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STATE OF THE ART

On the Interplay Between Business Process Management and Internet-of-Things

A Systematic Literature Review

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Abstract In the last years, the increasing scientific and industrial interest in Business Process Management (BPM) approaches and methods on the one side, and Internet-of-Things (IoT) technologies and tools on the other. Are these fields complementary? What are their respective interplays and the research challenges to their realizations? The article presents a Systematic Literature Review (SLR) to gain in-depth insights into the maturity of existing approaches to IoT-aware BPM. The analysis of the retrieved studies, framed along the research questions addressed in the SLR, enables us to systematically evaluate the literature on IoT-aware BPM concerning the phases of the process life cycle covered by the different approaches, the specific topics addressed, the application domains involved, and the possibility to tackle the research challenges. Future research directions are also highlighted.

Keywords Systematic literature review · Internet-of-things · Business process management · IoT-aware business processes

1 Introduction

In the last decade, the possibility to manufacture micro-controllers and CPUs of small physical dimensions at reduced cost has made it feasible to embed these devices alongside various everyday physical objects at a massive scale – e.g. home appliances and industrial equipment, just (to name a few). Combining this increased computing capacity with sensors, actuators, and communication modules allows such objects to interface with the physical world and operate autonomously, thus becoming *smart objects*. In this context, Internet-of-Things (IoT) broadly refers to the network of connected smart objects able to collect and exchange data over the Internet, thus providing advanced functionalities such as real-time monitoring, data sharing, and remote control (Kopetz and Steiner 2022).

Typical early adopters of smart objects and IoT can be found in industrial manufacturing, logistics and healthcare domains. For these areas, the tools and practices of Business Process Management (BPM) play a relevant role (Leotta et al. 2019). BPM is a research area concerned with the identification, modeling, analysis, redesign, implementation, monitoring and mining of business processes (BPs) (Dumas et al. 2018). A BP is a collection of related, structured activities, events and decisions that accomplish a specific organizational goal. According to the BPM approach, BPs are formalized through explicit BP models expressed with a suitable graphical notation, such as the standard BPMN.[1] A specific type of information system, called Process Management System (PMS), is employed to support the execution and monitoring of BPs and analyze historical traces of BP execution (Weske 2019).

IoT's presence in BPM activities continuously increasing since IoT data allows for finer-grained automated monitoring, analysis, and control during BP execution. Consequently, organizations' BPs must be aligned to take advantage of IoT capabilities. This has resulted in the rise of relevant studies focused on IoT-aware BPM (Cheng et al. 2018, 2019; Grefen et al. 2019). The Industry 4.0

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[1] The Business Process Modeling Notation (BPMN) is the ISO standard (ISO/IEC 19510:2013) for modeling BPs.

revolution was one of the significant accelerators for integrating IoT and BPM. In addition to the increased usage of smart objects, Industry 4.0 prescribes a factor of high degree of individual customizability for manufactured products, an aspect that IoT-aware BPM can effectively capture (Grefen et al. 2018). In this direction, Janiesch et al. in their manifesto about "*The Internet of Things Meets Business Process Management*" (*IoT-Meets-BPM Manifesto* for short in the following) identified many open challenges to address in order to achieve a more comprehensive and targeted integration of the main concepts of the two areas (Janiesch et al. 2020).

This study aims to gain profound insights into the nature and maturity of existing approaches to IoT-aware BPM. In particular, we present results from a Systematic Literature Review (SLR) conducted to systematically evaluate the literature on IoT-aware BPM concerning the phases of the BP life cycle covered by the different approaches, the specific topics addressed, the application domains involved, and the possibility to tackle the research challenges identified by Janiesch et al. (2020).

Our SLR, which follows the scientific and reproducible approach proposed by Keele (2007), consists of 3 phases: (1) the *planning* phase identifies the needs of the SLR, defines the research questions and develops a protocol for the review; (2) the *conducting* phase selects the studies, extracts and synthesizes relevant data; (3) the *reporting* phase analyzes the collected data and presents the results based on the prior research analysis.

With the support of the SLR, we identify 93 primary studies that are thoroughly analyzed. Based on this evaluation, we examine *(i)* which phases of the BPM life cycle were investigated by each study, *(ii)* which specific topics relating to IoT integration in BPM were primarily discussed by each study, and *(iii)* which are the main application domains addressed so far. Based on this analysis, we compare the studies according to which of the research challenges identified in the *IoT-Meets-BPM Manifesto* (Janiesch et al. 2020) are addressed. It emerges that the field of IoT-aware BPM is still in the development stage. Therefore, we consider our analysis beneficial for researchers and practitioners addressing such a novel and interesting field.

The paper is structured as follows. Section 2 shows the methodology we applied, including the research questions and the search protocol we adopted. In contrast, Sect. 3 describes the application of the protocol, and Sect. 4 gives an overview of the results achieved. Finally, to conclude our paper, Sect. 5 comprises a discussion of our results, including a presentation of the validity of the SLR, and Sect. 6 provides some concluding remarks.

2 Planning the Systematic Literature Review

In this section, we describe the *planning* phase of the SLR. Planning includes the following activities:

1. Related work analysis to motivate the need of the SLR;
2. Formulation of research questions to narrow the search;
3. Definition of the search strings;
4. Selection of data sources;
5. Definition of inclusion and exclusion criteria.

2.1 Related Work

The increased research community's interest in the interplay between IoT and BPM has led to the publication of relevant literature reviews and surveys on the topic. In Del Giudice (2016), a literature review is conducted to analyze the impact and the role of IoT in fostering innovation within organizations, and which implications this phenomenon may have on BPM and the competitiveness of firms.

In Chang et al. (2016), the authors analyze existing PMSs for IoT and identify the limitations and their drawbacks based on a mobile cloud computing perspective.

In Stoiber and Schönig (2021), a survey on event-driven BPM is conducted focusing on its capabilities to enable the scale-up of IoT applications. Research on incorporating IoT into BPM has shown that the majority of SLRs focus on the IoT-aware BP modeling phase. In Torres et al. (2020), a SLR is performed to collect and describe ways to model IoT-aware BPs. Compagnucci et al. (2023, 2020) for example, investigated modeling views related to different types of IoT-aware BPs and the IoT requirements supported by the various modeling notations. Abouzid et al. (2022) conducted a SLR on BPMN extensions for IoT domains and their integration in supply chain BPs. Compared to the other papers, this SLR not only addressed the modeling of IoT-aware processes, but also the other phases of BPM lifecycle. Finally, the work Fattouch et al. (2020) presents a survey of different approaches that integrate IoT technologies within BPs. The authors provide a brief overview of each approach and compare them based on specific criteria by identifying some open challenges. This survey shares our objective and an intersection of 8 out of 93 primary studies, but it was conducted in a non-systematic way, thus not permitting the results' replicability. Therefore another contribution of our approach is that it includes this replicability.

Whereas the above studies focus on analyzing specific aspects of the integration of IoT and BPM, in this SLR we provide a holistic view of such an integration by exploring its impact on the different BP life cycle phases and BPM-related application domains. As opposed to our approach, none of the works employ a generative statistical model to discover the most discussed topics in the collection of studies and automatically classify individual studies based on their relevance to these topics essential for achieving the integration of IoT and BPM.

Moreover, we discuss which challenges of the ones identified by the *IoT-Meets-BPM Manifesto* (Janiesch et al. 2020) have been (to date) adequately addressed or are still far from being tackled.

2.2 The Research Questions

Our main goal is to assess the current state of research on the IoT integration in the BPM ecosystem, consisting of methods, approaches and tools to manage the life cycle of a BP. To achieve this, we formulated the following research questions from collaborative brainstorming sessions among the authors:

RQ1: *Which phases of the BP life cycle was mainly impacted by the integration of IoT?*

RQ2: *Which topics relating to IoT integration in BPM are discussed in the literature?*

RQ3: *Which application domains are used to study IoT and BPM integration?*

RQ4: *What are the research challenges addressed so far to support the management of IoT-aware BP?*

2.3 Data Sources

We applied the search string on three search engines: Google Scholar (GS) and two more specialized in information systems and computer science, namely the IEEE Xplore Digital Library and ACM Digital Library. This approach has enabled us to overcome limitations associated with relying solely on a single search engine, specifically: *(i)* accessing a broader spectrum of pertinent sources beyond GS, *(ii)* mitigating the risk of missing relevant studies, *(iii)* reducing the inclusion of low-quality sources, and *(iv)* overcoming potential biases towards popular and recent publications.

As a further data source, we also reviewed the literature cited by the studies, performing a *backward reference search*. Additionally, we carried out a *conference and journal search* to retrieve other studies without any time constraints. The relevant studies for this SLR include publications from the most relevant conferences, seminar proceedings, and journals within the BPM and IoT fields and those focusing on practical solutions and applications. These sources have been selected through a well-defined and consistent process and align with the review's topic and objective. The journals and conferences were initially selected based on the authors' research experience. Subsequently, we expanded the search and defined criteria for adding new sources. Specifically, these were chosen because *(i)* they are subject to a peer-review process and *(ii)* they are registered in the libraries used to conduct this SLR. As a result, we included nine conferences, a dedicated workshop and eight journals, namely:

- Conference on: Business Information Systems (BIS), Business Process Management (BPM), Advanced Information Systems Engineering (CAiSE), Enterprise Distributed Object Computing (EDOC), Conceptual Modeling (ER), Process Mining (ICPM), Computational Intelligence and Computing Research (ICCIC), Service Science (ICSS), Workshop on Business Processes Meet Internet-of-Things (BP-Meet-IoT), Business Process Modeling, Development and Support (BPMDS).
- ACM Transactions on Intelligent Systems and Technology (ACM TIST), Business and Information Systems Engineering (BISE), Business Process Management Journal (BPMJ), Computers in Industry, Information Systems, IEEE Transactions on Knowledge and Data Engineering (TKDE), Software and Systems Modeling (SoSyM), Journal on Data Semantics (JoDS).

2.4 The Search String

The search terms for our SLR were constructed using the authors' knowledge of the subject matter. We started with the two most relevant acronyms, *BPM* and *IoT*. Starting from these, a first survey of the databases was carried out to capture more information on the topic, thus identifying the advantages and disadvantages of the possible choices. However, the acronym *BPM* produced many studies that did not relate to BPM but referred to the concept of beats per minute. For this reason, we expanded it to include the terms *process* and *workflow*. On the other hand, we included the term *Internet of Things* in its longer version to avoid the appearance of improper studies. From this initial set, we extended the search by adding synonyms to increase the possible configurations and create a final string that avoided excluding relevant studies. For example, we included *cyber physical*, *industry 4.0* and *smart* because IoT technologies were primarily observed in specific domains (Leotta et al. 2019). The search terms were linked using boolean AND, while alternative spellings and synonyms were combined using boolean OR.[2] The resulting search string is given below:

(process **OR** workflow **OR** processes **OR** workflows **OR** BPM) **AND** (IoT **OR** internet of things **OR** cyber physical **OR** industry 4.0 **OR** smart)

2.5 Inclusion and Exclusion Criteria

The SLR also includes identifying specific criteria that allow us to guarantee that only relevant studies are selected. Consequently, we defined the following inclusion and exclusion criteria. We did not use all filters simultaneously, but each criterion was applied within a specific process step.

2.5.1 Inclusion Criteria

We define one criterion for study inclusion. *Criterion I.1* includes the studies proposing a case study, an approach, a technique or a conceptual framework that deals with the concrete use of IoT to tackle issues from the BPM community. Consequently, studies using BPM techniques for IoT community problems or merely mentioning IoT and BPM without being the primary focus of the research do not meet the inclusion criteria.

2.5.2 Exclusion Criteria

Five criteria for study exclusion were also been defined.

Criterion E.1 excludes the studies not written in English.

Criterion E.2 excludes the studies that are not available. This mainly concerns studies that are not electronically accessible, require payment for access, or are only partially available (e.g., abstracts only).

Criterion E.3 excludes the studies that are not peer-reviewed.

Criterion E.4 excludes the studies that do not satisfy any inclusion criteria.

Criterion E.5 excludes studies with fragmented results, where findings are reported across multiple publications. In such cases, only the most comprehensive publication is considered for inclusion.

A study was considered for inclusion in the SLR if it met at least one inclusion criterion and did not meet any exclusion criteria.

[2] Note that while GS lacks explicit Boolean operator functionality, we simulated it in our search process using the Publish or Perish software (https://harzing.com/resources/publish-or-perish).

3 Conducting the Systematic Literature Review

This section describes the search protocol developed to identify and select studies.

3.1 Study Selection

To carry out the selection, we follow a three-phase search process as suggested by Keele (2007):

1. Phase 1 – Digital library search: During this phase, 5,315 studies were identified after entering the search string on GS,[3] IEEE and ACM. Then duplicate studies were removed, obtaining as a result a total of 4,869 potential studies. We then applied the inclusion/exclusion criteria, resulting in 309 potentially relevant studies. These studies were assessed based on their titles, abstracts, conclusions, and keywords to determine their relevance to the SLR.
2. Phase 2 – Conference and journal search: In the second phase, we selected the leading conferences and journals of the domain of interest and carried out a new search to add 233 studies. Then, duplicate studies were removed, obtaining, as a result, a total of 195 potential studies. We then applied the inclusion/exclusion criteria that allowed us to add 38 potential relevant studies to the studies included in the previous phase.
3. Phase 3 – Backward snowballing search: In the third phase, we performed a backward snowballing search to analyze references and citations of the studies from the previous two phases and from both searches to identify other relevant studies. Thus, we obtained further 8 studies.

In summary, at the end of the three search phases, 355 studies were obtained, which were further processed into 93 final studies after applying the inclusion/exclusion criteria. The search was formally completed in June 2023, and we decided to start from 1999 when the term IoT was coined. Data extraction involved collecting such data in an Excel spreadsheet. The Excel file can be found at http://tinyurl.com/m7j4x9mm. Figure 1 shows all the steps of the selection process by the guideline for reporting systematic reviews (PRISMA) proposed by Page et al. (2021). Table 1 shows all the primary studies.

3.2 Data Extraction

The data extraction and synthesis phase aims to design an appropriate form to record and collect the relevant

[3] We used Publish or Perish software to overcome Google Scholar's 1000-results limit. We segmented our search into multiple time intervals and iteratively refined the query until each search yielded fewer than 1000 results. Accessed 10 Nov 2023.

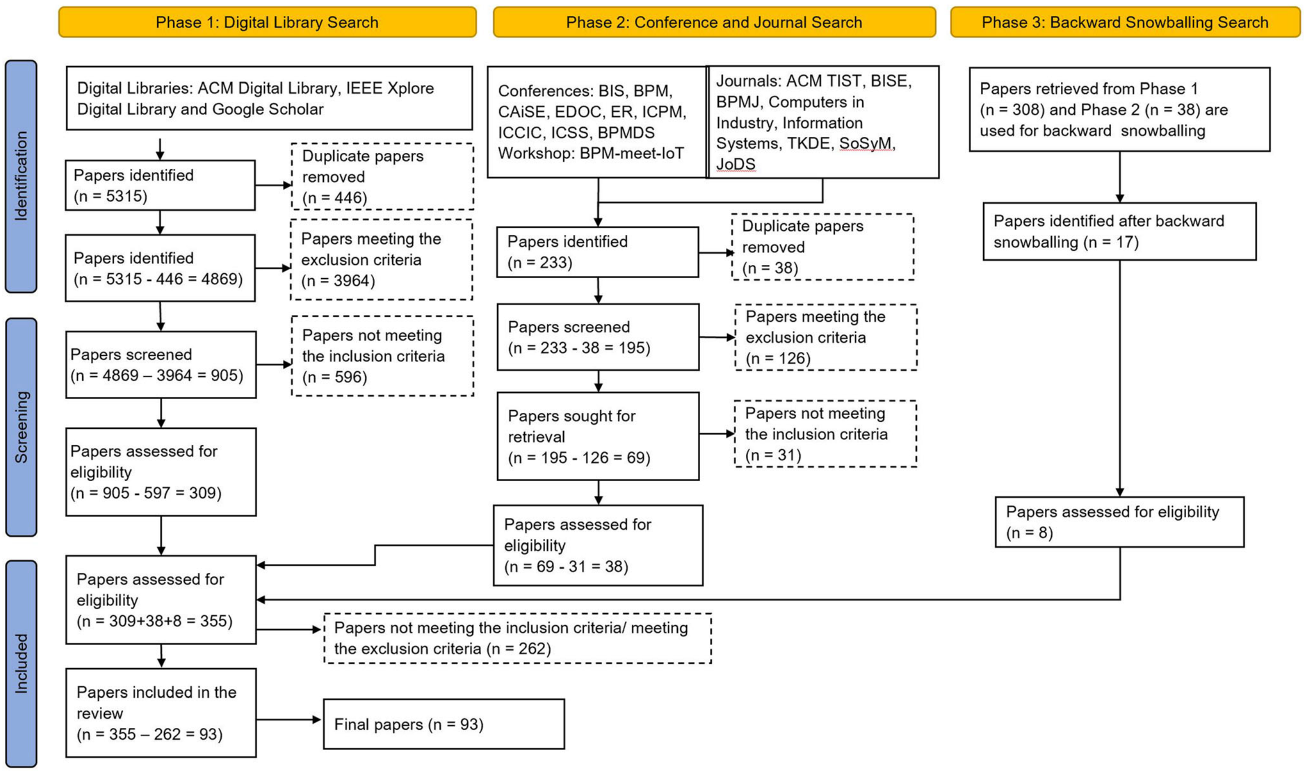

Fig. 1 Flow diagram summarizing the selection of the studies along the three search phases

information from reading the selected studies. The data collection form includes a common set of general fields such as title, author, year of publication and type of publication. We have also included multiple choice fields for each research question RQ1, RQ2, RQ3 and RQ4 (see Table 2). A section summarizing the research carried out in the study also includes its strengths and weaknesses in the form. The forms of the selected studies are available at this link: http://tinyurl.com/2udm342b.

4 Results of the Systematic Literature Review

In this section, we discuss the SLR results based on the research questions listed in Sect. 2. We cover: *(i)* the BPM life cycle phases affected by the IoT, *(ii)* the main topic of the study on BPM and IoT, *(iii)* the application domain on the usage of BPM and IoT solutions, and *(iv)* the addressed research challenge(s).

4.1 Which Phases of the BP Life Cycle Were Mainly Impacted by the Integration of IoT?

The research question RQ1 seeks to group the studies dealing with the BPM life cycle phases. We found that all the selected studies (93) refer to, or in some cases explicitly mention, one or more phases of the BPM's life cycle to contextualize their work (cf. Table 3). In detail, phases are considered by the identified studies with regard to the following aspects (cf. Figure 2): Identification (3.8%), Modeling (35.4%), Analysis (7%), Redesign (5.7%), Implementation (31.6%) and Monitoring and Mining (16.5%).

- *Identification* Hu et al. (2014) propose a dynamic integration mechanism of BPs to adapt to the dynamic characteristics of IoT, redirect and restructure the process logic using rules that can be edited at runtime and design a dynamic integration algorithm to implement this mechanism. Schief et al. (2011) propose a centralized framework that extends the process design and execution phases of BPM considering events generated by smart objects.
- *Modeling* Based on the analysis, we have categorized the studies according to several key areas: *Integration of IoT concepts in BPMN 2.0*Gao et al. (2011) propose a BPMN 2.0 extension with sensor and smart device business functions to enhance the integration between the physical world and BPs. Meyer et al. (2011) extend the BPMN 2.0 to explicitly consider IoT basic

Table 1 List of selected studies

ID study	References	ID study	References
S1	Antonius and Dachyar (2020)	S48	Malburg et al. (2020)
S2	Bertrand et al. (2021)	S49	Marrella and Mecella (2017)
S3	Bocciarelli et al. (2017)	S50	Martins and Domingos (2017)
S4	Chadli et al. (2022)	S51	Martins et al. (2020)
S5	Chen et al. (2012)	S52	Mass et al. (2016)
S6	Cheng et al. (2018)	S53	Meroni et al. (2018)
S7	Cheng et al. (2019)	S54	Meyer et al. (2011)
S8	Cherrier and Deshpande (2017)	S55	Meyer et al. (2013)
S9	Chiu and Wang (2015)	S56	Meyer et al. (2015)
S10	de Leoni and Pellattiero (2021)	S58	Montali and Plebani (2017)
S12	Diamantini et al. (2023)	S57	Mottola et al. (2019)
S11	Di Martino et al. (2022)	S59	Muhsin et al. (2016)
S13	Domingos et al. (2010)	S60	Park et al. (2018)
S14	Domingos et al. (2014)	S61	Pastor et al. (2022)
S15	Domingos et al. (2015)	S62	Pryss et al. (2015)
S16	Elali et al. (2022)	S63	Ruiz-Fernández et al. (2017)
S17	Elhami et al. (2020)	S64	Ruppen and Meyer (2013)
S18	Elkodssi et al. (2022)	S65	Schief et al. (2011)
S19	Engels et al. (2018)	S66	Schmidt and Schief (2010)
S20	Friedow et al. (2018)	S67	Schönig et al. (2018)
S21	Gallik et al. (2022)	S68	Schönig et al. (2020)
S22	Gao et al. (2011)	S69	Seiger et al. (2018)
S23	Gómez-Valiente et al. (2023)	S70	Seiger et al. (2019)
S24	Graja et al. (2019)	S71	Seiger et al. (2020)
S25	Grambow et al. (2021)	S72	Seiger et al. (2021)
S26	Grefen et al. (2019)	S73	Seiger et al. (2023)
S27	Hasić et al. (2020)	S74	Senderovich et al. (2016)
S28	Hornsteiner and Schönig (2023)	S75	Shamsuzzoha et al. (2014)
S29	Hou et al. (2016)	S76	Song et al. (2022)
S30	Hu et al. (2014)	S77	Sora et al. (2017)
S31	Ismaili-Alaoui et al. (2018)	S78	Suri et al. (2017)
S32	Jain and Tata (2017)	S79	Suri et al. (2018)
S33	Janssen et al. (2020)	S80	Tôn and Lê (2019)
S34	Kahl et al. (2015)	S81	Ugljanin et al. (2018)
S35	Keates (2019)	S82	Valderas et al. (2022)
S36	Kikuchi et al. (2018)	S83	Valderas et al. (2023)
S37	Kirikkayis et al. (2022a)	S84	van Eck et al. (2016)
S38	Kirikkayis et al. (2022b)	S85	Varga et al. (2018)
S39	Kirikkayis et al. (2023c)	S86	Vitali and Pernici (2016)
S40	Kirikkayis et al. (2023b)	S87	Wang et al. (2022)
S41	Kirikkayis et al. (2023a)	S88	Wehlitz et al. (2017)
S42	Koschmider et al. (2020)	S89	Wieland et al. (2008)
S43	Kunz et al. (2011)	S90	Wombacher (2011)
S44	Li et al. (2021)	S91	Xing et al. (2012)
S45	Loke et al. (2007)	S92	Zanfack et al. (2015)
S46	Maamar et al. (2018)	S93	Zhu et al. (2014)
S47	Maamar et al. (2020)		

Table 2 Attributes for data extraction

Research questions	Attributes
All	Title, Year, Authors, Source, Publisher, ArticleURL, Query, Cites, CitesPerYear, AuthorCount.
RQ1	Identification, Modeling, Analysis, Redesign, Implementation, Monitoring and Mining.
RQ2 RQ3	Healthcare, Industrials, Public, Consumer Services, Consumer Goods, Services.
RQ4	C1, C2, C3, C4, C5, C6, C7, C8, C9, C10, C11, C12, C13, C14, C15, C16.

concepts, enabling the modeling and development of IoT Services in terms of BPs. Meyer et al. (2013) integrate IoT devices as BP resources in the form of dedicated lanes and extend the BPMN 2.0 specification to include such IoT devices. Meyer et al. (2015) explore the representation of the IoT domain component "Thing" in a process model, introducing potential BPMN extension for IoT concepts. *Verification and validation of IoT-BPs* Graja et al. (2019) extend BPMN to sustain the various cyber-physical system concepts and a verification approach at design time to detect the mistakes in specifying the CPS process. Senderovich et al. (2016) derive events from sensor data, aligning them with process activities. Hornsteiner and Schönig (2023) extend BPMN to map security aspects and thus obtain security- and IIoT-aware BPs. *Context management and IoT adaptation* Schönig et al. (2018) propose a set of concepts for an IoT-enhanced process model re-engineering, addressing model changes and adaptation tasks. Suri et al. (2018) propose configuration concepts for handling IoT resource variability in the Configurable Process Model. *IoT-aware BP decentralization and distribution* Domingos et al. (2015) present an automatic approach to decentralize IoT-aware BPs defined using the BPMN 2.0. Jain and Tata (2017) have designed a distributed IoT application with annotated components and location information. *IoT event integration and management* Chadli et al. (2022) define the role of the IoT concept of smart business processes modeling SBPM, using an ad hoc approach with active help to detect data flow anomalies. Li et al. (2021) propose a business user-oriented BP modeling method supporting IoT event stream integration, with a framework that separates CEP and BP execution. Wang et al. (2022) monitor and model IoT sensing data in real-time, transforming it into IoT services for BP systems. Kirikkayis et al. (2023b) model IoT-driven events using BPMN 2.0 extension and DMN concepts. Kirikkayis et al. (2022b) introduce a BPMN 2.0 extension with IoT artifacts, enabling data acquisition and actuator control. *Other aspects related to IoT and BPM*Zanfack et al. (2015) present a GSM[4]-IoT framework which aims to represent the physical workflows in logistics, extending them by adding physical workflow concepts and considering particularities of IoT smart entities and their mutual interactions. Mottola et al. (2019) propose a BPMN extension for wireless sensor network context modeling. Bocciarelli et al. (2017) model and manage resource management during runtime. Hasić et al. (2020) compare standard BPMN and BPMN + DMN for IoT process modeling. Grefen et al. (2019) introduce a time and space specification for IoT-aware collaborative BPs. Hou et al. (2016) suggest fragmenting IoT-aware BP for performance improvement. Grambow et al. (2021) propose context-awareness integration in IIoT BPs, visual AR support, and enhanced BPMN modeling.

- *Analysis* Antonius and Dachyar (2020) model and simulate the cardiac remote patient monitoring process, identifying weaknesses needing improvement. Vitali and Pernici (2016) present an approach based on the temporal events analysis for building a graph of dependencies between the whole set of events, unveiling interconnections between processes of cooperating organizations. Seiger et al. (2023) develop an interactive method for analyzing low-level IoT data to detect higher-level process activity executions based on sensor-actuator-activity patterns. Diamantini et al. (2023) discuss the role of semantic models when integrating IIoT data streams into an Industry 4.0 context. They propose a process-aware knowledge graph that enriches sensor data using ontological descriptions of IIoT sensors, processes, and KPIs. Gómez-Valiente et al. (2023) present the DOMINIoT architecture to address scheduling, resource allocation, and state management challenges.
- *Redesign* The redesign phase is often applied across other BPM life cycle stages. In Ruiz-Fernández et al. (2017), a redesign of a given clinical process is presented, while in Ismaili-Alaoui et al. (2018), interdisciplinary healthcare processes are redesigned to

[4] The GSM (Guard-Stage-Milestone) refers to an approach to structuring Event-Condition-Action rules in the BPM context. Hull et al. (2010)

Table 3 Studies distribution by BPM life cycle (RQ1)

References	Identification	Modeling	Analysis	Redesign	Implementation	Monitoring and mining
Antonius and Dachyar (2020)		✓	✓	✓		
Bertrand et al. (2021)						✓
Bocciarelli et al. (2017)		✓				
Chadli et al. (2022)		✓				
Chen et al. (2012)					✓	
Cheng et al. (2018)		✓			✓	
Cheng et al. (2019)		✓			✓	
Cherrier and Deshpande (2017)	✓	✓	✓	✓	✓	✓
Chiu and Wang (2015)		✓			✓	
de Leoni and Pellattiero (2021)						✓
Di Martino et al. (2022)					✓	
Diamantini et al. (2023)			✓			
Domingos et al. (2010)		✓			✓	
Domingos et al. (2014)		✓			✓	
Domingos et al. (2015)		✓				
Elali et al. (2022)						✓
Elhami et al. (2020)				✓	✓	✓
Elkodssi et al. (2022)						✓
Engels et al. (2018)		✓			✓	
Friedow et al. (2018)					✓	
Gallik et al. (2022)		✓			✓	✓
Gao et al. (2011)		✓				
Gómez-Valiente et al. (2023)			✓			
Graja et al. (2019)		✓				
Grambow et al. (2021)		✓				
Grefen et al. (2019)		✓				
Hasić et al. (2020)		✓				
Hornsteiner and Schönig (2023)		✓				
Hou et al. (2016)		✓				
Hu et al. (2014)	✓					
Ismaili-Alaoui et al. (2018)				✓	✓	
Jain and Tata (2017)		✓				
Janssen et al. (2020)						✓
Kahl et al. (2015)		✓			✓	
Keates (2019)	✓		✓	✓	✓	✓
Kikuchi et al. (2018)					✓	
Kirikkayis et al. (2022a)		✓			✓	✓
Kirikkayis et al. (2022b)		✓				
Kirikkayis et al. (2023c)		✓			✓	✓
Kirikkayis et al.		✓				
Kirikkayis et al. (2023a)		✓			✓	✓
Koschmider et al. (2020)						✓
Kunz et al. (2011)					✓	
Li et al. (2021)		✓				
Loke et al. (2007)					✓	✓
Maamar et al. (2018)		✓			✓	
Maamar et al. (2020)		✓			✓	
Malburg et al. (2020)					✓	✓

Table 3 continued

References	Identification	Modeling	Analysis	Redesign	Implementation	Monitoring and mining
Marrella and Mecella (2017)					✓	
Martins and Domingos (2017)		✓			✓	
Martins et al. (2020)		✓			✓	
Mass et al. (2016)					✓	
Meroni et al. (2018)		✓			✓	✓
Meyer et al. (2011)		✓				
Meyer et al. (2013)		✓				
Meyer et al. (2015)		✓				
Montali and Plebani (2017)		✓			✓	
Mottola et al. (2019)		✓				
Muhsin et al. (2016)					✓	
Park et al. (2018)					✓	
Pastor et al. (2022)					✓	
Pryss et al. (2015)		✓			✓	✓
Ruiz-Fernández et al. (2017)	✓	✓	✓	✓	✓	✓
Ruppen and Meyer (2013)		✓		✓	✓	
Schief et al. (2011)	✓					
Schmidt and Schief (2010)		✓			✓	
Schönig et al. (2018)		✓				
Schönig et al. (2020)		✓			✓	✓
Seiger et al. (2018)					✓	
Seiger et al. (2019)		✓	✓	✓	✓	
Seiger et al. (2020)						✓
Seiger et al. (2021)		✓			✓	
Seiger et al. (2023)			✓			
Senderovich et al. (2016)		✓				
Shamsuzzoha et al. (2014)						✓
Song et al. (2022)				✓		
Sora et al. (2017)		✓	✓			✓
Suri et al. (2017)		✓			✓	
Suri et al. (2018)		✓				
Tôn and Lê (2019)		✓			✓	
Ugljanin et al. (2018)		✓			✓	
Valderas et al. (2022)		✓			✓	
Valderas et al. (2023)					✓	
van Eck et al. (2016)						✓
Varga et al. (2018)					✓	
Vitali and Pernici (2016)			✓			✓
Wang et al. (2022)		✓				
Wehlitz et al. (2017)		✓			✓	
Wieland et al. (2008)					✓	
Wombacher (2011)						✓
Xing et al. (2012)	✓	✓				
Zanfack et al. (2015)		✓				
Zhu et al. (2014)					✓	

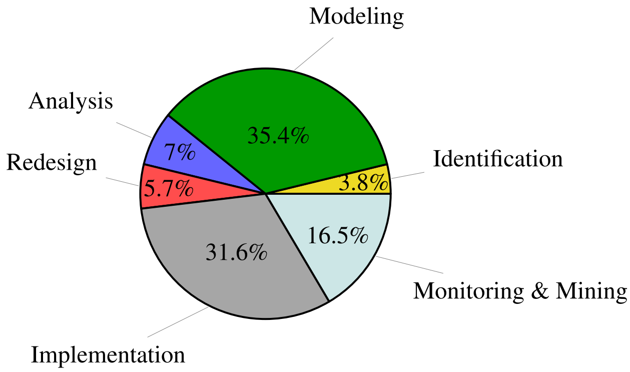

Fig. 2 Distribution of selected studies according to the aspect of integration of IoT into the BP life cycle phases

ensure direct and real-time interaction between the patient and the medical staff. Song et al. (2022) mainly address this phase by proposing an IoT-enabled Context-aware BPM (IoT-CaBPM) framework, which facilitates the evolution of BPs in combination with IoT advances.

- *Implementation* Chen et al. (2012) propose to extend WS-BPEL[5] with IoT characteristics for a new process definition language. Friedow et al. (2018) implement and write adapters using the Bosch IoT Things service to connect IoT devices and BPs via event influence. Kikuchi et al. (2018) develop a cloud-IoT orchestration framework with IoT device. Kunz et al. (2011) provide novel components and architectural concepts for improved IoT communication. These include a scalable discovery service and a decentralized control structure, cloud EPCIS,[6] which facilitates access to RFID[7] data, and middleware that enables flexible adaption of object-specific event processing rules. Marrella and Mecella (2017) automate process adaptation in cyber-physical domains during the occurence of exceptions and exogenous events. Mass et al. (2016) propose a system architecture enabling continuous, delay-tolerant BP execution on mobile nodes. Muhsin et al. (2016) present a mobile workflow management system for seamless and accurate data exchange between mobile devices and remote hubs. Seiger et al. (2018) propose an IoT workflow management system with dynamic service selection, complex event processing, human interactions and self-adaptation. Varga et al. (2018) propose a supporting system for service chaining and workflow execution using a Petri Net-based method, similar to a recent article that provide further insights into this area (Kozma et al. 2019). Wieland et al. (2008) define and implement two smart workflows and provide an architecture for transforming sensor data into business-level information. Zhu et al. (2014) design and implement a dynamic adaptation framework using an adaptive algorithm, allowing the system to infer the process when the environment changes. Di Martino et al. (2022) provide a methodology for the smart management of irrigation systems using ontologies, BPMN semantic annotation, and logical inference. Park et al. (2018) propose modeling and implementation methods for IoT execution design. Pastor et al. (2022) integrate IoT sensors for improved user comfort in shared spaces, emphasizing semantic representation and process mining (PM) techniques. Valderas et al. (2023) apply the SoC principle for the interdisciplinary development of IoT-enhanced BPs using BPMN, ontology-based technologies, and a microservices architecture.
- *Monitoring and Mining* Seiger et al. (2020) propose a framework correlating IoT sensor streams with process events and activities using Complex Event Processing. Shamsuzzoha et al. (2014) discuss collaborative BP monitoring across organizations using IoT and cloud-based data repositories. Wombacher (2011) monitors workflow-state correlation with sensor data for online conformance checking. de Leoni and Pellattiero (2021) propose a technique to discover readable human-habit models for optimizing human experience with IoT systems. Janssen et al. (2020) present a technique that combines clustering and PM to discover activities and process models from motion sensors. Koschmider et al. (2020) present a framework to discover activities and process models from event location sensor data. van Eck et al. (2016) map sensor measurements to human activities, group them into process instances and convert them into an event log as input for any PM technique. Sora et al. (2017) transform raw movement measurements into actions and adapt sensor logs to apply BPM techniques. Bertrand et al. (2021) propose a model bridging the gap between IoT and PM using IoT ontologies and BP context models. Elali et al. (2022) enhance process models derived from PM with contextual information from sensor data. Elkodssi et al. (2022) present a PM approach for discovering and analyzing IoT-aware BPs and transforming sensor logs into structured event logs enriched with IoT concepts using a BPMN Ontology.

[5] The WS-BPEL (Web Services Business Process Execution Language) is an XML-based language that allows web services, APIs and human processes to interconnect and share data in a business workflow.

[6] EPC Information Services is a standard enables disparate applications to create and share visibility event data, both within and across enterprises.

[7] RFID (radio-frequency identification) refers to a technology whereby digital data are captured by a reader via radio waves.

Table 4 The four topics mostly discussed in the 93 selected studies and terms related tp them

Topic	Topic label	Relevant terms
1	Event mining from sensors	**sensor** + **event** + **mining** + task + system + mobile + discover + activity + concept + service
2	Physical resource management	**resource** + **management** + **physical** + time + system + event + object + cyber + physical + activity + property
3	Context-aware execution	**context** + sensor + **execution** + application + system + environment + service + information + technology + user
4	IoT-aware process modeling	**bpmn** + context + information + **extension** + system + sensor + concept + execution + language + event

- *More phases* A BPMN 2.0 IoT-enabled extension for modeling, executing and monitoring IoT-aware BPs is proposed by Gallik et al. (2022), while Kirikkayis et al. (2023a) also present a framework for IoT-driven business rules. Kirikkayis et al. (2023c) present a BPMN 2.0 extension for IoT, enabling real-time interaction with devices which aids decisions through collected data but lacks high-level aggregation consideration. Kirikkayis et al. (2022a) present a web-based framework integrating IoT data into BPs, enhancing real-time decision-making and monitoring.

4.2 Which Topics Relating to IoT Integration in BPM are Discussed in the Literature?

To answer the question RQ2, we analyzed the identified studies based on the Latent Dirichlet allocation (LDA) technique (Blei et al. 2003), which is one of the most effective ones for latent topics distribution within a corpus (Chauhan and Shah 2021). LDA is a generative probabilistic model of a corpus where the documents are represented as a random mixture of latent topics each characterized by a mix of words. The application of the LDA to identify the topics in the 93 studies is detailed in a specific appendix (available online via http://link.springer.com). The resulting four topics are listed in Table 4, where the bolded words represent the most relevant terms in terms of estimated frequency within the selected topic. Once we trained the model and derived the four topics, we observed the keywords associated with each topic using a web-based interactive visualization (see the appendix) to understand what they refer to from the semantic point of view. Then, we tried to contextualize them within a semantic context. Table 5 shows the 93 studies and their topics. Note that the topics associated with each study are not exclusive, as a study can be related to one or more topics. We then discuss the four topics concerning specific studies.

- *Topic 1 – Event mining from sensors* Knowledge extraction from sensor data has gained significant attention in the BPM community. Process mining techniques can greatly enhance BPM management when applied to analyze and transform raw data into usable information. The information provided by the sensors can be expressed through a functional business view, as demonstrated in Gao et al. (2011), representing the classification, storage, and distribution procedure of floral products within a flower company. This model in BPMN is connected to a functional model to import an ontology of the sensors and related instance data and then integrate the information modeled using the Semantic Sensor Network ontology with BPs. Similarly, various frameworks address the correlation between workflow states, sensor data, and events generated by IoT devices that initiate instances of BPs (Seiger et al. 2020; Wombacher 2011; Ismaili-Alaoui et al. 2018; Ruiz-Fernández et al. 2017; Ruppen and Meyer 2013; Chadli et al. 2022; Diamantini et al. 2023; Pastor et al. 2022). Koschmider et al. (2020) detect high-level events from raw event data and discover BPs from derived instances. Zhu et al. (2014) present a multi-agent framework that chooses the best step to move in the BP when an event caused by agents occurs. In addition, Sora et al. (2017) present an approach to discover process models from activities in the field of smart spaces where sensors must turn the sensor log into an event log consisting of human actions. Another interesting challenge when applying PM techniques in the context of sensor data is mapping sensor measurements to human activities and grouping activities into process instances (van Eck et al. 2016; de Leoni and Pellattiero 2021). The problem of mapping sensor data to event logs based on process knowledge is solved by Senderovich et al. (2016), which maps location-based events to activities by recognizing interactions between various agents and transforming historical sensor data registers into standardized event logs. Another contribution to translating sensor data into higher-level ones comes from Janssen et al. (2020). They discretize sensor data into activities using unsupervised learning through clustering, while Seiger et al. (2023) analyze sensor data to detect higher-level process activities.

Table 5 Associations between papers and their topics (the study topic number is in bold)

References	Topic and weights	References	Topic and weights
Antonius and Dachyar (2020)	[(**3**,0.99982256)]	Malburg et al. (2020)	[(**3**,0.9998445)]
Bertrand et al. (2021)	[(**4**,0.99982256)]	Marrella and Mecella (2017)	[(**4**,0.9995924)]
Bocciarelli et al. (2017)	[(**2**,0.9996488)]	Martins and Domingos (2017)	[(**4**,0.9998037)]
Chadli et al. (2022)	[(**1**,0.9996488)]	Martins et al. (2020)	[(**2**,0.9997762)]
Chen et al. (2012)	[(**4**,0.9998403)]	Mass et al. (2016)	[(**2**,0.99983656)]
Cheng et al. (2018)	[(**3**,0.99978745)]	Meroni et al. (2018)	[(**3**,0.9997963)]
Cheng et al. (2019)	[(**4**,0.9998455)]	Meyer et al. (2011)	[(**3**,0.9997317)]
Cherrier and Deshpande (2017)	[(**4**,0.99976087)]	Meyer et al. (2013)	[(**4**,0.99983186)]
Chiu and Wang (2015)	[(**4**,0.99961144)]	Meyer et al. (2015)	[(**2**,0.9998026)]
de Leoni and Pellattiero (2021)	[(**1**,0.9998342)]	Montali and Plebani (2017)	[(**2**,0.99982536)]
Di Martino et al. (2022)	[(**4**,0.9998342)]	Mottola et al. (2019)	[(**2**,0.99981886)]
Diamantini et al. (2023)	[(**1**,0.9998342)]	Muhsin et al. (2016)	[(**1**,0.99967504)]
Domingos et al. (2010)	[(**3**,0.99981683)]	Park et al. (2018)	[(**1**,0.99967504)]
Domingos et al. (2014)	[(**2**,0.79961824), (**3**,0.20029789)]	Pastor et al. (2022)	[(**1**,0.99967504)]
Domingos et al. (2015)	[(**1**,0.99971336)]	Pryss et al. (2015)	[(**3**,0.99984723)]
Elali et al. (2022)	[(**3**,0.99971336)]	Ruiz-Fernández et al. (2017)	[(**1**,0.99975556)]
Elhami et al. (2020)	[(**3**,0.99977887)]	Ruppen and Meyer (2013)	[(**1**,0.7505519), (**2**,0.24931632)]
Elkodssi et al. (2022)	[(**4**,0.99977887)]	Schief et al. (2011)	[(**1**,0.99975836)]
Engels et al. (2018)	[(**3**,0.99954796)]	Schmidt and Schief (2010)	[(**2**,0.99982256)]
Friedow et al. (2018)	[(**3**,0.74724096), (**1**,0.25259858)]	Schönig et al. (2018)	[(**1**,0.9997492)]
Gallik et al. (2022)	[(**2**,0.74724096), (**1**,0.25259858)]	Schönig et al. (2020)	[(**2**,0.9997704)]
Gao et al. (2011)	[(**1**,0.9998314)]	Seiger et al. (2018)	[(**3**,0.9997471)]
Gómez-Valiente et al. (2023)	[(**2**,0.9998314)]	Seiger et al. (2019)	[(**3**,0.99976456)]
Graja et al. (2019)	[(**2**,0.9997895)]	Seiger et al. (2020)	[(**1**,0.9997381)]
Grambow et al. (2021)	[(**2**,0.9997817)]	Seiger et al. (2021)	[(**4**,0.99979335)]
Grefen et al. (2019)	[(**4**,0.99935937)]	Seiger et al. (2023)	[(**1**,0.99979335)]
Hasić et al. (2020)	[(**4**,0.9996807)]	Senderovich et al. (2016)	[(**1**,0.99960095)]
Hornsteiner and Schönig (2023)	[(**4**,0.74724096), (**2**,0.25259858)]	Shamsuzzoha et al. (2014)	[(**4**,0.9997693)]
Hou et al. (2016)	[(**3**,0.83022827), (**2**,0.16968323)]	Song et al. (2022)	[(**1**,0.9997116)]
Hu et al. (2014)	[(**3**,0.9997634)]	Sora et al. (2017)	[(**1**,0.99975955)]
Ismaili-Alaoui et al. (2018)	[(**1**,0.99982774)]	Suri et al. (2017)	[(**2**,0.99981886)]
Jain and Tata (2017)	[(**1**,0.99967504)]	Suri et al. (2018)	[(**2**,0.9998837)]
Janssen et al. (2020)	[(**1**,0.9997858)]	Tôn and Lê (2019)	[(**3**,0.9998131)]
Kahl et al. (2015)	[(**2**,0.52115947), (**1**,0.47873807)]	Ugljanin et al. (2018)	[(**2**,0.9998286)]
Keates (2019)	[(**3**,0.9997905)]	Valderas et al. (2022)	[(**4**,0.9998286)]
Kikuchi et al. (2018)	[(**2**,0.99991345)]	Valderas et al. (2023)	[(**4**,0.9998286)]
Kirikkayis et al. (2022a)	[(**2**,0.99991345)]	van Eck et al. (2016)	[(**1**,0.9996706)]
Kirikkayis et al. (2022b)	[(**4**,0.99991345)]	Varga et al. (2018)	[(**4**,0.99975)]
Kirikkayis et al. (2023c)	[(**2**,0.99991345)]	Vitali and Pernici (2016)	[(**2**,0.9998141)]
Kirikkayis et al. (2023b)	[(**4**,0.99991345)]	Wang et al. (2022)	[(**4**,0.9998141)]
Kirikkayis et al. (2023a)	[(**2**,0.99991345)]	Wehlitz et al. (2017)	[(**2**,0.8333249), (**1**,0.1666117)]
Koschmider et al. (2020)	[(**1**,0.99970394)]	Wieland et al. (2008)	[(**3**,0.99978536)]
Kunz et al. (2011)	[(**2**,0.9998101)]	Wombacher (2011)	[(**1**,0.9997905)]
Li et al. (2021)	[(**4**,0.9998101)]	Xing et al. (2012)	[(**2**,0.69569945), (**1**,0.3042095)]
Loke et al. (2007)	[(**4**,0.9998411)]	Zanfack et al. (2015)	[(**4**,0.9993372)]
Maamar et al. (2018)	[(**2**,0.8772322), (**1**,0.122608565)]	Zhu et al. (2014)	[(**1**,0.999856)]
Maamar et al. (2020)	[(**4**,0.99977696)]		

- *Topic 2 – Physical resource management* This topic tackles the specification and management of the resources associated with the BPs supporting Cyber-Physical Systems (CPSs). Graja et al. (2019) propose a verification framework to support the various CPS concepts and properties, which enables the designer to handle CPS process features. To integrate and utilize smart devices as BP resources to support the modeling, a service-oriented BPM system architecture was developed by Wehlitz et al. (2017). The resource management during runtime of a system to model a CPS-aware resource associated with a BP activity is proposed by Bocciarelli et al. (2017), while the DOMINIoT architecture is designed by Gómez-Valiente et al. (2023). In scenarios where physical resources are exchanged, knowing how a resource owned by a party is managed on anothers party's premises is impossible. Thus possible misalignments can be detected too late. In Montali and Plebani (2017), the authors investigated an approach for compliance checking that mixes commitments and smart devices. Suri et al. (2017) developed a framework that describes IoT resources (e.g. extending the BP models with energy cost parameters to enable the energy-aware management of IoT resources in BPs).
- *Topic 3 – Context-aware execution* A context-aware execution environment involves processes continuously observed and adapted according to the model specified when required by context changes. Contextual information enhances process execution, incorporating situation-aware insights for improved effectiveness. Such information is often gathered from sensors within intelligent environments, enabling pervasive execution known as intelligent workflows (Wieland et al. 2008). Frameworks that enhance process awareness and self-adaptation are proposed (Seiger et al. 2019; Pryss et al. 2015; Friedow et al. 2018; Malburg et al. 2020; Engels et al. 2018). To support context variables and sensors as well as communication paradigms for IoT, Domingos et al. (2014) extend the WS-BPEL workflow language, dynamically selecting IoT services based on availability, functionality, and context (Seiger et al. 2018; Elali et al. 2022). Other studies focused on the adaptability of BPs during the execution phase. A dynamic integration mechanism for coping with changes in BPs is proposed by Hu et al. (2014); Domingos et al. (2010); Tôn and Lê (2019). An application to the predictive process monitoring field using IoT events as a process context and developing a predictive model to predict the next activity is provided by Elhami et al. (2020). A new trend in running the IoT-aware BP is running on *fog computing*.[8] In this context, Cheng et al. (2018) dealt with IoT-aware BPs at the execution level, where they introduced a new intermediate layer consisting of a set of distributed fog nodes to perform certain parts of the process.
- *Topic 4 – IoT-aware process modeling* To create IoT-aware BPs and exploit the full potential of IoT and BPM, this must be integrated into process models. Modeling strategies for IoT-aware BPs fall into two categories (Brouns et al. 2018): those utilizing known modeling languages and those proposing new domain-specific languages. The former includes integrating BPMN with ontologies (Valderas et al. 2022; Di Martino et al. 2022; Valderas et al. 2023; Bertrand et al. 2021; Elkodssi et al. 2022) and extending BPMN with IoT devices (Chiu and Wang 2015; Kirikkayis et al. 2022b; Hornsteiner and Schönig 2023), as well as using Petri Nets (Varga et al. 2018), or DMN[9] (Hasić et al. 2020; Kirikkayis et al. 2023b). In the latter, Chen et al. (2012) provide a new process definition language for IoT-enabled BPs, encapsulating physical devices as SOA services. IoT device interaction is critical. To this end, the application of mixed reality as a new interaction paradigm to facilitate the modeling and configuration of processes among IoT devices was elaborated on Seiger et al. (2021). From an access IoT data perspective, Cherrier and Deshpande (2017) present a gateway for transferring IoT events to BPs, managing device heterogeneity. Meyer et al. (2013) map IoT concepts to process models, and Martins and Domingos (2017) use BPMN to model IoT device behaviours. Other studies focus on collaborative structures to improve physical and digital collaboration between multiple actors to achieve a common goal (Maamar et al. 2020; Shamsuzzoha et al. 2014; Li et al. 2021; Wang et al. 2022). For example, Grefen et al. (2019) discuss synchronizing physical objects for successful IoT-aware digital processes.

4.3 Which Application Domains are Used to Study IoT and BPM Integration?

Question number three was answered based on data from research conducted by HSPI[10] Accessed 6 January 2022.

[8] Fog computing provides data, compute, storage and application services to end-users where the difference is where data processing occurs.

[9] DMN (Decision Model and Notation) is a standard approach for describing and modeling repeatable decisions within organizations to ensure that decision models are interchangeable across organizations.

[10] Process mining: A database of applications, HSPI SpA – Management Consulting. https://www.hspi.it/wp-content/uploads/2020/01/HSPI_Process_Mining_Database2020.pdf

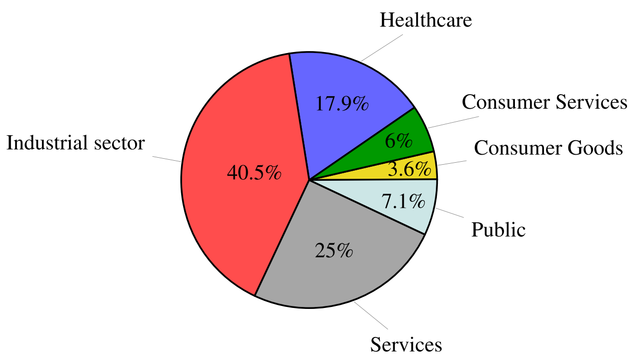

Fig. 3 Distribution of selected studies by application domains

Thus, from the HSPI process mining application database, we collected and analyzed the studies to map the applications provided through different industries and markets and understand the adoption of BPM and IoT. The application domains which the found studies refer to are (cf. Figure 3): Healthcare (17.6%); Industrial sector (41.2%); Public (7.1%); Consumer Services (5.9%); Consumer Goods (3.5%) and Services (24.7%). Only eight studies (11%) do not refer to any application domain.

- *Healthcare* Most healthcare applications are related to remote patient monitoring systems, within hospitals or at home, and constantly enriched with IoT devices (Antonius and Dachyar 2020; Cheng et al. 2018; Jain and Tata 2017; Pryss et al. 2015; Seiger et al. 2018; Vitali and Pernici 2016; Ruiz-Fernández et al. 2017; Ruppen and Meyer 2013; Tôn and Lê 2019; Kirikkayis et al. 2022b; Gómez-Valiente et al. 2023). Maamar et al. (2018) use the example of a hospital that is on high alert being close to a severe car accident, where departments equipped with environmental sensors or smart wrists, enable the real-time transmission of patients' vital signs to appropriate recipients, demonstrating how IoT can facilitate operations and improve efficiency. Senderovich et al. (2016) present an example of a process of treatment in a day hospital for cancer patients through Real-Time Locating System (RTLS) receivers that monitor all corporate entities involved in the process (e.g., patients, doctors, nurses) as well as some of the medical devices that record the data emitted and use it for real-time monitoring of process entities and equipment. Another frequent scenario is elderly care. Integrating the real-time event streams from bed pressure sensors into the BP field can reflect the health status of the elderly in real-time and thus monitor them through immediate warnings (Li et al. 2021).
- *Industrial sector* In the domain of transportation, IoT might be used to realize monitoring of goods, such as dangerous or perishable goods (Domingos et al. 2010, 2014, 2015; Valderas et al. 2022; Suri et al. 2017; Valderas et al. 2023; Gallik et al. 2022; Seiger et al. 2023; Diamantini et al. 2023). These systems react to events that occur during transport using sensors and location technologies to improve the monitoring of transport conditions, such as temperature and pressure (Mass et al. 2016). Sensors and smart devices have great potential to provide further automation in various domains including logistics (Meroni et al. 2018; Gao et al. 2011; Grefen et al. 2019; Zanfack et al. 2015; Wombacher 2011; Schief et al. 2011; Song et al. 2022). Take, for example, the maritime transport scenario of heavy fog where disasters can be prevented in sea-land transport (Wang et al. 2022). Montali and Plebani (2017) use an example of a seafood company that organizes fish delivery and aims to verify if all actors operate correctly because of the complexity of the delivery process (deviations to the plan may occur). Several studies focus on smart factories as representatives of IoT environments (Grambow et al. 2021; Bocciarelli et al. 2017; Malburg et al. 2020; Wieland et al. 2008; Seiger et al. 2020; Kirikkayis et al. 2023c, a, b, 2022a). In the manufacturing industry, BPM and IoT support could improve both management by closely linking digital production and machine data (Schönig et al. 2018, 2020; Shamsuzzoha et al. 2014; Keates 2019) and cybersecurity by integrating security requirements into modeling using a "security by design" paradigm (Hornsteiner and Schönig 2023).
- *Public* Cheng et al. (2019) develop an actual sensor-aware BP application and validate it by using the designed system to protect a large area of forest in North China. Graja et al. (2019) evaluate their study through an example of disaster recovery systems. Maamar et al. (2020) present a city that runs many systems like transportation for traffic control and environment for air pollution monitoring; Marrella and Mecella (2017) rely on a case study previously conducted by the same authors in (Humayoun et al. 2009b, a; Marrella et al. 2011) to evaluate their study in an emergency management domain, in which teams of first responders act in disaster locations with the primary purpose of assisting potential victims and stabilizing the situation. Chadli et al. (2022) propose a classroom case study involving the deployment of hardware device and management software to measure the environmental parameters and control ventilation, lighting, and air conditioning. Pastor et al. (2022) employ a smart camera with active sensors for vehicle identification in road traffic.
- *Consumer Services* Kahl et al. (2015) test their study for common BPs in the retail domain within the

Table 6 Studies distribution by application scenario (RQ3)

ID study	Healthcare	Industrial sector	Public	Consumer services	Consumer goods	Services
Antonius and Dachyar (2020)	✓					
Bocciarelli et al. (2017)		✓				
Chadli et al. (2022)			✓			
Cheng et al. (2018)	✓					
Cheng et al. (2019)			✓			
Cherrier and Deshpande (2017)						✓
Chiu and Wang (2015)						✓
de Leoni and Pellattiero (2021)						✓
Di Martino et al. (2022)						✓
Diamantini et al. (2023)		✓				
Domingos et al. (2010)		✓				
Domingos et al. (2014)		✓				
Domingos et al. (2015)		✓				
Elali et al. (2022)						✓
Friedow et al. (2018)						✓
Gallik et al. (2022)		✓				
Gao et al. (2011)		✓				
Gómez-Valiente et al. (2023)	✓					
Graja et al. (2019)			✓			
Grambow et al. (2021)		✓				
Grefen et al. (2019)		✓				
Hasić et al. (2020)	✓	✓				✓
Hornsteiner and Schönig (2023)		✓				
Hou et al. (2016)						✓
Hu et al. (2014)						✓
Ismaili-Alaoui et al. (2018)						✓
Jain and Tata (2017)	✓					
Janssen et al. (2020)						✓
Kahl et al. (2015)				✓		
Keates (2019)		✓				
Kikuchi et al. (2018)						✓
Kirikkayis et al. (2022a)		✓				
Kirikkayis et al. (2022b)	✓					
Kirikkayis et al. (2023c)		✓				
Kirikkayis et al. (2023b)		✓				
Kirikkayis et al. (2023a)		✓				
Kunz et al. (2011)						✓
Li et al. (2021)	✓					
Loke et al. (2007)						✓
Maamar et al. (2018)	✓					
Maamar et al. (2020)			✓			
Malburg et al. (2020)		✓				
Marrella and Mecella (2017)			✓			
Martins and Domingos (2017)						✓
Martins et al. (2020)						✓
Mass et al. (2016)		✓				
Meroni et al. (2018)		✓				
Meyer et al. (2011)				✓		

Table 6 continued

ID study	Healthcare	Industrial sector	Public	Consumer services	Consumer goods	Services
Meyer et al. (2013)				✓		
Montali and Plebani (2017)		✓				
Mottola et al. (2019)						✓
Muhsin et al. (2016)						✓
Park et al. (2018)						✓
Pastor et al. (2022)			✓			
Pryss et al. (2015)	✓					
Ruiz-Fernández et al. (2017)	✓					
Ruppen and Meyer (2013)	✓					
Schief et al. (2011)		✓				
Schönig et al. (2018)		✓				
Schönig et al. (2020)		✓				
Seiger et al. (2018)	✓					
Seiger et al. (2019)						✓
Seiger et al. (2020)		✓				
Seiger et al. (2021)						✓
Seiger et al. (2023)		✓				
Senderovich et al. (2016)	✓					
Shamsuzzoha et al. (2014)		✓				
Song et al. (2022)		✓				
Suri et al. (2017)		✓				
Suri et al. (2018)				✓		
Tôn and Lê (2019)	✓					
Ugljanin et al. (2018)				✓		
Valderas et al. (2022)		✓				
Valderas et al. (2023)		✓				
van Eck et al. (2016)						✓
Vitali and Pernici (2016)	✓					
Wang et al. (2022)		✓				
Wehlitz et al. (2017)						✓
Wieland et al. (2008)		✓				
Wombacher (2011)		✓				
Xing et al. (2012)						✓
Zanfack et al. (2015)		✓				
Zhu et al. (2014)						✓

innovative retail lab of a large European supermarket chain; Meyer et al. (2011) evaluate their study using a use case from the domain of retail and show how sensors monitor perishable goods in a store; Meyer et al. (2013) test their study using a dynamic pricing process in the retail domain and show how the IoT device temperature sensor monitors the perishable good orchid in a store; Suri et al. (2018) evaluate their study using a process family from the Retail/Supply Chain Management domain; Ugljanin et al. (2018) test their study using a Smart City Tourism Organization (SCTO) scenario to automate its BPs related to visitor mobility by communicating with them using social networks and collecting their feedback.

- *Consumer Goods*Friedow et al. (2018) use a simple coffee machine billing system to automate the process of counting the coffee amount for each user; Kunz et al. (2011) use the lifecycle of a fish fillet within the different domains of manufacturer, logistics service provider, wholesaler distribution hub, wholesaler store, and the customer; van Eck et al. (2016) use a case study

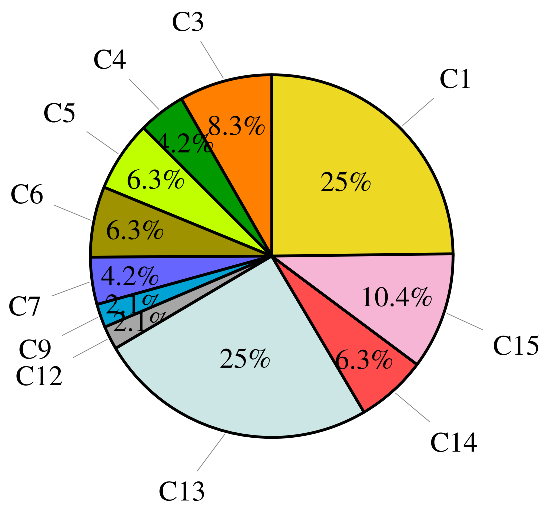

Fig. 4 Distribution of the studies by research challenges addressed in the *IoT-Meets-BPM Manifesto*

performed at Philips where a smart baby bottle has been developed.

- *Services* Scenarios that use smart device detection and implementation capabilities in smart home environments have been extensively addressed (Janssen et al. 2020; Loke et al. 2007; Wehlitz et al. 2017; Xing et al. 2012; Seiger et al. 2019; Hu et al. 2014; Chiu and Wang 2015; Elali et al. 2022). Examples of instances where service applications play a crucial role include the intruder detection system in a security scenario (Kikuchi et al. 2018); office supply processes (Cherrier and Deshpande 2017), temperature control processes (Seiger et al. 2021), warehouse management system monitoring processes (Hou et al. 2016), automatic irrigation control processes (Martins and Domingos 2017; Martins et al. 2020; Di Martino et al. 2022), processes for adaptive ventilation in a student dormitory (Mottola et al. 2019) or on student thesis defence

Table 7 Definitions of the research challenges of the *IoT-Meets-BPM Manifesto*

ID	Definition	References
C1	Placing Sensors in a Process-Aware Way	Mottola et al. (2019); Malburg et al. (2020); Schönig et al. (2020); Ruppen and Meyer (2013); Gallik et al. (2022); Song et al. (2022); Senderovich et al. (2016); van Eck et al. (2016); Koschmider et al. (2020); Di Martino et al. (2022); Valderas et al. (2023); Diamantini et al. (2023)
C2	Support for Managing Manually Executed Physical Processes	
C3	Connection of Analytical Processes with the IoT	Elhami et al. (2020); Kirikkayis et al. (2023b); Li et al. (2021)
C4	Integrating the IoT with Process Correctness Checks	Seiger et al. (2018); Malburg et al. (2020)
C5	Dealing With Unstructured Environments	Domingos et al. (2010); Malburg et al. (2020)
C6	Managing the Link Between Microprocesses	Malburg et al. (2020); Gao et al. (2011); Kirikkayis et al. (2023c)
C7	Breaking Down End-to-End Processes	Kahl et al. (2015); Malburg et al. (2020)
C8	Detecting New Process from Data	
C9	Specifying the Autonomy Level of Things	Malburg et al. (2020)
C10	Specifying the roles of things	
C11	Concretizing Abstract Process Models	
C12	Dealing With New Situations	Malburg et al. (2020).
C13	Bridging the Gap Between Event-Based and Process-Based Systems	de Leoni and Pellattiero (2021); Janssen et al. (2020); Keates (2019); Elhami et al. (2020); Schönig et al. (2018); Sora et al. (2017); Vitali and Pernici (2016); Koschmider et al. (2020); Senderovich et al. (2016); Malburg et al. (2020); van Eck et al. (2016); Bertrand et al. (2021)
C14	Improving Online Conformance Checking	Seiger et al. (2020); Malburg et al. (2020); Wombacher (2011)
C15	Improving Resource Utilization Optimization	Suri et al. (2017); Bocciarelli et al. (2017); Ismaili-Alaoui et al. (2018); Meyer et al. (2013); Suri et al. (2018)
C16	Improving Resource Monitoring and the Quality of Task Execution	

(Zhu et al. 2014), processes for repair and maintenance of computers and peripherals (Muhsin et al. 2016); while Park et al. (2018) implement smart toilets for companion animals by simply attaching sensors and introducing BPM technology.

4.4 What are the Research Challenges Addressed So Far to Support the Management of IoT-Aware BP?

In this section, we present the results related to research question RQ4. Enriching BPs with IoT technologies brings several advantages and many challenges (Janiesch et al. 2020); therefore, we provide the distribution of the studies according to the *IoT-Meets-BPM Manifesto* (cf. Figure 4 and Table 7). Not all studies face one of these challenges, actually, only 38% of them do.

- *C1 – Placing sensors in a process-aware way* The research challenge C1 is considered by 25% (i.e., 12) of the studies. The link between the position of the sensors and that of the corresponding actuator is discussed in Mottola et al. (2019). Using a physical simulation model, Malburg et al. (2020) conducted research in BPM and Industry 4.0, aiming to program a smart factory for BPs by selecting hardware components to detect process-relevant events. To place IoT sensors in a process-aware way and link them to the running process, a BPMS must be aware of the current values of IoT objects, and based on an established mapping from IoT variables to process models IoT data is sent to a BPMS (Schönig et al. 2020). Process model discovery from sensors or wearable devices depends on their location and amount (Koschmider et al. 2020; Senderovich et al. 2016; van Eck et al. 2016). Other interesting studies on how to integrate sensors with other services and into existing BPs have been conducted (Ruppen and Meyer 2013; Gallik et al. 2022; Song et al. 2022; Di Martino et al. 2022). Regarding sensors, the presented ontological model covers domain configuration, including IoT resources' placement and gathered observations over time (Diamantini et al. 2023; Valderas et al. 2023).
- *C3 – Connection of analytical processes with IoT* The research challenge C3 is considered by 8.3% (i.e. 4) of the studies. Elhami et al. (2020) use contextual events in the decision point to control the process execution and incorporate contextual changes with process rules and exaction logic at the runtime. With the proposed extension Kirikkayis et al. (2023b) can specify event-driven behaviour at various points in a BP but also demarcate IoT-based data sources from other process inputs for monitoring and error handling. BP execution necessitates updated information availability. Li et al. (2021) proposed a framework separating event processing and BP execution, reducing BPM engine load.
- *C4 – Integrating the IoT with process correctness checks* The research challenge C4 is considered by 4.2% (i.e. 2) of the studies. By connecting individual tasks and workflow executions to the respective effects in the physical and virtual world with the help of additional sensor data, you can verify the correct execution and behaviour of the IoT entities involved (Seiger et al. 2018; Malburg et al. 2020).
- *C5 – Dealing with unstructured environments* The research challenge C5 is considered by 6.3% (i.e. 3) of the studies. In the IoT world, which is much more ad hoc and situative, Domingos et al. (2010) introduce mechanisms to perform ad-hoc changes in IoT-aware BPs by identifying change primitives that support the change operations needed to modify parts of the BP.
- *C6 – Managing the link between micro-processes* The research challenge C6 is considered by 6.3% (i.e. 3) of the studies. An example is to achieve an efficient and flexible production line by investigating the micro-processes at the individual machines and stations and their interconnections to achieve a more flexible composition of smaller processes (Malburg et al. 2020). By extending BPMN 2.0, Gao et al. (2011) links process models with business functions, connecting them to external open data, including sensor and instance ontology data; another extension suggest using low-level IoT data for decision-making, not including high-level data aggregation (Kirikkayis et al. 2023c).
- *C7 – Breaking down end-to-end processes* The research challenge C7 is considered by 4.2% (i.e. 2) of the studies. Malburg et al. (2020) suggest relaxing and detailing the static and coarse-grained "hardwired" processes to achieve a more flexible composition of smaller processes. Kahl et al. (2015) propose a system that provides an agent-assisted realization and adaptation of BPs with semantic service selection and facilitates an event-driven selection and controlled execution of relevant BPs in intelligent environments.
- *C9 – Specifying the autonomy level of things* The research challenge C9 is considered by 2.1% (i.e. 1) of the studies. Ensuring appropriate autonomy for resource constrained IoT device is investigated by Malburg et al. (2020).
- *C12 – Dealing with new situations* The research challenge C12 is considered by 2.1% (i.e. 1) of the studies. Malburg et al. (2020) use past successful process executions to automatically learn possible adaptations of process instances to deal with new or similar situations.

Table 8 Trends for research studies to support IoT-aware BPs life cycle phases

Trends	BPM life cycle phase	References
The modeling of IoT-driven BPs must be integrated into a standard modeling language such as BPMN	Modeling	Graja et al. (2019), Grambow et al. (2021), Hasić et al. (2020) Meyer et al. (2011), Meyer et al. (2013), Meyer et al. (2015) and Mottola et al. (2019)
It should be possible to have a built-in workflow engine to make quick changes to the running model or to implement middleware that makes the process independent of device technology, i.e. aware of the involvement of IoT devices	Execution	Kunz et al. (2011), Keates (2019) and Friedow et al. (2018)
It should be possible to monitor IoT devices in real time	Monitoring	Shamsuzzoha et al. (2014) and Wombacher (2011)

- *C13 – Bridging the gap between event-based and process-based systems* The research challenge C13 is considered by 25% (i.e. 12) of the studies. The complex IoT system is event-driven due to the large number of sensors and process-based (Malburg et al. 2020). While in the past, process models have been detected by documents or interviews with domain experts, today the challenge of automatically discovering the process model from the network of sensors or wearable devices also depends on their location and amount (Koschmider et al. 2020; Senderovich et al. 2016; van Eck et al. 2016). Therefore, considering the physical context and revealing the correlation between IoT data and process events is crucial (Bertrand et al. 2021).
- *C14 – Improving online conformance checking* The research challenge C14 is considered by 6.3% (i.e. 3) of the studies. Seiger et al. (2020) mainly focus on generating event logs from streams of IoT sensor data with smart factories as an application domain.
- *C15 – Improving resource utilization optimization* The research challenge C15 is considered by 10.4% (i.e. 5) of the studies. Suri et al. (2017) present a framework that formalizes IoT properties and rules to optimize resource management in BPs, defining resource constraints to be mapped to a task during the design phase.

5 Discussion

In this section, we discuss the relationships between the topics extracted from the studies, the application domains, the life cycle phases of the BPM and the research challenges introduced by Janiesch et al. (2020). Finally, the main issues which seem to need further investigation are discussed.

- *BPM life cycle phases* Our results suggest that many studies include more than one phase, and most (43%, 40 studies) combine the modeling and implementation phases. The impact of IoT technology on the modeling phase has been widely studied, giving rise to the so-called IoT-aware BP modeling that has attracted the attention of researchers. Introducing IoT entities into the modeling phase has encountered difficulties with the entities' heterogeneity. Analysis of the studies showed that the approaches used to model IoT entities involve: the expression of entities through the use of standard elements of process modeling languages, although increasingly rarely, or more commonly, the extension of languages through the introduction of specific IoT elements. However, the existing BPM solutions have not yet precisely defined the behaviour of IoT entities, and this absence proves a significant obstacle to running BPs of traditional BPM systems on IoT devices automatically. The analysis showed that an integrated workflow engine approach can rapidly change the model and its execution, avoiding the situation where the process model changes. The system must re-convert the model into an executable source code and distribute the code to IoT devices. A second common approach involves the implementation of a middleware that makes BP independent of the device's technology. However, the proposal of an approach that covers most of the phases of an IoT-aware BP is the most critical challenge to date. Based on the findings, we have defined a set of trends (or directions for research studies) for the life cycle phases of IoT-aware BPs (cf. Table 8).

- *Topic Modeling* One of the biggest challenges we have encountered in topic analysis, which is to extract knowledge from sensor data, is to bridge the gap between sensor data clouds and event logs. To be more precise, the goal is to identify events from raw event data, discover their activities and correlate them with the process instance. Another interesting topic that emerged from the analysis concerns the modeling approaches of IoT-aware BPs. For example, based on the review conducted in this article, we have seen several approaches to modeling IoT devices. Most authors modeling IoT-aware BPs propose methods that rely on a BPMN extension to integrate IoT devices within the process model. Another interesting approach uses a linked data mechanism to create links between the BP model and external open data, including the ontology of sensors and instance data, to achieve better integration between the physical world and BPs. Many authors see IoT as the external data source for BPM, most commonly in terms of process context. Physical resource management was the last topic of interest in the BPM and IoT field. We have seen that it is essential to specify the resources used to perform tasks because IoT resources are active. However, the challenge remains to formalize the relationship between IoT resources to ensure efficient management.

- *Application domains and case studies* Our results show that there are application domains that benefit more than others from the integration of IoT concepts into BPM application scenarios. Among these, the industrial categories (41.2%, 35 studies) and services (24.7%, 21 studies) are the most used as application scenarios in BPM and IoT. Within the industrial category, we have further classified studies into several sectors, and we have seen that many studies have introduced BPM for IoT-based logistics. It emerged that filtering and processing events are important but are only the first steps to obtaining transparent BPs. It is necessary to consider the quality of the information because the data in the logistics area are often incomplete and inconsistent. Data quality is a topic that needs to be addressed if you want to build approaches that integrate IoT into the BPM community. Existing solutions presuppose persistent and relatively static data sets contrary to the physical world's needs. Notice that among these only a few studies utilize real scenarios, such as a temperature controlling process (Chiu and Wang 2015), a small scale physical smart factory model (Kirikkayis et al. 2022a), a smart hospital (Jain and Tata 2017) or a clinical process of the hypertension (Ruiz-Fernández et al. 2017). Furthermore, two studies propose that their future work will be dedicated to devising a comprehensive evaluation of the real-case approach (Maamar et al. 2018; Diamantini et al. 2023).
- *Research challenges* Another essential aspect that we have observed in some of the studies analysed (38%, 35 studies) is the discussion of the challenges presented in the BPM-IoT Manifesto (Janiesch et al. 2020). Complex IoT environments consist of many sensors, actuators, and control units. In addition to IoT components, a further software stack is also needed to elevate programming and research to the level of abstraction of BPs and thus exploit the potential of BPM's integration with IoT. This type of system can often be driven either by events, due to a large number of sensors, or by the process (C13 - Sect. 4.4). One of the research activities associated with this challenge concerns the functionality analysis of the available sensors and actuators and their grouping and abstraction at the BPM-oriented level. Identifying process events from IoT data, perfecting them, and generating associated events is often insufficient. What may remain are ambiguities and uncertainties, typical of the nature of IoT environments, as part of the event log and this must be considered in the following analysis steps (e.g. in the compliance check). The analysis of the research challenges also showed that it is necessary to place IoT sensors in a process-aware way and that these must be connected to running processes (C1 - Sect. 4.4). To date, this challenge mainly involves BPMS which must be aware of the current values of IoT objects. In addition, it is also necessary to investigate how to acquire current values from different data variables and obtain a mapping between IoT variables and process models so that IoT data can be sent to a BPMS. This process is fundamental as, on the one hand, based on the current values of some variables, tasks are activated or canceled and decisions are made; on the other hand, this allows IoT data variables to be more configurable and traceable.

5.1 Threats to Validity

The SLR's validity should be rigorously assessed to ensure the level of scientific value in its conduct and findings. In this section, we discuss the factors (threats to validity) that dispute the results of an SLR or decrease the meaningfulness of the results. Our review adopted the guidelines specified by Zhou et al. (2016) in assessing the validity of Software Engineering. The authors classify validity categories and associate identified threats with them. One of the main threats to the validity of this SLR is incompleteness. In our case, what risk this threat poses depends heavily on the limitations of available search engines. A multidisciplinary search engine such as GS and two more specific ones, ACM and IEEE Digital Libraries, should significantly decrease such constraints. Another critical issue is bias in the selection of studies which could lead to inaccuracies in the data. To solve this, we employed various strategies. The reviewer thoroughly read the documents during the selection process to minimize misinterpretations from relying solely on titles and abstracts. Additionally, explicit reasons for exclusion decisions were documented during the screening phase. This approach aided in mitigating the threat of overlooking relevant studies. To maximize study coverage, we employed snowballing as a complementary search to reduce the possibility of missing relevant studies. Another action taken, which could be traced back to a wrong search method (Zhou et al. 2016), was the combination of automated and manual search methods.

6 Concluding Remarks

This article has provided an in-depth overview of the interplay between BPM and IoT. Unlike the existing surveys that deal with specific aspects of the interaction, we aimed to provide a holistic view in this study. The systematic analysis of reviewed studies provides answers to several research questions, enabling us to *(i)* identify the hottest topics studied within the literature (Mining from event sensors, Physical resource management, Context-aware execution, IoT-aware process modeling), *(ii)* classify the integration of IoT within the BP life cycle phases (Identification, Modeling, Analysis, Re-design, Implementation, and Monitoring and mining), *(iii)* identify which are the application domains where integration between IoT and BPM have the most significant expansion (Consumer goods, Consumer services, Healthcare, Industrials, Services and Public), and *(vi)* highlight the research challenges provided by the *IoT-Meets-BPM Manifesto* faced so far to support the management of IoT-aware BPs.

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References

Abouzid I, Bekali YK, Saidi R (2022) Modelling IoT behaviour in supply chain business processes with BPMN: a systematic literature review. J ICT Stand 439–468

Antonius N, Dachyar M (2020) The internet of things (IoT) design for cardiac remote patient monitoring using business process re-engineering. In: 2020 3rd international conference on applied engineering (ICAE), pp 1–7

Bertrand Y, De Weerdt J, Serral E (2021) A bridging model for process mining and IoT. In: International conference on process mining (ICPM), pp 98–110

Blei DM, Ng AY, Jordan MI (2003) Latent Dirichlet allocation. J Mach Learn Res 3:993–1022

Bocciarelli P, D'Ambrogio A, Giglio A, Paglia E (2017) A BPMN extension for modeling cyber-physical-production-systems in the context of industry 4.0. In: 2017 IEEE 14th international conference on networking, sensing and control (ICNSC), pp 599–604

Brouns N, Tata S, Ludwig H, Asensio ES, Grefen P (2018) Modeling IoT-aware business processes-a state of the art report. CoRR

Chadli N, Elhoseny M, Kabbaj MI, Bakkoury Z (2022) Smart business process modeling: Toward an IoT to detect the data flow anomalies in ad hoc mesh network. Distrib Sens Intell Syst 13–27

Chang C, Srirama SN, Buyya R (2016) Mobile cloud business process management system for the internet of things: a survey. ACM Comput Surv CSUR 49(4):1–42

Chauhan U, Shah A (2021) Topic modeling using latent Dirichlet allocation: a survey. ACM Comput Surv CSUR 54(7):1–35

Cheng Y, Zhao S, Cheng B, Chen J (2018) A service-based fog execution environment for the IoT-aware business process applications. In: 2018 IEEE international conference on web services (ICWS), pp 323–326

Cheng Y, Zhao S, Cheng B, Chen X, Chen J (2019) Modeling and deploying IoT-aware business process applications in sensor networks. Sensors 19(1):111

Chen F, Ren C, Wang Q, Shao B (2012) A process definition language for internet of things. In: 2012 IEEE international conference on service operations and logistics, and informatics (SOLI), pp 107–110

Cherrier S, Deshpande V (2017) From BPM to IoT. In: International conference on business process management (BPM), pp 310–318

Chiu HH, Wang MS (2015) Extending event elements of business process model for internet of things. In: 2015 IEEE international conference on computer and information technology; ubiquitous computing and communications; dependable, autonomic and secure computing; pervasive intelligence and computing, pp 783–788

Compagnucci I, Corradini F, Fornari F, Polini A, Re B, Tiezzi F (2023) A systematic literature review on IoT-aware business process modeling views, requirements and notations. Softw Syst Model 22(3):969–1004

Compagnucci I, Corradini F, Fornari F, Polini A, Re B, Tiezzi F (2020) Modelling notations for IoT-aware business processes: a systematic literature review. In: Business process management workshops – BPM 2020 international workshops, lecture notes in business information processing, vol 397, pp 108–121

de Leoni M, Pellattiero L (2021) The benefits of sensor-measurement aggregation in discovering IoT process models: a smart-house case study. In: Business process management workshops, BPM 2021 international workshops, vol 436, pp 403–415

Del Giudice M (2016) Discovering the internet of things (IoT) within the business process management. Bus Process Manag J 22(2):263–270

Di Martino B, Cante LC, Esposito A, Graziano M (2022) Towards a methodology for the semantic representation of IoT sensors and BPMNs to discover business process patterns: a smart irrigation case study. In: International conference on broadband and wireless computing, communication and applications, pp 248–258

Diamantini C, Mircoli A, Potena D, Storti E (2023) Process-aware IIoT knowledge graph: a semantic model for industrial IoT integration and analytics. Future Gener Comput Syst 139:224–238

Domingos D, Martins F, Cândido C, Martinho R (2014) Internet of things aware WS-BPEL business processes context variables and expected exceptions. J Univers Comput Sci 20(8):1109–1129

Domingos D, Martins F, Caiola L (2015) Decentralising internet of things aware BPMN business processes. In: Sensor systems and software, pp 110–119

Domingos D, Martins F, Martinho R, Silva M (2010) Ad-hoc changes in IoT-aware business processes. In: 2010 internet of things (IoT), pp 1–7

Dumas M, La Rosa M, Mendling J, Reijers HA (2018) Fundamentals of business process management, vol 2

Elali R, Kornyshova E, Deneckère R, Salinesi C (2022) Mining contextual process models using sensors data: a case of daily activities in smart home. In: European, Mediterranean, and Middle Eastern conference on information systems, pp 409–425

Elhami E, Ansari A, Farahani B, Aliee FS (2020) Towards IoT-driven predictive business process analytics. In: 2020 international conference on omni-layer intelligent systems (COINS), pp 1–7

Elkodssi I, Laanaoui MD, Sbai H (2022) Toward a new framework for process-aware IoT discovery. In: International conference on smart city applications, pp 793–803

Engels G, Strothmann T, Teetz A (2018) Adapt cases 4 BPM – a modeling framework for process flexibility in IIoT. In: 2018 IEEE 22nd international enterprise distributed object computing workshop (EDOCW), pp 59–68

Fattouch N, Ben Lahmar I, Boukadi K (2020) IoT-aware business process: comprehensive survey, discussion and challenges. In: 2020 IEEE 29th international conference on enabling technologies, infrastructure for collaborative enterprises (WETICE), pp 100–105

Friedow C, Völker M, Hewelt M (2018) Integrating IoT devices into business processes. In: International conference on advanced information systems engineering, pp 265–277

Gallik F, Kirikkayis Y, Reichert M (2022) Modeling, executing and monitoring IoT-aware processes with bpm technology. In: 2022 international conference on service science (ICSS), pp 96–103

Gao F, Zaremba M, Bhiri S, Derguerch W (2011) Extending BPMN 2.0 with sensor and smart device business functions. In: 2011 IEEE 20th international infrastructure for collaborative enterprises, workshops on enabling technologies, pp 297–302

Gómez-Valiente P, Pérez J, Lillo-Castellano J, Marina-Breysse M (2023) Smart-IoT business process management: a case study on remote digital early cardiac arrhythmia detection and diagnosis. IEEE Internet Things J 10(19):16,744-16,757

Graja I, Kallel S, Guermouche N, Cheikhrouhou S, Kacem AH (2019) Modelling and verifying time-aware processes for cyber-physical environments. IET Softw 13(1):36–48

Grambow G, Hieber D, Oberhauser R, Pogolski C (2021) A context and augmented reality BPMN and BPMS extension for industrial internet of things processes. In: Business process management workshops – BPM 2021 international workshops, lecture notes in business information processing, vol 436, pp 379–390

Grefen P, Brouns N, Ludwig H, Serral E (2019) Co-location specification for IoT-aware collaborative business processes. In: Information systems engineering in responsible information systems, pp 120–132

Grefen P, Ludwig H, Tata S, Dijkman R, Baracaldo N, Wilbik A, D'hondt T (2018) Complex collaborative physical process management: a position on the trinity of BPM, IoT and DA. In: Working conference on virtual enterprises, pp 244–253

Hasić F, Serral E, Snoeck M (2020) Comparing BPMN to BPMN + DMN for IoT process modelling: a case-based inquiry. In: 35th annual ACM symposium on applied computing, SAC '20, pp 53–60

Hornsteiner M, Schönig S (2023) SIREN: designing business processes for comprehensive industrial IoT security management. In: 18th international conference on design science research in information systems and technology, (DESRIST), lecture notes in computer science, vol 13873, pp 379–393

Hou SL, Zhao S, Cheng B, Cheng YY, Chen JL (2016) Fragmentation and optimal deployment for IoT-aware business process. In: 2016 IEEE international conference on services computing (SCC), pp 657–664

Hull R, Damaggio E, Fournier F, Gupta M, III FFTH, Hobson S, Linehan MH, Maradugu S, Nigam A, Sukaviriya P, Vaculín R (2010) Introducing the guard-stage-milestone approach for specifying business entity lifecycles. In: 7th international workshop, web services and formal methods WS-FM 2010, lecture notes in computer science, vol 6551, pp 1–24

Humayoun SR, Catarci T, de Leoni M, Marrella A, Mecella M, Bortenschlager M, Steinmann R (2009b) The WORKPAD user interface and methodology: developing smart and effective mobile applications for emergency operators. In: Universal access in human-computer interaction. Applications and services, pp 343–352

Humayoun SR, Catarci T, de Leoni M, Marrella A, Mecella M, Bortenschlager M, Steinmann R (2009) Designing mobile systems in highly dynamic scenarios: the WORKPAD methodology. Knowl Technol Policy 22:25–43

Hu G, Wu B, Zou H, Chen J (2014) Dynamic integration mechanism of business process for internet of things. In: 2014 IEEE international conference on services computing, pp 852–853

Ismaili-Alaoui A, Baïna K, Benali K, Baïna J (2018) Towards smart incident management under human resource constraints for an IoT-BPM hybrid architecture. In: International conference on web services, pp 457–471

Jain R, Tata S (2017) Cloud to edge: distributed deployment of process-aware IoT applications. In: 2017 IEEE international conference on edge computing (EDGE), pp 182–189

Janiesch C, Koschmider A, Mecella M, Weber B, Burattin A, Di Ciccio C, Fortino G, Gal A, Kannengiesser U, Leotta F (2020) The internet of things meets business process management: a manifesto. IEEE Syst Man Cybern Magn 6(4):34–44

Janssen D, Mannhardt F, Koschmider A, Zelst SV (2020) Process model discovery from sensor event data. In: ICPM workshops

Kahl G, Klusch M, Zinnikus I, Schimmelpfennig J, Zapp M (2015) ADIGE: semantic business process management for smart retail environments. In: 17th international conference on information integration and web-based applications & services (iiWAS), pp 53:1–53:5

Keates O (2019) Integrating IoT with BPM to provide value to cattle farmers in Australia. In: Business process management

workshops – BPM 2019 international workshops, lecture notes in business information processing, vol 362, pp 119–129
Keele S (2007) Guidelines for performing systematic literature reviews in software engineering. Technical report, Ver. 2.3 EBSE technical report. EBSE
Kikuchi S, Thomas I, Jallouli O, Doerr J, Morgenstern A, Baccelli E, Schleiser K (2018) Orchestration of IoT device and business workflow engine on cloud. In: 2018 3rd cloudification of the internet of things (CIoT), pp 1–2. https://doi.org/10.1109/CIOT.2018.8627118
Kirikkayis Y, Gallik F, Winter M, Reichert M (2023c) BPMNE4IoT: a framework for modeling, executing and monitoring IoT-driven processes. Future Internet 15(3):90
Kirikkayis Y, Gallik F, Reichert M (2022a) IoTDM4BPMN: an IoT-enhanced decision making framework for BPMN 2.0. In: International conference on service science, (ICSS) 2022, pp 88–95
Kirikkayis Y, Gallik F, Reichert M (2022b) Towards a comprehensive BPMN extension for modeling IoT-aware processes in business process models. In: International conference on research challenges in information science, pp 711–718
Kirikkayis Y, Gallik F, Reichert M (2023a) Modeling, executing and monitoring IoT-driven business rules. In: BPMDS/EMMSAD 2023, lecture notes in business information processing, vol 479, pp 88–102
Kirikkayis Y, Gallik F, Seiger R, Reichert M (2023b) Integrating IoT-driven events into business processes. In: CAiSE forum 2023, vol 477, pp 86–94
Kopetz H, Steiner W (2022) Internet of things. In: Real-time systems, pp 325–341
Koschmider A, Janssen D, Mannhardt F (2020) Framework for process discovery from sensor data. In: 10th international workshop on enterprise modeling and information systems architectures, CEUR workshop proceedings, vol 2628, pp 32–38
Kozma D, Varga P, Larrinaga F (2019) Data-driven workflow management by utilising BPMN and CPN in IIoT systems with the arrowhead framework. In: 24th IEEE international conference on emerging technologies and factory automation, ETFA 2019, pp 385–392
Kunz S, Fabian B, Ziekow H, Bade D (2011) From smart objects to smarter workflows – an architectural approach. In: 2011 IEEE 15th international enterprise distributed object computing conference workshops, pp 194–203
Leotta F, Marrella A, Mecella M (2019) IoT for BPMers. Challenges, case studies and successful applications. In: 17th international conference on business process management (BPM), pp 16–22
Li Q, Wang J, Chen G, Yuan Y, Ye S (2021) Business-oriented IoT-aware process modeling and execution. In: 18th international conference web information systems and applications (WISA), lecture notes in computer science, vol 12999, pp 747–755
Loke S, Ling S, Indrawan M, Kurniati S (2007) Adaptive workflows for smart devices – a concrete approach towards device failures. In: Ninth international conference on enterprise information systems (ICEIS), pp 191–197
Maamar Z, Kajan E, Guidara I, Moctar-M'Baba L, Sellami M (2020) Bridging the gap between business processes and IoT. In: 24th symposium on international database engineering & applications, IDEAS '20
Maamar Z, Sellami M, Faci N, Ugljanin E, Sheng QZ (2018) Storytelling integration of the internet of things into business processes. In: International conference on business process management (BPM) – BPM Forum, pp 127–142
Malburg L, Seiger R, Bergmann R, Weber B (2020) Using physical factory simulation models for business process management research. In: Business process management workshops – (BPM) 2020 international workshops, lecture notes in business information processing, vol 397, pp 95–107
Marrella A, Mecella M (2017) Adaptive process management in cyber-physical domains. Adv Intell Process Aware Inf Syst Concepts Methods Technol 123:15
Marrella A, Mecella M, Russo A (2011) Collaboration on-the-field: suggestions and beyond. In: 8th international conference on information systems for crisis response and management, ISCRAM 2011
Martins F, Domingos D (2017) Modelling IoT behaviour within BPMN business processes. Procedia Comput Sci 121:1014–1022
Martins F, Domingos D, Vitoriano D (2020) A graph pattern based approach for automatic decomposition of IoT aware business processes. In: 21st international conference enterprise information systems, (ICEIS), lecture notes in business information processing, vol 378, pp 498–513
Mass J, Chang C, Srirama SN (2016) WiseWare: a device-to-device-based business process management system for industrial internet of things. In: 2016 IEEE international conference on internet of things (iThings) and IEEE green computing and communications (GreenCom) and IEEE cyber, physical and social computing (CPSCom) and IEEE smart data (SmartData), pp 269–275
Meroni G, Baresi L, Montali M, Plebani P (2018) Multi-party business process compliance monitoring through IoT-enabled artifacts. Inf Syst 73:61–78
Meyer S, Ruppen A, Hilty L (2015) The things of the internet of things in BPMN. In: Advanced information systems engineering workshops – CAiSE 2015 international workshops, lecture notes in business information processing, vol 215, pp 285–297
Meyer S, Ruppen A, Magerkurth C (2013) Internet of things-aware process modeling: integrating IoT devices as business process resources. In: 25th international conference on advanced information systems engineering (CAiSE), pp 84–98
Meyer S, Sperner K, Magerkurth C, Pasquier J (2011) Towards modeling real-world aware business processes. In: Second international workshop on web of things, pp 1–6
Montali M, Plebani P (2017) IoT-based compliance checking of multi-party business processes modeled with commitments. In: Service-oriented and cloud computing, pp 179–195
Mottola L, Picco GP, Oppermann FJ, Eriksson J, Finne N, Fuchs H, Gaglione A, Karnouskos S, Montero PM, Oertel N, Römer K, Spiess P, Tranquillini S, Voigt T (2019) makeSense: simplifying the integration of wireless sensor networks into business processes. IEEE Trans Softw Eng 45(6):576–596
Muhsin ZJ, Al-Taee A, Al-Taee MA, Al-Nuaimy W, Al-Ataby A (2016) Mobile workflow management system based on the internet of things. 2016 13th international multi-conference on systems, signals devices (SSD), pp 436–441
Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Int J Surg 88(105):906
Park M, Kim H, Ahn H, Kim KP (2018) A process-aware IoT application execution environment design. In: 2018 20th international conference on advanced communication technology (ICACT), pp 724–727
Pastor FJF, Horcajadas MP, Davo JAL, Iglesias VG (2022) Developing environmental adaptative comfort using internet of things and business process management: application in a university building. In: International conference on ubiquitous computing and ambient intelligence (UCAmI), pp 535–546
Pryss R, Reichert M, Bachmeier A, Albach J (2015) BPM to go: supporting business processes in a mobile and sensing world. In: BPM everywhere: internet of things, process of everything, pp 167–182

Ruiz-Fernández D, Marcos-Jorquera D, Gilart-Iglesias V, Vives-Boix V, Ramírez-Navarro J (2017) Empowerment of patients with hypertension through BPM, IoT and remote sensing. Sensors 17(10):2273

Ruppen A, Meyer S (2013) An approach for a mutual integration of the web of things with business processes. In: Workshop on enterprise and organizational modeling and simulation, pp 42–56

Schief M, Kuhn C, Rösch P, Stoitsev T (2011) Enabling business process integration of IoT-events to the benefit of sustainable logistics. In: International conference on logistics, informatics and service science (LISS), pp 40–49

Schmidt B, Schief M (2010) Towards agile business processes based on the internet of things. In: Advanced manufacturing and sustainable logistics, pp 257–262

Schönig S, Ackermann L, Jablonski S, Ermer A (2020) IoT meets BPM: a bidirectional communication architecture for IoT-aware process execution. Softw Syst Model 19(6):1443–1459

Schönig S, Ackermann L, Jablonski S (2018) Internet of things meets BPM: a conceptual integration framework. In: SIMULTECH, pp 307–314

Seiger R, Huber S, Heisig P, Assmann U (2019) Toward a framework for self-adaptive workflows in cyber-physical systems. Softw Syst Model 18(2):1117–1134

Seiger R, Kühn R, Korzetz M, Aßmann U (2021) HoloFlows: modelling of processes for the internet of things in mixed reality. Softw Syst Model 20(5):1465–1489

Seiger R, Franceschetti M, Weber B (2023) An interactive method for detection of process activity executions from IoT data. Future Internet 15(2):77

Seiger R, Assmann U, Huber S (2018) A case study for workflow-based automation in the internet of things. In: 2018 IEEE international conference on software architecture companion (ICSA-C), pp 11–18

Seiger R, Zerbato F, Burattin A, García-Bañuelos L, Weber B (2020) Towards IoT-driven process event log generation for conformance checking in smart factories. In: IEEE 24th international enterprise distributed object computing workshop (EDOCW), pp 20–26

Senderovich A, Rogge-Solti A, Gal A, Mendling J, Mandelbaum A (2016) The ROAD from sensor data to process instances via interaction mining. In: 28th international conference advanced information systems engineering (CAiSE), pp 257–273

Shamsuzzoha A, Abels S, Kuspert S, Helo P (2014) Smart collaborative processes monitoring in real-time business environment. In: 16th international conference on enterprise information systems (ICEIS) – Volume 2, ICEIS 2014, pp 556–563

Song R, Cui W, Vanthienen J, Huang L, Wang Y (2022) Business process redesign towards IoT-enabled context-awareness: the case of a Chinese bulk port. Bus Process Manag J 28(3):656–683

Sora D, Leotta F, Mecella M (2017) An habit is a process: a BPM-based approach for smart spaces. In: Business process management workshops - BPM 2017 international workshops, lecture notes in business information processing, vol 308, pp 298–309

Stoiber C, Schönig S (2021) Event-driven business process management enhancing IoT – a systematic literature review and development of research agendas. In: International conference on Wirtschaftsinformatik, innovation through information systems, pp 645–661

Suri K, Gaaloul W, Cuccuru A (2018) Configurable IoT-aware allocation in business processes. In: International conference on services computing, pp 119–136

Suri K, Gaaloul W, Cuccuru A, Gerard S (2017) Semantic framework for internet of things-aware business process development. In: 2017 IEEE 26th international conference on enabling technologies, infrastructure for collaborative enterprises (WETICE), pp 214–219

Tôn LP, Lê LS (2019) Enacting a rule-based alert business process in smart healthcare using IoT wearables. In: 2019 IEEE 23rd international enterprise distributed object computing workshop (EDOCW), pp 104–107

Torres V, Serral E, Valderas P, Pelechano V, Grefen P (2020) Modeling of IoT devices in business processes: a systematic mapping study. In: 2020 IEEE 22nd conference on business informatics (CBI), vol 1, pp 221–230

Ugljanin E, Stojanović D, Kajan E, Maamar Z (2018) Re-engineering of smart city's business processes based on social networks and internet of things. Facta Univ Ser Autom Control Robot 16:275

Valderas P, Torres V, Serral E (2022) Modelling and executing IoT-enhanced business processes through BPMN and microservices. J Syst Softw 184(111):139

Valderas P, Torres V, Serral E (2023) Towards an interdisciplinary development of IoT-enhanced business processes. Bus Inf Syst Eng 65(1):25–48

van Eck ML, Sidorova N, van der Aalst WMP (2016) Enabling process mining on sensor data from smart products. In: 2016 IEEE tenth international conference on research challenges in information science (RCIS), pp 1–12

Varga P, Kozma D, Hegedús C (2018) Data-driven workflow execution in service oriented IoT architectures. In: 2018 IEEE 23rd international conference on emerging technologies and factory automation (ETFA), vol 1, pp 203–210

Vitali M, Pernici B (2016) Interconnecting processes through IoT in a health-care scenario. In: 2016 IEEE international smart cities conference (ISC2), pp 1–6

Wang G, Fang J, Wang J, Yu J, Zhang L, Han Y (2022) Service-based event penetration from IoT sensors to businesses: a case study. In: 2022 international conference on service science (ICSS), pp 72–79

Wehlitz R, Rößner I, Franczyk B (2017) Integrating smart devices as business process resources – concept and software prototype. In: International conference on service-oriented computing (ICSOC), pp 252–257

Weske M (2019) Business process management. Concepts, languages, architectures

Wieland M, Kaczmarczyk P, Nicklas D (2008) Context integration for smart workflows. In: 2008 sixth annual IEEE international conference on pervasive computing and communications (PerCom), pp 239–242

Wombacher A (2011) How physical objects and business workflows can be correlated. In: 2011 IEEE international conference on services computing (SCC), pp 226–233

Xing Z, Hong Z, Yulong L (2012) A petri-net based context-aware workflow system for smart home. In: 2012 IEEE 26th international parallel and distributed processing symposium workshops PhD forum, pp 2336–2342

Zanfack DG, Nait-Sidi-Moh A, Durand D, Fortin J (2015) Modeling business entities and physical workflow in the context of internet of things: the GSM-IoT framework. In: 2015 third world conference on complex systems (WCCS), pp 1–7

Zhou X, Jin Y, Zhang H, Li S, Huang X (2016) A map of threats to validity of systematic literature reviews in software eng. In: 23rd Asia-Pacific software engineering conference (APSEC), pp 153–160

Zhu L, Cai H, Jiang L (2014) Minson: a business process self-adaptive framework for smart office based on multi-agent. In: 2014 IEEE 11th international conference on e-business engineering (ICEBE), pp 31–37