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A Systematic Literature Review on IoT-Aware Business Process Modeling Views, Requirements and Notations

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Abstract The Internet of Things has been adopted in several sectors both influencing how people work, and enhancing organizations' business processes. This resulted in the rising of relevant research topics such as IoT-Aware business processes. The modeling of these processes makes it possible to better understand working scenarios, and to support the adoption of model-driven development approaches for IoT-Aware and process-oriented software systems. Since much research has been performed on this topic, a better awareness of the current status is needed. This paper reports a systematic literature review to develop a map on modeling notations for IoT-Aware business processes. The survey mainly adopts an academic point of view, resulting in the detailed analysis of 84 research works from the leading computer science digital libraries. The output of the review is in the form of schemes and reflections. In particular, our research aims to shed light on (i) the relevant modeling views referring to different types of IoT-Aware business processes; (ii) the IoT requirements supported by the modeling notations; and (iii) the modeling notations proposed and/or adopted to model IoT-Aware business processes. Finally, our research work highlights possible future research lines needing further investigations.

Keywords IoT-Aware Business Process · IoT · Business Process Management · Modeling Notation

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1 Introduction

Nowadays, we are witnessing continuous growth in adopting IoT devices and, consequently, IoT-based applications. Disruptive innovations have been introduced in several sectors such as agriculture, industries, and city management with the rising relevance of smart agriculture, smart industry, and smart city sectors [4]. CISCO estimates that "the number of devices connected to IP networks will be more than three times the global population by 2023. [...] There will be 29.3 billion networked devices by 2023, up from 18.4 billion in 2018" [25]. This is mainly due to the capability of the IoT to create a link between the physical world and the digital one, especially by making physical objects accessible and available to end-users at any time. The merging of physical and digital worlds enables monitoring real phenomena based on sensing data, and the consequent possibility of actuating choices based on such data. As a consequence, organizations' business processes ask to be aligned in a way to take advantage of IoT capabilities [83], and the notion of "IoT-Aware business process" is becoming prominent in all the sectors in which IoT technologies have been introduced [10, 19, 20, 58, 83].

More effective integration of business processes and IoT-related topics has been recognized as a *win-win* situation, making it possible for both IoT and business processes to overcome their natural limitations [69]. However, as suggested by the *Business Processes Meet the Internet-of Things* group and its manifest, integrating IoT and business processes poses challenges to the research community that, among various things, ask for appropriate modeling notations [61].

This increased the research community's interest in proposing several modeling notations. In recent years, many proposals have been defined to support modeling such IoT-Aware business processes. This also led to the publication of surveys on the topic [10, 17, 41, 51, 108, 110]. Such works are meritorious and permitted to shed light on different aspects of such integration. However, they refer to a reduced time frame (2009 - 2020), they do not illustrate how the different notations support relevant IoT modeling views and IoT-related requirements, and none of the mentioned surveys provides guidelines for selecting an approach based on the specific needs of a given application scenario (see Section 7 for further details).

This paper describes the procedure we adopted for conducting our Systematic Literature Review (SLR) and reports on its results, emphasizing research works in the academic literature. To present a fair evaluation of the research works on this topic, we conducted the SLR using a trustworthy, rigorous, and auditable methodology following the guidelines suggested by Kitchenham et al. [64].

The conducted study is based on the following research questions. They have been defined based on an overview of the literature and the experience of the authors who have been researching this and related topics for some years.

- *RQ1. What are the relevant modeling views to consider when modeling IoT-Aware business processes?*
- *RQ2. What are the IoT requirements supported by the modeling notations used to model IoT-Aware business processes?*
- *RQ3. What are the modeling notations proposed and/or adopted to model IoT-Aware business processes?*

By answering the listed research questions, the paper targets: (i) *researchers/academics*, by providing them with a list of possible future research directions regarding the modeling of IoT-Aware business processes; (ii) *tool builders*, by clarifying the maturity of the supporting modeling environments that could suggest the development of novel tools or the improvement of those already available; and (iii) *practitioners*, by providing a list of the available notations for modeling IoT-Aware business processes that could guide them in selecting the most appropriate notation according to the supported views and requirements.

This work is an extension of the paper "Modelling Notations for IoT-Aware Business Processes: A Systematic Literature Review" [27], published in the proceedings of the *4th International Workshop on BP-Meet-IoT*. Besides describing the method we followed in greater detail, this article extends the scope of the original conference paper. In particular, this paper:

- is based on a different search query that considers a different time frame and different research questions, whose objective is to investigate additional findings related to modeling views, IoT requirements, and tools availability;
- reports and analyses 36 additional research works (for a total of 84);
- includes a cross-cutting analysis of the data retrieved to answer the research questions, and it underlines how the different findings refer to each other.

The paper is organized as follows. Section 2 describes the methodology we applied. Section 3 discusses the research questions and the search strategy we adopted. Section 4 describes the application of the protocol and gives an overview of the obtained results that are then detailed in Section 5. Section 6 contains a discussion on the results. Related works are presented in Section 7. Finally, Section 8 concludes the paper, reporting our main contribution.

2 Methodology

In this paper, to perform a systematic literature review according to a well-established protocol, we refer to the methodology proposed by Kitchenham et al. [64]. This methodology is structured over three phases to be performed in chronological order and structured as presented below.

- **Planning** - This phase refers to the definition of a clear reviewing protocol. It requires to precisely define the objective of the SLR, clearly state a set of research questions, derive a query to be submitted to digital libraries, select a list of digital libraries to be used for retrieving relevant research works,

and then to clearly define the inclusion/exclusion criteria needed to filter the list of research works retrieved from the digital libraries.
- **Conducting** - This phase focuses on performing the search activity and analyzing the retrieved research works. The search step consists of submitting the defined search query to the specified digital libraries and collecting the research papers returned by the query. All the retrieved papers are then scrutinized, and the inclusion/exclusion criteria are applied. The result of this step is the identification of the first set of relevant papers. In this phase, it is possible to extend the corpus of relevant papers by applying additional techniques such as backward and forward snowballing [60, 113]. These techniques require analyzing each paper's reference section to identify additional relevant papers (backward) or to use digital libraries to identify papers that cite one of the papers already judged relevant (forward). The exclusion/inclusion criteria also have to be applied to filter the research works identified, using the snowballing procedure to keep only relevant papers in the considered set. Finally, data extraction is performed from the identified set of relevant research works. This step generally results in the definition of a possible classification and clustering of the identified papers, and it requires organizing the retrieved information to answer the identified research questions.
- **Reporting** - This phase involves writing up the review results to effectively communicate them by illustrating the answers to the research questions.

3 Planning the Systematic Literature Review

This section illustrates the steps to plan the SLR, such as the definition of the research questions and the adopted search strategy.

3.1 Research Questions

Our research questions resulted from a set of brainstorming sessions carried out by the authors. In particular, the brainstorming activity has been preceded by analysis and reflection on some relevant research works such as [10, 17, 41, 51, 108, 110], as well as the BP-meet-IoT manifesto [61]. The outcome of the brainstorming has been summarized in the following research questions:

- *RQ1. What are the relevant modeling views to consider when modeling IoT-Aware business processes?*
  The question focuses on the possibility of highlighting different views considering the type of IoT-Aware business processes representing either the behavior of single IoT devices or the one of the whole application.
- *RQ2. What are the IoT requirements supported by the modeling notations used to model IoT-Aware business processes?*
  This question aims to define the alignment of each modeling notation with IoT-related requirements.
- *RQ3. What are the modeling notations proposed and/or adopted to model IoT-Aware business processes?*
  This question aims to provide an insight into the available notations that can be used to model business processes integrating IoT concepts. The main characteristics of each notation will be explained with a focus on the actual graphical representation. In answering this question, the following additional sub-questions have been identified.
  - *RQ3.1. Which are the considered application domains used to study and validate the proposed notations?*
    This question aims to define which application domains are commonly used to show the characteristics of the considered notation.
  - *RQ3.2. What is the maturity of the tool supporting the modeling of IoT-Aware process?*
    This question aims to check if a proposed notation is supported by an associated modeling tool and what is the maturity level of such a tool.
  - *RQ3.3. What are the notations used to support the enactment of IoT-Aware business processes?*
    This question aims to check if the considered notations can be used only to support the design of IoT-Aware business processes or whether they also support enactment activities.

3.2 Search strategy

This section provides details on the adopted strategy to collect relevant research works from the literature, mainly focusing on the search query, the selection of the involved digital libraries, the criteria used to include or exclude research works from the survey, and finally on the snowballing step.

Search Query. After defining the research questions, we carefully planned a search query for scouting the literature. The query definition is based on consolidated recommendations as reported in Brereton et al. [9]. Especially, we identified three main areas which our questions refer to: *Business Process Management*, *Internet of Things*, and *Modeling*. Starting from these areas, we identified relevant terms to be included in our query. The words used for the search query were thought up and discussed through brainstorming among the paper authors. We did various iterations between the authors before agreeing on the final set of terms reported in Table 1, and discussed in the following.

Referring to the area of Business Process Management we included the terms: *BPM*, *business process**, *intelligent process** and *workflow**. In the selection, we include *BPM* to refer to the whole field of study, and *business process* since it is the focus of our research, and the term directly comes from the research questions. We also add *intelligent process* referring to the capability of the process enriched by IoT to become smart. Finally, we include *workflow* since the *Workflow Management Coalition* consortium initially used it to equally refer to a business process [57].

In the area of Internet of Things we included the terms: *IoT*, *Internet of Thing**, *Internet of Everything**, *Web of Thing**, *Cyber Physical System**, *CPS*, *Sensor Network**, *WSN*, *Context Aware**. In the selection, we include the *Internet of Things* since it is the focus of our research, and the *Internet of Everything*, the *Web of Things*, and the *sensor networks* since are terms directly related to IoT. At the same time, we have included *Cyber Physical System* which is often interchangeably used for IoT, as suggested by the NIST research [12, 53]. We also include *WSN*, which stands for Wireless Sensor Networks, since there are research works considering WSN applications as IoT applications without distinguishing them [71]. Finally, we add in this area the combined term *Context Aware*, which is commonly considered a relevant property of IoT environments.

Considering the area of Modeling we included the terms: *Model**, *Behavio**, *Diagram**. We include *model* since it is the focus of our research. We also include *behavior/behaviour* since it can express the concept of an operating mechanism connected to a model. Finally, the choice of integrating *diagram* is motivated by the fact that it is the result of the modeling activity.

Upon the identified terms, we constructed the search query, using the logical disjunction connective ("OR") to connect terms of the same area, and the logical conjunction connective ("AND") to join the sets of terms of the different areas.[1]

Digital Libraries. After having specified the query, we selected the digital libraries to be used, and the choice fell on the three most commonly used in the area of Information System and Computer Science: Scopus, Web of Science, and AIS eLibrary. Interestingly Web of Science and Scopus usually index articles from other popular digital libraries such as IEEE Xplore and the ACM Digital Library. For this reason, we decided not to include the latter two. In addition, we also defined the fields in which the used digital libraries should look for a match of the specified query. We restricted the query to title, abstract, and keywords. This means that if a combination of one term for the areas of Business Process modeling, Internet of Things, and Modeling is present in the title, in the abstract or in the keywords list of research work, that research work will be part of the query results. Moreover, we defined a time frame to limit the results returned by the query. We chose to start the search from 1999, which is considered the year of birth of the term Internet of Things [5], and to end with the year 2020 to have stabilized data at the time when the SLR has been conducted. Notice that as the term "IoT" does not appear in the literature before 1999, we decided to consider such a year as the starting date for selecting relevant works.

Inclusion/Exclusion Criteria. As part of the protocol implementation, a set of inclusion/exclusion criteria has been defined to guarantee the selection of relevant research works. In particular, we consider two inclusion and one exclusion criteria as described in the following. ***IC.1 Criterion*** states "*the research work has to be a primary study*". The objective is to include only research works proposing novel solutions and not reviewing available literature. In particular, in the following, the term "research work" is used only for primary studies. ***EC.1 Criterion*** states "*the research work is not written in English language*". ***EC.2 Criterion*** states "*the research work does not propose, and does not refer to any modeling notation for IoT-Aware business processes*". Some works resulting from the search activity were not directly related to the topic under study; for instance, papers related to non-process-oriented modeling notation were excluded. Moreover, modeling approaches that were not directly related to the Internet of Things world were not considered.

4 Conducting the Systematic Literature Review

This section describes how we performed the SLR. In particular, we provide details related to the research works' identification, selection, and reporting activities. In addition, we discuss the categories used to classify them.

[1] It is also worth clarifying that the * character is used to include in our search any word that starts with the string of characters preceding the *. For example, by specifying *business process** allows us also to include *business processes*; *Cyber Physical System** allows us to include *Cyber Physical Systems*; *model** allows us to include *models*.

BPM	(BPM **OR** "business process*" **OR** "intelligent process*" **OR** "workflow*")
IoT	**AND** (IoT **OR** "Internet of Thing*" **OR** "Internet of Everything*" **OR** "Web of Thing*" **OR** "Cyber Physical System*" **OR** CPS **OR** WSN **OR** "Sensor Network*" **OR** "Context Aware")
Model	**AND** (Model* **OR** Behavio* **OR** Diagram*)

Table 1: Search query terms by domains

4.1 Identification and selection of the research works

As a result of the search protocol, 84 relevant research works have been identified. Figure 1 reports the selection steps we applied in a BPMN diagram.

From the application of the search query over the digital libraries we collect 2609 research works potentially relevant for the research topic - *Scopus* (1352), *Web of Science* (858) and *AIS eLibrary* (399). Then, after having applied ***IC.1*** and ***EC.1***, we deleted the duplicates from this initial set, and we noticed that 47% of the initially identified research works were duplicates (1235); their removal from the initial set resulted in 1374 unique research works.

After removing the duplicates, we read the title and abstract of the remaining 1374 research works. The objective of this phase was to determine the most appropriate works for our research. In particular, applying the exclusion criterion EC.2, we removed many papers as already from the reading of the title, and the abstract was clear that no new proposal and no notation for IoT-Aware BP were referred to in such papers. After this step, we kept 182 works in the set. Successively, we entirely read and analyzed the papers still considering the exclusion criterion EC.2, and we reduced to 68 the research works considered relevant for our review.

Finally, to improve the review's accuracy and validate the selection done on research works, we apply the snowballing technique [60, 113] starting from the 68 papers left. The snowballing technique can be applied for multiple iterations, and it was reapplied on the relevant papers discovered during the previous snowballing iteration.

With the first iteration of the snowballing, we found 16 additional research works (7 backward and 9 forward); we stopped at the second iteration of the snowballing since no other relevant papers were found.

We used a Google worksheet to categorize and classify the research work resulting from the literature during the research. The worksheet is available online at `http://pros.unicam.it/BP-meet-IoT/Modeling-SLR2020`. The worksheet is divided into tabs, each containing relevant information: the *All* tab includes general information such as title, publication year, publication venue, and publication type (conference, workshop, journal, or other). We also included other tabs for each question and sub-questions. To fill such a tab, we selected multiple-choice fields after a content analysis step according to the data extraction and synthesis described in the next section.

4.2 Data extraction and synthesis

The data extraction and synthesis steps aim to design a suitable form to record and collect the relevant information from reading the selected research works. Attributes included in the multiple-choice questions RQ1, RQ2, and RQ3, and the sub-questions RQ3.1, RQ3.2, and RQ3.3 were selected after a content analysis step. General and multiple-choice fields are summarized in Table 2.

To answer the research question *RQ1 - What are the relevant modeling views to consider when modeling IoT-Aware business processes?* We selected the following attributes referring to the classification proposed by Maamar et al. [69].

- **Process of Things (PoT).** This class includes research works on the usage of business process modeling notations to design the internal behaviors of IoT devices and their cooperation.
- **Things-aware process (TaP).** This class includes research works referring to the usage of business process modeling notations to design business processes integrating IoT devices into the IT system, resulting in complementary components within the work system.

To answer the research question *RQ2 - What are the IoT requirements supported by the modeling notations used to model IoT-Aware business processes?* We selected the following attributes that have been defined by the IoT-A European Project [83, 84], which is generally regarded as one of the pioneering collaborative activities on IoT-Aware business processes.

- **R.1 - Entity-based concept**. This class includes research works discussing modeling notations to represent the various real-world entities, with their characteristics, involved in an IoT-Aware business process.
- **R.2 - Distributed execution**. This class includes research works discussing modeling notations to describe how activities execution is distributed over

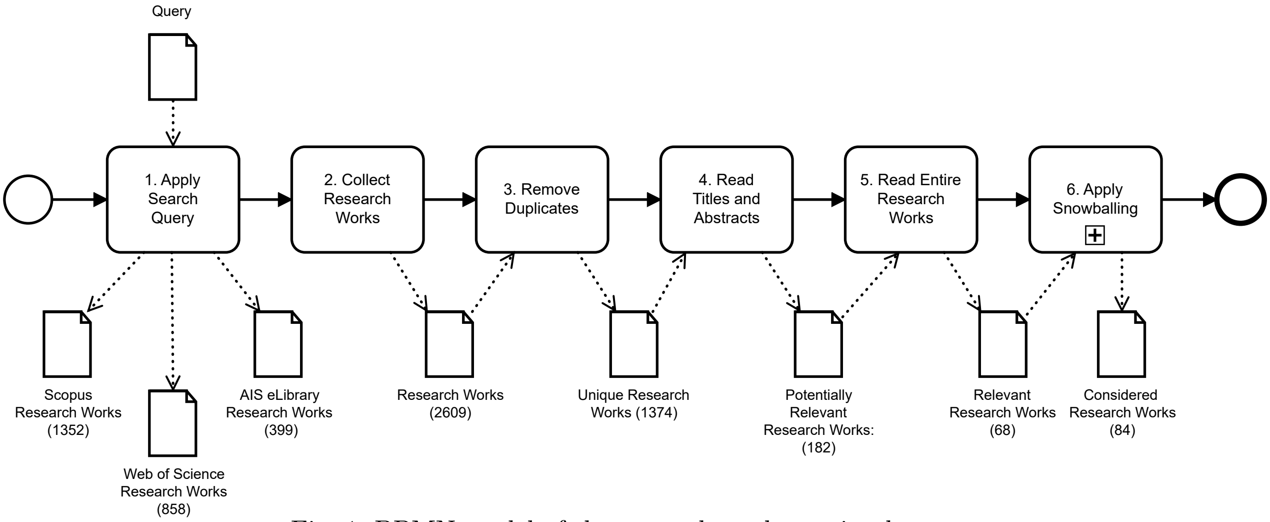


Fig. 1: BPMN model of the research works retrieval process

Research Questions	Attributes
All	Title, Publication year, Publication venue and Publication type.
RQ 1	Process of Things, Things-aware Process.
RQ 2	Entity-based concept, Distributed execution, Interaction, Distributed data, Scalability, Abstraction, Availability/Mobility, Fault tolerance, Flexibility/Event-based, Uncertainty of information, Real-time.
RQ 3	BPMN 2.0, BPMN Extension, Not-BPMN
RQ 3.1	Healthcare, Environmental, Smart City, Commercial, Industrial, General.
RQ 3.2	Mature Prototype, Early Prototype, No Tool Provided.
RQ 3.3	Design Only, Enactment/Execution.

Table 2: Attributes for data extraction

the multitude of heterogeneous IoT devices and related IoT-Aware software systems presenting different characteristics to be optimized (like the energy consumption) [34].

- **R.3 - Interactions**. This class includes research works presenting how to represent the interactions among many IoT devices and software components related to IoT software systems. IoT devices cannot be seen as isolated; they act synergically, communicating and interacting with each other to achieve the business goals that guide the behavior of an IoT system. In particular, we refer to the interaction modalities considering protocols like HTTP, MQTT, Wi-Fi, Bluetooth, and their characteristics (e.g., the response time).
- **R.4 - Distributed data**. This class includes research works on representing data and describing how data are produced, consumed, and distributed in IoT devices. The entities involved in IoT-Aware processes are seen as prosumers of high quantity and variety of data. Such data can be stored and distributed across the involved entities (e.g., many IoT devices can store information thanks to their internal storage system or use the cloud, while other data may be entirely discarded).
- **R.5 - Scalability**. This class includes research works considering notations supporting the representation of expected performance, also when the number of involved entities can vary. This enables the maintenance of the IoT-Aware software system performance while offering the possibility of inserting new IoT devices, if necessary.
- **R.6 - Abstraction**. This class includes research works presenting modeling notations able to provide a different level of abstraction, representing low-level details of the various involved entities. However, it should also be able to abstract from them,

providing a higher perspective over higher-level aspects related to the entire integration process.
- **R.7 - Availability/Mobility**. This class includes research works considering modeling notations able to represent the mobile nature of IoT devices, which can sometimes make them unavailable, leading to the impossibility of performing actions that depend on them.
- **R.8 - Fault tolerance**. This class includes research works considering modeling notations able to represent the handling of faulty situations. Indeed, while using data retrieved from IoT devices to guide the execution of a process, it is important to determine ways to manage failures (that may be due, e.g., to the IoT device's unavailability) to invalidate the whole process.
- **R.9 - Flexibility/Event-based**. This class includes research works considering modeling notations to design context-adaptive business processes that vary depending on occurring events. We refer to modeling notations considering events that can happen at any time due to certain conditions.
- **R.10 - Uncertainty of information**. This class includes research works describing the information sources and defining their reliability. This is particularly important since the information accuracy differs strongly according to the IoT devices.
- **R.11 - Real-time**. This class includes research works discussing modeling notations suitable to express time constraints based on which IoT-Aware business process activities have to occur. This means dealing with time-based modeling elements that, for example, can trigger an action in a specific period.

To answer the research question *RQ3 - What are the modeling notations proposed and/or adopted to model IoT-Aware business processes?* We collected and inspected all the notations reported in the analyzed literature and categorized them based on three clusters that emerged from our analysis.

- **BPMN 2.0.** This class includes research works using the Business Process Model and Notation (BPMN)[2] to model IoT-Aware business processes. BPMN is considered the "de facto" standard for modeling business processes.
- **Not-BPMN.** This class includes research works using already defined notations or proposing novel notations to model IoT-Aware business processes that are not related to BPMN.
- **BPMN Extension.** This class includes research works extending BPMN with IoT-specific stereotypes. In this class, we include three types of extension: (i) *Meta-Model Only extensions* referring to those research papers that extend the standard meta-model of the BPMN with new attributes, entities, and relations without changing the graphical part; (ii) *Graphical Only extensions* referring to those research papers that add graphical notation elements over the BPMN standard; and (iii) *Meta-Model and Graphical extensions* referring to those research papers combing both types of extensions.

To answer the research sub-question *RQ3.1 - Which are the considered application domains used to study and validate the proposed notations?* We selected the following attributes coming from a well-known classification proposed by Asghari et al. [4].

- **Healthcare.** This class includes research works considering healthcare as a reference application domain to integrate IoT, to move from a traditional model where treatments take place only in hospital centers to a new one, where care is accessible anywhere.
- **Environmental.** This class includes research works considering the environment as a reference application domain to model aspects regarding the continuous control of the environment (e.g., pollution levels) to try to keep it under control environmental conditions and possibly send alarm signals.
- **Smart City.** This class includes research works considering the smart city as a reference application domain to have a smarter utilization and deployment of public resources, better efficiency of services, better quality of life, and the reduction of waste and costs for the public administration. This class also includes works related to smart buildings and smart homes.
- **Commercial.** This class includes research works considering commercial applications as a reference domain to use IoT to improve the customer experience and the services offered.
- **Industrial.** This class includes research works considering industrial applications as reference domain to use IoT to improve working conditions, ensuring safer machines and tracking real-time goods; at the same time, creates new business models and an efficient and secure supply chain, and flexible and adaptive production processes, intending to increase the productivity.
- **General.** This class includes research works that do not consider a specific application domain or do not fit within any of the already introduced classes.

To answer the research sub-question *RQ3.2. What is the maturity of the tool supporting the modeling*

[2] `https://www.omg.org/spec/BPMN/2.0`

of IoT-Aware process? We selected the following attributes considering the tools used in the selected research works.

- **Mature Prototype.** This class includes research works proposing notations supported by ready-to-use and well-validated modeling environments and tools.
- **Early Prototype.** This class includes research works proposing notations that are supported by early tool prototypes that are still in an early version.
- **No Provided Tool.** This class includes research works that do not discuss modeling environments and tools.

To answer the research sub-question *RQ3.3 What are the notations used to support the enactment of IoT-Aware business processes?* We selected the following attributes.

- **Design Only.** This class includes research works providing notations and languages with the only aim of representing IoT-Aware business processes.
- **Enactment/Execution.** This class includes research works considering notations that support the design of IoT-Aware business processes up to their actual enactment/execution at run-time.

According to the identified relevant attributes, the classification of the research works required us to apply an iterative approach that permitted us to refine our findings after having considered each research paper at least three times. At each iteration, a reader and a reviewer were identified among the authors. The first one read the paper and provided a report, while the reviewer checked, after having read the paper, if he/she was in line with the report. Finally, all disagreements were solved through discussions.

5 Reporting of the Systematic Literature Review

This section first illustrates some general remarks over the 84 identified research works, then focuses on the data extracted for answering the research questions.

5.1 General remarks on collected works and data

We collected information regarding the publication type of the research work (i.e., Conference, Journal, Deliverable). Table 3 shows the distribution concerning the venue type of the relevant papers selected for the research, and it groups the research works by year of publication. Most of the works in the resulting final selection have been presented at conferences or published in journals. Among the selected works, we also found one project deliverable [83] that we considered worthy of inclusion since it was referenced by several of the reviewed scientific works. Notice that the 84 papers are published in more than 70 venues, and according to our selection, we can conclude that there are no consolidated target venues. Figure 2 reports those conferences and journals in which some selected research works appeared more frequently. The most common journals related to the selected papers are *Software and Systems Modeling*[3], *Information Systems*[4] and *Sensors*[5]. Regarding conferences, the most common venues are *Business Process Management*[6], *Services Computing*[7] and *Internet of Things*[8].

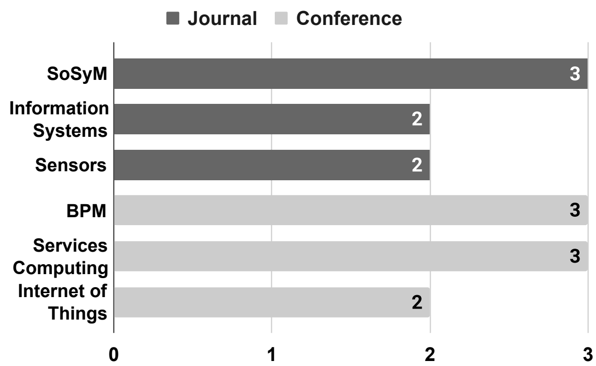


Fig. 2: Papers distribution by main events or journals

Moreover, considering publication distribution over the years, it is worth noticing that no relevant papers emerged before 2010. As we can see, more than 60% of the works were published between 2016 and 2020. Furthermore, there has always been at least one contribution related to the considered topic every year, with a peak of 12 papers in 2017. This testifies that the research community has been actively modeling IoT-Aware business processes and that the interest seems to increase in recent years.

[3] `https://www.sosym.org/`
[4] `https://www.editorialmanager.com/infosys`
[5] `https://www.mdpi.com/journal/sensors`
[6] `https://www.bpm-conference.org/`
[7] `https://www.servicessociety.org/scc`
[8] `https://www.iot-conference.org/`

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	**# of research works (%)**
Conference	1	6	5	3	4	5	6	7	7	8	4	56 (67%)
Journal	-	-	-	-	2	3	4	5	4	3	6	27 (32%)
Deliverable	-	1	-	-	-	-	-	-	-	-	-	1 (1%)
Total	1	7	5	3	6	8	10	12	11	11	10	84

Table 3: Amount of research works divided by publication type and year (the dash (-) symbol denotes that no research work of that kind has been retrieved for that year)

5.2 Relevant modeling views to consider when modeling IoT-Aware business processes (RQ1)

The research question RQ1 wants to clarify the relevant modeling views to consider when modeling IoT-Aware business processes, mainly focusing on the case studies presented in the research works. Indeed we found that 99% of the selected research works explicitly refer to a modeling view. Among the research papers selected, only one, by Sperner et al. [104] was classified neither as *Process of Things* nor as *Things-aware Process*, since it did not provide a modeling example. Table 4 summarizes the results. In the following, we present two examples of PoT and TaP.

Process of Things refers to using business process modeling notations to design the internal behaviors of involved IoT devices and their orchestration. Figure 3 reports an example concerning the management of the devices integrated into a ventilation system [105]. The process starts with a message with the room number, the reservation period, and the maximum desired value of CO_2. Then, when the meeting starts, the process continuously requests the updated value of the CO_2. Depending on the CO_2 value, the ventilation is adjusted. When the meeting finishes, the process execution is interrupted.

Things-aware Process refers to the modeling of standard business processes integrating smart devices into the system, resulting in complementary components within the execution of the entire process. Figure 4 shows an example of TaP [117]. The process describes the operation of the ordering of the eyeglass frame. The user sends his location, and based on age and gender, the shopping system generates recommendations for buying a frame. Finally, augmented reality allows the user to try the frame.

Type of view	**Source**	**# of research works (%)**
PoT	[13, 15, 18, 19, 23, 45, 47, 63, 70, 95, 96, 97, 100, 101, 105, 109, 121]	17 (20%)
TaP	[2, 3, 6, 8, 14, 16, 20, 21, 22, 24, 29, 32, 33, 34, 35, 36, 37, 38, 39, 42, 43, 48, 49, 50, 52, 54, 56, 58, 62, 65, 66, 67, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 88, 89, 90, 91, 93, 94, 98, 99, 102, 103, 106, 107, 111, 112, 115, 116, 117, 118, 119, 120]	66 (80%)

Table 4: Papers distribution by IoT-Aware modeling views (RQ1)

5.3 IoT requirements supported by the modeling notations used to model IoT-Aware business processes (RQ2)

The research question RQ2 wants to clarify the IoT requirements supported by the modeling notations used to model IoT-Aware business processes. We found that 100% of the selected research works refer to at least one requirement. Table 5 indicates the source of these works and shows the number of selected works that meet or partially meet the requirements.

Those notations that support the **R1. Entity Based Concept** requirement do so by offering the possibility to represent real-world objects of the Internet of Things, such as sensors, actuators, cloud systems, and environment in the design of the IoT-Aware model. Some notations partially cover this requirement, as they do not provide a direct modeling construct to the object [45, 78, 106, 107, 112].

The **R2. Distributed Execution** requirement is satisfied when the modeling approaches allow the execution to be distributed over many devices. For example, Suri et al. [106, 107] propose a framework for distributing process execution across resource availability.

The **R3. Interactions** requirement refers to the possibility of defining the link, in the design phase, of the physical entities with the other constructs of the model. The IoT-A notation [83], for example, enriches this interaction through the addition of attributes related to how and which devices communicate or are connected with other entities in the model.

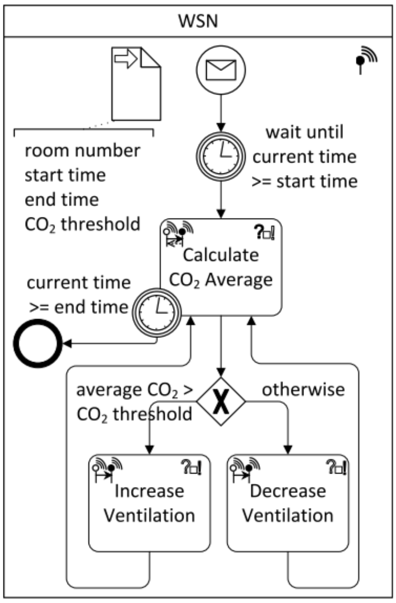


Fig. 3: An example of PoT Modeling from Sungur et al. [105]

The **R4. Distributed Data** requirement is met if the notation provides the possibility to define a data source derived from physical entities. For example, Meyer et al. [83] implement a smart data object, referring to the device from which the data are extracted.

A notation meets the **R5. Scalability** requirement if it can provide information about the physical entities modeled during the design phase of the process. For example, the approaches based on BPEL [37, 49, 63] use information to assess the system's scalability from entities, resources, and services involved in the process.

All the approaches met the **R6. Abstraction** requirement because the reported modeling notations can abstract activities to a higher level.

To meet the **R7. Availability - Mobility** requirement, a modeling notation has to provide the capability to indicate if a device is available for a desired activity or service. A device can be unavailable due to its mobility at execution time. Meyer et al. [83] permit to model the mobility aspect to address this problem. This marker can categorize a pool or a lane as a mobile process. Another example is given from the notation of [23], which introduces the location-based event for triggering actions based on the position of an entity.

The **R8. Fault Tolerance** requirement is met if the modeling notation can support failures that can happen in the IoT system. At the moment, all the selected approaches discussing this requirement partially satisfy it since the resulting notation gives the possibility to represent the fault, generally missing the motivations and its effect.

The **R9. Flexibility - Event based** requirement is met if the notations allow dynamically changing the execution flow. Handling the typical event-driven decisions of IoT systems during run time is a complex challenge for business processes. Suri et al. [106, 107] introduce the Configurable Process Model (CPM) approach to facilitate flexibility and reuse by sharing a set of process variants.

The **R10. Uncertainty of information** requirement is met if the notation can define whether the data source of a device is accurate. In the first version of IAPM [84], the usage of an indicator, based on a percentage scale, permitted to define the degree of certainty of the information coming from a specific device.

The **R11. Real-Time** requirement is met in all of the considered modeling notations since all the retrieved approaches can model the real-time restrictions and constraints of IoT systems.

5.4 Modeling notations proposed and/or adopted to model IoT-Aware business processes (RQ3)

The research question RQ3 wants to clarify what modeling notations are proposed and/or adopted to model IoT-Aware business processes. Table 6 summarize the results.

Not-BPMN. This category groups all modeling approaches that do not use the BPMN standard as a core notation.

Serral et al. [101] propose Context-Adaptive Petri-Net (CAPN), a formalism to construct Petri-Nets that are context-adaptive in smart environments. Song et al. [103] use CAPN for acquiring IoT-Awareness in an industrial application. Also, Zhang et al. [121] applied a Petri-Net-based modeling approach, including information about the ubiquitous environment through context-aware information.

Domingos et al. [36] extend the Business Process Execution Language (BPEL) to include context variables regarding IoT devices' information to establish communication between process instances and sensors. Kim et al. [63] propose BPEL to cover the technical problems in IoT computing regarding the management of the technical implementation of smart devices like the protocol supported, interface language, data exchange scheme, and type of mobility provided. Glombitza et al. [49] propose BPEL again as an input model for the generation of a custom-tailored and standard-compliant code that allows the integration of the IoT technology in the industrial environment.

Forbrig and Buchholz [45] use Cooperative Task Language (CoTaL), a subject-oriented and task-based

IoT Modeling Requirements	**Source**		**# of research works (%)**
	Full Satisfaction	**Partial Satisfaction**	
R1. Entity Based Concept	[2, 3, 16, 18, 20, 23, 38, 48, 52, 62, 67, 73, 78, 81, 82, 83, 84, 85, 86, 89, 90, 91, 93, 94, 95, 97, 101, 103, 104, 105, 111, 116, 117, 118, 119, 121]	[8, 13, 14, 15, 19, 21, 22, 24, 32, 33, 34, 35, 37, 39, 42, 43, 45, 47, 50, 56, 58, 66, 70, 74, 75, 76, 77, 80, 88, 96, 102, 106, 107, 109, 112, 115]	72 (86%)
R2. Distributed execution	[2, 6, 16, 18, 23, 36, 38, 45, 49, 54, 63, 73, 79, 81, 82, 83, 84, 85, 90, 93, 98, 99, 100, 105, 106, 107, 111, 112]	[8, 13, 14, 15, 19, 21, 22, 24, 32, 33, 34, 35, 37, 39, 42, 43, 47, 50, 56, 58, 66, 70, 74, 75, 76, 77, 80, 88, 96, 102, 109, 115]	58 (69%)
R3. Interaction	[2, 3, 6, 16, 18, 20, 23, 29, 45, 52, 62, 67, 73, 78, 81, 82, 83, 84, 85, 86, 89, 90, 91, 93, 94, 95, 97, 100, 101, 103, 104, 105, 111, 112, 116, 117, 118, 119, 120, 121]	[89]	39 (46%)
R4. Distributed data	[3, 6, 18, 23, 29, 38, 48, 54, 67, 73, 78, 81, 82, 83, 84, 90, 91, 93, 112, 116, 117, 118, 119, 120]	[8, 13, 14, 15, 19, 21, 22, 24, 32, 33, 34, 35, 37, 39, 42, 43, 47, 50, 56, 58, 66, 70, 74, 75, 76, 77, 80, 88, 96, 101, 102, 103, 109, 115, 121]	59 (70%)
R5. Scalability	[36, 49, 63, 101, 103, 121]	[8, 13, 14, 15, 18, 19, 21, 22, 23, 24, 32, 33, 34, 35, 37, 39, 42, 43, 47, 50, 56, 58, 66, 70, 73, 74, 75, 76, 77, 80, 81, 82, 83, 84, 88, 89, 90, 93, 96, 102, 109, 112, 115]	49 (58%)
R6. Abstraction	*All selected papers*		84 (100%)
R7. Availability/Mobility	[6, 18, 23, 38, 54, 65, 73, 81, 82, 83, 84, 86, 90, 93, 112]	[45, 101, 103]	18 (21%)
R8. Fault tolerance		[6, 8, 13, 14, 15, 18, 19, 21, 22, 23, 24, 32, 33, 34, 35, 36, 37, 39, 42, 43, 47, 49, 50, 56, 58, 63, 66, 70, 73, 74, 75, 76, 77, 78, 80, 81, 82, 83, 84, 88, 90, 93, 96, 101, 102, 103, 109, 112, 115, 121]	50 (60%)
R9. Flexibility/Event-based	[8, 13, 14, 15, 18, 19, 21, 22, 23, 24, 32, 33, 34, 35, 37, 38, 39, 42, 43, 45, 47, 50, 56, 58, 66, 70, 73, 74, 75, 76, 77, 80, 81, 82, 83, 84, 88, 90, 93, 95, 96, 97, 102, 106, 107, 109, 112, 115, 116, 117, 118, 119]	[65, 94, 101, 103, 120]	56 (67%)
R10. Uncertainty of information	[101, 103, 120, 121]	[18, 23, 62, 73, 81, 82, 83, 86, 90, 93, 94, 112]	17 (20%)
R11. Real-time	*All selected papers*		84 (100%)

Table 5: Papers distribution by modeling requirements (RQ2)

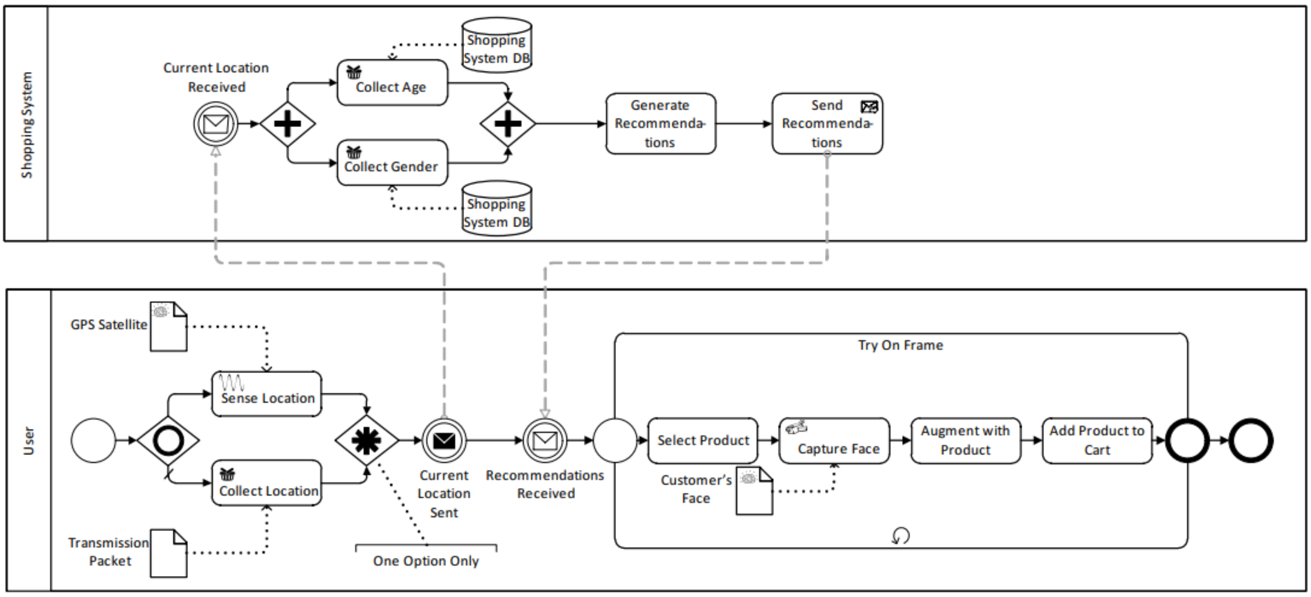


Fig. 4: An example of a TaP Modeling from Yousfi et al. [117]

Core Notation	Source	# of research works (%)
Not-BPMN	[6, 36, 45, 49, 63, 98, 99, 100, 101, 103, 112, 121]	12 (14%)
BPMN 2.0	[13, 14, 15, 19, 21, 22, 24, 32, 33, 34, 35, 37, 39, 42, 47, 50, 56, 58, 66, 70, 74, 75, 76, 77, 80, 88, 96, 102, 109, 115]	30 (36%)
BPMN Extension	[2, 3, 8, 16, 18, 20, 23, 29, 38, 43, 48, 52, 54, 62, 65, 67, 73, 78, 79, 81, 82, 83, 84, 85, 86, 89, 90, 91, 93, 94, 95, 97, 104, 105, 106, 107, 111, 116, 117, 118, 119, 120]	42 (50%)

Table 6: Papers distribution by category of core notations (RQ3)

approach for specifying activities in smart scenarios. Fleischmann et al. [44] use Subject-Oriented Business Process Management (S-BPM), a modeling paradigm using standard natural language semantics with subjects, predicates, and objects to describe business processes of a smart environment. The Subject Behavior Diagram is generated for each subject involved in the business process to define its interactions with other subjects.

Seiger et al. [98, 99] propose a self-adaptive workflow for cyber-physical environments based on MAPE-K, a feedback loop for constantly monitoring and analyzing context data and for the management of errors in the physical world. Seiger et al. [100] propose an object-oriented workflow language for the formalization of the environment by adding a domain-specific description. Baresi et al. [6] propose a novel approach mentioned as Guard-Stage-Milestone (GSM), which consists of a declarative notation extended with specific information regarding the specification of smart objects.

BPMN 2.0. This category refers to all the research works that perceive BPMN as adequate in capturing process specifications of IoT scenarios; they represent IoT aspects using the standard BPMN elements.

Caracaş and Bernauer [14] and Caracaş and Kramp [15] suggest an approach to model wireless sensor networks using standard BPMN to close the gap between the specification of the devices and the actual implementation of business processes. Ferreira et al. [43] represent conditions that must always be valid within an IoT process using BPMN annotations attached to a pool. Cherrier and Deshpande [22] propose a way to adapt an already available IoT platform to the BPM approach's needs and analyze the difficulties that arise therein using BPMN in the design phase. Song et al. [102] propose a framework to connect the IoT infrastructure to the context-aware BPM ecosystem using IoT-integrated ontologies and IoT-enhanced decision models, which enable the capabilities of IoT to make business processes modeled via BPMN and the tough decision-making aware of the dynamic context.

Domingos and Martins [34, 74] propose a restricted set of BPMN elements for the design of smart scenarios. A scenario is modeled with standard BPMN, and then the diagram is transformed with recognition pattern techniques into executable code. Mass et al. [77] use BPMN as a starting point to model IoT scenarios managed by BPM Systems, proposing an architecture for decentralized device-to-device business process execution over mobile nodes. Friedow et al. [47] present a contribution that allows coordinating the devices used in an IoT application using a business process engine with the design of BPMN models for the processing logic.

Meroni et al. [80] focus on monitoring the compliance of the execution of multi-party business processes. They exploit the IoT paradigm by instructing smart objects. The scenario is modeled in BPMN, translated into a set of artifact-centric process models, and rendered in another notation called Extended-GSM. Schönig et al. [96] introduce an integrated architecture approach for IoT-Aware business process execution that exploits IoT for BPM, focusing on managing IoT data. The idea is to connect smart devices to the BPMS to keep track of the data coming from the devices and then consider them. Panfilenko et al. [88] use BPMN to control the maintenance procedure in an industrial cyber-physical production environment.

Xu et al. [115] propose a smart home service architecture that classifies smart home scenarios into home IoT, home service network, and family social network. Each of these scenarios is modeled with standard BPMN, meeting the requirements of the three classified scenarios. Ruiz et al. [42] propose a model based on the BPM paradigm and IT principles to model and enhance the process of a specific scenario. Teixeira et al. [109] propose an open-source and service-oriented architecture called LAURA (**L**ean **AU**tomatic code generation for situation-aware and business-awa**R**e **A**pplications) for supporting the modeling and the deployment of IoT applications.

Cheng et al. [21] perform a translation from BPMN to Petri-Net constructs to model smart scenarios. Cimino et al. [24] propose an approach to evaluate the impact of smart ICT technologies using standard BPMN as a workflow engine. Hasic et al. [56] compare the use of BPMN with and without a DMN engine in modeling three different smart scenarios, highlighting the strong need for a rule engine in modeling IoT systems.

Domingos et al. [37] and Martins et al. [75] propose to model IoT scenarios with BPMN by applying a decomposition approach to identify IoT operations that usually are performed in smart environments and then reproduce them in the modeling phase. The first work tries to generalize the patterns used to identify the part of BPMN processes that IoT devices can execute, respecting, at the same time, the original flow dependencies. In the second work, from a business process model, the decomposition approach is applied to assign the operations that should be performed to IoT devices.

Kozma et al. [66] propose Arrowhead, a framework that supports automated manufacturing processes for Industry 4.0 to provide an easy-to-use model in standard BPMN that leads the implementation of production goals. D'Hondt et al. [33] propose a novel combination of existing technologies concerning Business Process Management and Distributed Analytics. Containerized micro-services are modeled in BPMN to enable their use on the IoT edge.

Hou et al. [58] model a smart scenario with standard BPMN and then apply a location-based fragmentation algorithm to divide the entire IoT-Aware business process into a set of decentralized processes. Domingos et al. [35] suggest decentralizing device activities executions with an automatic procedure using BPMN. Starting from the actual process, a set of communicating pools are defined, each representing a device performing an activity. Goncalves et al. [50] propose REFlex Water, flexible and robust architecture for combining IoT technology, Complex Event Processing, and declarative processes.

Martins et al. [76] propose a decentralization of the IoT-Aware process to reduce the exchange of messages between central systems and IoT devices to reduce battery consumption and device resources. Bocciarelli et al. [8] suggest an approach to support business processes that integrates IoT technology in Cyber-Physical Production Systems (CPPS) or smart factories. The goal is to enable a simulation-based analysis of the smart environment regarding adaptability and reliability. Cheng et al. [19] model a smart scenario in BPMN standard communicating with a fog environment composed of smart devices for measuring essential vital signs of the patient.

Caracas [13] proposes a mechanism for mapping the business process of a wireless sensor network into an event-based code for the management of the devices. Mandal et al. [70] emphasize the necessity to integrate within the business process external events that occur in the process context of the IoT technology. The gap between the conceptual process model, and its implementation, needs to be bridged to perform this integration properly. To this aim, a framework is proposed that handles smart system events to which the process subscribes. Elhami et al. [39] propose a context-aware

Extension Type	Source	# of research works (%)
Meta-Model Only	[8, 38, 43, 48]	4 (10%)
Graphical Only	[2, 20, 29, 54, 62, 65, 67, 78, 84, 86, 89, 90, 94, 95, 97, 104, 111]	17 (40%)
Meta-Model and Graphical	[3, 16, 18, 23, 52, 73, 79, 81, 82, 83, 85, 91, 93, 105, 106, 107, 116, 117, 118, 119, 120]	21 (50%)

Table 7: Extension type distribution

methodology for device data integration into the business process. In particular, contextual events and data are integrated at run time using BPMS capabilities. In addition, this approach involves using deep neural networks to forecast business process activities.

BPMN Extensions. In this category are reported all the research works presenting extensions to the BPMN notation for better representing IoT aspects in a designed model. These research works have been additionally grouped based on the type of extension they apply: *Meta-Model Only*, *Graphical Only*, *Meta-Model and Graphical*. Table 7 summarize the results.

The research works that only extend the standard meta-model of BPMN with new attributes are [8, 38, 43] and [48]. The first work, by Ferreira et al. [43], defines a set of process constraints that must be respected during the execution. This mechanism is managed by the concept of process invariants and ensures more dynamism in IoT-Aware business processes. The second work, by Bocciarelli et al. [8], introduces a BPMN meta-model extension for managing the resources of the smart devices modeled in the business process. This notation aims to provide low-level information (e.g., performance, reliability, resources) about the devices within the business process during the modeling phase. Dorndorfer and Seel [38] propose *SenSoMod*, a domain-specific modeling language for IoT. This approach acts as a dedicated language for the data aggregation from sensors to the business process. The authors propose an extension of the BPMN meta-model to provide the possibility to interact and obtain data from smart devices through the *SenSoMod* context model. Gao et al. [48] propose a novel approach for integrating the sensor/smart device layer with the business process. This approach adopts a Semantic Sensor Network ontology with business processes to integrate sensor data at the process layer.

For what concerns the research works that only extend the graphical notation and those that extend both meta-model and graphical notation, we describe the modeling approaches by grouping them by type of notation element and new graphic constructs introduced. Table 8 and Table 9 offer a graphical overview of all added modeling constructs. We grouped the selected works by notation name and reported them, in chronological order, to see how the proposed extended notations have changed over time. The graphical notation elements have been reported and grouped based on the original construct to which an extension is applied: *Activity*, *Event*, *Data*, *Pool/Lane*, *Gateway* and *Group*.

Activity. Starting from the extensions applied to activity elements, the IAPM project [84] proposes an extension of the Normal Task to represent an activity of a smart device. This task has a different design and includes two additional attributes: the grade of certainty of information from the device (from 0 to 100) and the availability/potential fault of the devices. In 2012, with the deliverable [83], Meyer et al. defined three new activities for the description of IoT scenarios: the sensing task for representing the sensing action of a device; the actuation task for representing the actuation of a device; the location-based activity to relate an activity with the position in which it occurs.

The uBPMN modeling notation proposed by Yousfi et al. [118], introduces four types of tasks: the sensor task for the sensing action of a device; the actuator task for the actuation of a device; the reader task for the smart reading of RFID, bar code or bio-metrics; the collector task for the collection of any piece of context aside from using sensors or smart readers. Each task includes an additional attribute that defines its type (e.g., the sensor task may be of type Accelerometer). In a subsequent version of the proposal [117], custom extensions of the tasks are added to each smart device, increasing the level of detail. In addition to the collector, sensing, actuator, and reader task, tasks for capturing images and sounds have been added.

The BPMN4CPS approach [52] also proposes a sensor and an actuator task. In addition, this notation offers the possibility to model three new types of tasks: the web service task for modeling web services, the embedded service task for executing code inside the devices, and the cloud service task to perform operations in the cloud. The BPMN-MDM [67] proposes the customization of tasks as described above in Yousfi et al. [118]. The oldest selected paper on this topic [104] had already introduced two types of extended tasks: the sensing task and the actuating task.

The BPMN-E^2 approach [79] proposes extra customization of tasks with a construct that can assign

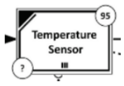
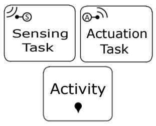
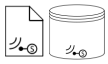
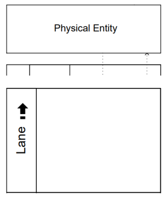
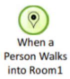
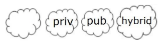
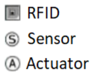
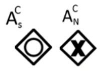
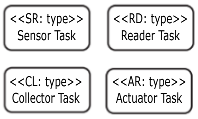
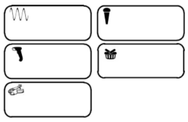
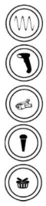
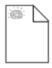
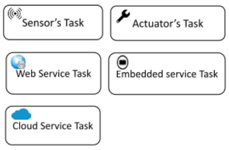
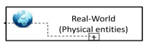
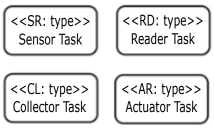
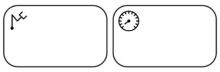
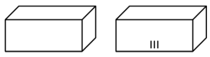
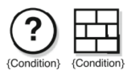
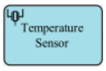
Source	Year	Notation	Activity	Event	Data	Pool/Lane	Gateway	Group
[84]	2011	IAPM		-	-	-	-	-
[83]	2012	IAPM		-			-	-
[82]	2013	IAPM	-	-	-	-	-	-
[93]	2013	IAPM	-	-	-	-	-	-
[73]	2014	IAPM	-	-	-	-	-	-
[23]	2015	IAPM	-		-	-	-	-
[90]	2015	IAPM	-	-	-		-	-
[18]	2017	IAPM	-	-	-	-	-	-
[91]	2016	I4PML	-	-	-		-	-
[107]	2017	IOT-BPO	-	-	-			-
[106]	2018	IOT-BPO	-	-	-	-	-	-
[118]	2016	uBPMN		-		-	-	-
[117]	2016	uBPMN				-	-	-
[119]	2018	uBPMN	-	-	-	-	-	-
[116]	2019	uBPMN	-	-	-	-	-	-
[52]	2016	BPMN4CPS		-	-		-	-
[67]	2016	BPMN-MDM		-		-	-	-
[104]	2011	Sperner et al.		-	-		-	-
[79]	2019	BPMN-E^2		-	-		-	-
[20]	2018	Cheng et al.		-	-	-	-	-

Table 8: BPMN IoT graphical extensions - Part 1

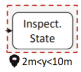
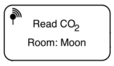
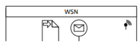
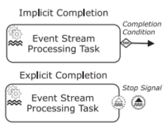
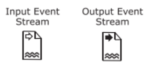
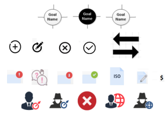
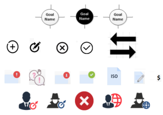
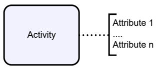
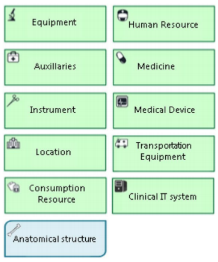
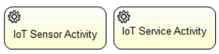
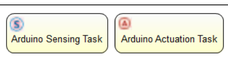
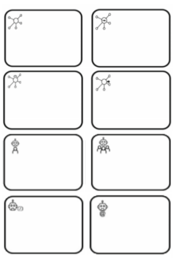
Source	Year	Notation	Activity	Event	Data	Pool/Lane	Gateway	Group
[65]	2010	Kozel T.	-		-	-	-	-
[94]	2015	Sang et al.			-		-	-
[95]	2018	Schöning et al.		-	-	-	-	-
[97]	2020	Schöning et al.	-	-	-	-	-	-
[54]	2019	Grefen et al.	-	-	-	-	-	
[16]	2012	BPMN4WSN		-	-	-	-	-
[111]	2012	BPMN4WSN	-	-	-	-	-	-
[105]	2013	BPMN4WSN		-	-		-	-
[85]	2017	BPMN4WSN	-	-	-	-	-	-
[2]	2014	SPU		-		-	-	-
[120]	2020	Zareen et al.		-			-	-
[29]	2020	Corallo et al.		-	-	-	-	-
[86]	2018	BPMSIX		-	-	-	-	-
[89]	2018	Park et al.		-	-	-	-	-
[78]	2020	STEP-ONE		-	-	-	-	-
[62]	2017	Kim et al.		-	-	-	-	-
[3]	2020	BPMN-X		-	-	-	-	-

Table 9: BPMN IoT graphical extensions - Part 2

time constraints or conditions to the execution of the task. Cheng et al. [20] define only a task for the sensing. Sang et al. [94] propose a Security Task for representing security-related activities. Schöning et al. [95] extend the normal task into a cyber task. This extended task allows representing an action derived from devices.

The BPMN4WSN approach [16] introduces a new extended task with three extra elements: a special marker, the task to be performed from the device, and the location in which the task should be performed. Sungur et al. [105] propose an extension of the normal task named "wsn task". It models an action performed in a WSN process and includes five extra attributes: *tWSNOperation* to bind a WSN operation to a WSN Task; *actionType* to define a WSN operation as a sense (?) or an actuation (!); *isCommandAction* to define if the task represents a command action; *tWSNPerformer* to define the resource who will perform the action; *isEventDriven* to define if the task represents an event-driven action.

The SPU extension [2] proposes two tasks for managing a data stream processing of IoT scenarios. This extension adds two different tasks: the *Event Stream Specification* task for the management of the stream events and their parameters with an implicit conditional for stopping the data stream; the *Event Stream Processing Task* for the management of the stream events and their parameters with clear conditions for the data stream stops. Zareen et al. [120], instead, propose a set of markers that customize standard BPMN objects to implement information system security features. In particular, for the activities, we have only two types of markers applicable to the tasks: "Goals" for the activity's mission and "Access Mechanism" in order to define the access type to the activities and to increase process security. Also, Corallo et al. [29] implement a particular task for smart activities, which includes a set of customized and domain-based attributes to increase the level of detail.

Neumann et al. [86] suggest a set of customized tasks is defined to meet medical needs: the equipment task; the auxiliaries task; the instrument task; the medicine task; the human resources task; the medical device task; the location task; the clinical IT system task and the consumption task. In [89] the IoT activities are represented as service tasks extended with extra attributes. Mass et al. [78] introduce a particular task with extra attributes extended from the normal task of BPMN standard in order to establish a communication between the business process and smart devices. Kim et al. [62] propose an extension of the normal task for the interaction with Arduino for both sensing and actuation of the device.

Ardito et al. [3] suggest a set of extended tasks for the management of IoT devices and for representing interactions with a chatbot. IoT entities are represented by: a sensor and actuator task, a task for the connection between the cloud and devices, and a streaming task for managing the IoT data stream. The interactions with a chatbot are represented by: the chat notification task for the chat receipt notification; the group and channel notification chat for the group or channel receipt notification; the command task for the execution of specific bot commands; the inline task for REST communications between the bot and external services.

Event. We identified fewer approaches that extend BPMN events. Only in one work related to the IAPM notation [23], proposes the introduction of a location event. This event is triggered when something happens in a defined space, room, or location. In uBPMN, Yousfi et al. [117] propose a set of intermediate events corresponding to the extended tasks mentioned above. The events implemented are the sensor event for triggering a sensing action, the reader event for triggering a reading action, the image event for triggering the capture of an image, the audio event for triggering the capture of a sound, and the collector event for triggering the acquisition of information. In [65], Kozel proposes three types of event: the location-based event that can occur if the mobile participant reaches a pre-defined location; the position update event notifies an entity's change of position; the conditional positional event occurs if a mobile participant reaches a region in a predefined maximum distance. These events are proposed as catching, throwing, starting, and ending types.

Sang and Zhou [94] introduces four extended boundary events and three intermediate events. For the boundary set, we have the Authentication event that implements the authentication function of the business process model; the Access Control event for managing the permissions on the access to a particular place or resource from a group of authenticated users in the business process; the Authorization for already authenticated users, in order to perform further actions; the Harm Protection which activates a protection mechanism for the business process which offers functionalities similar to a firewall. For the intermediate events set, we have the Encrypted Message event, which aims to encrypt a business process message; the Non-Repudiation event for the agreement of the interactions between two different entities; the Secure Communication event to certify that the communication between two entities is secure.

Data. Similar solutions have been presented for data elements in the identified different modeling approaches. In the deliverable of the IAPM project [83], the Data Object and the Data Store are extended with a marker to define that they contain *real-world* data derived from smart devices. uBPMN [118], extends the standard Data Object in new element named "Smart Data Object". It consists of a specific data collection derived from sensors or smart readers. The Smart Object is introduced in a subsequent version of uBPMN [117]. It is an extended data object used to collect certain data from sensors, smart readers, microphones, or a camera. The BPMN-MDM approach [67] implements the same Smart Data Object already discussed by Yousfi et al. [118].

In SPU [2], where the concept of the data stream is introduced, the standard data object has been extended into the Input/Output event stream data object. This element can collect input or output smart device data streams. Zareen et al. [120] implement a set of specific markers for the data objects. We have Goals for the mission of the data object; the Threat for defining the possible problems and vulnerabilities in the security of the business process; the Data Object States for indicating different types of data objects; Access Mechanisms to define the access type and to increase process security.

Pool/Lane. The extension regarding pool and lane elements focuses on the representation of smart devices. In the deliverable from Meyer et al. [83], the pool is marked with the location-based symbol to mark a process as "mobile". A mobile process represents a process that can change the position in which it operates over time. In addition, the possibility of modeling a new participant representing a real-world physical entity called "Physical Entity" is introduced. This element is not considered in the execution of the process, but it is used in the modeling phase to represent the interaction of the process with real-world entities.

Petrasch and Hentschke [90] highlight pools with a symbol of a cloud containing the word "IoT" to indicate an IoT device process. It is used as a smile marker to indicate whether there is human intervention in the pool or lane. Petrasch and Hentschke [91] propose a marker with a cloud to indicate that the pool models the operation of a cloud communicating with a smart scenario. This marker can contain the word *pub* to indicate public clouds, *priv* to indicate private clouds, and *hybrid* to indicate hybrid clouds.

Suri et al. [107] allow the possibility to specify the resources of sensors, actuators, and tag devices (RFID) with the addition of specific markers while modeling a pool. These markers are defined as "IoT Resource Definitions" and include attributes such as accuracy or response time; their values are considered during the process flow execution. Graja et al. [52] introduce the Physical Entity concept for a participant pool marked with the symbol of the world. Sperner et al. [104] introduce the physical entity as a participant in an IoT-Aware process for the first time. In this case, no additional marker is provided in the pool, and it is also suggested that a physical entity pool can be multi-instance.

Ramos-Merino et al. [79] introduce two markers in the pool for adding extra conditions that should be respected in the execution of the process. Sang et al. [94] propose a pool or lane marked with a symbol that defines its degree of Integrity, Confidentiality, and Availability of the process. Each of these characteristics can take on a value from 1 to 3, which is indicated by the number of stars represented by the marker. Sungur et al. [105] assign a mark to pools or lanes that model a behavior expressed by an IoT device. Zareen et al. [120] implement the same markers already mentioned in the Data extensions.

Gateway. Referring to gateway extensions, only Suri et al.[107] propose customization of the gateways to route the IoT-Aware process execution according to the available resources of the devices or the IoT system. They represent three operators: Configurable IoT Assignment operator, Configurable IoT Replication operator, and Configurable IoT Shareability operator, which can be assigned to gateways.

Group. An extension regarding group elements is proposed by Grefen et al. [54] that introduce the concept of geographic co-location to specify where activities are performed in IoT-Aware business processes. Tasks are grouped by a dotted set that specifies the location and the maximum radius in which they can be performed. It is also possible to define an exception handler for notifying alarms and restarting critical activities.

Most of the approaches do not provide the possibility to be used for several reasons: from the deprecation of the tool that implements the notation to the unavailability of the site reported as a reference for the proposed extension. In particular, approaches that adopt BPMN standard can be replicated, while concerning extended notations, we only have access to the solution in a few cases. The available extensions are: IoT-BPO [106, 107], IAPM [82], STEP-ONE [78]. However, many research works that refer to the same notation can present a different maturity of the proposed approach. Generally, the first research works on a notation propose the approach from a theoretical point of view and then move on to the implementation in subsequent works. Table 10 intends to clarify this distinction.

Notation	Theoretical Works	Implementation Works
IAPM/I4PML	[23, 83, 84, 90, 91]	[18, 73, 82, 93]
IOT-BPO	[107]	[106]
uBPMN	[117, 118]	[116, 119]
BPMN4WSN	[16, 105]	[85, 111]
Schöning et al.	[95]	[97]

Table 10: Distinction of approaches by maturity

Application Domain	Source	# of research works (%)
Healthcare	[19, 42, 52, 56, 86, 89, 94, 101]	8 (9%)
Environmental	[20, 21, 34, 37, 74, 75, 76]	7 (8%)
Smart City	[3, 13, 16, 18, 22, 23, 32, 38, 45, 47, 56, 62, 63, 67, 78, 85, 90, 98, 99, 100, 105, 111, 112, 115, 121]	25 (29%)
Commercial	[2, 6, 14, 15, 35, 43, 65, 70, 73, 77, 80, 81, 82, 83, 84, 93, 102, 106, 107, 116, 117, 119]	22 (26%)
Industrial	[8, 24, 29, 36, 39, 48, 49, 50, 54, 56, 58, 66, 79, 88, 91, 95, 96, 97, 103, 109]	20 (23%)
General	[33, 104, 118, 120]	4 (5%)

Table 11: Papers distribution by application domains (RQ3.1)

5.5 Considered application domains used to study and validate the proposed notations (RQ3.1)

The research question RQ3.1 wants to clarify the application domains considered to study and validate the proposed notations. Each analyzed paper refers to one application domain, except for a paper by Hasic et al. [56] that refers to three application domains. Table 11 summarizes the results.

Regarding the distribution of application domains in which the selected relevant approaches are engaged, we notice an evident prevalence of three domains: Industrial, Commercial, and Smart City. Table 12 highlights the various domains subject to these IoT-Aware business process modeling activities over the years. The number has been increasing, probably due to the increasingly widespread of IoT technologies. We report details on the specific case study discussed in each research work in the following. We group them by application domains.

Healthcare. Serral et al. [101] propose a Petri-net approach for describing how a patient fall is handled adaptively up to the execution context. Cheng et al. [19] propose an intelligent medical assistance system to support and continuously monitor older people. Sang et al.[94] discuss a generic model for remote healthcare monitoring focusing on security. Ruiz et al. ruiz2017empowerment model the process for diagnosing high blood pressure. This involves some tests and physical explorations to monitor the vital values of a patient potentially at risk. Hasic et al. [56] discuss a data monitoring system for a chronic obstructive pulmonary disease patient. Graja et al. [52] model the process of an ambulance drone transporting a defibrillator to a patient. Neumann et al. [86] propose a model describing a typical cataract surgery. Park et al. [89] model a smart companion toilet for dogs that can monitor activity and trigger alarms by monitoring the animal's activities and health.

Environmental. Martins et al. [75, 76], Martins and Domingos [34, 74] and Domingos et al. [37], propose the same use case. The model consists of an automatic irrigation system that can decide when to irrigate the soil according to environmental conditions, such as rain or humidity. Cheng et al. [20, 21] propose an IoT-Aware model for protecting a large area of forest in North China.

Smart City.[9] Mass et al. [78] model a hypothetical Smart City scenario of Tartu, in Estonia. The aim is to monitor streets through real-time image processing techniques. Zhang et al. [121], Kim et al. [62, 63], Seiger et al. [100], Venkatakumar et al. [112], Xu et al. [115], Petrasch and Hentschke [90], Lee and Ma [67] and Tranquillini et al. [111] discuss the same case study considering a smart home environment. Dar et al. [32] propose a model for monitoring the daily routine of an elderly patient at home. Cherrier and Deshpande [22] propose a model for monitoring the availability of paper for printers, also providing the possibility of automatic purchase of paper if the stock is low.

Dorndorfer and Seel [38] designed an IoT-Aware process for the printer maintenance of an office. Chiu and Wang [23], Hasic et al. [56], Chen and Wang [18], Casati et al. [16], Sungur et al. [105], Mottola et al. [85] and Caracas [13] model a smart ventilation system of an office. In the process are modeled presence

[9] We recall that according to [4], this application domain also includes Smart Building and Smart Home scenarios.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Healthcare	-	-	-	-	-	2	1	1	2	1	1	8
Environmental	-	-	-	-	-	-	-	2	2	2	1	7
Smart city	-	-	5	1	1	4	2	5	1	2	4	25
Commercial	1	3	1	2	3	2	2	3	3	2	-	22
Industrial	-	2	-	-	1	-	3	2	3	3	6	20
General	-	1	-	-	-	-	1	-	-	1	1	4
Total	1	6	6	3	5	8	9	13	11	11	13	86

Table 12: Distribution of the modeled application domains by year

sensors and smart fans, activated according to a preset threshold temperature. Forbrig and Buchholz [45] model the business process of a smart meeting room, which consists of a room equipped with smart devices to optimize the needs of a meeting. Seiger et al. [98, 99] design an IoT-Aware model with the aim to keep constant room illumination. Friedow et al. [47] model the business logic of a smart coffee machine. Ardito et al. [3] design a process for managing a telegram bot used by the municipality of Lecce in Italy, designed to deliver real-time communications to citizens.

Commercial. Baresi et al. [6] propose a scenario in which different parties exchange physical goods monitored by sensors to guarantee the quality of goods. Caracaş and Bernauer [14], Caracaş and Kramp [15], Mass et al. [77], and Domingos et al. [35] propose a model that manages delivery parcels and monitors the environmental temperature for maintaining the quality of goods. Meroni et al. [80] discuss logistics referring to entities that participate in the multimodal transport of goods. Ferreira et al. [43] propose a transporting process where smart devices constantly monitor the quality of the goods. SPU [2] proposes the process for the receipt of goods from a wholesaler that is constantly monitored by a sensing device. Mandal et al. [70] propose a logistics scenario starting from the collection of goods to the delivery. Song et al. [102] propose a business process for a pick-up truck cargo. Meyer et al. [81, 83, 84], Ruppen and Meyer [93], Martinho and Domingos [73], and Suri et al. [106] model a process for the constant monitoring and control, thanks to smart devices, of the goods for sale by a shop. Meyer et al. [82] consider the same scenario, but they focus on the quality management of orchid sales. Kozel [65] models the business process of traveling salesmen that provide ordering support service at the customer's place using a mobile terminal and application systems.

Suri et al. [107] propose a model for monitoring goods in the retail industry for two categories of products: fast-moving consumer goods such as food or flowers; and durable goods such as electric appliances, cars, and clothes. Yousfi et al. [117, 119] design a process for the online order of eyeglass frames. The model includes interaction with smart technologies to allow the buyer to try eyeglass frames before purchase. Yousfi et al. [116] model a process of ship parcel management adopted by many companies in the delivery industry, such as USPS, DHL, UPS, and FedEx.

Industrial. Sing et al. [103] propose a Petri-net model of an operational scenario of a seaport. Domingos et al. [36] propose a model for constantly monitoring the process of a transportation system to guarantee industry efficiency in the transportation of perishable goods, particularly considering the temperature and the humidity of strawberries. Glombitza et al. [49] model an industrial logistic process of shipping companies in which the quality of goods is monitored with smart devices. The model takes the point of view of shipping companies' operativeness. Schöning et al. [95, 96, 97] propose a model of an automatic management system for the filling of the empty paper rolls for corrugated cardboard production. Panfilenko et al. [88] propose the business process scenario for the industrial maintenance of gas turbine. Teixeira et al. [109] implement an IoT-Aware model to control the temperature of medical products production in real-time, such as botulinum toxin. Hasic et al. [56] model a scenario for transport and quality monitoring of goods. In particular, the temperatures of perishable food on a truck equipped with a refrigeration system should be monitored to ensure the quality of the transport system. Kozma et al.[66] model a general Industry 4.0 scenario. Hou et al. [58] propose an integrated warehouse management system monitoring process. Goncalves et al. [50] model a scenario concerning the activity of a real water supply system from a Brazilian water company. Bocciarelli et al. [8] design a model for producing and delivering different parts created with a 3D printer and transported using a conveyor belt.

Gao et al. [48] model the business of a flower logistics company, particularly categorizing, storing, and distributing flower products. Hasic et al. [54] model a business process of container logistics in the international seaport in Rotterdam. Petrasch and Hentschke [91] propose a model to maintain and monitor a belt conveyor system. Ramos-Merino et al. [79] propose a scenario from a pharmaceutical company considering monitoring and treatment of medicines. Corallo et al. [29] propose a scenario from the Aquaculture industry linked to fish production. Cimino et al. [24] consider the operativeness of a smart marine container terminal. Elhami et al. [39] propose an aircraft take-off process supported by the use of IoT technology in order to consider contextual events and, if needed, take real-time decisions.

General. In this set, we categorize all the models that do not belong to the previously mentioned domains. Yousfi et al. [118] propose to model a time-banking information system. Hasic et al. [33] suggest a model for managing distributed analytics in an IoT context, providing scalability and safeness of data. Zareen et al. [120] propose a process model including security concerns of information systems integrating IoT aspects. Finally, Sperner et al. [104] do not refer to any application domain.

5.6 Modeling environments and tools supporting modeling notations (RQ3.2)

The research question RQ3.2 aims to clarify the maturity of the supportive modeling environments and available tools. Table 13 groups the research works based on the tool support they provide for modeling IoT-Aware business processes while Table 14 lists such tools.

Tool Maturity	Source	# of research works (%)
Mature Tool	[14, 15, 20, 21, 42, 45, 66, 78, 96, 97, 98, 99, 100, 101, 106, 107]	16 (19%)
Early Prototype	[3, 16, 22, 32, 34, 36, 38, 47, 62, 76, 79, 82, 85, 88, 89, 90, 91, 93, 94, 102, 105, 109, 111, 112]	24 (29%)
No Provided Tool	[2, 6, 8, 13, 18, 19, 23, 24, 29, 33, 35, 37, 39, 43, 48, 49, 50, 52, 54, 56, 58, 63, 65, 67, 70, 73, 74, 75, 77, 80, 81, 83, 84, 86, 95, 103, 104, 115, 116, 117, 118, 119, 120, 121]	44 (52%)

Table 13: Papers distribution by tools availability (RQ3.2)

Tool	Source
Activiti	[62, 66, 89, 94]
ARIS	[79]
Bonita	[42]
BPEL Designer Project	[36]
bpmn-js	[3, 47]
Camunda	[88, 96, 97]
CoTaSe	[45]
CPN Tools	[101]
Eclipse BPMN2	[21, 22, 76, 109]
Eclipse Modeling Framework	[98, 99, 100]
Flowable	[78]
jBPM	[20, 32, 34]
MagicDraw	[90, 91]
Metasonic Build	[112]
Oryx	[14, 15]
Signavio	[82, 93, 102]
Signavio Core Component	[16, 85, 105, 106, 107, 111]

Table 14: Tools for modeling IoT-Aware business processes

For presentation purposes, we reported in Figure 5 the extracted tools, including the year and the number of times they have been used in the selected works. The tools have been arranged so that we can see the tools that appeared first by looking at the figure clockwise and from the inside to the outside. Oryx was the first tool in the identified literature (2011), while Flowable was the last (2020). The total number of appearances from 2011 to 2020 is reported in brackets under the tool's name (e.g., Oryx appeared twice in total, while Activiti appeared five times).

We deepened the investigation of the tools that emerged by extracting some general information from the tools' websites or their primary research papers; we collected them in Table 15[10]. This information may not necessarily regard the modeling of IoT-Aware BPs, however they can serve as indicators to help researchers in the choice of a modeling tool suitable for their needs. All the modeling tools, but Oryx and Signavio Core Component, which are now deprecated, are available online. As can be seen from the *Last Release* column,

[10] Note, this list is not meant to be exhaustive, but it represents only the tools that emerged from the research works we identified as a result of the literature review process.

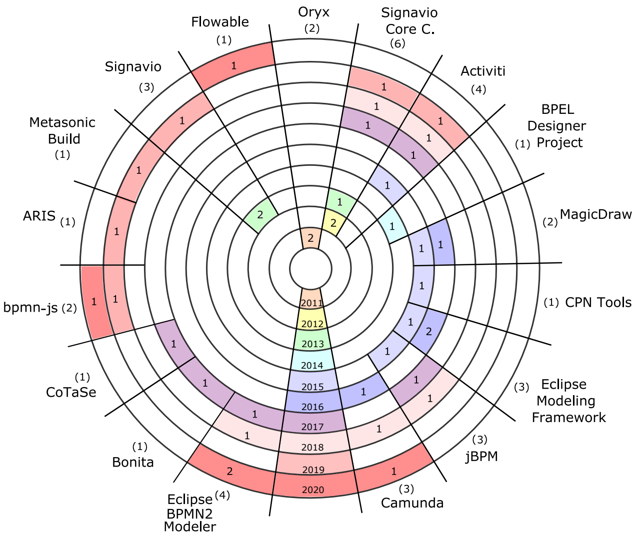


Fig. 5: Tools usage for modeling IoT-Aware business processes during years

several of such modeling tools are not updated anymore (i.e., Oryx, Signavio Core component, and BPEL Designer Project), while some tools have not been updated for a couple of years (i.e., CPN Tools, CoTaSe, ARIS, and MetaSonic Build). The remaining tools (i.e., Activiti, MagicDraw, Eclipse Modeling Framework, jBPM, Camunda, Eclipse BPMN2 Modeler, Bonita, bpmn-js, Signavio, Flowable) have been updated at least once in the last year.

The identified tools also differ for the associated *License*. Some of them are proprietary (i.e., MetaSonic Build and Signavio) while others have less restrictive or open licenses. Tools with open licenses can be modified or extended to better fit users' needs.

With the term *Extensibility*, in Table 15, we refer to whether the tool allows adding new notation elements to the provided standard ones. Some tools (e.g., Activiti, Flowable, jBPM) offer the possibility to add graphical elements in the modeling palette supported by a custom class already extended and validated by default on the meta-model. This class provides an interface for integrating new attributes, icons, and behavior in the design phase. Other tools (e.g., Camunda, ARIS) do not provide direct support for extending modeling constructs. The engine must be extended to add new custom modeling constructs, and the desired features must be manually integrated. The BPEL Designer Project eclipse plugins offer the possibility to extend the WS-BPEL 2.0 specifications by adding new features and attributes in a dedicated *extensions* section. The Eclipse Modeling Framework allows extending existing models via inheritance. The framework defines a base model and provides the possibility to define an extension based on it. In MagicDraw, extending the standard BPMN meta-model at the formal level is possible by modifying the UML classes for BPMN. Some tools (e.g., Signavio and Bonita) provide API for extending the BPM engine and adding features. By extending the *MyBaseClass* it is possible to add methods and attributes through inheritance in Java. However, some tools (e.g., MetaSonic Build, CoTaSe, CPN Tools) are not extended because they are used with *as-is* approaches.

5.7 Notation used to support the enactment of IoT-Aware business processes (RQ3.3)

The research question RQ3.3 wants to clarify the notation used to enact IoT-Aware business processes. Table 16 summarize the results. Some of those works make usage of BPMN only for the design of business process models. Others propose entire architectures and frameworks based on BPMN and related tools to enable the execution phase. It is important to state that the approaches that implement the enactment of business processes are required to design their models previously. For what concerns the approaches using BPMN for design, we refer to Section 5.4, where we have already extensively discussed them. Therefore, in the rest of this section, we only focus on the approaches used for the execution phase.

Serral et al. [101] propose a context-adaptive Petri-net model to accurately design and enact the behavior of their dynamic systems integrating IoT technologies. Doing so can be taken more informed decisions, and better use of resources increases competitiveness. Seiger et al. [98, 99, 100] adopt the MAPE-K feedback loop to monitor and enact the IoT-Aware business process and to correlate sensing data to the process execution. The model extensions and execution components for the MAPE-K loop are then applied to a process notation and engine, resulting in a generic framework for self-adaptive real-world processes. Martins and Domingos [34, 74] directly focus on IoT and business processes, proposing first to use BPMN to model IoT scenarios, then to transform the models into an intermediate language, such as Callas Byte Code, to describe WSN systems, and finally to execute such code on the IoT devices. Domingos et al. [36] propose an executable extension of BPEL, which defines a set of context variables for handling sensor values.

Caracaş and Bernauer [14], Caracaş and Kramp [15] and Caracaş [13] use BPMN to capture IoT scenarios and transform such models into code to be executed. In particular, the transformation of the model into executable code is performed with patterns to code

Tool	First Release	Last Release	License	Extensibility
Activiti	2010	2019	Apache License 2.0	✓
ARIS	2009	2017	Freeware	✓
Bonita	2009	2020	GNU	✓
BPEL Designer Project	2005	2015	Eclipse Public License	✓
bpmn-js	2015	2020	bpmn.io	✓
Camunda	2013	2020	Apache License 2.0	✓
CoTaSe	2017	2018	Freeware	✗
CPN Tools	2000	2018	GNU GPL2	✗
Eclipse BPMN2 Modeler	2015	2020	Eclipse Public License	✓
Eclipse Modeling Framework	2004	2019	Eclipse Public License	✓
Flowable	2016	2020	Apache License 2.0	✓
jBPM	2016	2020	Open Source	✓
MagicDraw	2011	2020	Trialware	✓
MetaSonic Build	2012	2018	Proprietary	✗
Oryx	2009	2009	Open Source	✗
Signavio	2009	2020	Proprietary	✓
Signavio Core Component	2009	2011	Open Source	✗

Table 15: List of identified tools and their characteristics

techniques. Dar et al. [32] propose an integration between IoT technologies and BPM using a REST architecture that allows bilateral communication to support the business process execution. Mass et al. [77] propose a system architecture for the decentralization of the execution of IoT-Aware business processes. The idea is to distribute the execution of the processes to multiple parties and into different nodes. Friedow et al. [47] integrate the IoT concepts into business processes via cloud services. For each device is defined a code for the communication with the process via REST API calls using the cloud as an intermediary.

Meroni et al. [80] focus on the communication and coordination among multiple BPMSs between imperative languages, used to model the process quickly, and declarative languages used to configure the monitoring of an IoT system. Cimino et al. [24] propose an approach to evaluate the effectiveness of smart technologies by enacting and monitoring a BPMN business process in a real-world scenario. Hou et al. [58] propose an approach to execute IoT-Aware business processes in a distributed way due to the high degree of mobility of devices strictly linked to their geo-location. The process is split thanks to the location-based fragmentation algorithm, and each part of the starting process can collaborate to complete a common goal. D'Hondt et al. [33] containerize micro-services are modeled and executed in BPMN language to enable distributed analytics on the IoT edge.

Domingos et al. [35] design a scenario with BPMN and then translate the output model into executable code that is running on the physical devices to optimize the overall WSN communication and computational capability usage of devices. Cheng et al. [19, 21] propose a service-based fog execution environment to fit the dynamic smart scenario with an IoT-Aware business process. Schönig et al. [96, 97] propose the integration of an IoT data provenance framework so that data from smart devices can be considered when executing an IoT-Aware business process. In addition, based on the sensing of this data and in the occurrence of certain conditions, it can dynamically trigger the execution of parallel processes.

Panfilenko et al. [88] propose the BPMN standard for designing and executing an industrial CPS system to achieve real-time knowledge of the system's anomalies. Ruiz et al. [42] propose an architecture that includes, on the one hand, the execution of a business process in the BPMN standard and, on the other hand, the management of wearable sensors to monitor the condition of a patient. All this information from sensors guides the business process flow in making real-time decisions based on data. Teixeira et al. [109] implement LAURA, a conceptual architecture that provides the possibility to enact a business process supported by a rule layer for the management of real-time events in the IoT world. Kozma et al. [66] propose using standard BPMN and CPN-based production-level descriptions to define the IIoT (Industrial Internet of Things) entities involved in the process. Goncalves et al. [50] propose an approach composed of IoT, CEP, and the enactment of declarative business process technologies for the management of IoT-Aware business processes.

Mass et al. [78] enact an IoT-Aware business process to capture metrics and performance and to manage edge and fog computing situations of the IoT network. Martins et al. [76] aim to decentralize the execution of IoT-Aware business processes by moving them directly into the IoT devices, using their computational capabilities. This process's decentralization is done through a decomposition technique of the main process. Mandal et al. [70] propose a mechanism to integrate external events, such as web services or IoT device interactions, within the execution of a business process. Tranquillini et al. [111], Sungur et al. [105], and Mottola et al. [85] propose a layered approach for developing, deploying, and managing WSNs that interact with information systems.

SPU [2] models an abstraction of the event stream processing, which generally represents a data stream produced from smart sensors. The approach integrates new concepts that manage data flow from devices during process execution. Park et al. [89] extend a standard BPMN workflow engine to implement the management of smart services by sensing data directly from smart devices and analyzing it in the process execution. Kim et al. [62] focus on executing IoT-Aware processes capable of integrating ARDUINO's functionalities. Suri et al. [106, 107] propose an executable semantic framework to bridge the gap between IoT resources and business process management. After a formal description of the IoT resources, they were considered at the process modeling and execution phases.

Elhami et al. [39] propose a mechanism for the integration of IoT contextual information in run-time process prediction. The idea is to design a predictive IoT-Aware business process starting from contextual events collected in the environment. Ardito et al. [3] develop a telegram bot by enacting an extended business process that can monitor the interactions between IoT devices and telegram commands typed by the users. Dorndorfer and Seel [38] introduce a domain-specific modeling language for modeling the contextual environment by extracting data from sensors. Then the context model generated is used to aggregate device data and make them available to model the IoT-Aware business process.

Notation Usage	Source	# of research works (%)
Design Only	[6, 8, 16, 18, 20, 22, 23, 29, 37, 43, 45, 48, 49, 52, 54, 56, 63, 65, 67, 73, 75, 79, 81, 82, 83, 84, 86, 90, 91, 93, 94, 95, 102, 103, 104, 112, 115, 116, 117, 118, 119, 120, 121]	43 (51%)
Enactment/ Execution	[2, 3, 13, 14, 15, 19, 21, 24, 32, 33, 34, 35, 36, 38, 39, 42, 47, 50, 58, 62, 66, 70, 74, 76, 77, 78, 80, 85, 88, 89, 96, 97, 98, 99, 100, 101, 105, 106, 107, 109, 111]	41 (49%)

Table 16: Research works distribution by notation usage (RQ3.3)

6 Discussion

This section discusses the need for a process-oriented modeling notation integrating IoT-related aspects. We compared relevant approaches found in the literature with the requirements identified within the European project called IoT-A [83], a reference point for this topic. In addition, the data extracted from the research questions are compared to determine possible correlations between the use of notations, the modeling views, the application domains, and the modeling requirements of IoT-Aware processes. Future developments about each phase of the IoT-Aware process lifecycle are discussed. Finally, threats to validity are presented.

6.1 On the need for an IoT-Aware business process modeling notation

From the analysis of the papers in this SLR, and as also motivated by Beverungen et al. [7], there is a clear need to **enrich modeling languages with additional constructs** to grasp aspects and characteristics of the IoT world, that influence business processes modeling. IoT's physical and tangible nature has to be reconducted into an abstract graphical representation. Current research usually extends the standard meta-model, typically the BPMN meta-model, which defines the nature of such graphical representation. This is crucial to ensure compatibility between modeling editors and workflow engines. A standardization effort involving the OMG organization, that maintains the BPMN notation [87], would be much beneficial in deriving standard notation elements for modeling IoT-aware business processes. OMG could activate a dedicated working group that could extend the existing BPMN standard, to incorporate IoT dedicated attributes and elements. This could be much beneficial for consolidating a standard notation that could foster support and portability for IoT-aware business process models among different tools. However, extending a notation with additional constructs can affect its complexity; the more constructs are present, the more complex a notation is perceived by its users.

Furthermore, given the advantages of the model-driven development paradigm, it is crucial to pay spe-

Source	Notation	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11
Non BPMN 2.0 Standard Notation												
[101, 103]	Context-Adaptive PN	✓		✓	≈	✓	✓	≈	≈	≈	✓	✓
[121]	Context-Aware PN	✓		✓	≈	✓	✓		≈		✓	✓
[45]	CoTaL	≈	✓	✓			✓	≈		✓		✓
[112]	S-BPM	≈	✓	✓	✓	≈	✓	✓	≈	✓	≈	✓
[98, 99]	Abstract State Machine		✓				✓					✓
[100]	Domain Specific Language		✓	✓			✓					✓
[36, 49, 63]	BPEL		✓			✓	✓		≈			✓
[6]	GSM Workflow		✓	✓	✓		✓	✓	≈			✓
BPMN 2.0 Standard Notation												
[8, 13, 14, 15, 19, 21, 22, 24, 32, 33, 34, 35, 37, 39, 42, 43, 47, 50, 56, 58, 66, 70, 74, 75, 76, 77, 80, 88, 96, 102, 109, 115]	BPMN 2.0	≈	≈		≈	≈	✓		≈	✓		✓
BPMN 2.0 IoT-Aware Extensions												
[18, 23, 73, 81, 82, 83, 84, 90, 93]	IAPM	✓	✓	✓	✓	≈	✓	✓	≈	✓	≈	✓
[91]	I4PML	✓		✓	✓		✓					✓
[106, 107]	IoT-BPO	≈	✓				✓			✓		✓
[116, 117, 118, 119]	uBPMN	✓		✓	✓		✓			✓		✓
[52]	BPMN4CPS	✓		✓			✓					✓
[67]	BPMN-MDM	✓		✓	✓		✓					✓
[104]	Sperner et al.	✓		✓			✓					✓
[79]	BPMN-E^2		✓				✓					✓
[48]	Gao et al.	✓			✓		✓					✓
[20]	Cheng et al.	✓		✓			✓					✓
[65]	Kozel T.						✓	✓		✓		✓
[94]	Sang et al.	✓		✓			✓			≈	≈	✓
[95, 97]	Schönig et al.	✓		✓			✓			≈		✓
[54]	Grefen et al.		✓		✓		✓	✓				✓
[16, 85, 105, 111]	BPMN4WSN	✓	✓	✓			✓					✓
[2]	SPU	✓	✓	✓			✓					✓
[120]	Zareen et al.			✓	✓		✓			≈	✓	✓
[29]	Corallo et al.				✓		✓					✓
[86]	BPMNSIX	✓		✓			✓	✓			≈	✓
[89]	Park et al.	✓		≈		≈	✓					✓
[78]	STEP-ONE	≈		✓	✓		✓		≈			✓
[62]	Kim et al.	✓		✓			✓				≈	✓
[3]	BPMN-X	✓		✓	✓		✓					✓

Table 17: Notations comparison based on IoT-A requirements (Fully satisfied: ✓; Partly satisfied: ≈)

cial attention to modeling aspects impacting the development of complex smart systems. Thus, the need to **enrich the modeling notation with concepts from the IoT world impacting the development** is highlighted.

Research works on context-aware applications [55, 82] state that IoT technologies **sensing and actuating the environmental context** directly affect the link between the execution of a process and the physical environment in which it is enacted. While, on the one hand, modeling these technologies allows context awareness, on the other hand, it reduces the abstraction level of the business process model. Even if IoT environments operate at a low abstraction level depending on the device's nature, business processes should guarantee separation of concern, avoiding introducing low-level aspects. PoT and TaP types of views should guide the model abstraction since they are used to define respectively the internal behavior of devices or the system in which they operate.

Another important aspect to consider in **modeling IoT devices refers to the possibility to express information regarding their physical resources** (e.g., the battery level, the available processing power, or the sampling rate). Being able to model such quantitative aspects also allows to reason in advance on device resources, optimally manage them to avoid errors, and provide fault tolerance in critical tasks at run time [73]. The available graphical notations do not directly support quantitative aspects related to the use of physical resources. In most cases, meta-model extensions are applied to add attributes to already available elements, or textual annotations are used to report that quantitative information. This is especially valid in cases where models guide the performance analysis of the represented systems [29].

6.2 Notation comparison

Different notations related to different approaches support similar IoT concepts. The most common concepts related to the IoT world that are represented in those notations are: physical entities, sensors, actuators, and the surrounding environment. Given the data and the event-driven nature of IoT systems, it is necessary to consider these data and events while modeling such scenarios. BPMN provides several constructs [28], especially it already provides a set of data objects and events, that have been extended by the analyzed approaches to integrate IoT aspects. Some notations also add the possibility to represent a concept of mobility of the device, by using markers to indicate that the behavior of a device can change its position. The specification of this kind of information prevents critical errors that could occur during the execution.

By analyzing the various contributions in the literature, we noticed that many research works consider multiple IoT requirements of the European IoT-A Project [83] (details have been already provided in Section 5.3). In Table 17 we report an overview of the requirements supported by the different modeling notations extracted from the literature. Notice that we grouped research works referring to the same notation, leading to the identification of 17 different approaches. In addition, we have defined a score related to the coverage of the requirements by the modeling notations. In doing this, we weighted the coverage distinguishing if the requirement is fully fulfilled (one point), only partially fulfilled (half a point), or not fulfilled (zero points). The final score is calculated in percentage considering the total points obtained from all the eleven requirements. Figure 6 shows the scores obtained by the various notations. It is worth noticing that most approaches have a score under 50%. In particular, the average score of the modeling notations is about 46%. This certainly highlights the overall difficulty of the approaches in modeling smart environments in a fully process-oriented way.

The notation that achieved the highest score is IAPM that satisfied 86% of the listed requirements. IAPM results from a project funded by the European Union [83], and it is described in several research works discussing the different details of the notation [18, 23, 73, 81, 82, 84, 90, 93]. The IAPM approach is considered the pioneer in this field. Many of the field's research work is based on assumptions and insights. The first requirement referring to entity-based concepts (*R1*), is satisfied by adhering to the IoT Domain Model defined by Meyer et al. [83] which covers all the entity-related concepts of the IoT domain (e.g., Physical Entity, Devices, Resources). The distributed execution requirement (*R2*) is satisfied by modeling the IoT activities in a specific pool dedicated to IoT devices. These pools are identified by a special marker indicating that a pool represents the process of a specific device. The interaction requirement (*R3*) is met by introducing two additional forms of interactions. First, the device interacts with Physical Entities. Second, the services known by enterprise systems processes interact with the software components of devices [83]. The distributed data requirement (*R4*) is provided by extending the data object and data store of BPMN with the real-word data object. The scalability requirement (*R5*) is *partly* satisfied due to the ability to specify additional parameters, which, however, have no direct effect on the real IoT system's scalability. Finally, the availability/mobility requirement (*R7*) is introduced with a special marker for mobile processes and pools to express the mobile nature of IoT devices. The Fault Tolerance requirement (*R8*) is *partly* met because it is provided only the possibility to express a percentage value that defines the fault tolerance rate on each IoT-related activity. The Flexibility/Event-based requirement (*R9*) is met by the introduction of specific events that can trigger actions depending on the position. The Uncertainty of information requirement (*R10*) is partly met due to the impossibility of verifying the correctness of the information derived by IoT devices. However, such information can be accessed by a manual inspection. Finally, Abstraction (*R6*) and Real-Time (*R11*) are requirements that are met in all of the considered modeling notations. Concerning the Real-Time requirement, we recall that it refers to the suitability to express time constraints based on which IoT-aware business process activities have to occur (Section 4.2); all the scouted notations are equipped with time-based modeling elements that support it.

Given all the research works focusing on the IAPM notation and all the IoT requirements it supports, we could consider it a reference notation. However, IAPM does not support some requirements, i.e., R5 - Scalability, R8 - Fault Tolerance, and R10 - Uncertainty of information. Support for requirements R5 and R10 can be retrieved from other approaches. The former requirement is supported by Song et al. [103] who propose an approach that allows representing information about the entities involved in the system. The latter, instead, is supported by Zareen et al. [120] who provide an approach that can represent security mechanisms to allow safe communication between authorized and certified parties involved in the IoT-aware business process.

6.3 Relationships among notation usage, applications domains, modeling views, and notation requirements

To better understand the relationships of the IoT-aware modeling approaches, we analyze the adopted modeling views, the IoT requirements, the considered application domains, and the notation usage by putting together results from research questions RQ1, RQ2, RQ3.1, and RQ3.3. The findings related to the modeling environment on the tool resulting from RQ3.2 are not considered here since they mainly constitute a technical contribution, not relevant for this cross-cutting analysis.

We first consider the interplay between PoT and TaP types of views and the life-cycle phases of IoT systems to which the proposed notation refers. Figure 7 highlights such relations. Among the works discussing Design Only, we found that 37 works (86%) model the scenario with a TaP view, whereas the remaining six works (14%) adopt the PoT view. Regarding the notations that support the Enactment/Execution phase of the IoT-aware systems, we found that 30 works (73%) model the scenario with a TaP view, and 11 works (27%) model the scenario with a PoT view. The results' analysis shows no correlations between modeling views and the life-cycle phases can be highlighted.

We then concentrate our study on the implications given by the application domains. In Figure 8 we report the interplay between PoT and TaP types of views and the application domains. TaP is mainly used for modeling Commercial, Industrial, and Smart City domains, while PoT appears to be primarily related to Smart City. However, it is worth noticing that, independently from the view, the smart city domain seems to be the most attractive scenario for modeling approaches providing internal behavior of IoT devices and their cooperation, as well as a more comprehensive view of integrating IoT devices into the work system.

In Figure 9 we also report the interplay between the application domains and the business process life-cycle phases to which the proposed notation refers. Overall, the notations that support only the design phase and those that support also the enactment evenly consider the application domains with slight differences for Industrial and Commercial domains that are mainly considered only from a design perspective.

We also focus our study on the implications given by the IoT requirements. Figure 10 shows the number of works that satisfy (even partially) an IoT requirement concerning PoT and TaP views. Although the TaP view is adopted more often than the PoT one, we can observe that their graphs present similar shapes. Therefore, we can conclude that the requirements do not influence the modeling type of view.

Figure 11, instead, highlights how Design Only and Enactment/Execution phases relate to the IoT modeling requirements. The graph shows that modeling approaches used for supporting the enactment generally meet fewer requirements than those for supporting the design. This is the case of R7 Availability - Mobility and R10 - Uncertainly of information, which are not met by any notation that supports the execution phase. More generally, the notations that support Design Only or Enactment/Execution phases fulfill requirements R1, R5, R6, R8, R9, and R11. Requirements R3, R4, R7, and R10 are satisfied only by approaches considering the Design Only phase, while only R2 is satisfied by notations supporting the Enactment/Execution phase.

6.4 Directions for future research

Based on our collected results, we envision several directions for future research to bridge the gap between IoT and business processes. As discussed in the paper, much is done referring to the modeling of IoT-aware business processes as well as how the modeling affects all the other phases of the business process life cycle [114]. However, there is not a standard approach that can consider at the same time all the characteristics needed to support all the different phases. Indeed for each phase, we see space for contributions. We discuss possible directions for future research, considering one phase at a time.

Process Modeling. Referring to the modeling of business processes enhanced with IoT concepts, we extensively analyzed the literature through our investigation. As a result, we have shed light on the various proposals made over the years, discussing the lack of a standard way to model IoT-aware business processes. All the presented approaches, indeed, tackle the modeling of IoT-aware business processes from different perspectives, introducing specific graphical elements. The intervention of a well-recognized authority/group would be beneficial for defining a comprehensive and primarily used extension of BPMN for IoT. To start, graphical elements to be included in such a standard could be taken from the available literature, focusing on those attracting more attention or that are used the most (e.g., sensing and actuation tasks and smart data objects). However, a notation incorporating the best proposal from all the presented approaches is still missing.

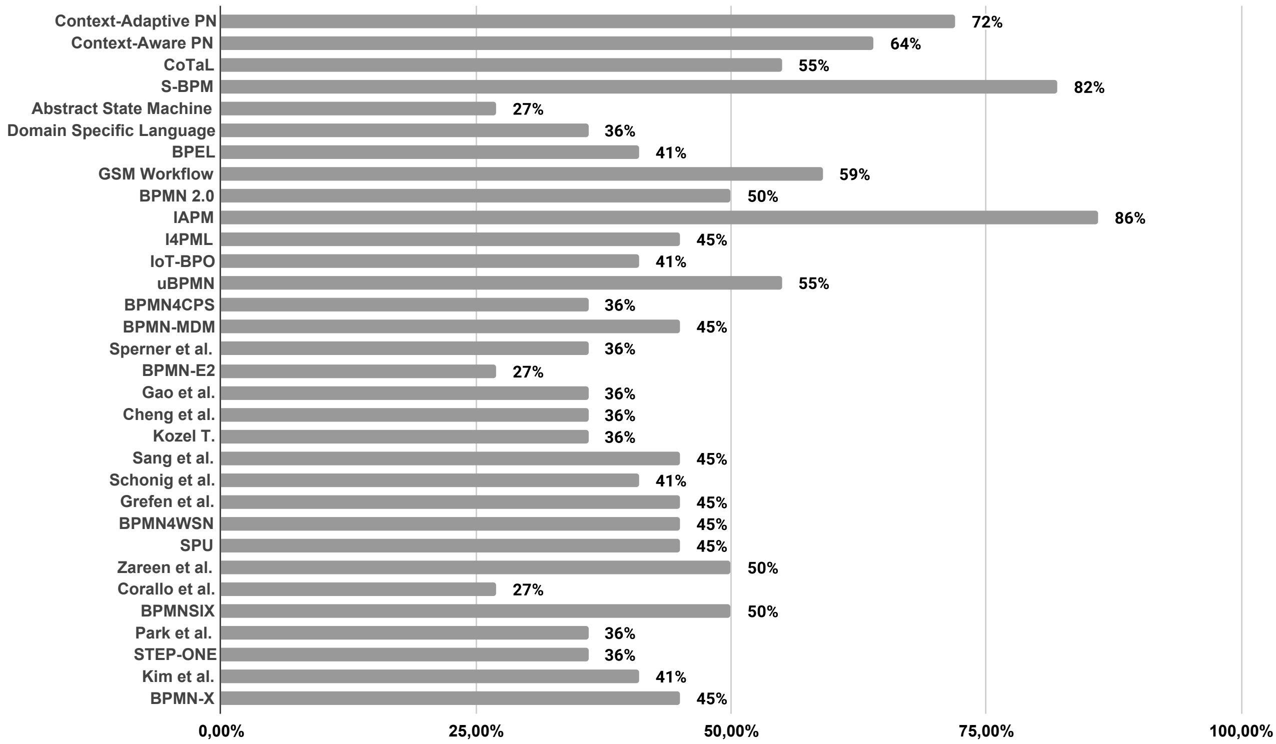


Fig. 6: IoT-aware modeling notation scores on the IoT requirements satisfaction

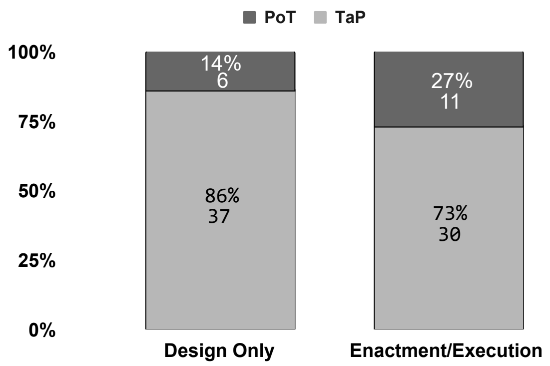


Fig. 7: Notation Usage in the Modeling Views

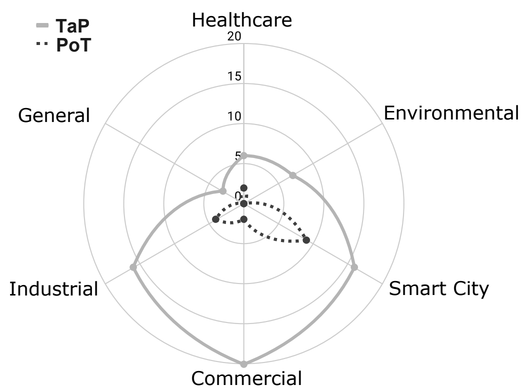


Fig. 8: Modeling Views with respect to Application Domains

Once standardized, such extension would help practitioners design models that IoT-aware Business Process stakeholders can unambiguously understand.

Process Analysis. Business processes that interact with the IoT world by automatizing the sensing and performing actions (using actuator devices) demand special attention. Such processes can affect the environment, and in many cases, it is hard (if not impossible) to reverse the actions they perform. Thus, there is a need for techniques to analyze, simulate, and test such processes before actually executing them. Already available techniques and tools focusing on process analysis (e.g., [30, 31, 59]), together with those referring to process simulation (e.g., [11, 46, 92]), could be adapted to handle the distinctive features of IoT-aware business processes.

Process Implementation. Business process models are often used as input in process engines that support companies in the organization and optimiza-

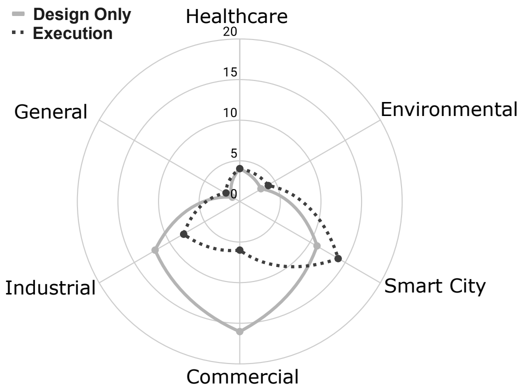


Fig. 9: Notation Usage concerning Application Domains

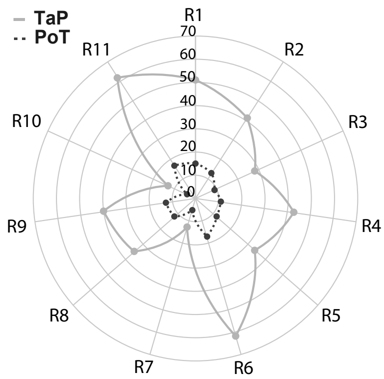


Fig. 10: Modeling Views with respect to Notation Requirements

Fig. 11: Notation Usage concerning Notation Requirements

tion of their processes and the resources involved in such processes. To the best of our knowledge, no engine presents specific functionalities for implementing IoT-aware business processes. Using already available process engines can be a starting point for process implementation. On the one hand, this approach prevents anyone from 're-inventing the wheel' regarding business process implementation. On the other hand, it requires some compromises since process engines usually handle process models designed with precise notations (e.g., BPMN, Petri Net, BPEL). However, these notations have some expressiveness limitations. In particular, if a notation does not provide support for IoT concepts such as sensors, actuators, real-time and event streams, those concepts must be handled by the process designer with some workaround to make it still possible to use the process engine as it is. From our study, it emerged that there is no standard way to let already available process engines handle IoT-aware business processes. A study on shared practices may be helpful. In addition, open-source process engines may be suitable for handling this limitation since they may allow for incorporating previously unforeseen aspects (e.g., using extensions). Moreover, much work has been done to provide users with IoT platforms that can ease the configuration and the usage of IoT systems [40]. Also, IoT platforms may benefit from an integration that aims to bridge the gap between tool support for IoT and tool support for business process management.

Process Monitoring. IoT systems can be deployed to keep track of business process activities. Therefore, enhancing the support for monitoring IoT-aware business processes could allow business analysts to keep the status of the monitored processes under control by leveraging the data retrieved by the IoT. For example, data can be reported and analyzed using dashboards, which are commonly used in IoT. The possibility of actually seeing the retrieved data and putting it into the business process activity that is being performed may empower business analysts with the support to spot erroneous or exceptional situations (e.g., an activity not being performed). This can enable process participants to perform near real-time corrective actions. In this respect, IoT data can also be used as a support for predicting which activity will be performed next or to predict the entire process result.

Process Mining. In process mining, IoT data logs could be combined with activity logs to discover business processes based on historical data. This can enable retrospective analysis based on performance and detect process instances drifting from the specified behavior initially intended for the process. However, data provided by IoT systems and process engines differ in size and production rate. IoT data can quickly degenerate in Big Data, so being characterized by the well-known dimensions of volume, velocity, variety, and veracity [72]. Instead, data produced by process engines depends on: the number of process activities to be performed, their kind (e.g., manual vs. automatized), and the speed required to perform them. How to handle these differences to make the best out of those data demands some research efforts. Especially, mapping IoT data to process activities is a research area that is under investigation [68].

6.5 Threats to validity

To assess the validity and to identify possible threats of the SLR, we follow the classification schema for secondary studies defined by Ampatzoglou et al. [1]. It comprises three areas: study selection validity, data validity, and research validity.

The **study selection validity** aims to validate the procedure of harvesting and filtering relevant works [1]. The selection of the digital libraries and the construction of the search string can strongly influence the results and must be carefully planned. Differently from the previous version of this work [27] we reduced the number of digital libraries that we considered since, Web of Science and Scopus usually index articles from IEEE and ACM digital libraries. However, we cannot guarantee that this is valid for all the relevant works. Despite our effort in defining the most complete search query (Section 4) we cannot guarantee that the query allows us to find all the relevant research work. To mitigate this threat, we added a snowballing step that allowed us to include research works that did not resulted from the performed query. Moreover, it is worth noticing that some potentially relevant research works released after the time frame we consider may be missing. Another threat to validity comes from our defined set of selection criteria. In the studies, we do not refer to all business process life cycle phases, but we focus only on the modeling phase and in the context of a top-down approach. However, even if we also consider other phases, we are confident that our results focusing on the modeling phase will help the research community to broaden their vision on this topic. Finally, it is worth noticing that, according to the ***EC.1 Criterion***, we only consider research works written in the English language, meaning that there may be related works written in other languages that was not included.

The **data validity** aims to validate the data extraction, and the analysis of secondary studies [1]. Examples of threats in this category are data collection bias and analysis bias. Different researchers might interpret a study differently, especially regarding the classification of extracted data. In this regard, we used an online Google worksheet during data extraction. In this way, the authors shared and discussed the data extracted. We also run a cross-check consisting of a continuous revision of the data by researchers not directly involved in the original data extraction. Finally, we solved conflicts during the cross-check revision process using discussions. Although we aimed to give the exact definitions and instructions for extracting data from the included studies in Subsection 4.2, some values might still be subjective.

The **research validity** aims to validate all the phases of the secondary research method and concern coverage of research questions and survey repeatability [1]. To address the threat of the research coverage, in Section 3 we proposed three main research questions, focusing on the modeling views, IoT requirements, and modeling notations. We concentrate the analysis in the context of a top-down approach investigating mainly the modeling phase. An exception was made for the execution phase as it may bring relevant information to the research of an IoT-Aware modeling approach. Other phases like monitoring and mining are out of scope for this research effort. The last research question contains three fundamental sub-questions for extracting relevant information for the research. To ensure the repeatability of the work reported in this article, in Section 2, we carefully described the search protocol that reports the use of a systematic process that researchers can replicate. This can open the possibility of making subsequent additions and extensions to the research in this field.

7 Related work

While scouting the literature for retrieving scientific contributions concerning modeling IoT-Aware business processes, we found six secondary studies with similar objectives concerning our work. Table 18 provides an overview and emphasizes the differences between these papers. We categorized these works based on the methodology applied by the authors for conducting and reporting the research, i.e., Systematic/Not Systematic. Some of them are systematic literature reviews [51, 108, 110], while others propose overviews of works related to our topic [10, 17, 41] without adopting a systematic strategy.

Systematic Reviews. Torres et al. [110] performed a systematic mapping study, considering the time frame 2009-2019, to collect and describe ways to model IoT-enhanced business processes. They considered two research questions that guided their search: *(i) Which modeling strategies are provided to build IoT-enhanced BPs?*; *(ii) How IoT devices are represented at the modeling level?*. They gathered research works using a query over a set of digital libraries (i.e., Scopus, Science Direct, Google Scholar, Springer, Crossref search). The entire procedure resulted in a collection of 36 primary

Review	Methodology	Publ. Year	Context	Period	Intersection with Our Work	# of study [a]
[110]	Systematic	2020	Modeling strategies for IoT enhanced process	2009-2019	27	36
[51]	Systematic	2020	Modeling cyber-physical systems	2009-2016	4	35
[108]	Systematic Study	2016	Modeling and automatic code generation for WSN	2005-2015	10	55
[41]	Not Systematic	2020	IoT technology within business process	2014-2020	15	18
[10]	Not Systematic	2018	Modeling IoT-Aware business process	2010-2018	15	17
[17]	Not Systematic	2017	BPM systems for IoT	2012-2016	8	9
Our	**Systematic**		**IoT-Aware business process modeling languages**	**1999-2020**	**84**	**84**

[a] Note that for the not systematic works, the total number does not correspond to the total number of references in the paper but to the references related to IoT-Aware business processes.

Table 18: IoT-Aware business processes related literature reviews

studies. In terms of gathered research works, we share with Torres et al. [110] an intersection of 27 primary studies. However, they do not focus on the detail of the languages concerning modeling views and requirements. In addition, the methodology they used for gathering such a collection of primary studies is not fully documented, which hinders the possibility of replicating the study to clarify better the differences between the sets considered by them and us, respectively.

Graja et al. [51] produces a survey on existing approaches to model Cyber-Physical Systems (CPS), considering the time frame 2009-2016. They study CPS properties, classify modeling technologies, and review some existing approaches discussing their importance in different application domains. The following research questions guided the research work: *(i) Which modeling languages are used to specify CPS*?; *(ii) What are the supported CPS aspects within the modeling approaches*? *Which non-functional properties are specified when modeling these systems*?; *(iii) What are the studied application domains of CPS*?. They gathered 35 research works using a query over a set of digital libraries (i.e., IEEE, Science Direct, Google Scholar, ACM, Springer). Even though the authors target the modeling of CPS in its wider form, they also identified four different approaches that model CPS from a business process perspective. We considered these works relevant for our survey and included them in our analysis.

Teixeira et al. [108] performed a systematic mapping study investigating the modeling and automatic code generation initiatives for Wireless Sensor Network applications based on the IEEE 802.15.4 standard considering the time frame 2005-2015. This research was based on the following five research questions: *(i) Which high-level aspects are treated by the modeling or code generation process?*; *(ii) Which strategies are used for controlling or reducing the node energy consumption?*; *(iii) Is there any middleware supporting the modeling or code generation process*?; *(iv) Does the approach for modeling and code generation apply some service-orientation in their conceptual architecture or deployment process*?; *(v) Does the approach allow any dynamic code update after the code generation process*? They gathered research works using a query over a set of digital libraries (i.e., Scopus, WoS, IEEE, Science Direct, ACM, Springer, Compendex). Even though this study presents a significant amount of retrieved research works (55), it focuses on aspects related to the technology used by the various approaches, the kind of supported middleware, and the proposed service-oriented architecture. Therefore, while limiting the notation comparison to the support for aspects linked to WSN (e.g., energy consumption), they miss some less specific notations retrieved by us. Moreover, the identified modeling notations were published in 2005-2015, so they do not include more recent works. Despite that, we considered this work related to ours since it also reports some approaches for modeling WSN from a business process perspective. Indeed, ten works mentioned in this survey have also been included in our SLR.

Not Systematic. Fattouch et al. [41], present a review of different approaches that integrate the IoT technology within business processes, considering the time frame 2014-2020. They provide a brief overview of each approach and compare them based on a set of criteria. They also identify some initiatives and challenges for the IoT-Aware business process paradigm. This work shares our objective, and there is an intersection of 15 works between the two surveys.

Brouns et al. [10] provide an IBM report targeting the modeling of IoT-Aware business processes considering the time frame 2010-2018. The work overviews some BPMN extensions incorporating IoT aspects in business process models. We share with this work an intersection of 15 primary studies.

Chang et al. [17] provide an analysis of existing Business Process Management Systems for IoT frameworks and identifies the limitations, and their drawbacks, based on a mobile cloud computing perspective considering the time frame 2012-2016. They also summarize some BPMN extensions incorporating IoT aspects into business process models. Considering its specificity, we share an intersection of 8 primary studies with this work.

General Remarks. Compared to the identified related works, our research presents a wider set of papers discussing modeling IoT-Aware business processes. In particular, this stems from the fact that our SLR covers a wider period (1999-2020), resulting in a larger set of identified primary studies. Moreover, the reviews included as related works do not focus their analysis on the types of views and requirements that are supported by the notations under scrutiny.

In addition, the comparison highlights the difference between adopting a systematic approach versus a non-systematic one; the latter generally results into a smaller set of retrieved primary studies. Overall, the considered non-systematic literature misses many research works that we instead found by applying a systematic approach. The drawback of the systematic approach is that it is more demanding concerning the time needed. We also observe that relatively small differences in the definition of the research questions can result in significant differences in the set of considered primary works. The results are strongly connected to possible differences in the choice of the keywords used to compose the query and the adoption of different Inclusion/Exclusion criteria [26].

Finally, we observe that some papers included in the other systematic surveys were not included in our study. Most of the excluded research works were initially identified by our search query. However, they were then discarded by the application of the exclusion criteria ***EC.2*** after having read the title and abstract. They do not propose or use a process-oriented notation to model IoT-Aware business processes. Notice that our focus is more specific, and modeling cyber-physical systems and wireless sensor networks without directly referring to the business processes-oriented vision in a top-down approach was not relevant for our study.

8 Conclusion

This paper reports the results of a Systematic Literature Review on modeling notations for IoT-Aware business processes. The SLR has been conducted adopting Kitchenham's guidelines [64], moreover backward and forward snowballing steps [60, 113] were applied to improve the recall of our SLR. The considered methodology has been described to permit the full replicability of the study. As a result of searching and filtering activities, we selected and analyzed 84 research works. This literature review can guide modelers in choosing the notation that better fits their needs to model IoT-Aware business processes. We introduced the need to merge business processes and the Internet of Things aspects. Then, after discussing the methodology, we organized the sections reflecting the followed systematic protocol: *planning* (Sec. 3), *conducting* (Sec. 4), and *reporting* (Sec. 5).

Answering our research questions, we recognized that modeling notations for IoT-Aware business processes result in being a hot topic, both considering *Process of Things* and *Things-aware Process* type of views. During our study, we observed that a lack of standardization led to the definition of different modeling notations. However, they do not fit all the IoT-related requirements mentioned by Meyer et al. [84], typically used by the community as a reference for comparing IoT-Aware business process notations. We also discuss the use of the notations concerning specific application domains, and we underline a general lack of tool support for using the notations proposed by the various research works. Finally, we pointed out some research directions for future works related to IoT-Aware business processes, which embrace all the business process life-cycle phases instead of focusing only on the design phase.

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