conference	Entertainment	No
	W07	2017	Journal	Entertainment	No
	W08	2019	Journal	No specific one	No
	W09	2019	Conference	Entertainment	No
	W10	2020	Conference	No specific one	No
	W11	2019	Journal	Hotel	No
	W12	2017	Conference	No specific one	Yes
	W13	2019	Journal	No specific one	No
	W14	2021	Journal	No specific one	No
	W15	2018	Journal	Telecommunication	No
	W16	2018	Conference	Cross-domain	No
	W17	2019	Journal	Public services	No
	W18	2021	Journal	Telecommunication	No
	W19	2020	Journal	Public services	No
	W20	2018	Journal	No specific one	No
	W21	2020	Conference	No specific one	No
	W22	2018	Conference	Education	No
	W23	2020	Conference	Home	No
	W24	2020	Journal	Cross-domain	Yes
	W25	2019	Conference	No specific one	No
	W26	2019	Conference	No specific one	No
	W27	2018	Journal	Telecommunication	No
	W28	2018	Journal	Resource management	No
	W29	2017	Journal	Public services	No
	W30	2017	Journal	Resource management	No
	W31	2015	Conference	Cross-domain	Yes
	W32	2015	Conference	Education	No
	W33	2019	Conference	Entertainment	No
	W34	2019	Conference	Public services	No
	W35	2021	Journal	Home	No
	W36	2021	Journal	Cross-domain	No
	W37	2018	Journal	Cross-domain	No
	W38	2019	Conference	Automotive	No
Gray Literature	G12	2019	Opinion Paper	Cross-domain	No
	G01	2020	Webinar	Cross-domain	Yes
	G02	2020	Student assignment	Cross-domain	No
	G03	no date	Education materials	Cross-domain	No
	G04	2017	Research project deliverable	Cross-domain	No
	G05	2020	Whitepaper	Cross-domain	Yes
	G06	2021	Research project deliverable	Cross-domain	No
	G07	2018	Research project deliverable	Cross-domain	No
	G08	2017	Blog post	Sales	No
	G09	2019	Blog post	Cross-domain	Yes
	G10	2020	Technical report	Cross-domain	Yes
	G11	2017	Evaluation research	Mobility	No
	G13	2019	Blog post	Cross-domain	Yes
	G14	2015	Blog post	Cross-domain	No
	G15	2018	Blog post	Cross-domain	No
	G16	2015	Blog post	Cross-domain	No
	G17	2015	Blog post	Cross-domain	Yes
	G18	2018	Magazine article	Cross-domain	No
	G19	2018	Blog post	Cross-domain	Yes
	G20	2015	Blog post	Cross-domain	No
	G21	2017	Master thesis	Cross-domain	Yes
	G22	2018	Blog post	Cross-domain	No
	G23	2015	Blog post	Cross-domain	No
	G24	2017	Blog post	Cross-domain	No
	G25	2016	Blog post	Cross-domain	No
	G26	2020	Opinion paper	Cross-domain	No

A.6. Definitions of usage context quality characteristics

IoT Strategy	
Business strategy	Aspects related to the IoT strategy aimed at increasing success by means of shaping the ecosystem, gaining a market position, generating revenue, and identifying opportunities, including the service provided.
Financial strategy	Aspects related to the potential of increased gains, turnover, revenue, or reduced costs associated with the IoT system, including purchases of resources and determining the appropriateness of the pricing model.
Stakeholder Focus	
Stakeholder outreach	Aspects related to organizational visibility and brand awareness through dissemination channels, and the way the organization is perceived by stakeholders.
Stakeholder understanding	Aspects related to determinants of the scope, intensity, duration, and frequency of an IoT platform's use by any kind of stakeholder, not relating to direct contact between the stakeholder and the organization.
Stakeholder interaction	Aspects related to the intensity and valuation of direct contact between a stakeholder and the organization, and personal (psychological) characteristics of the stakeholder.
Stakeholder environment	Aspects related to the context in which the IoT system is used. These aspects are neither system properties nor related to decisions made during development, but are external influences on the IoT system or its usage.
System Constraints	
Architectural constraints	Aspects related to the constraints and design decisions (during system development) regarding the IoT system's structure. Not to be confused with the operational aspects of <i>maintainability</i> during runtime.
Regulatory constraints	Aspects related to design decisions (during system development) related to compliance, standardization, harmonization, regulation adherence, process conformity, and certification of the IoT system. Not to be confused with the operational aspects of <i>interoperability</i> during runtime.

A.7. List of primary studies from the white literature

- [W01] Jalal, L., Anedda, M., Popescu, V., & Murrioni, M. (2018). QoE assessment for IoT-based multi sensorial media broadcasting. *IEEE Transactions on Broadcasting*, 64 (2), 552–560. DOI: <https://doi.org/10.1109/TBC.2018.2823914>
- [W02] Lee, M., Jeong D., Jeong, H., Lee, E., & Song, M. (2016). A framework for designing UX of sharing 'Internet of Things (IoT)' system and service: Case study of UX development of community laundry machines. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 9748, 365–372. DOI: https://doi.org/10.1007/978-3-319-40,406-6_35
- [W03] Baraković, S., Husić, J. B., Maraj, D., Maraj, A., Krejcar, O., Maresova, P., & Melero, F. J. (2020). Quality of life, quality of experience, and security perception in web of things: An overview of research opportunities. *Electronics (Switzerland)*, 9 (4), article 700. DOI: <https://doi.org/10.3390/electronics9040700>
- [W04] Leminen, S., Rajahonka, M., Wendelin, R., & Westerlund M. (2020). Industrial Internet of Things business models in the machine-to-machine context. *Industrial Marketing Management*, 84(January), 298–311. DOI: <https://doi.org/10.1016/j.indmarman.2019.08.008>
- [W05] Lin, Z., Sommer, B., & Ahmed-Kristensen, S. (2021). IoT Product pleasurability: Investigating the pleasurable user experiences between conventional products and IoT products through watches. *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering* 367, 394–408. DOI: https://doi.org/10.1007/978-3-030-73,426-8_24
- [W06] Chianese, A. & Piccialli, F. (2015). Improving user experience of cultural environment through IoT: The beauty or the truth case study. *Smart Innovation, Systems and Technologies*, 40, 11–20. DOI: https://doi.org/10.1007/978-3-319-19,830-9_2
- [W07] Shin, D.-H. & Shim, Y. (2017). Mapping user experience of multiplatform services: The quality factors in multiplatform television. *International Journal of Mobile Communications*, 15 (5), 554–575. DOI: <https://doi.org/10.1504/IJMC.2017.10005360>
- [W08] He, X., Wang, K., & Xu, W. (2019). QoE-driven content-centric caching with deep reinforcement learning in edge-enabled IoT. *IEEE Computational Intelligence Magazine*, 14 (4), 12–20. DOI: <https://doi.org/10.1109/MCI.2019.2937608>
- [W09] Akhtar, Z., Siddique, K., Rattani, A., Lutfi, S. L., & Falk, T. H. (2019). Why is multimedia quality of experience assessment a challenging problem? *IEEE Access*, 7, 117,897–117,915. DOI: <https://doi.org/10.1109/ACCESS.2019.2936470>
- [W10] Almeida, R. L. A., Andrade, R. M. C., Darin, T. G. R., & Paiva, J. O. V. (2020). CHASE: Checklist to assess user experience in IoT environments. In: *Proceedings of the 2020 ACM/IEEE 42nd International Conference on Software Engineering: New Ideas and Emerging Results (ICSE-NIER)*, 41–44. DOI: <https://doi.org/10.1145/3377816.3381737>
- [W11] Choi, D.-H. (2019). Impact of Internet of Things (IoT)'s service quality on the hotel customer satisfaction. *International Journal of Recent Technology and Engineering*, 8(2S6), 362–366. DOI: [10.35940/ijrte.B1069.0782S619](https://doi.org/10.35940/ijrte.B1069.0782S619)
- [W12] Fraifer, M., Kharel, S., Hasenfuss, H., Elmangoush, A., Ryan, A., Elgenaidi, W., & Fernstrom, M. (2017). Look before you leap: Exploring the challenges of technology and user experience in the Internet of Things. In: *Proceedings of the IEEE 3rd International Forum on Research and Technologies for Society and Industry (RTSI)*. DOI: <https://doi.org/10.1109/RTSI.2017.8065920>
- [W13] Sidek, N. & Ali, N. B. (2019). Analysing the critical quality factors in IoT-based service implementation: A systematic evaluation. *International Journal of Engineering and Advanced Technology*, 9 (1), 2276–2281. DOI: [10.35940/ijeat.A2631.109119](https://doi.org/10.35940/ijeat.A2631.109119)
- [W14] Lu, Y. (2021). Examining user acceptance and adoption of the internet of things. *International Journal of Business Science and Applied Management*, 16 (3), 1–17. DOI: [10.13140/RG.2.2.36737.58728](https://doi.org/10.13140/RG.2.2.36737.58728)
- [W15] Al-Momani, A. M., Mahmoud, M. A., & Ahmad, M. S. (2018). Factors that influence the acceptance of internet of things services by customers of telecommunication companies in Jordan. *Journal of Organizational and End User Computing*, 30 (4), 51–63. DOI: <https://doi.org/10.4018/JOEUC.2018100104>
- [W16] Bergman J., Olsson T., Johansson I., & Rasmus-Gröhn, K. (2018). An exploratory study on how internet of Things developing companies handle user experience requirements. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 10,753, 20–36. DOI: https://doi.org/10.1007/978-3-319-77,243-1_2
- [W17] Suryanegara, M., Prasetyo, D. A., Andriyanto, F., & Hayati, N. (2019). A 5-step framework for measuring the Quality of Experience (QoE) of Internet of Things (IoT) services. *IEEE Access* 7, 175,779–175,792. DOI: <https://doi.org/10.1109/ACCESS.2019.2957341>
- [W18] Martinez-Caro, J.-M. & Cano, M.-D. (2021). A novel holistic approach for performance evaluation in Internet of Things. *International Journal of Communication Systems*, 34 (2), article e4454. DOI: <https://doi.org/10.1002/dac.4454>
- [W19] Chen, T., Guo, W., Gao, X., & Liang, Z. (2020). AI-based self-service technology in public service delivery: User experience and influencing factors. *Government Information Quarterly*, 38 (4), article 101,520. DOI: <https://doi.org/10.1016/j.giq.2020.101520>
- [W20] Mani, Z. & Chouk, I. (2018). Consumer resistance to innovation in services: Challenges and barriers in the Internet of Things era. *Journal of Product Innovation Management*, 35 (5), 780–807. DOI: <https://doi.org/10.1111/jpim.12463>

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- [W21] Baba, N. M. & Baharudin, A. S. (2020). Determinants of users' intention to use IoT: A conceptual framework. *Advances in Intelligent Systems and Computing*, 1073, 980–990. DOI: https://doi.org/10.1007/978-3-030-33,582-3_92
- [W22] Orehovački, T., Plantak Vukovac, D., Džeko, M., & Stapić, Z. (2018). Evaluating relevant UX dimensions with respect to IoT ecosystem intended for students' activities tracking and success prediction. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 10,924, 279–293. DOI: https://doi.org/10.1007/978-3-319-91,743-6_22
- [W23] Chalhoub, G., Flechais, I., Nthala, N., Abu-Salma, R., & Tom, E. (2020). Factoring user experience into the security and privacy design of smart home devices: A case study. In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA)*. DOI: <https://doi.org/10.1145/3334480.3382850>
- [W24] Minovski, D., Ahlund, C., Mitra, K., & Zhohov, R. (2020). Defining quality of experience for the Internet of Things. *IT Professional*, 22 (5), 62–70. DOI: <https://doi.org/10.1109/MITP.2020.2968259>
- [W25] Khattab, A., Hamza, H. S., & Khattab S. M. (2018). Enhancing user experience in IoT mashup using semantic technology. In: *Proceedings of the IEEE Global Conference on Internet of Things (GCIoT)*. DOI: <https://doi.org/10.1109/GCIoT.2018.8620164>
- [W26] Zhang, C., Jia, B., & Hao, L. (2019). A multi-objective service selection method based on ant colony optimization for QoE restrictions in the Internet of Things. *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering* 284, 342–353. DOI: https://doi.org/10.1007/978-3-030-21,373-2_26
- [W27] Huang, X., Xie, K., Leng, S., Yuan, T., & Ma, M. (2018). Improving Quality of Experience in multimedia Internet of Things leveraging machine learning on big data. *Future Generation Computer Systems*, 86(C), 1413–1423. DOI: <https://doi.org/10.1016/j.future.2018.02.046>
- [W28] Curry, E., Hasan, S., Kouroupetroglou, C., Fabritius, W., Ul Hassan, U., & Derguech, W. (2018). Internet of Things enhanced user experience for smart water and energy management. *IEEE Internet Computing*, 22 (1), 18–28. DOI: <https://doi.org/10.1109/MIC.2018.011581514>
- [W29] Shin, D.-H. (2017). Conceptualizing and measuring quality of experience of the Internet of Things: Exploring how quality is perceived by users. *Information and Management*, 54 (8), 998–1011. DOI: <https://doi.org/10.1016/j.im.2017.02.006>
- [W30] Baskar, S. (2017). 6 Reasons why designing UX for IoT is so difficult. *Machine Design*, 89 (9), 56–61. Retrieved October 24, 2022 from <https://www.machinedesign.com/automation-iiot/article/21835791/6-reasons-why-designing-ux-for-iiot-is-so-difficult>
- [W31] Pallot, M., Pawar, K., & Santoro, R. (2013). A user experience framework and model within experiential living labs for Internet of Things. In: *Proceedings of the 2013 International Conference on Engineering, Technology and Innovation (ICE) & IEEE International Technology Management Conference (ITMC)*. DOI: <https://doi.org/10.1109/ITMC.2013.7352688>
- [W32] Li, L., Rong, M., & Zhang, G. (2015). An Internet of Things QoE evaluation method based on multiple linear regression analysis. In: *Proceedings of the 10th International Conference on Computer Science and Education (ICCSE)*, 925–928. DOI: <https://doi.org/10.1109/ICCSE.2015.7250382>
- [W33] Aazam, M. & Harras, K. A. (2019). Mapping QoE with resource estimation in IoT. In: *Proceedings of the IEEE 5th World Forum on Internet of Things (WF-IoT)*, 464–467 DOI: <https://doi.org/10.1109/WF-IoT.2019.8767254>
- [W34] Sidek, N. & Ali, N. (2019). Quality challenges in Internet of Things-based services Implementation: An exploratory study. In: *Proceedings of the IEEE Conference on Application, Information and Network Security (AINS)*, 60–65. DOI: <https://doi.org/10.1109/AINS47559.2019.8968702>
- [W35] Liang, Y., Xu, Q., & Jin, L. (2021). The effect of smart and connected products on consumer brand choice concentration. *Journal of Business Research*, 135(C), 163–172. DOI: <https://doi.org/10.1016/j.jbusres.2021.06.039>
- [W36] Kasilingam, D. & Krishna, R. (2022). Understanding the adoption and willingness to pay for Internet of Things services. *International Journal of Consumer Studies*, 46 (1), 102–131. DOI: <https://doi.org/10.1111/ijcs.12648>
- [W37] Page, X., Bahirat, P., Safi, M. I., Knijnenburg, B. P., & Wisniewski, P. (2018). The internet of what? Understanding differences in perceptions and adoption for the Internet of Things. In: *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 2 (4), article 183. DOI: <https://doi.org/10.1145/3287061>
- [W38] Shahzad, M. & Antoniou, J. (2019). Quality of user experience in 5G-VANET. In: *Proceedings of the IEEE 24th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*. DOI: <https://doi.org/10.1109/CAMAD.2019.8858442>

A.8. List of primary studies from the gray literature

- [G01] Shankar Datta & Vinay Rao (presenters), Devanshi Mehta (moderator) (2020). *NASSCOM Engineering R&D webinar: Enhancing user experience with IoT verification & validation*. Webinar: Business Process Incubator. Retrieved June 28, 2022, from <https://www.businessprocessincubator.com/content/nasscom-engineering-rd-webinar-enhancing-user-experience-with-iiot-verification-validation/>
- [G02] Hamdan Hejazi & Istvan Majzik (2020). *Verification and validation of IoT systems*. Student assignment: Budapest University of Technology and Economics. Retrieved June 28, 2022, from https://inf.mit.bme.hu/sites/default/files/edu/doktori/szvv/referatum2020/Verification_And_Validation_of_IoT_Systems_%28Hejazi_Hamdan_Y_H%29.pdf
- [G03] Arcitura (n.d.). *Internet of Things (IoT) patterns, mechanisms, layers and metrics*. Education materials: Arcitura. Retrieved June 28, 2022, from <https://patterns.arcitura.com/internet-of-things-iiot-patterns>
- [G04] Giulia Micheletti & Ovidiu Vermesan (eds.) (2017). *Cross fertilisation through alignment, synchronisation and exchanges for IoT*. Research project deliverable: CREATE-IoT. Retrieved June 28, 2022, from https://european-iiot-pilots.eu/wp-content/uploads/2017/10/D01_04_WP01_H2020_CREATE-IoT_Final.pdf
- [G05] PTC (2020). *3 KPIs that improve customer satisfaction*. (Original in German: *3 KPIs für mehr Kundenzufriedenheit*). Whitepaper: PTC. Retrieved June 28, 2022, from <http://view.ceros.com/ptc/3-kpis-that-improve-customer-satisfaction>
- [G06] Pavel Smirnov (2021). *D7.2 – Prototypes for end-user evaluation*. Research project deliverable: IoT Crawler. Retrieved June 28, 2022, from <https://iotcrawler.eu/index.php/project/d7-2/>
- [G07] Javier Valiño (2018). *Cross fertilisation through alignment, synchronisation and exchanges for IoT*. Research project deliverable: CREATE-IoT. Retrieved June 28, 2022, from <http://ec.europa.eu/research/participants/documents/downloadPublic?documentId=080166e5bbdcefb&appId=PPGMS>
- [G08] Charlie Isaacs (2017). *IoT and AI: Taking customer satisfaction measurement to new levels*. Blog post: CIO. Retrieved June 28, 2022, from <https://www.cio.com/article/3161195/iiot-and-ai-taking-customer-satisfaction-measurement-to-new-levels.html>
- [G09] Bosch (2019). *Our ranking in IoT User Survey 2019*. Blog post: Bosch. Retrieved June 28, 2022, from <https://bosch.io/resources/report/the-iiot-user-survey-2019/>
- [G10] Arnold Vogt & Klaus Holzhauser (2020). *The IoT C&SI survey 2020*. Technical report: Teknowlogy Group. Retrieved June 28, 2022, from <https://de.nttdata.com/-/media/NTTDataGermany/Files/2020-EN-Study-NTT-DATA-Teknowlogy-The-IoT-C-SI-Survey-2020-full-report.pdf>
- [G11] C. Lopez (ed.) (2017). *D4.1 Service requirements and KPIs*. *Evaluation research: Wise IoT*. Offline; originally retrieved from <http://wise-iiot.eu/wp-content/uploads/2017/06/D4.1-Service-requirements-and-KPIs-v1.7.pdf>
- [G12] Teknowlogy (2019). *The IoT survey 2019: The world's first comprehensive IoT platform provider survey*. Opinion paper: Device Insight. Offline; originally retrieved from http://www.device-insight.com/wp-content/uploads/2019/03/the_iiot_survey_2019_highlights_device_insight.pdf
- [G13] Aurora Font (2019). *What are UX challenges designing for IoT?* Opinion paper: Atos. Retrieved June 28, 2022, from <https://atos.net/en/blog/ux-challenges-designing-iiot/>
- [G14] Yona Gidalevitz (2015). *UX for enterprise: Using IoT to design integrated systems for the workplace*. Opinion paper: Usability Geek. Retrieved June 28, 2022, from <https://usabilitytygeek.com/ux-for-enterprise-using-iiot-to-design-systems-for-workplace/>
- [G15] Ana Rosa González Blanco (2018). *UX design for IoT: The UX of security 3/3*. Opinion paper: LinkedIn. Retrieved June 28, 2022, from <https://www.linkedin.com/pulse/ux-design-iiot-security-33-ana-rosa-gonzalez-blanco?articleId=6465960267544043520>
- [G16] Claire Rowland et al. (2015). *Chapter 5: Cross-device interactions and interusability*. Opinion paper: O'Reilly. Retrieved June 28, 2022, from <https://www.oreilly.com/library/view/designing-for-the/9781491971468/ch05.html>
- [G17] Thaiyalnayake Selvaraj (2015). *The importance of UX in IoT*. Blog post: HCL Technologies. Retrieved June 28, 2022, from <https://www.hcltech.com/blogs/importance-iiot-ux-iiot>

(continued on next page)

(continued)

- [G18] Kianosh Pourian (2018). *Don't discount the role of UX in IoT*. Magazine article: User Experience. Retrieved June 28, 2022, from <https://uxpamagazine.org/dont-discount-the-role-of-ux-in-iot/>
- [G19] Katherine Lazarevich (2018). *5 keys to designing user experience for IoT products: What is the key to a consistent user experience across multiple IoT products?* Blog post: IoT For All. Retrieved June 28, 2022, from <https://www.iotforall.com/designing-user-experience-iot-products>
- [G20] *eBook des Monats: O'Reilly: Expertise in UX design + design for the IoT + data-informed design and more*. Published May 31, 2018. Technical report: Open Text Web Solutions Usergroup. Retrieved June 28, 2022, from <https://www.opentext-usergroup.org/ebook-des-monats-o-reilly-expertise-in-ux-design-design-for-the-iot-data-informed-design-and-more-4429.htm>
- [G21] Johanna Bergmann & Isabelle Johansson (2017). *The user experience perspective of Internet of Things development*. Master thesis: Lund University. Retrieved June 28, 2022, from <https://lup.lub.lu.se/luur/download?fileId=8919053&func=downloadFile&recordId=8919050>
- [G22] Rajesh PK (2018). *IoT and UX: Advantages, difficulties, challenges and opportunities*. Blog post: Acodez. Retrieved June 28, 2022, from <https://acodez.in/iot-and-ux/>
- [G23] Alex Brisbourne (2015). *The unique UX challenges of the Internet of Things*. Blog post: SitePoint. Retrieved June 28, 2022, from <https://www.sitepoint.com/unique-ux-challenges-internet-of-things/>
- [G24] Isaac Joekong (2017). *User experience design for IoT devices*. Blog post: WorkingMouse. Retrieved June 28, 2022, from <https://workingmouse.com.au/ux-design/user-experience-design-for-iot-devices/>
- [G25] Sampath Kumar (2016). *Engineering analytics uses IoT to improve UX*. Blog post: ISG. Retrieved June 28, 2022, from <https://isg-one.com/industries/automotive/articles/engineering-analytics-uses-iot-to-improve-ux>
- [G26] Beschnitt, M., Hartwig, R., Termer, F., & Wolter, S. (2020). *Mensch-Zentrierung in Zeiten der Digitalisierung: Auf Interview-Safari mit UX-Experten*. Opinion paper: Bitkom e.V. Retrieved December 3, 2022, from https://www.bitkom.org/sites/default/files/2020-07/200715_If_mensch-zentrierung-in-zeiten-der-digitalisierung.pdf

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.digbus.2023.100057>.

References

- Adams, J., Hillier-Brown, F. C., Moore, H. J., Lake, A. A., Araujo-Soares, V., White, M., et al. (2016). Searching and synthesising 'gray literature' and 'gray information' in public health: Critical reflections on three case studies. *Systematic Reviews*, 5(1). <https://doi.org/10.1186/s13643-016-0337-y>. article 164.
- Adams, R. J., Smart, P., & Huff, A. S. (2017). Shades of gray: Guidelines for working with the gray literature in systematic reviews for management and organizational studies. *International Journal of Management Reviews*, 19(4), 432–454. <https://doi.org/10.1111/ijmr.12102>
- Aguilar, F. J. (1967). *Scanning the business environment*. New York: Macmillan. London: Collier-Macmillan.
- Ampatzoglou, A., Bibi, S., Avgeriou, P., & Chatzigeorgiou, A. (2020). Guidelines for managing threats to validity of secondary studies in software engineering. In M. Felderer, & G. Travassos (Eds.), *Contemporary empirical methods in software engineering* (pp. 415–441). Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-030-32489-6_15.
- Asghari, P., Rahmani, A., & Javadi, H. (2018). Service composition approaches in IoT: A systematic review. *Journal of Network and Computer Applications*, 120, 61–77. <https://doi.org/10.1016/j.jnca.2018.07.013>
- Atzori, L., Iera, A., & Morabito, G. (2010). The internet of things: A survey. *Computer Networks*, 54(15), 2787–2805. <https://doi.org/10.1016/j.comnet.2010.05.010>
- Basili, V., Trendowicz, A., Kowalczyk, M., Heidrich, J., Seaman, C., Münch, J., & Rombach, D. (2014). *Aligning organizations through measurement: The GQM² strategies approach*. Heidelberg: Springer. ISBN: 978-3319050461.
- Bergman, J., Olsson, T., Johansson, I., & Rasmus-Gröhn, K. (2018). An exploratory study on how internet of things developing companies handle user experience requirements. In *Proceedings of the 24th International working conference on Requirements Engineering: Foundation for Software Quality (REFSQ), LNCS 10753* (pp. 20–36). <https://doi.org/10.1007/978-3-319-05047-8>
- Boyes, H., Hallaq, B., Cunningham, J., & Watson, T. (2018). The industrial internet of things (IIoT): An analysis framework. *Computers in Industry*, 101, 1–12. <https://doi.org/10.1016/j.compind.2018.04.015>
- Data Protection Conference. (2020). The Standard Data Protection Model: A method for data protection advising and controlling on the basis of uniform protection goals (Version 2.0b). Retrieved May 16, 2022, from https://www.datenschutzzentrum.de/uploads/sdm/SDM-Methodology_V2.0b.pdf.
- Demarco, T. (1986). *Controlling software projects: Management, measurement & estimation*. Upple Saddle River, NJ: Prentice Hall PTR. ISBN: 978-0131717114.
- Elizalde, D. (2017). Why it's so hard to create a good user experience in IoT. Retrieved June 10, 2022, from <https://danielelizalde.com/iot-ux-is-hard/>.
- Garousi, V., Felderer, M., & Mäntylä, M. V. (2019). Guidelines for including gray literature and conducting multivocal literature reviews in software engineering. *Information and Software Technology*, 106, 101–121. <https://doi.org/10.1016/j.infsof.2018.09.006>
- Gil, D., Ferrández, A., Mora-Mora, H., & Peral, J. (2016). Internet of things: A review of surveys based on context aware intelligent services. *Sensors*, 16(7). <https://doi.org/10.3390/s16071069>. article 1069.
- Glinz, M. (2007). On non-functional requirements. In *Proceedings of the 15th IEEE International Requirements Engineering Conference (RE)* (pp. 21–26). <https://doi.org/10.1109/RE.2007.45>
- Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems*, 29(7), 1645–1660. <https://doi.org/10.1016/j.future.2013.01.010>
- Haindl, P., Plösch, R., & Körner, C. (2019). An extension of the QUAMOCO quality model to specify and evaluate feature-dependent non-functional requirements. In *Proceedings of the 45th Euromicro Conference on Software Engineering and Advanced Applications (SEAA)* (pp. 19–28). <https://doi.org/10.1109/SEAA.2019.00012>
- Hassenzahl, M. (2010). Experience design: Technology for all the right reasons. In *Synthesis lectures on human-centered informatics (SLHCI)*. Cham, Switzerland: Springer. <https://doi.org/10.1007/978-3-031-02191-6>.
- Helmold, M. (2019). Excellence in PM. In M. Helmold, & W. Samara (Eds.), *Progress in performance management: Industry insights and case studies on principles, application tools, and practice* (pp. 39–49). Cham: Springer. <https://doi.org/10.1007/978-3-030-20534-8>.
- Hinderks, A., Schrepp, M., Domínguez Mayo, F. J., Escalona, M. J., & Thomaschewski, J. (2019). Developing a UX KPI based on the user experience questionnaire. *Computer Standards & Interfaces*, 65, 38–44. <https://doi.org/10.1016/j.csi.2019.01.007>
- Hornbæk, K. (2006). Current practice in measuring usability: Challenges to usability studies and research. *Int. J. Hum. Comput. Stud.*, 64(2), 79–102. <https://doi.org/10.1016/j.ijhcs.2005.06.002>
- ISO. (2008). ISO/IEC 25012:2008, Software engineering — Software product Quality Requirements and Evaluation (SQuARE) — Data quality model. Retrieved May 18, 2022, from <https://www.iso.org/standard/35736.html>.
- ISO. (2011). ISO/IEC 25010:2011, Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuARE) — System and software quality models. Retrieved May 18, 2022, from <https://www.iso.org/standard/35733.html>.
- ISO. (2015). ISO 9001:2015, Quality management systems — Requirements. Retrieved May 18, 2022, from <https://www.iso.org/standard/62085.html>.
- ISO. (2019). ISO 9241-210:2019, Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems. Retrieved May 16, 2022, from <https://www.iso.org/standard/77520.html>.
- Jain, R., Aagja, J. P., & Bagdare, S. (2017). Customer experience: A review and research agenda. *Journal of Service Theory and Practice*, 27(3), 642–662. <https://doi.org/10.1108/JSTP-03-2015-0064>
- Jeschke, S., Brecher, C., Meisen, T., Özdemir, D., & Eschert, T. (2016). Industrial internet of things and cyber manufacturing systems. In S. Jeschke, et al. (Eds.), *Springer Series in Wireless Technology/Industrial internet of things* (pp. 3–19). Cham: Springer. https://doi.org/10.1007/978-3-319-42559-7_1.
- Kaplan, R. S., & Norton, D. P. (1996). *The balanced scorecard: Translating strategy into action*. Boston, MA: Harvard Business Review Press. ISBN: 9780875846514.
- Kaplan, R. S., & Norton, D. P. (2004). *Strategy maps: Converting intangible assets into tangible outcomes*. Boston, MA: Harvard Business Press. ISBN: 978-1591391340.
- Kitchenham, B., & Charters, S. (2007). *Guidelines for performing systematic literature reviews in software engineering. Technical report. EBSE 2007-001*. Keele University and Durham University Joint Report.
- Lamnabhi-Lagarrigue, F., Annaswamy, A. M., Engell, S., Isaksson, A. J., Khargonekar, P. P., Murray, R. M., et al. (2017). Systems & control for the future of humanity, research agenda: Current and future roles, impact and grand challenges. *Annual Reviews in Control*, 43, 1–64. <https://doi.org/10.1016/j.arcontrol.2017.04.001>
- Lamprecht, C., Gebauer, H., Fleisch, E., & Wortmann, F. (2022). A KPI set for steering the IoT business in product companies. *Research-Technology Management*, 65(2), 53–63. <https://doi.org/10.1080/08956308.2022.2015951>
- Li, S., Xu, L., & Zhao, S. (2015). The internet of things: A survey. *Information Systems Frontiers*, 17(2), 243–259. <https://doi.org/10.1007/s10796-014-9492-7>
- Lin, Z., Sommer, B., & Ahmed-Kristensen, S. (2021). IoT product pleasurable – Investigating the pleasurable user experiences between conventional products and

- IoT products through watches. In A. Brooks, E. I. Brooks, & D. Jonathan (Eds.), *Vol. 367. Interactivity and game creation (ArtsIT 2020), lecture notes of the Institute for Computer Sciences, social informatics and telecommunications engineering*. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-030-73426-8_24.
- McGrath, Y., Sumnall, H., Edmonds, K., McVeigh, J., & Bellis, M. (2006). *Review of gray literature on drug prevention among young people*. London/Manchester: National Institute for Health and Clinical Excellence. ISBN: 1-84629-184-4.
- Meskendahl, S. (2010). The influence of business strategy on project portfolio management and its success — A conceptual framework. *International Journal of Project Management*, 28(8), 807–817. <https://doi.org/10.1016/j.ijproman.2010.06.007>
- Mo, J. P. T., & Beckett, R. C. (2020). Transdisciplinary system of systems development in the trend to X4.0. In J. Pokojski, et al. (Eds.), *12. Transdisciplinary engineering for complex socio-technical systems: Real-life applications. Advances in transdisciplinary engineering* (pp. 21–35). Amsterdam: IOS Press. <https://doi.org/10.3233/ATDE200055>.
- Morelli, N. (2006). Developing new product service systems (PSS): Methodologies and operational tools. *Journal of Cleaner Production*, 14(17), 1495–1501. <https://doi.org/10.1016/j.jclepro.2006.01.023>
- Munappy, A. R., Mattos, D. I., Bosch, J., Olsson, H. H., & Dakkak, A. (2020). From ad-hoc data analytics to DataOps. In *Proceedings of the international conference on software and system processes (ICSSP)* (pp. 165–174). <https://doi.org/10.1145/3379177.3388909>
- Nass-Bauer, C., & Trapp, M. (2019). Tangible ecosystem design: developing disruptive services for digital ecosystems. In *Extended abstracts of the 2019 CHI conference on human factors in computing systems (CHI EA), article C20*. <https://doi.org/10.1145/3290607.3298819>
- Negri, E., Fumagalli, L., & Macchi, M. (2017). A review of the roles of digital twin in CPS-based production systems. *Procedia Manufacturing*, 11, 939–948. <https://doi.org/10.1016/j.promfg.2017.07.198>
- Norman, D., & Nielsen, J. (2022). The definition of user experience (UX). Retrieved May 16, 2022, from <https://www.nngroup.com/articles/definition-user-experience/>.
- Osterwalder, A., & Pigneur, Y. (2010). *Business model generation: A handbook for visionaries, game changers, and challengers*. Hoboken, NJ: Wiley. ISBN: 9780470876411.
- Pichler, R. (2012). The product canvas. Retrieved May 22, 2022, from <https://www.romanpichler.com/tools/the-product-canvas>.
- Rodrigues, S. S., Genesio, V. L., Paiva, D. M., & Fortes, R. (2020). A case study on how Brazilian companies deal with the user experience in IoT projects. In *Proceedings of the 38th ACM International Conference on Design of Communication (SIGDOC)*, article 39. <https://doi.org/10.1145/3380851.3416779>
- Roubtsova, E., & Michell, V. (2013). Modelling and validation of KPIs. In *Proceedings of the 3rd International Symposium on Business Modeling and Software Design (BMSD)* (pp. 96–105). <https://doi.org/10.5220/00047744009601>
- Rowland, C., & Charlier, M. (2015). *User experience design for the internet of things*. Boston, MA: O'Reilly.
- Rowland, C., Goodman, E., Charalier, M., Lui, A., & Light, A. (2015). *Designing connected products: UX for the consumer internet of things*. Sebastopol, CA: O'Reilly. ISBN: 9781449372569.
- Schmitt, H., & Groen, E. C. (2021). Qualitätsmodell zur Förderung des Beschäftigtendatenschutzes. *Datenschutz und Datensicherheit*, 45(1), 28–32. <https://doi.org/10.1007/s11623-020-1385-y>
- Shin, D. (2014). A socio-technical framework for internet-of-things design: A human-centered design for the internet of things. *Telematics and Informatics*, 31(4), 519–531. <https://doi.org/10.1016/j.tele.2014.02.003>
- Wagner, S., Goeb, A., Heinemann, L., Kläs, M., Lampasona, C., Lochmann, K., et al. (2015). Operationalised product quality models and assessment: The Quamoco approach. *Information and Software Technology*, 62, 101–123. <https://doi.org/10.1016/j.infsof.2015.02.009>
- Weader, J., & Schmidt-Subramanian, M. (2022). *The state of customer experience teams 2022. Our global study betrays organizations' continued low CX maturity*. Data Overview Report, Forrester Research.
- Wieringa, R., Maiden, N. A. M., Mead, N. R., & Rolland, C. (2006). Requirements engineering paper classification and evaluation criteria: A proposal and a discussion. *Requirements Engineering*, 11(1), 102–107. <https://doi.org/10.1007/s00766-005-0021-6>
- Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. In *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering*, article 38. <https://doi.org/10.1145/2601248.2601268>
- Yüksel, I. (2012). Developing a multi-criteria decision making model for PESTEL analysis. *International Journal of Business and Management*, 7(24), 52–66. <https://doi.org/10.5539/ijbm.v7n24p52>
- Zhao, J. (2022). *Strategies that improve UX (user experience) design through product innovation*. Doctoral dissertation. Minneapolis, MN: Walden University. ProQuest Dissertations & Theses Global, Publication No. 28971431.