

# BPMN in healthcare: Challenges and best practices

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## ABSTRACT

The design and analysis of process models is a critical factor for organizational improvement across various industries. Thanks to its potential to enable common understanding and foster automation, process modeling is increasingly adopted in the healthcare sector. However, the complexity of the healthcare domain makes process modeling a challenging task, potentially explaining the modest uptake of process modeling standards like the Business Process Model and Notation (BPMN). In this paper, we identify common challenges of process modeling in healthcare, elicited from healthcare process modeling initiatives and supported by the literature. For each challenge, we present some BPMN best practices in the form of ready-to-use process fragments that guide the standard modeling of complex healthcare aspects. Also, we report the results of a first evaluation of the use and perceived usefulness of best practices conducted with junior experts in medicine and IT. We observed that the domain-specific process fragments help to capture healthcare aspects in detail and are perceived as a source of learning, turning out to be especially useful for modelers with a basic understanding of BPMN and the healthcare domain.

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## 1. Introduction

Within the industry, healthcare is one of the fastest-growing sectors, driven by the enactment of complex and dynamic processes targeting optimal patient outcomes and always seeking increased effectiveness and efficiency [1]. To face the growing demand for assistance and technological innovation, care providers are increasingly resorting to business process management (BPM) initiatives to systematically analyze and (re-)design their processes and streamline care delivery, reduce costs, and increase quality [2].

In particular, process modeling is more and more integrated into healthcare management routines thanks to its potential to enable common understanding among different stakeholders, foster digital transformation, and enhance care delivery [3,4]. The use of process models in healthcare brings manifold benefits. First of all, graphical representations of processes serve as an intuitive and more immediate reference for *training* and *communicating* with health professionals as they are easier to grasp and less ambiguous than textual documents [5]. Secondly, they support the *standardization* of clinical procedures and decision-making, thus fostering compliance with shared protocols and minimizing

variability [3]. Finally, process models allow different kinds of *process analyses* [6], and serve as a blueprint for the *automation* of clinical and organizational activities and information flows [2,7].

The leading standard for process modeling is the Business Process Model and Notation (BPMN), overseen by the Object Management Group (OMG), featuring a graphical notation aimed to be “readily understandable by all business users” [8]. BPMN allows defining process diagrams at different levels of abstraction [9], which can be used for documentation purposes and support implementation efforts. Besides, BPMN is supported by a wide range of modeling tools and benefits from the availability of professional and academic training opportunities [10]. Moreover, BPMN can be complemented by other OMG standards, such as the Decision Model and Notation (DMN) [11], which can be used to capture information and decision-making aspects typical of healthcare domains [12].

Nevertheless, albeit the rich expressiveness of the standard, BPMN-based modeling approaches have seen a modest uptake in the healthcare domain, and the adoption of BPM approaches still lags behind compared to other sectors [13]. This trend can be partially explained by the inherent complexity of healthcare processes [14], the highly regulated hospital environments, and the relatively slow adoption of IT technologies [13], which contribute to increased modeling complexity [15]. A possible direction to improve the uptake of BPMN in healthcare contexts is to propose domain-specific extensions, such as those in [4,16–19]. However, such extensions need to come to terms with a lack of comprehensive evaluation and little or no support by modeling tools [20]. For

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this reason, in this paper, we focus on the BPMN standard and on unraveling its suitability for modeling relevant yet complex healthcare aspects.

In line with literature [21], we define a healthcare process as “a set of medical and organizational activities that are performed in coordination to provide medical care for one or more patients”. Healthcare processes have some specific characteristics that pose unique modeling challenges [14,22,23]. Among others, we focus on the following specifics:

- *Patient-centered*. The key entity on which activities are executed is usually not a document or an item. It is a patient – a human being. He or she needs to be actively involved in medical decision-making and therapeutic activities and may require individualized care [24,25].
- *Time-critical*. Diagnostic and treatment processes need to be scheduled based on patient conditions, resource availability, and hospital regulations, and need to respect several time constraints [23,26,27].
- *Decision-intensive*. Decision-making builds upon medical knowledge and requires health workers to consider clinical evidence and available patient information [22]. Such information is stored not only in IT systems but also in paper documents and medical devices, thus complicating the understanding and automation of information exchange and transformation tasks [3,12,13].
- *Multidisciplinary*. For providing the best possible treatment for a patient, different medical disciplines and organizational units need to be integrated and coordinated [16,22].
- *Resource-intensive*. Medical specialists, equipment, and rooms are usually scarce and expensive resources, shared among different departments and, thus, need to be properly managed and optimized [22,23].

For all these reasons, we advocate that healthcare process modeling tasks require systematic guidance in terms of modeling tools and methods, especially to support shared understanding by different stakeholders. Indeed, process modelers often lack advanced healthcare knowledge, while domain experts may perceive the richness of the BPMN language as a drawback [28] and may benefit from a demonstration by concrete examples [12,20]. Building upon existing literature [3,13,16,22,29–31] and our experience in the field, in this paper, we aim to support the modeling of healthcare processes in BPMN by proposing best practices to model common yet challenging aspects of healthcare processes. Supporting process modeling initiatives with reusable process fragments is a common practice, as shown in a literature overview by Haddar et al. [32]. Furthermore, domain-specific modeling patterns have already been proposed in the BPM field, e.g., patterns for ordering and manufacturing processes [33]. However, to the best of our knowledge, no such proposal has focused on healthcare.

Following this research direction, the goal of the presented work is to increase the applicability of BPMN for healthcare process modeling, considering the digital transformation of healthcare as a long-term goal. In line with this goal, this work provides the following main contributions:

1. **Structured elicitation of relevant modeling needs and challenges in healthcare processes.** These were observed in a set of healthcare process modeling initiatives conducted in different health institutions, and their practical relevance was confirmed by literature.
2. **Definition of a set of one or more BPMN best practices for each identified challenge** in the form of ready-to-use process fragments. These fragments should guide process designers in capturing (challenging) healthcare process aspects at different levels of process abstraction, encouraging

good design practices and supporting a shared understanding among different groups of stakeholders. BPMN and DMN are rich and expressive modeling languages, such that the goal of this work is to provide process modeling support with the modeling concepts already included in the standards. The advantage of such an approach is that existing BPMN and DMN modeling and execution tools already support these concepts, without the need for extensions. The proposed best practices are meant to be used by health workers with a basic understanding of BPMN and process modelers and business analysts working for healthcare organizations. Indeed, the best practices may also help experienced modelers to come up with ideas or explain a particular concept [34].

3. **First evaluation of the use and perceived usefulness** of the BPMN best practices through an exploratory study where junior experts in medicine and IT solve modeling tasks with and without the help of the best practices. The results of our study showed that, with the help of the best practices, participants were able to capture (complex) medical aspects in detail and to obtain process models containing fewer errors. Besides, the best practices have been perceived as useful to increase the general understanding of BPMN.

The rest of this paper is structured as follows. Section 2 provides a brief introduction to the BPMN and DMN standards, which the expert reader may skip. Section 3 discusses related work. Section 4 describes the research method followed to identify relevant challenges and the related best practices. Section 5 summarizes recurrent challenges in healthcare process models and the suggested best practices. Section 6 describes the study conducted to evaluate the best practices and reports our findings. Finally, Section 7 discusses the results and limitations of this work, and Section 8 summarizes our contribution and discusses future research directions.

## 2. Introduction to the BPMN and DMN standards

The Business Process Model and Notation (BPMN) [8] and the Decision Model and Notation (DMN) [11] are among the most widespread process and decision modeling languages. They aim to provide highly understandable models for business users, which can also be used for implementation purposes. Based on the modeling goal, process models exhibit different levels of abstraction with regard to the underlying business process [9]. On an *organizational* level, the high-level textual description of a process including the process inputs, outputs, and responsibilities are given. An *operational* process model captures activities, their relation as well as organizational information. The operational level is sub-divided by BPMN, in *descriptive* models, for a high-level documentation, and *analytical* models, to analyze the process in detail. Based on this, an *implemented* process model extends and adapts it with technical aspects needed for the implementation.

This section aims to quickly introduce both standards with a clinical example. The focus is more on BPMN because our focus is mostly on process modeling, and DMN includes a smaller set of modeling constructs. Although DMN will be only applied in one of the best practices in this research work, an introduction is included below due to its relevance and to make the paper self-contained. More details about the semantics of specific BPMN and DMN constructs will be given in Section 5 when introducing the best practices and can be easily found in the standard specifications [8,11].

Fig. 1 shows a simplified version of an emergency care process, which is triggered by a worsening of the patient's conditions. As a first task, the physician assesses the conditions of the patient.

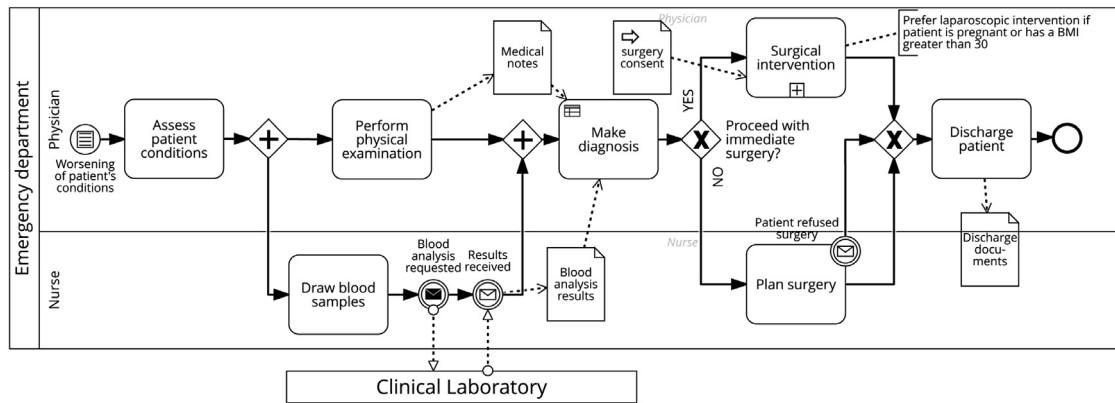


Fig. 1. Simplified emergency care process shown as a BPMN process diagram.

Then, while he or she performs the physical examination, a nurse draws blood from the patient. The blood samples are then sent to the clinical laboratory for analysis and, once ready, results are sent back to the emergency department. With the notes from the examination and the blood analysis results, the physician has to make a diagnosis. Based on the results, a surgical intervention is either immediately performed by the physician or it is planned for the following days by the nurse, keeping in mind that the patient may also refuse to undergo surgery. In all cases, the patient is discharged while being provided with discharge documents. BPMN diagrams can represent the control flow, data flow, and organizational aspects of a process with the following concepts.

- BPMN process diagrams can represent the control flow of a process with activities (e.g., *Perform physical examination*), relevant events (e.g. *Receive results*), and sequence flows connecting them. Gateways, which depicted as diamonds, are used to control sequence flows and to define parallel and alternative behaviors.
- Activities can be atomic (tasks) or compound (sub-processes). Tasks (e.g., *Perform physical examination*) represent atomic units of work, while sub-processes represent compound activities, which can be collapsed to hide details (e.g., *Surgical intervention*). BPMN features different types of tasks having different inherent behavior. For example, business rule tasks are used to represent decision-making tasks (e.g., task *Make diagnosis*). Such a task can be linked to a DMN model, which captures the decision logic, i.e., how to make the decision.
- Relevant external events are shown as BPMN events (e.g. *Worsening of patient's conditions*), which capture process triggers to which the process reacts such as messages, signals, conditions (e.g., *Worsening of patient's conditions*, exceptions (e.g., *Patient refused surgery*), and outputs produced by the process (e.g., *Blood analysis requested*).
- Relevant data and documents used or produced by process activities can be represented with the help of data objects (e.g., *Medical notes*) or data stores when the considered data is persistent. Text annotations can be attached to control flow elements to enhance their description, such as the annotation "*Prefer laparoscopic [...]*" associated with the sub-process *Surgical intervention*.
- Interactions between organizations can be shown through the concept of pools (each one owning a process) (e.g., the *Emergency department* and the *clinical laboratory*) and a message flow between them.
- Lanes in pools (e.g., the *Nurse* and *Physician*) can be used to represent different roles or systems executing the included activities.

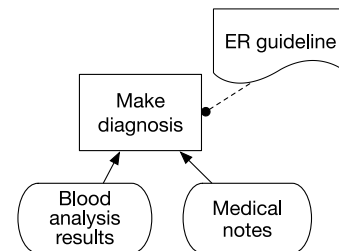


Fig. 2. DMN Decision Requirement Graph representing the decision *Make diagnosis* made in the corresponding business rule task of Fig. 1.

For describing in more detail how the *Make diagnosis* decision is made, a DMN decision model such as the one shown in Fig. 2 can be associated with the BPMN process model. A DMN model includes a decision requirements graph (DRG), which allows one to describe the decision-making at a higher abstraction level. The DRG in the provided example shows that for the *Make diagnosis*-decision, the *Blood analysis results* and the *Medical notes* are needed input data, and the *ER guideline* supports the decision-making as a knowledge source. For each decision in a DRG, the underlying decision logic can be specified either by a decision table or with a Friendly Enough Expression Language expression [11], a DMN-specific expression language for decision logic. We will focus on decision tables in this work.

### 3. Related work

In this section, we discuss related work in the context of healthcare process modeling and touch upon related work about the use of BPMN best practices in general. In healthcare working environments, a wide range of processes with different features and requirements is managed and executed daily [31]. Such processes usually require the structuring and logical coordination of interlinked clinical and administrative tasks [22], posing different challenges for IT support. To improve the understanding of such challenges, Lenz and Reichert [22] distinguish between organizational processes, which focus on the coordination of different healthcare professionals and organizational units, and medical treatment processes having the patient as their main focus. This categorization is often recalled in the literature to classify healthcare process modeling languages and approaches proposed over the years by the BPM and medical informatics communities [7, 31,35].

In Section 3.1, we introduce research on computer-interpretable languages and the modeling of clinical practice guidelines (CPGs) [36,37]. Then, in Section 3.2, we review approaches

for modeling processes enacted within healthcare organizations, with a focus on BPMN.

### 3.1. Healthcare processes and computer-interpretable guidelines

Over the past decades, research in medical informatics has put forward approaches for computer-interpretable guidelines (CIGs) to improve the accessibility and maintainability of narrative CPGs and to support the implementation of (guideline-based) decision support systems [37]. CIGs allow to represent and execute clinical guidelines over patient-specific clinical data [37], being particularly suitable for modeling medical treatment processes. Among them, approaches based on task-network models (e.g., Asbru [38], EON [39], GLARE [40], GLIF3 [41], and ProForma [42]) allow one to formally represent and execute CPGs through an execution engine, and explicitly support the management of temporal aspects. From a control-flow perspective, CIG-based approaches based on task-network models share similarities with imperative process modeling languages [31,43]. However, in contrast with general-purpose, standard BPM techniques, they are mainly based on specialized modeling formalisms and execution environments [31], which, together with the complexity deriving from their local adaption, seems to have limited their broad adoption [37]. It is beyond the scope of this paper to provide a complete overview of such approaches. The interested reader may consult the systematic comparison by Peleg [37] and the recent work by Gatta et al. [44] for more details on CIGs and their synergy with BPM methods.

### 3.2. Application of BPM techniques in healthcare

In the BPM field, standard-based methods have been developed to support the modeling and enactment of healthcare processes [3,30], mainly focusing on pre-specified and repetitive routines requiring standardization. For example, the UML-based methodology by Ferrante et al. [3] is driven by the need to integrate medical processes and health information systems. Instead, the work by Combi et al. [30] addresses the integrated design and enactment of decision-intensive care pathways in BPMN. Vanwersch et al. [45] build upon best practice process models to introduce a systematic redesign technique for care processes. Chiao et al. [46] propose an object-based approach based on the PHILharmonicFlows framework to coordinate interactions among healthcare processes based on business objects.

Although BPM methods for the use in healthcare exist and are helpful to represent complex and multidisciplinary procedures, their application for healthcare process modeling is still modest [13]. In the following, we review studies supporting the process modeling in healthcare considering approaches (1) using BPMN and other process modeling languages for healthcare, and those (2) defining healthcare-specific extensions of BPMN.

(1) *BPMN for healthcare process modeling.* Several studies focus on analyzing the benefits of BPMN for healthcare by applying it to specific medical contexts, as discussed next. Rolon et al. [47] use BPMN to capture programmed surgical patient processes to visualize, understand, and improve them. Rojo et al. [48] analyze the use of BPMN for the modeling of anatomic pathology processes. Scheuerlein et al. [5] present a pilot project aimed to identify the advantages of combining BPMN with tangible business process modeling [49] for the design of clinical pathways for colon and rectum carcinomas. In [50], BPMN is used to model standard operating pathways, to analyze the challenges related to operating room planning and scheduling.

One of the first works studying the use of BPMN for healthcare process modeling in general is presented by Ruiz et al. [24], which

includes an overview of the main challenges posed by healthcare processes. The authors give high-level insights into typical challenges in modeling healthcare processes, such as the need to support shared activities and multidisciplinary tasks. Müller and Rogge-Solti [16] have selected one specific challenge and discuss in their work different options to facilitate the shared working behavior with BPMN (and conservative extension of BPMN) in healthcare processes. Zerbato et al. [51] use BPMN diagrams to model clinical pathways for catheter-related bloodstream infections and focus thereby on representing temporal constraints, another relevant aspect of healthcare processes that is difficult to capture. Evidence-based decision-making, also a challenging aspect, is studied in [29]. This work lays the groundwork for the methodology in [30] which suggests combining BPMN and DMN to represent decision-intensive healthcare processes coming from chronic care.

Overall, the introduced studies remark the need to model healthcare processes in a graphical and standard way to promote common understanding among the different stakeholders involved in the collaborative process design and support model sharing and reuse [52]. However, although some of these works partially pick up challenges of using BPMN in healthcare processes and provide initial solutions, a comprehensive overview of challenges and related solutions is still missing.

(2) *BPMN extensions for healthcare.* Some domain-specific BPMN extensions have been introduced to improve the modeling relevant aspects of clinical domains [4,17–19]. Braun et al. [18] introduce BPMN4CP, a BPMN extension incorporating concepts retrieved from the context of clinical pathways to enhance evidence-based decision activities related to the considered domain. New task types are added to model medical diagnoses and therapies, while different data object types are used for representing documents related to medical and administrative procedures. Neumann et al. [17] introduce BPMN<sup>SIX</sup> as an enhanced modeling language for the design and execution of surgical processes in an integrated operating room. BPMN<sup>SIX</sup> incorporates extension elements taken from BPMN4CP and includes new concepts for representing surgical activities at different levels of granularity, as well as anatomical structures and medical instrumentation. In [4], BPMN<sup>SIX</sup> is extended with the IEEE 11073 SDC family of standards for the interoperability of networked medical devices to enable rule-based medical device orchestration. Finally, Onggo et al. [19] propose BPMN4SIM an extension of the BPMN analytic conformance subclass supporting the explicit representation of tasks shared by multiple process instances, queues, and attributes and data-driven decision points.

The introduced extensions remark that BPMN cannot straightforwardly represent specific aspects of healthcare processes. BPMN extensions are one possible approach to model challenging aspects of healthcare processes through the definition of healthcare-specific solutions. Still, BPMN extensions have the disadvantage of lacking support from existing modeling tools, which adds to the lack of precise execution semantics needed for process implementation [20], making them difficult to use in practice.

Building upon the introduced research and observed healthcare practice, this paper aims to pick up challenges common to various healthcare settings and provide a set of native BPMN process fragments serving as best practices to support healthcare process modeling. Thus, our work is also related to approaches providing modeling support for process design, e.g., through the reuse of modeling patterns and best practices derived from *empirical evidence* [32]. In the BPM field, there has been extensive research on the definition of patterns to ease the comparison of process-aware modeling languages and systems [27,53–55]. The most notable example is the workflow patterns [53], which

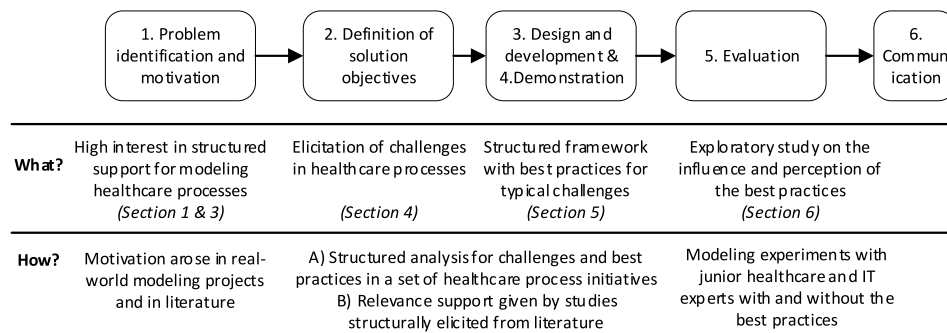


Fig. 3. Design science process adapted from Peffers et al. [58] and its application in this research work.

put a strong emphasis on the syntactical structure of process models. Thom et al. [55] proposed the Activity Patterns, a set of seven recurring patterns describing business functions derived from real-world process models. However, as opposed to the best practices proposed in this paper, these patterns are language- and domain-independent, i.e., they do not focus on the content of business activities within a particular application domain [33]. Another stream of research has emphasized the support of domain-specific process modeling. For example, Koschmider and Reijers [33] have proposed Domain Process Patterns to foster reuse in the ordering and manufacturing domain, while Scholta et al. [56] have put forward the RefPA method for detecting and representing best practices in the public administration domain.

While our work also aims to support process modelers with best practices, similar to [33], we specifically start from recurring *modeling challenges and related solutions* in the *healthcare* domain. We propose to use BPMN as modeling language given the significant uptake of the standard in business domains and the availability of training opportunities and tool support that could also benefit healthcare settings.

#### 4. Research method

This research work complies with the principles of design science research [57,58] and follows the steps of the design science process as described by Peffers et al. [58], i.e., a procedure to identify real-world problems and create useful research artifacts for solving them and, consequently, contributing to the body of scientific knowledge. Fig. 3 outlines the application of the design science process in this work.

In line with the design science guidelines of problem relevance by Hevner et al. [57], we observed in the first step in several process modeling initiatives, in which we were involved, as well as in the literature [16,18] that even advanced process modelers face challenges while modeling healthcare processes due to their specific characteristics. This is described in Section 1 as well as in Section 3. After problem identification and motivation, in the second step, we defined the solution objectives. As presented in this section, Section 4, we identified typical modeling challenges for healthcare processes with the help of a structured analysis of a broad set of healthcare process modeling projects. Then, we checked their relevance based on literature identified by a structured literature review. Based on the identified challenges, we collected in the third step – for the treatment design [59] – a set of solutions from the modeling projects and the literature, and synthesized from them ready-to-use process fragments structured into different types of process abstractions. The design and development step resulted in a best practice framework for modeling healthcare processes that is presented and demonstrated with examples in Section 5. Our resulting design artifact, the best

practice framework, was evaluated in the fifth step through a modeling experiment with junior medical and IT professionals. The exploratory study compares the treatment against a setting without any modeling support, and it analyzes its use and perceived usefulness (cf. Section 6).

In Section 4.1, we describe how we derived an initial set of challenges and the corresponding solutions from process elicitation and modeling projects. Then, in Section 4.2, we report on the process we followed to select the final set of challenges and best practices based on their relevance in the literature.

##### 4.1. Identification of challenges and best practices from real-world projects

Since we are interested in challenges having practical implications for healthcare process modeling, we considered real process modeling initiatives as our primary data source. In detail, we considered different healthcare process elicitation and modeling projects in which we were involved as modeling experts or consultants. The projects, which are summarized in Table 1, had different goals and were conducted from 2015 to 2018 in various healthcare organizations, mostly university hospitals located in Germany, Italy, Spain, and the Netherlands. As a result of these projects, 38 process models were designed, each one comprising an average of 15.4 activities and 5.5 roles.

The challenges were identified as follows. First, we created a list of 42 individual challenges considering *all* the challenges mentioned in the projects. Our focus was on modeling challenges concerning internal healthcare processes to understand, analyze, compare, or redesign the healthcare process as a first step of digital transformation. Thus, we did not consider challenges related to inter-organizational clinical processes or model-driven process implementation. In detail, for each challenge, we collected information about the main process, the medical department involved, the challenge description, and the details about the proposed solutions, if available. Then, since we observed that challenges were recurring, we grouped challenges addressing similar modeling aspects into more abstract categories. For example, challenges described as “Aftercare needs to last at least 30 min” and “Examination shall be prescribed within 30 days from the first appointment” were both categorized as challenge “temporal constraints”. After this grouping, multiple solutions existed from different projects for each challenge. Thus, we grouped solutions addressing the same issue with a similar level of modeling abstraction and transformed them into general applicable BPMN fragments. For example, if a clear decision logic for a decision-making task in a healthcare process exists, we used a business rule task referencing a DMN model. If a medical expert mainly takes the decision, then we chose a user task. Additionally, we re-checked that the developed fragments conformed to the BPMN standard. In the end, we obtained a final list of 10 candidate challenges, each one having one or multiple solutions.

**Table 1**

Summary of healthcare process elicitation and modeling projects used as a source for the challenges along with information concerning the total number of process models (column #PM) and activities (column #Act) designed during the project.

| Main process                                               | Department                          | Country | #PM | #Act | Project goal                                                                                          |
|------------------------------------------------------------|-------------------------------------|---------|-----|------|-------------------------------------------------------------------------------------------------------|
| Admission of patients for an elective surgery              | Center for musculoskeletal surgery  | DE      | 1   | 17   | Process design and analysis                                                                           |
| Management of catheter-related bloodstream infections      | Intensive care                      | ES      | 14  | 217  | Process analysis for evaluating adherence to clinical pathways and supporting decision-making [51,60] |
| Emergency care                                             | Trauma emergency                    | DE      | 3   | 42   | Process evaluation                                                                                    |
| Endoscopic procedure                                       | Gastroenterology                    | DE      | 4   | 68   | Process comparison of different sites                                                                 |
| Pre-surgical consultation                                  | Trauma center                       | DE      | 4   | 29   | Process design and analysis                                                                           |
| Pre-surgical consultation                                  | Center for musculoskeletal surgery  | DE      | 4   | 41   | Process design and analysis                                                                           |
| Management of chronic obstructive pulmonary disease (COPD) | Internal medicine, Primary care, ER | IT      | 3   | 104  | Process design and analysis for standardization and improvement [29,30]                               |
| Elective surgery                                           | Surgery                             | NL      | 5   | 67   | Process redesign                                                                                      |

#### 4.2. Checking the relevance of the candidate challenges in literature

As shown in Table 2, some candidate challenges were observed more often in the projects (up to eight times), than others (only two times). Our goal is to provide a set of challenges and related solutions of general interest and relevant for different kinds of internal healthcare modeling projects. For avoiding a potential bias due to our personal experience, we conducted a literature search for studies addressing the application of standard graphical process modeling languages in healthcare to find evidence supporting the practical relevance of each candidate challenge. In the following, we first describe how we searched and selected the studies for our relevance check (cf. Fig. 4). Then, we explain how we established that a candidate challenge from the analyzed real-world projects was also considered relevant in the literature.

**Literature search.** Since we are interested in healthcare process modeling challenges related to the practical use of standard modeling languages, we focused on approaches supporting process modeling in healthcare and describing modeling initiatives using BPMN and UML.<sup>1</sup> In detail, we began with searching the DBLP<sup>2</sup> and IEEE Xplore<sup>3</sup> databases for conference and journal articles explicitly focusing on approaches based on BPMN or UML activity or sequence diagrams [61] for healthcare process modeling. For retrieving work about BPMN in healthcare we constructed search queries combining the term BPMN with the terms *clinical*, *medical*, and *health* for the article title and metadata. For retrieving work about healthcare process modeling in UML, constructed search queries combining the terms ‘UML’ and *process* with *clinical*, *medical* and *health*. We quoted ‘UML’ to avoid retrieving results about the Unified Medical Language System, while the search term *process* was added to narrow down results to process modeling approaches. In addition, we combined the keywords *process modeling* and *healthcare*

and searched for document titles referring to BPMN-based approaches. Our search was conducted in September 2019. Since the first official version of the BPMN standard was released in 2006, we considered results published starting from January 2006 for BPMN, and starting from January 2005 for UML. At the end of this search, we obtained 229 articles, which we narrowed down to 128<sup>4</sup> by manually removing duplicates.

**Study selection.** Then, we examined the title, abstract, and scanned the content of each article looking for articles with a strong focus on the use of BPMN or UML for modeling healthcare processes. For the selection, we considered the following inclusion and exclusion criteria:

- I1 The article describes the use of standard modeling languages, i.e., BPMN or UML, for healthcare process modeling potentially discussing benefits, challenges and domain-specific extensions;
- I2 The article describes a study about healthcare process modeling with a standard language, i.e., BPMN or UML;
- E1 The article has a modeling focus but does not use BPMN or UML;
- E2 The article focuses only on the use of BPMN and UML to support the development of healthcare applications.
- E3 The article focuses on process mining, analysis, and simulation rather than process modeling.
- E4 The article focuses on the BPMN ontology instead of the BPMN notation.
- E5 The article refers to the healthcare domain as a motivating/application example but does not provide an approach tailored to healthcare-specific settings.
- E6 The article is not written in English or its full-text or relevant parts related to process modeling are not available.
- E7 The article is an application in another scenario of concepts presented in another publication by the same authors.
- E8 The article is related to one of the projects used to identify the challenges (cf. Table 1).

<sup>1</sup> Although the notation of UML is different from BPMN, the basic modeling concepts are similar and, thus, we assume that similar challenges can be observed and only the modeling solutions differ in their notation details.

<sup>2</sup> <https://dblp.uni-trier.de>.

<sup>3</sup> <https://ieeexplore.ieee.org/Xplore/home.jsp>.

<sup>4</sup> The list of the identified papers as well as inclusion and exclusion criteria can be found here: <https://tinyurl.com/r47gl8r>.

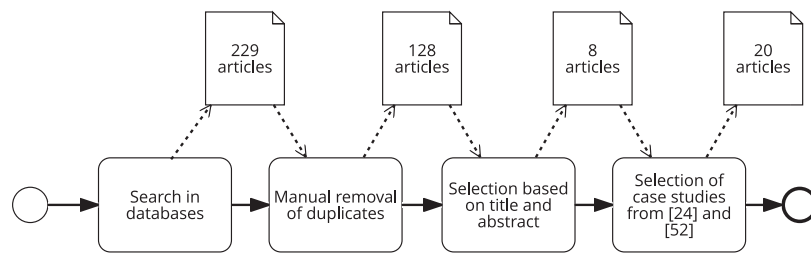


Fig. 4. Process followed for the literature search and study selection.

Table 2

List of candidate challenges identified in modeling projects and relevance in literature.

| Candidate BPMN modeling challenge               | Found in Projects | Evidence in literature | Related work on challenges | Process modeling case studies in healthcare |
|-------------------------------------------------|-------------------|------------------------|----------------------------|---------------------------------------------|
| Centralized scheduling of patients              | 3                 | Yes                    |                            | [47,50,68]                                  |
| Evidence-based decision-making                  | 5                 | Yes                    | [18,19,24]                 | [63–65,67]                                  |
| Involvement of diagnostic or treatment services | 5                 | Yes                    |                            | [48,65,68,69]                               |
| Involvement of the patient                      | 8                 | Yes                    |                            | [25,67,70,71]                               |
| Limited resources                               | 2                 | Minor                  |                            | [47]                                        |
| Monitoring of the patient                       | 4                 | Yes                    |                            | [5,63,69]                                   |
| Patient-specific needs                          | 2                 | Yes                    | [18,24]                    | [5,47,50,71]                                |
| Scheduled vs. emergency patients                | 2                 | No                     |                            |                                             |
| Shared working behavior                         | 7                 | Yes                    | [16,18,24,62]              | [50]                                        |
| Temporal constraints                            | 4                 | Yes                    | [18]                       | [64,66]                                     |

As a result of our selection, we obtained 8 articles. Then, we conducted another search for modeling studies starting from the systematic literature review authored by Mincaroni et al. [52] and the overview of process modeling initiatives presented in [24], considering the same inclusion and exclusion criteria. As a result of this search, we found 12 additional articles, including [24], which also discusses challenges of using BPM in healthcare.

Then, we distinguished the selected articles into (1) works explicitly summarizing and discussing the challenges with standard process modeling languages in the healthcare domain [16, 18,19,24,62] and (2) studies reporting on process modeling initiatives enacted in a specific healthcare organization [5,25,47, 48,50,63–71]. The first group consists of 5 studies focusing on the same topic as this article, i.e., mentioning challenges and possible solutions explicitly, sometimes proposing extensions. The other 14 articles report on case studies, often mentioning challenges only implicitly but providing modeling solutions for them. The latter ones cover hospital processes (e.g., surgical processes [47,50]), prevention and rehabilitation processes (e.g., falling prevention [70], stroke rehabilitation processes [63]), and diagnostic processes (e.g., anatomic pathology [47] and radiology processes [68]). One study did not fall in any of these two categories because it proposes a domain-specific BPMN extension for healthcare but does not discuss any challenge [4].

**Relevance evaluation.** The candidate challenges are provided in alphabetical order in Table 2, together with the evaluation of their relevance. A candidate challenge is evaluated as relevant if it is mentioned by at least one peer-reviewed work focusing on challenges related to the use of standard process modeling languages in healthcare, or by at least three modeling case studies

in healthcare organizations. Whereas the first group of articles focuses on challenges in general, the second group does not explicitly report on challenges and provides insights into a specific healthcare process. Therefore, we required the support of at least one article of the first category, because their results are generalizable, and of at least three studies of the second category, as their results cannot be universalized and are specific to one process. By applying such relevance criteria, from the 10 initially identified challenges, we ended up with 8 main challenges.

Table 2 also shows that existing related work on process modeling challenges in healthcare has focused so far only on four of our challenges: evidenced-based decision-making, patient-specific needs, shared working behavior, and temporal constraints. Nevertheless, through the analysis of the projects, we found that also other challenges are present in practice.

In the selected studies, we found mention of a few other challenges, such as the collaboration with external care providers, the media break (scanning and printing out documents at several points of the healthcare process), the education of medical students, and the visualization of critical clinical documents, which, as concluded by Braun et al. [62], could be easily realized with BPMN data objects. Whereas the latter three were reported only once, the first one is relevant to consider. Cross-organizational patterns need additional modeling concepts and will also encompass a number of patterns, such that we decided to leave cross-organizational challenges out of scope and, thus, we did not include collaboration with external care providers among our candidate challenges. Based on this analysis, we can conclude that we identified a set of relevant modeling challenges for internal healthcare processes.

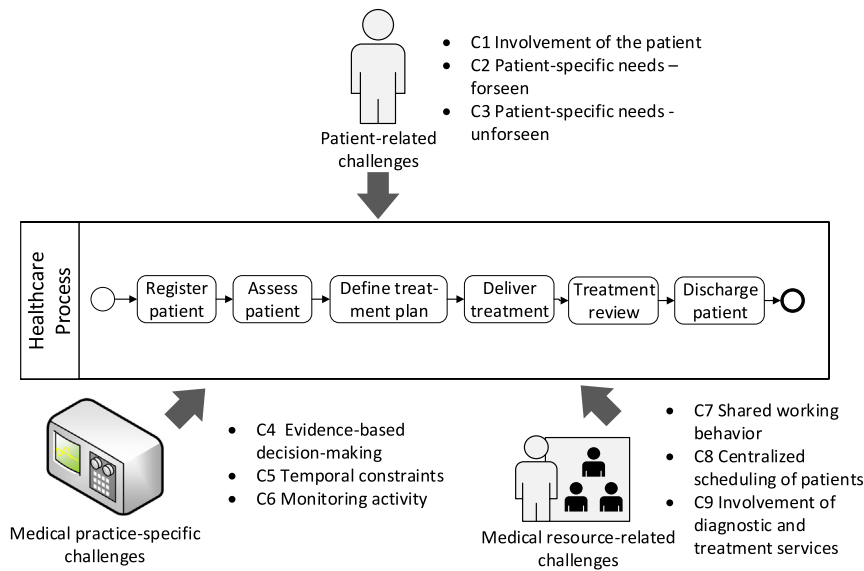


Fig. 5. Overview of common challenges arising when modeling healthcare processes in BPMN.

## 5. BPMN best practices in healthcare

This section presents the challenges and best practices for modeling healthcare processes in BPMN. For giving an overview of the selected challenges and related best practices, we start from the general structure of a healthcare process [31] and consider the six high-level activities shown in Fig. 5. In general, a healthcare process modeling initiative might focus only on selected aspects of a specific treatment or on the complete care process for a specific patient group. However, regardless of the scope of the modeled processes, there exist some common aspects of care practice that contribute to increasing the complexity of modeling a healthcare process.

Fig. 5 shows the modeling challenges identified in Section 4 categorized in (1) patient-related, (2) medical practice-specific, and (3) medical resource-related challenges. For them, we aim to provide some BPMN best practices to support process modelers in capturing complex aspects of healthcare processes. As previously mentioned, in this paper, we focus on processes that are enacted within the boundaries of a single medical organization. That is, we do not consider best practices for cross-organizational healthcare processes describing the interactions between different healthcare organizations.

In the remainder, we discuss the salient features of the challenges introduced above; for each challenge, we discuss possible BPMN best practices that address the respective challenge entirely or partially. Thereby, we structure the description of each challenge as follows:

- An overview of a representative clinical situation;
- The challenging aspects of modeling it in BPMN;
- Best practice modeling solution as ready-to-use BPMN fragments. When possible, we discuss different solutions (identified by a numerical enumeration) for capturing the same aspect. Further, we propose, where possible, best practices at different levels of process abstraction (c.f. Section 2): descriptive process models (D) – i.e., suitable for high-level documentation purposes, analytic process models (A) – i.e., suitable for analysis purposes, and implementable process models (I) – i.e., suitable to prepare an implementation. These abstraction levels should be understood as proposals.

### 5.1. Patient-related challenges

In this paragraph, we describe patient-related challenges and illustrate the proposed BPMN best practices. As already mentioned, the key entity of a healthcare process is a human being, who usually moves independently through the healthcare organization and interacts with different health workers. Representing the involvement of a patient in care activities (C1) is already one of the most prominent challenges. Besides, healthcare processes are flexible enough to react to different and changing patient-specific needs, among which we distinguish foreseen (C2) and unforeseen (C3) needs.

#### 5.1.1. C1 – involvement of the patient

In contrast to traditional processes acting on a product or documents, activities of a healthcare process are executed together with a patient – a human being with wishes, expectations, fears, etc. [25]. Patients bring documents, they may move on their own through a healthcare organization, they are usually actively involved in therapeutic decisions, as exemplified in [71], and they have to give consent to treatment or to the sharing of personal data. In healthcare processes, patients may have an active role (e.g., if a patient has to agree to therapy) and a passive role (e.g., when a patient undergoes blood testing).

BPMN assumes that a business case is usually executed based on its documents, which are read or written by activities [8]. Certain interactions with a customer, e.g., the update of the customer's address, are shown as message flow between the main process and the customer, who is represented in a separate pool. Although some healthcare activities can be executed based on patient documents or patient samples (e.g., blood analyses make use of blood samples), the majority of the activities are actually happening together with the patient, be it actively or passively. Thus, the challenge is to understand how and at which abstraction level the patient and his/her involvement in the healthcare process should be represented.

Table 3 shows the different abstraction levels that we identified to represent the patient's involvement in BPMN. We suggest using option (D) for most of the activities in a healthcare process to have a more readable model. However, if the patient plays an active role in the process that cannot be disregarded, e.g., he/she has to deliver certain medical documents, needs to give consent to treatment, or has to make a decision, then we suggest to

**Table 3**

C1 involvement of the patient.

### C1 Involvement of the Patient

**Description:** Healthcare processes are executed together with a patient – a human being who is involved and consulted during the medical procedure.

**Challenge:** How and at which level of abstraction should the patient and his/her interaction with the medical organization be represented in a BPMN healthcare process.

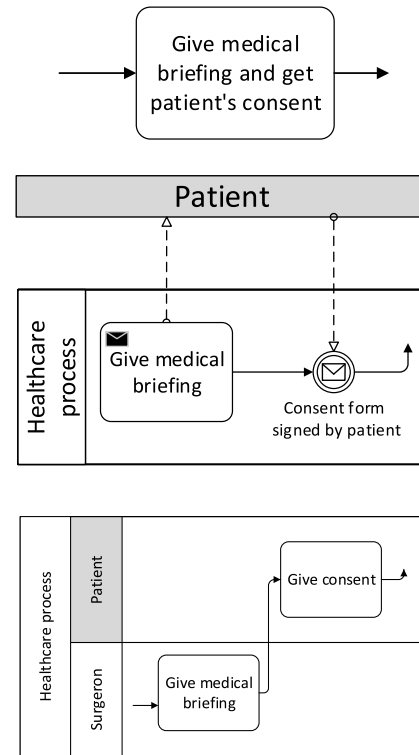
#### Proposed BPMN Best Practices:

Different abstraction levels can be used to represent the patient's involvement.

(D) The patient's involvement is hidden within a certain activity.

(A) The patient is shown as an independent pool. In this setting, the patient is not considered part of the healthcare organization, and the interaction with it is realized through message flows.

(I) The patient is represented as a lane in the healthcare process. In this setting, the patient is considered part of the healthcare organization and plays an active role.



represent this explicitly through option (A). Option (I) is a relevant alternative if the process model is used for implementation purposes. Indeed, if the patient should have a distinct role in the healthcare system, then it is essential to represent the patient as a lane to consider him/her when implementing user interfaces.

#### 5.1.2. C2, C3 patient-specific needs

Being driven by the individual needs of a patient, healthcare processes tend to be highly dynamic and subject to changes.

Clinical practice guidelines [37] and clinical pathways [72] are powerful methods for the standardization and streamlining of care based on medical knowledge, typically aiming to increase quality of care while decreasing costs [24]. However, the healthcare processes implementing such guidance need to be flexible to meet individual patient needs. Indeed, although the main therapeutic activities may be predefined, their course of action may change based on clinical evidence and organizational factors, such as resource availability. Thereby, we distinguish between foreseen and unforeseen patient needs and situations.

**C2 - patient-specific needs (foreseen).** Core diagnostic and treatment activities are usually described based on clinical guidelines, which serve as a standard reference for the care process. However, specific categories of patients may require the enactment of additional or slightly different diagnostic and treatment activities [18,24], e.g., if diagnostic results are inconclusive or the

patient shows adverse reactions to a certain drug. Such changes in the way certain activities are enacted lead to the definition of different process variants. The fact that patients require slightly different executions of a healthcare process based on their characteristics and needs, is known as *process variability* [73] in the BPM domain and different approaches exist to support the modeling of process variants [74]. However, capturing different process variants leads to more complex process diagrams, especially when using imperative process modeling languages. To abstract from such complexity, foreseen changes may be represented at different levels of abstraction and with different solutions, as shown in Table 4.

Option (D) should be used mainly for documentation purposes because of its compactness. However, the annotations have no execution semantics, such that option (AI<sub>1</sub>), which explicitly outlines specific process variants, is more suitable for analytical and implementation purposes. It considers different alternatives for the same activity or process path. Option (AI<sub>2</sub>) should be used to react with alternative/additional activities to the occurrence of relevant events. Finally, option (AI<sub>3</sub>) allows even more flexibility by having a set of individual, executable activities.

**C3 - patient-specific needs (unforeseen).** In this paragraph, we focus on unforeseen patient needs, i.e., exceptional situations that may cause changes or interruptions in the healthcare process [18,24]. In the literature, this is discussed at a generic level

**Table 4**

C2 patient-specific needs (foreseen).

**C2 Patient-specific Needs (Foreseen)**

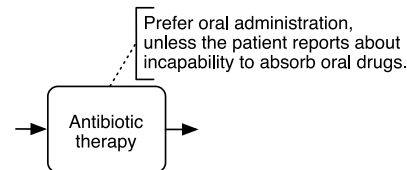
**Description:** Patients have different characteristics and requirements that need to be considered in the execution of a healthcare process. Points of variability in the healthcare process might exist to meet different patient needs.

**Challenge:** The reflection of different patient needs increases the complexity of a BPMN process diagram. Thus, the challenge is to understand how and at which abstraction level different process variants should be represented in a BPMN healthcare process for handling this complexity.

**Proposed BPMN Best Practices:**

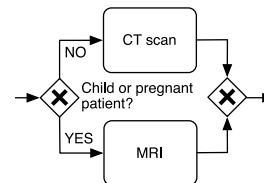
Different abstraction levels (D) and (AI) can be used to represent BPMN process variants and different solutions can be used to capture different aspects of flexibility (AI<sub>1</sub>)–(AI<sub>3</sub>).

(D) Activities are represented at a high, abstract level. BPMN annotations can be used to describe variations at a documentation level.

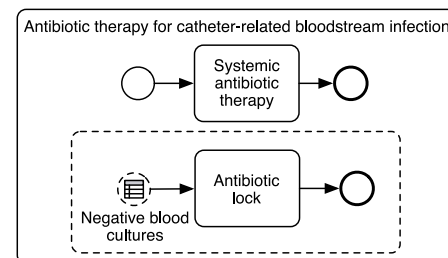


(AI) Different variants are represented in detail for analytical and implementation purposes, using different solutions to capture flexibility, namely exclusive gateways, event-sub-process or an ad-hoc sub-process.

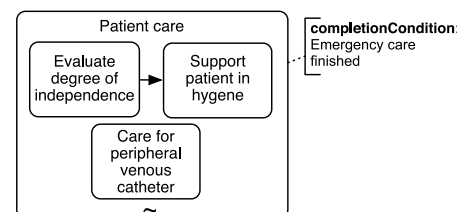
(AI<sub>1</sub>) An exclusive gateway is used to explicitly outline two or more variants, which represent alternative ways of doing a certain activity or process, which are chosen based on the needs of a specific patient.



(AI<sub>2</sub>) An event sub-process is used to execute activities that are alternative or additional to the main process flow. It is triggered by certain events or patient conditions occurring during the healthcare process or in a specific phase of a healthcare process, represented as a sub-process. Based on its configuration, the event sub-process can interrupt the main process execution or be executed in parallel.



(AI<sub>3</sub>) An ad-hoc sub-process can represent individual executed activities for a patient. Activities with an ad-hoc sub-process can be executed never, once, or multiple times until reaching the completion condition.



in the sense that all kinds of exceptions can occur [18]. In this work, we focus on two common unforeseen needs: (1) patient conditions change suddenly and the planned treatment cannot be continued [21], and (2) the initial diagnosis is disproved and the patient needs to enter a different healthcare process.

Table 5 shows the best practices for (1), which rely on BPMN boundary events, and for (2), which is based on the concept of event-sub-process [8]. For suddenly changing conditions, we propose two options based on different levels of process abstraction. Option (D) is useful for documentation purposes and shows that the process is interrupted because of such changes. Option (AI) is suitable for analytical and implementation purposes, and captures in detail that the changing conditions can be managed concurrently to the main healthcare process. These best practices

also inspire solutions for other similar exceptional situations that require changes to the planned healthcare flow.

## 5.2. Medical practice-specific challenges

In this section, we describe the medical-related challenges and illustrate the related BPMN best practices.

Medical activities have some specifics which are less observed in other more structured process domains – we refer to them as medical practice-specific challenges. During the patient assessment, treatment plan definition, or the review of treatment, medical experts have to make essential decisions for patient care. These are usually made by relying on medical evidence

**Table 5**

C3 patient-specific needs (unforeseen).

**C3 Patient-specific Needs (Unforeseen)**

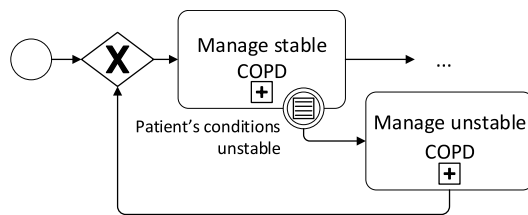
**Description:** Healthcare processes need to handle unexpected changes caused by the sudden worsening patient's conditions or wrong diagnoses.

**Challenge:** The representation of unexpected changes caused by different patient needs increases the complexity of a BPMN process diagram.

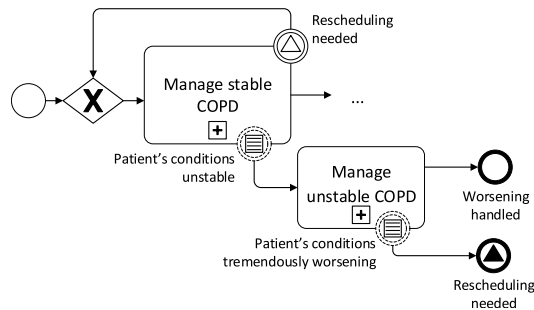
**Proposed BPMN Best Practices:**

(1) **Sudden changing of patient's conditions** can be caught by a conditional event placed on the boundary of the healthcare process (or parts of it) captured as sub-process. The worsening of the patient's conditions can be handled by a dedicated sub-process.

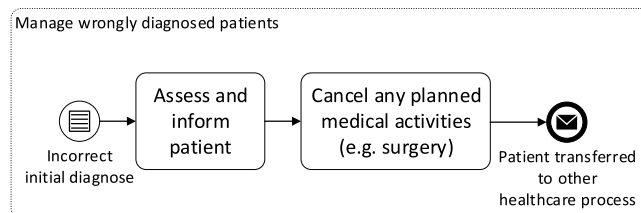
(D) The main healthcare process, e.g., the one shown below for managing Chronic Obstructive Pulmonary Disease (COPD), is interrupted because of a change in the patient conditions and repeated at a later time.



(AI) The changing of the patient's conditions is handled by a sub-process running concurrently to the main process and triggered by a non-interrupting boundary event. Only if the conditions can not be improved shortly, the main process is interrupted and repeated later.



(2) **Wrongly diagnosed patients** can be handled by an event sub-process which transfers the patient to another healthcare process.



systematically collected in CPGs, the state of the art in medical knowledge, and by considering the information about the patient. As a result, healthcare processes are characterized by frequent evidence-based decision-making (C4) tasks. Furthermore, diagnostic and treatment activities are time-sensitive and therefore require advanced temporal constraints (C5) to be observed during care delivery. Last but not least, monitoring activities (C6) play a crucial role in the observation of the patient's health conditions.

#### 5.2.1. C4 – evidence-based decision-making

Medical activities, such as diagnosis and treatment, are driven by observations, experiential evidence, and the decision-making of a medical expert. Lenz and Reichert [22] describe them as a diagnostic–therapeutic cycle in which patient-related information and medical knowledge are used as input for the decision-making by a medical expert. Evidence-based decision-making requires evidence for a specific decision based on existing medical knowledge, usually captured in CPGs, which provide recommendations for decision-making based on literature reviews and the best available evidence [31]. The results of the decision-making trigger the execution of certain diagnostic or treatment activities for a patient. Thus, in healthcare processes, it is common

to find one or several decision-making activities that trigger (patient-specific) diagnostic or treatment activities.

Evidence-based decision-making is not explicitly supported by BPMN [18]. Thus, Braun et al. [18] extended BPMN in order to properly manage evidence-based decision activities, the information referenced by CPGs and the relevant decision logic in a CPG to diagnose or treat a certain patient group. However, this is not supported by any existing BPMN modeling tools. Combi et al. [29] employ user tasks to model evidence-based decision-making activities. Additionally, BPMN provides business rule activities that can be used to represent operational decisions that are made according to particular decision logic, which can be directly linked to a DMN model [11]. This combination of BPMN and DMN is applied also in [30] to design decision-intensive care pathways. In clinical practice, it is challenging to select the best fitting CPG to the clinical environment as usually a broad range of CPGs are published for a specific disease. Another challenge is how to proceed if multi-morbid patients have to be handled. We assume that the selection of the CPGs and the possible ways to take care of a multi-morbid patient are determined by the clinical experts before the healthcare process modeling. Thus, the

**Table 6**  
C4 evidenced-based decision-making.

## C4 Evidenced-based Decision-Making

**Description:** Healthcare processes are driven by the decisions made by medical experts for diagnosing and treating patients. They rely on the best available evidence for justifying the decision.

**Challenge:** The concept of evidence-based decision-making is not a traditional aspect of industrial processes, and there is no specific concept for it in BPMN. However, business rule activities can be used to document the decision-making logic in combination with DMN.

### Proposed BPMN Best Practices:

Different abstraction levels can be used to represent evidence-based decision-making in healthcare processes. Each of the presented abstraction levels shows the decision logic with an increasing level of detail:

(D) The decision-making activity is modeled as a simple user task using relevant patient information (shown as input data objects). For representing the documentation of the decision, a data output object is connected to the user task.

```
graph LR; PR1[Patient record] --> D[Decide on treatment]; X[X-rays] --> D; D --> PR2[Patient record];
```

(DA) The decision-making activity is shown as a business rule task connected to a DMN model consisting of a high-level DRG visualizing the required inputs to the decision. Documents used as a reference for the decision, e.g., a CPG chapter or section, can be represented as knowledge sources in the DRG.

```
graph LR; PR1[Patient record] --> D1[Decide on treatment]; X1[X-rays] --> D1; D1 --> PR2[Patient record]; D1 --> D2[Decide on treatment]; D2 --> CPG[CPG chapter];
```

(AI) The decision-making activity is shown as a business rule task connected to DMN model with a DRG and a defined decision logic represented as a decision table.

```
graph LR; PR1[Patient record] --> D1[Decide on treatment]; X1[X-rays] --> D1; D1 --> PR2[Patient record]; D1 --> D2[Decide on treatment]; D2 --> CPG[CPG chapter];
```

| Unique | Patient record.Age | X-rays.highDamage | Treatment       |
|--------|--------------------|-------------------|-----------------|
|        | [1..110]           | Boolean           |                 |
| 1      | <=16               | TRUE              | Apply cast      |
| 2      | <=16               | FALSE             | Apply bandage   |
| 3      | >16                | TRUE              | Perform surgery |

modeling challenge is how to represent evidence-based decision-making activities in a BPMN process diagram, and further, if decision models are used, how to apply them to semi-formalized medical guidelines. Different abstraction levels can be employed to represent a decision-making activity, as shown in Table 6.

Option (D) should be used for cases where the decision-making is mainly driven by the medical expert and not supported by any guideline/standard. Option (DA) is suitable if a decision-making activity is supported by a CPG or internal standard. Option (AI) can be used if the decision rules are given in detail (e.g., in a CPG or in an internal document) so that the decision logic can be specified in a decision table to assist the medical experts in applying it or to use it as implementation blueprint. The advantage of explicitly using these different abstraction levels is that the existing support of decision-making is explicitly visible. Process analysis and redesign initiatives can analyze whether (D) decision user activities require increased support in order to streamline patient care. DMN models, as proposed in (DA) and (AI), can also support digital transformation initiatives as they show which data, guidelines, and decision logic has to be

made available to the medical expert to conduct decision-making activity.

5.2.2. C5 – temporal constraints

Temporal phenomena, and especially temporal constraints, play a significant role in healthcare domains [18,27], encompassing both administrative and medical activities. Proper process design entails the need for managing temporal constraints and coordinating the constraint-based interactions among the processes contributing to the overall patient treatment [23].

However, BPMN offers limited (direct) support to the modeling of the temporal perspective [27] as witnessed by recent works aimed to improve such support [23,26,75]. Indeed, although BPMN includes timer events, these cannot be used directly to capture all the above-introduced time constraints. In particular, BPMN supports three kinds of temporal constraints, namely (1) maximum activity duration, (2) waiting time between subsequent activities, and (3) iteratively performed activities. All these constraints can be represented with timer events as shown in Table 7.

Table 7

C5 temporal constraints.

**C5 Temporal Constraints**

**Description:** Healthcare processes witness several kinds of temporal constraints requiring proper specification and management.

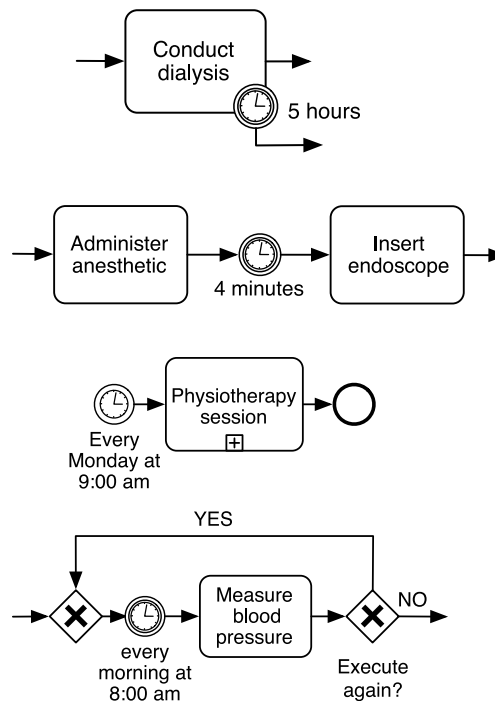
**Challenge:** BPMN offers limited (direct) support for modeling temporal constraints. Although timer events exist, they lack formal semantics and they support only a few temporal aspects.

**Proposed BPMN Best Practices:** In the following, BPMN best practices for temporal constraints, which can be supported by existing BPMN elements are introduced:

(1) **Maximum activity duration:** An interrupting timer event can be placed on the boundary of an activity to interrupt it after a certain amount of time has elapsed.

(2) **Waiting time between subsequent activities:** A timer event can be placed between two subsequent activities to set the minimum amount of waiting time between two activities.

(3) **Iteratively performed activities:** A start timer event with a specified time cycle can be used to trigger a process periodically, e.g., every Monday at 9.00 am. Iterations of activities can be realized through an intermediate timer event with a specific time cycle, which is enacted every time the control flow leading to it is chosen.



In our projects, we often observed more complex time constraints, e.g., a minimum activity duration (e.g., “aftercare needs to last at least 30 min”). To capture more complex temporal constraints, such as time-lags, minimum activity duration, schedule-restricted elements, and maximum patient waiting time, we suggest relying on BPMN extensions proposed in the literature. In particular, the proposal presented in [75] allows representing temporal constraints in a user-friendly manner, by defining constraints as activity attributes and by representing them on the process model through graphical icons, text annotations, and different kinds of edges, as shown in Fig. 6. Duration constraints and time-lags can be easily specified, whereas constraints such as “Start As Soon As Possible”, “Start No Later Than”, can be used to capture the maximum patient waiting time and to define schedule-restricted elements. Fig. 6 shows the graphical notation for a time lag of 12 to 24 h between the start of Activity 1 and the end of Activity 3, the minimum duration of 1 h and maximum duration of 3 h on Activity 1 and a constraint “Start No Later Than 10 am” on Activity 2.

An approach fully based on standard BPMN elements for capturing duration constraints is presented in [26]. Being completely based on BPMN semantics, this approach may be useful for implementation purposes, but can be complex for documentation purposes.

### 5.2.3. C6 – monitoring activity

Monitoring activities refer to continuous or repeated activities involving the observation of the patient, the measurement of

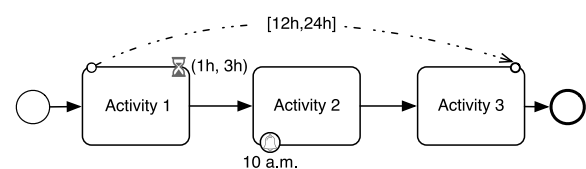


Fig. 6. Example of process with temporal constraints represented through the extension proposed in [75].

his/her physiological function, and the assessment of life support equipment. Usually, monitoring runs in parallel with other diagnostic or therapeutic activities to check their efficacy and possibly adjusting them [63].

Continuous monitoring is common practice in intensive care settings and is realized with the help of (electronic) sensors and data processing devices (e.g., continuous EEG, transducers, glucose monitoring systems) that monitor the vital signs of the patient in real-time. These systems are able to detect significant changes in the patient's conditions and to accordingly prompt alarms to alert care professionals. Instead, repeated monitoring activities consist of clinical observations carried out regularly by care professionals, typically several times per day. Although clinicians may rely on devices, the human role in this kind of monitoring activity is predominant. Examples of repeated monitoring are drug therapy assessment, blood pressure measurement, and catheter surveillance. Changes of patient conditions

**Table 8**

C6 monitoring activity.

**C6 Monitoring Activity**

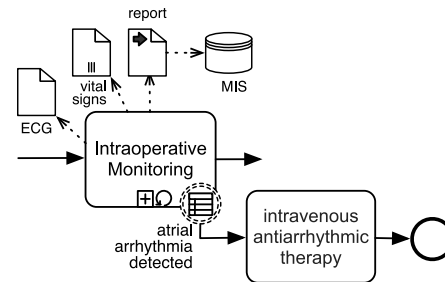
**Description:** A monitoring activity is performed continuously or repeatedly, requiring data acquisition and the possibility to adapt parallel running diagnostics or treatments.

**Challenge:** Represent monitoring activities considering (a) their continuous or repeated character, (b) the acquisition and processing of monitoring data, and (c) the detection and management of changes of the patient's condition.

**Proposed BPMN Best Practices:**

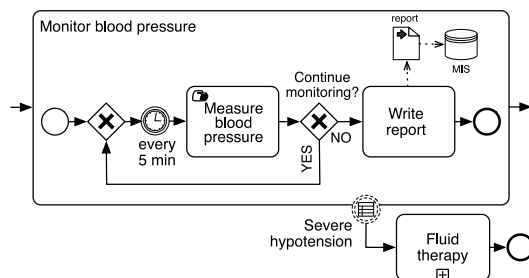
Monitoring activities can be represented at different abstraction levels:

(A) As a collapsed sub-process: in this case looping is defined at the sub-process level, data are generated from the sub-process and conditional events are non-interrupting and attached to the boundary of the sub-process.

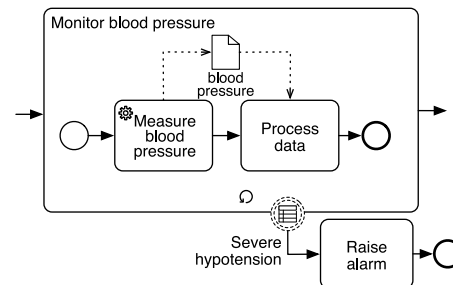


(I) As an expanded sub-process, for which we can distinguish between (I<sub>1</sub>) manual monitoring, realized periodically by a clinician, and (I<sub>2</sub>) automatic or semi-automatic monitoring, realized with the help of devices.

(I<sub>1</sub>) The clinician checks by monitoring periodically, and in the end provides a monitoring report. Boundary conditional events attached to the monitoring sub-process capture any relevant change and initiate an adjustment activity.



(I<sub>2</sub>) The automatic or semi-automatic character of device-based monitoring is captured by a loop defined at the sub-process level. Data are continuously generated and processed by the monitoring device.



detected during monitoring can be seen as events that need to be interpreted and managed in parallel to the diagnostic/treatment activities – these events may also prompt process adaptation (as also described in the challenges C2 and C3). As an example, consider the self-monitoring of glucose blood levels in patients affected by diabetes. Glucose monitoring is crucial to prevent hypo- and hyperglycemic excursions and can be realized in real-time, e.g., with the help of a wearable sensor device, or manually, with the help of a glycemic reader [76]. Patients can adjust their diet or insulin intake based on the measured glycemic level.

The challenge of representing monitoring activities in BPMN is the complexity, consisting of three aspects which need to be considered: capture the continuous or repeated character of monitoring activities, the generation and processing of monitoring data, and the detection of significant changes in such data and the possible adaptation of parallel running diagnostic or treatment activities [69]. Monitoring activities can be represented at different abstraction levels in a BPMN process diagram, as shown in Table 8. In detail, option (A) should be used when the

focus is on representing continuous execution and data elements, but the details on how the monitoring takes place are hidden in the sub-process. Instead, options (I<sub>1</sub>) and (I<sub>2</sub>) are useful for implementation, as they show the details of the monitoring sub-process. We can distinguish between (I<sub>1</sub>) manual monitoring (manual task), which is realized periodically by the medical staff who takes care of the monitoring, and (I<sub>2</sub>) automatic or semi-automatic monitoring (service task), which is conducted with the help of electronic medical devices and requires the clinician to interpret data.

### 5.3. Medical resource-related challenges

Medical staff and machines are often highly specialized and, thus, scarce and cost-intensive, thus giving rise to some medical resource-related challenges. Here, we focus on the involvement of multidisciplinary teams in clinical activities (C7), which is traditionally not considered in BPMN, on the centralized scheduling

**Table 9**  
C7 shared working behavior.

### C7 Shared Working Behavior

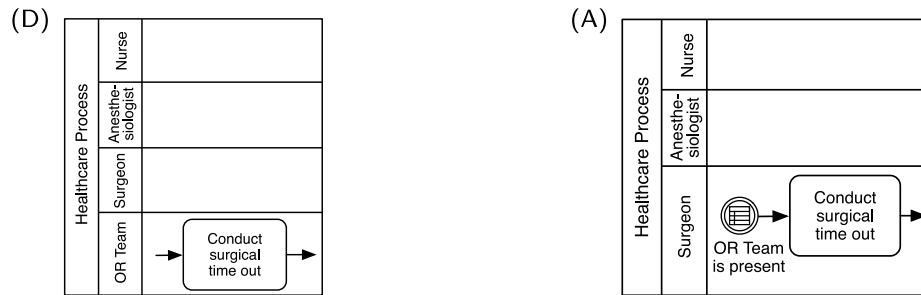
**Description:** For providing a good quality of care to patients, often multidisciplinary teams work together. Shared working behavior can be observed in the following forms: (1) several specialists work together on a shared activity, (2) an activity can be alternatively performed by different roles, or (3) an activity can optionally involve additional resources.

**Challenge:** The concept of lanes, used in BPMN for representing the responsibility of persons, roles, or units for certain tasks, is rather inflexible and not ideally suited for showing the flexibility of resource assignments in medical organizations.

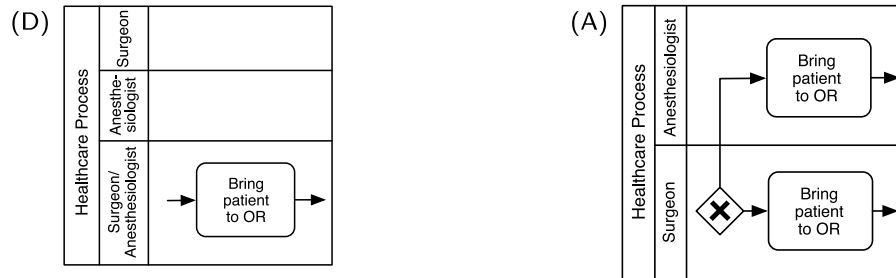
#### Proposed BPMN Best Practices:

The following best practices capture different kinds of shared working behavior:

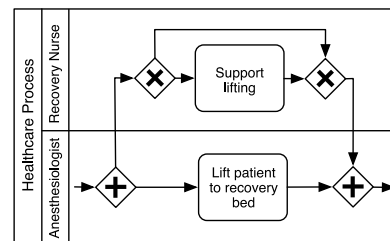
(1) **Shared activities** can be represented by an extra lane for a group of resources (e.g., OR team in (D)). This is especially suitable for multiple shared activities. Otherwise, (A) assigns the activity to the team leader with a conditional event requesting the presence of all other resources. Here no extra lane is necessary.



(2) **Alternatively performed activities** can be shown in an extra lane, where alternative roles are enumerated, as shown in option (D). This is useful if several such activities exist. In (A) the activity is added to all lanes of the possible responsible resources preceded by an XOR gateway, which implies that only one path can be followed.



(3) If an activity can be **optionally supported**, the supporting activity is shown in parallel to the main task in an XOR-construct for expressing that it is optional.



of patients (C8) motivated by the scarce and cost-intensive resources, and on the need of centralized treatment and diagnostic services at the service of different healthcare processes (C9).

#### 5.3.1. C7 – shared working behavior

Healthcare processes are often executed by multidisciplinary teams in order to provide the best healthcare service to a patient. This phenomenon has been extensively studied by Müller and

Rogge-Solti in [16], who identified the following scenarios for shared working behavior in healthcare processes: (1) several specialists work together on a shared task, (2) different roles can alternatively perform an activity, and (3) an activity can optionally involve additional roles. In BPMN process diagrams, the concept of lanes, which subdivide a pool, can be used to assign persons, roles, or units to activities [8]. All activities added to a specific lane are in the responsibility of the person, role, or unit

**Table 10**  
C8 centralized scheduling of patients.

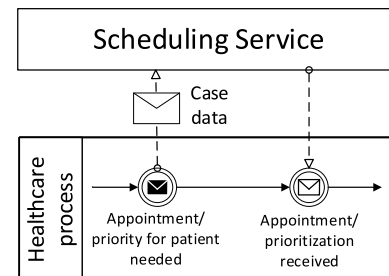
### C8 Centralized Scheduling of Patients

**Description:** Healthcare organizations need to schedule patients during the execution of healthcare processes to treat patient with the highest demand and to manage their scarce and cost-intensive resources efficiently.

**Challenge:** A BPMN process diagram focuses on the execution of individual cases of a process but cannot show the inter-dependency between cases, such as their order of treatment.

#### Proposed BPMN Best Practice:

The scheduling can be outsourced in an independent pool, where the information of the cases running in parallel can be collected. The output of the scheduling, e.g., an appointment, is then transferred back to the respective healthcare process. If details of the scheduling are of relevance, then the pool of the service can be expanded to design the process in detail.



assigned to this lane. Lanes make the representation of shared work and flexibility in healthcare processes more challenging and the flexibility in healthcare processes.

Müller and Rogge-Solti in [16] discuss several solutions on how shared tasks can be presented in BPMN process diagrams. Based on our experience gained through the conducted healthcare modeling initiatives, we suggest different best practices to capture the different kinds of shared working behavior introduced above. The best practices are shown in Table 9.

The proposed best practices use existing elements of BPMN process diagrams. Other proposals based on newly introduced, non-standard elements can be found in [16]. Our suggestions focus on the usage of the swimlane concept delineated in BPMN, which may help to understand the role of different participants and the activities they perform for documentation or analysis purposes. If the process model is designed for implementation purposes, swimlanes are often not used, as the information about resources is hidden in the properties of the activities. This solution can be considered if the involvement of the medical staff is not relevant for the process.

#### 5.3.2. C8 – centralized scheduling of patients

Healthcare processes are from time to time confronted with the situation that the number of patients requesting a medical service is higher than the number of resources available at a specific moment. Each patient has a different level of clinical priority based on which the care plans are scheduled. For example, for emergency care, patients' priority and their maximum waiting times are often defined based on the Manchester Triage system [77]. Based on this information, patients are dynamically scheduled, and treatment priorities are defined.

On the other hand, resources such as operating rooms need to be used efficiently. Similarly to the manufacturing area, the right order of surgeries can play a role in avoiding changeover times [50]. Thus, the scheduling of patients is also needed in healthcare processes with scarce and cost-intensive resources (e.g., operating rooms, medical imaging systems [68]). Although, this is especially a challenge of the process implementation, where specific resource planning or allocation mechanisms need to be used, we want to discuss in this part the related modeling challenge.

A BPMN process diagram traditionally represents the possible execution sequences of a specific set of process cases (or

instances). Thereby, it is assumed that these process cases have an independent existence and are executed without reference to each other [78]. When patients need to be ordered based on their medical priority or scheduled for appointments, several process cases running in parallel need to be enacted. However, running cases cannot be represented in a single BPMN process diagram.

We propose to represent the scheduling in an additional pool, as shown in Table 10.

#### 5.3.3. C9 – involvement of diagnostic and treatment services

In hospitals, certain diagnostic or treatment activities are organized centrally, such as radiologic tests, laboratory analysis, etc. [79]. They usually require certain specialists and equipment and are used within different healthcare processes running in a hospital. For example, blood analyses or X-ray scans can be requested during emergency care as well as during the pre-surgical consultation. Often, the service is requested via phone or over an IT system with all patient-related information [68,69]. Subsequently, if the patient is needed for the diagnostic or treatment service, the patient is sent to the responsible department, e.g. radiology. Instead, in the case of blood or laboratory analyses, only the sample has to be sent to the laboratory. The healthcare process can continue as soon as the results are received and, if the patient is needed for the diagnostic service, the patient is back. The single healthcare process usually does not influence the design and execution of the service process. In most cases, diagnostic and treatment services are individually running processes that collaborate with the to-be modeled healthcare processes [48, 65,68]. Thus, in a BPMN diagram, the service process needs to be presented as an own pool which communicates via message flow. Here, the challenge is to represent this interaction efficiently, also involving, in many cases, the patient.

We propose to use a collapsed pool to represent the diagnostic or treatment service to abstract from the details of the service execution, as shown in Table 11. In case that the details of the diagnostic/treatment service are relevant, an expanded pool can be used to capture the service process. We distinguish between two versions, i.e., (1) where only a sample from the patient is needed (e.g., a blood sample) and (2) where also the patient is needed (e.g., a radiologic test).

**Table 11**

C9 involvement of diagnostic and treatment services.

**C9 Involvement of Diagnostics and Treatment Services**

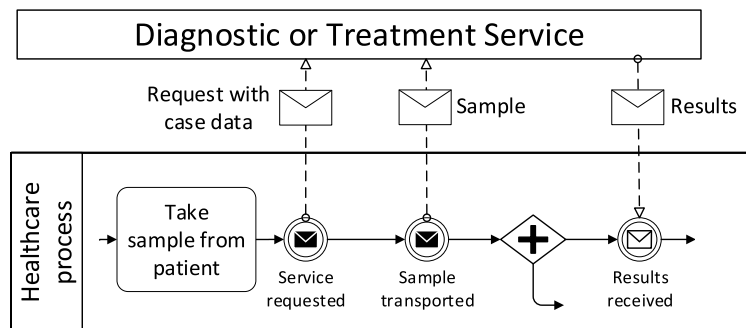
**Description:** Due to specialized personnel and equipment in healthcare organizations, some diagnostics and treatment services are centralized, and used within different healthcare processes, e.g., radiologic tests, blood analyses. Services are requested and the healthcare process is continued as soon as both the results and the patient are available again.

**Challenge:** The service is an individual running process collaborating with the healthcare process. In a BPMN diagram, the service needs to be presented in an own pool, interacting via message flow. The challenge is the effective presentation of this interaction, which usually also involves the patient or samples by the patient.

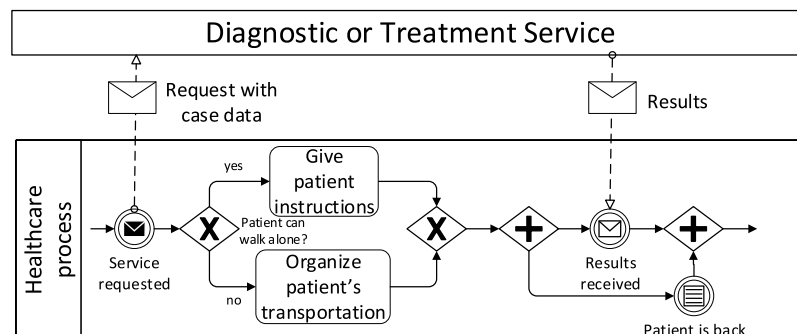
**Proposed BPMN Best Practice:**

The following best practices capture different kinds of interactions with a diagnostics/treatment service:

(1) **Sample from patient needed:** The healthcare process starts with taking a sample from the patient e.g., a blood sample. Then, a request via a throwing message event is sent, as well as the sample is transported to the service. The healthcare process might continue but also needs to be ready to receive the results with the help of a receiving message event in parallel to the continuing process flow. If the details of the diagnostic/treatment service are of relevance, then its respective pool can be expanded, and its process can be designed.



(2) **Patient needed:** If the patient is needed for the service (e.g., radiologic tests), the healthcare process sends a request via a throwing message event to the diagnostic/treatment service. Then, the patient is either provided instructions about where to go or, if the patient cannot walk on his/her own, transportation is organized. The process can continue as soon as the results are received (catching message event) and the patient is back (conditional event). If the details of the diagnostic/treatment service are of relevance, then its respective pool can be expanded, and its process can be designed.

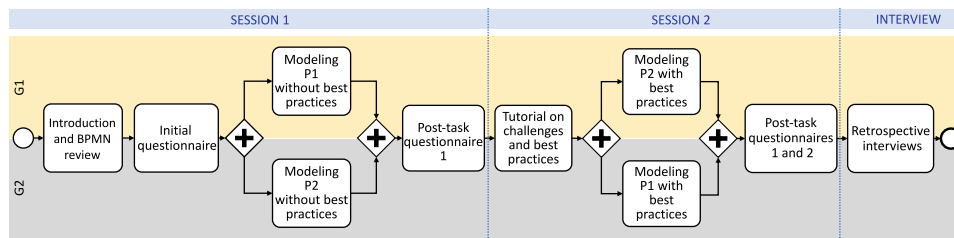
**6. A first evaluation of the best practices**

To evaluate the usefulness of the proposed best practices, we followed an exploratory approach to understand how the proposed best practices support process designers in modeling the challenging aspects of healthcare processes introduced in

Section 5. In this section, we describe the planning and execution of our study and report the findings.

**6.1. Exploratory study design and execution**

In this study, we investigate how process modelers use and perceive the best practices in the context of a process modeling



**Fig. 7.** Main steps of the conducted exploratory study, represented as a BPMN process. The colored bands and lines are used only for presentation purposes.

task. Specifically, we are interested in exploring how the use of the best practices is reflected in the obtained process models and how modelers perceive the usefulness of the best practices. Accordingly, we define the following two research questions.

- (RQ1) *How does the use of the best practices support the task of healthcare process modeling?* With RQ1, we investigate how the best practices are used in the modeled processes and whether they have an impact on the syntactic and semantic quality of the obtained models.
- (RQ2) *How do process modelers perceive the usefulness of the best practices?* With RQ2, we aim to gain insights into the perceived usefulness of the proposed best practices.

**Participants.** The proposed best practices are meant to support process modeling in healthcare organizations. Specifically, they are addressed to healthcare stakeholders experienced in process modeling with BPMN and business process modelers and analysts with experience in healthcare. Thus, for our evaluation, we target both healthcare and IT experts who are to some degree familiar with process modeling in BPMN. We want to avoid that participants encounter problems due to their lack of BPMN knowledge but also want to observe if our best practices can be used by participants that are moderately familiar with BPMN.

**Materials.** For our evaluation, we developed different materials. First, we prepared textual descriptions of two healthcare processes, P1 and P2. Each process included six of the modeling challenges introduced in Section 5, such that all challenges were covered. The process descriptions were derived from clinical guidelines and pathways related to real-world healthcare processes: P1 was taken from the clinical pathway for COPD presented in [29,30], while P2 was designed to include main diagnostic and treatment steps of acute appendicitis in emergency care [80]. We prepared the descriptions selecting relevant parts of the guidelines and balancing them in terms of the number and kind of BPMN elements needed in the expected solutions. We also prepared the best practice solutions for P1 and P2 to be able to compare the process models designed by the participants. Besides, we prepared a handout summarizing all the challenges and best practices, formatted as in Tables 3–11. However, options (AI<sub>3</sub>) for C2 and (1) for C9 were not included in the handout since they were added after our study, as discussed in Sections 7 and 6.2. Moreover, we designed an initial questionnaire to collect demographics and learn about the participants' process modeling and healthcare expertise and two post-task questionnaires. The first post-task questionnaire included multiple choice and open questions about the modeling task; the second included multiple-choice questions about the perceived usefulness of the best practices. Finally, we prepared a semi-structured protocol for the retrospective interviews, including general questions about the process modeling task, modeling choices, difficulties faced during the modeling task, and the perceived usefulness of the best practices.

**Design.** Fig. 7 shows the design of our study, which we organized into two sessions, each one centered around a modeling task, and a retrospective interview. The first session aims to investigate how participants deal with modeling challenges in absence of the best practices. The session begins with an introduction to the modeling tasks and a review of the main BPMN concepts. Then, we administer the initial questionnaire to gather information about the participants' background in process modeling and their experience as healthcare workers. For the modeling task, we follow a within-subjects design [81] and randomly divide participants into two groups, G1 and G2. For the first session, we ask participants in G1 to model P1 starting from its textual description and participants in G2 to do the same with P2 (cf. Fig. 5). Then, we administer the first post-task questionnaire to both groups. The second session focuses on investigating how participants deal with the modeling challenges with the best practices at hand. Initially, we provide a 30-minute tutorial to introduce the challenges and best practices. Then, we switch the process descriptions between groups and ask participants to model the processes with the help of the best practices, which remain at their disposal for the whole duration of the task. Then, we administer the two post-task questionnaires. Finally, we conduct semi-structured interviews with selected participants to learn how they perceive the process modeling task without and with the best practices and why they made specific modeling choices.

**Execution.** The study was conducted between November and December 2019 at the University of Potsdam, Germany. Participants were 28 graduate students attending the course "business process analysis in healthcare" which is part of the master's program in Digital Health. Our participants have varied backgrounds: 13 of them hold either a degree in medicine or medical and pharmaceutical sciences, 8 in IT-related subjects, three in biomedical or biotechnology engineering, two in healthcare management, and two in neuroscience and psychology. Regarding the requirements for participation, we would like to note that our participants are representatives of junior experts in IT and healthcare. Indeed, most of them have enrolled in the study program to obtain an additional qualification and have already gained significant experience in their field of study, as reported in the initial questionnaire. In detail, 18 participants have advanced or professional healthcare expertise, while 8 of them have advanced or professional IT expertise. Moreover, 13 participants had already gained working experience in a hospital at the time of the study, either as medical personnel or as quality consultants and hospital administrators. Speaking of process modeling experience, our participants indicated having designed a varying number of process models, with 6 participants reporting zero process models, 18 of them reporting 1–5 process models and four of them indicating 10–20 process models. However, since all participants had followed the introductory lectures about process modeling in BPMN (approximately 13 h covering teaching and guided studying), we could ensure that they have the BPMN modeling skills necessary for the study. Each session (cf. Fig. 7) lasted about 1.5 h, with 45 min

dedicated to the modeling task. After both modeling tasks were completed, we reviewed the process models designed by the participants in both sessions, focusing on the modeling challenges and evaluating their syntactic and semantic quality. To follow up on our evaluation, we interviewed nine participants, whom we selected considering both their different backgrounds and the low or high quality of the designed process models.

**Data analysis.** For each participant, we collected two process models, one designed without and one with the help of best practices. We also collected data in the post-task questionnaires and complementing interviews. For addressing RQ1, we focused on the obtained process models. In detail, for the models designed during the first session (i.e., without the best practices), we reviewed how participants tried to capture the challenging aspects and whether their modeling solution was similar to any of the best practices. For the second session, we investigated whether best practices were used and, specifically, for each challenge, we checked whether the described part was *missing*, *incorrect* (i.e., not compliant with the BPMN syntax or semantics), corresponding to a *best practice solution*, or corresponding to an *alternative solution*. To ensure consistency, two authors checked the process models designed with and without the best practices independently and, then, discussed differences in the results to reach consensus. For addressing RQ2, we relied on the answers to the second questionnaire and the interviews with selected participants. In the questionnaire, for each challenge, participants reported if they had used the corresponding best practice it in their models and, in general, if they find it helpful, easy to understand, and if they would use it in the future. In the interviews, we collected qualitative feedback about the perceived usefulness of the best practices.

## 6.2. Findings

The collected data provided insights into how best practices are used, especially when considering the different backgrounds of the participants and the influence of their prior experience on the modeling task. For each challenge, in Figs. 8–10, we summarize how the corresponding best practices were used in the process models (cf. RQ1). Besides, we report the results of the final questionnaire and the interviews related to the perceived usefulness of the best practices (cf. RQ2).

**Patient-related challenges.** Overall, the best practices for patient-related challenges were deemed relevant by most of the participants. However, when observing the process models designed during the study (cf. Fig. 8), it is clear that patient-specific needs are hard to capture in BPMN, particularly without the help of best practices.

The involvement of the patient (C1) was not modeled explicitly by most of the participants without best practices. In the resulting process models, relevant interactions with the patients, such as the patient has to give consent, were abstracted away and not shown, having a negative influence on the semantic model quality.

Four people, three of which with a background in IT, modeled the patient as a lane or an independent pool.

With the help of the best practices, more participants were able to model the patient correctly. Most subjects chose option (I) because it allows to highlight the interaction (“C1 was clear, the interaction was obvious, that is why I applied option (I)”) and is compact (“I choose option (I) as I find it stylistically better than having the patient mentioned in labels [option (D)], and takes less space than using a lane [option (A)]”).

Patient-specific needs, foreseen (C2) and unforeseen (C3), were indicated as the most difficult ones to understand in the post-task questionnaires. Accordingly, the analysis of the resulting

process models shows that the best practices were not used as much as the best practices addressing the other challenges. Without best practices, the alternative therapy options (C2) were shown successfully in some process diagrams with an exclusive gateway. In the remaining diagrams, this was either captured erroneously, as a simple activity hiding the relevant details, or not modeled. With the best practices, the challenging aspects of foreseen needs were almost always represented. However, many diagrams still included syntactic issues (e.g., missing conditions after the exclusive gateway) or used a simple activity. Thus, we assumed that the best practices were not used carefully. One student with a background in medicine used an ad-hoc sub-process, which we considered as a valid and relevant alternative, and thus we added it into the final version of best practices for C2. The challenging aspect of C3 was either not modeled when best practices were not available or included as an alternative path at the end of the model, such that it was not allowed to react to changing patient conditions during the whole process. With the best practices, we could observe in four process diagrams the correct application of the best practices, whereas the rest still not (correctly) captured the reaction to changing patient conditions.

A possible explanation for these findings could be that the best practices for C2 and C3 include advanced BPMN constructs (e.g., ad-hoc and event sub-processes), which require good BPMN knowledge and abstraction capabilities to be used properly. Still, some of the interviewed participants reported that the best practices for C2 and C3 were useful to show how advanced BPMN constructs could be used “I like that the best practices show how comments [text annotations] can be used on activities, I used them in several parts of my process model”. Another one reported “I liked to see how events and event-sub-processes can be used to interrupt an activity based on the patient’s wishes or sudden changes in the health conditions”.

**Medical practice-related challenges.** The observations related to the medical-related challenges are summarized in Fig. 9. Without best practices, most of the participants were not able to capture decision-making activities (C4), temporal constraints (C5), and monitoring activities (C6), and those who tried using timer events were often not able to use them properly. As a result, these process diagrams included syntactical errors and did not represent the aspects described in the textual process description correctly.

The best practices were improving the way medical practice-specific challenges are modeled. Mainly, the best practices for the time constraints (C5) were widely applied and contributed to increasing the syntactic and semantic quality of the obtained process models. The representation of C5 was most appreciated for its compactness “I was very helpful to see how timer events can be used for iteration and to replace loops in the process flow”. Decision-making activities were mostly modeled as simple tasks and only four subjects used the DMN DRG.<sup>5</sup> A couple of people reported that “I didn’t find C4 useful, as it is not clear to me how DMN can be used” and “It is not clear to me which abstraction level is the best from a process perspective”.

Without the best practices, the monitoring activity (C6) was not modeled, or the parallel and repetitive character of the monitoring activity was not correctly depicted. However, one student with a medical background modeled it as proposed in the best practice. With the best practice, the parallel and repetitive character of the monitoring activity was better captured by the participants. C6 was often compared to the ones for patient-specific needs (C2 and C3), as it was perceived as a useful example

<sup>5</sup> Apart from the details needed for C4, DMN was not explained in the BPMN course. Therefore, most people lacked the knowledge to use its advanced constructs properly.

| C1 Involvement of the patient          | Explicit representation of patient |           |                      |             |   |
|----------------------------------------|------------------------------------|-----------|----------------------|-------------|---|
|                                        | Missing                            | Incorrect | Annotation in labels | Alternative |   |
|                                        | without                            | with      | without              | with        | - |
| C2 Patient-specific needs (Foreseen)   | Text annotations/XOR gateway       |           |                      |             |   |
|                                        | Missing                            | Incorrect |                      |             |   |
|                                        | without                            | with      | -                    | -           | - |
| C3 Patient-specific needs (Unforeseen) | Interruption of process            |           |                      |             |   |
|                                        | Missing                            | Incorrect |                      |             |   |
|                                        | without                            | with      | -                    | -           | - |

**Fig. 8.** Summary of the observations for the patient-related challenges. The filling of the boxes shows the proportion of how often the best practice was missing, incorrect, etc..

| C4 Evidenced-based decision making | Business rule task with DMN/DRG |           |             |             |   |
|------------------------------------|---------------------------------|-----------|-------------|-------------|---|
|                                    | Missing                         | Incorrect | Simple task | Alternative |   |
|                                    | without                         | with      | without     | with        | - |
| C5 Time Constraints                | Timer events                    |           |             |             |   |
|                                    | Missing                         | Incorrect |             |             |   |
|                                    | without                         | with      | -           | -           | - |
| C6 Monitoring Activity             | Monitoring activity             |           |             |             |   |
|                                    | Missing                         | Incorrect |             |             |   |
|                                    | without                         | with      | -           | -           | - |

**Fig. 9.** Summary of the observations for the medical practice-related challenges. The filling of the boxes shows the proportion of how often the best practice was missing, incorrect, etc.

of connecting different BPMN constructs and to capture activity interruption, e.g., “I perceived the best practices very useful to model and understand how different BPMN construct can be connected, such as in the monitoring” or “I took inspiration from the monitoring activity and used boundary events for capturing interruptions in other parts of the process, e.g. C3”.

**Medical resource-related challenges.** The observations related to C7–C9 are reported in Fig. 10. As regards shared working behavior (C7), we observed a difference between the models requiring shared activities (option 1) and alternatively performed ones (option 2). Shared activities were modeled by half of the people already without the best practices, and almost everyone used the best practices correctly in the second session, such that the responsibilities are correctly shown in these process models. Instead, the best practice for alternatively performed activities was less applied. For both kinds of shared working behavior, participants also provided correct solutions already without the help of the best practices.

The centralized scheduling of patients (C8) was mostly captured as a simple activity without best practices and only one participant was applying the best practices, with the effect that the interrelation to other patients is missing in these process models. According to one of the interviewed participants, the centralized scheduling of patients “makes a lot of sense from an organizational perspective, but I focused more on the patient-flow”.

The modeling of C9, the involvement of the diagnostic service, requires capturing the interaction with the help of another pool and message flow. The group that started with P2 captured the interaction with the diagnostic service successfully in many process diagrams without the best practices. The majority of participants

in this group also applied the best practice correctly when modeling P1. Instead, the group starting with P1, had more challenges with representing an interaction: the diagnostic service was often represented as a simple lane, or the interaction with the main process was modeled incorrectly. When modeling P2, participants seemed not to have used this best practice and their process models contained several issues. From the initial questionnaire, we learned that this group included more participants with less BPMN experience, which can explain the presence of modeling issues. Another reason could lie in the differences between the processes. Indeed, in P1 the patient was needed explicitly for the diagnostic service whereas in P2 only a sample was needed. In the version of the challenges used for the evaluation, we provided only the best practice for the case in which the patient was needed explicitly (c.f., C9 option (2)) and only discussed the need for samples in the text. However, based on the results of the evaluation, we decided to extend C9 by including the current option (1) for the situation where only a sample is necessary.

## 7. Discussion

In this work, we have developed a set of best practices to support the modeling of healthcare processes. Modeling challenges and solutions were derived from real-world healthcare projects, and a comparison with literature helped us to generate a relevant set. The use and impact of the best practices on healthcare process modeling and their perceived usefulness were evaluated through an exploratory study with graduate students having working experience in healthcare and IT.

In this section, we discuss the main results and limitations of our work.

| C7 Shared working behavior                                  | Explicit representation of shared working |           |                 |                          |             |
|-------------------------------------------------------------|-------------------------------------------|-----------|-----------------|--------------------------|-------------|
|                                                             | Missing                                   | Incorrect |                 | Alternative              |             |
|                                                             | without                                   |           |                 |                          | -           |
| C8 Centralized scheduling                                   | with                                      |           |                 |                          |             |
|                                                             | Missing                                   | Incorrect | Simple activity | Scheduling service       | Alternative |
|                                                             | without                                   | -         |                 |                          | -           |
| C9 Involvement of centralized diagnostic/treatment services | with                                      | -         |                 |                          |             |
|                                                             | Missing                                   | Incorrect | Lane            | Interaction with Service | Alternative |
|                                                             | without                                   |           |                 |                          | -           |
|                                                             | with                                      |           |                 |                          | -           |

**Fig. 10.** Summary of the observations for the resource-related challenges. The filling of the boxes shows the proportion of how often the best practice was missing, incorrect, etc.

### 7.1. Results of the exploratory study

Our findings revealed that the process models obtained with the best practices contained fewer errors and captured healthcare aspects in greater detail. Results also showed that complex concepts, such as shared working behavior or patient needs, were not abstracted away so often. Moreover, the post-task questionnaires and interviews revealed that the best practices were perceived as “useful” by all the participants. Six best practices out of nine were also considered as “easy to understand”, whereas foreseen (C2) and unforeseen (C3) patient-specific needs, and the monitoring activity (C6) were pointed out as more challenging to understand by some participants because they included advanced BPMN constructs. This suggests that more BPMN training is needed to be able to use such best practices properly.

Having “ready-to-use” process fragments was perceived as a way to speed up the modeling and improve the appearance of the graphical model, as reported by some of the interviewed participants, e.g., “My goal was to make the process as concise and easy to understand as possible and the small examples helped me very much to achieve this” or “I find the best practices very helpful as they show how to apply BPMN for representing healthcare aspects and how to connect the different constructs correctly, for example, to represent the monitoring activity”. The results of the exploratory study also helped us to improve and enhance the best practices by adding two new options for challenges C2 and C9.

In general, we observed that participants with prior BPMN or software diagram modeling experience benefited more from the domain-specific best practices, which were used to find inspiration for modeling ideas, e.g., “I used the best practices as an inspiration to solve general issues, such as the shared working behavior”. Also, the best practices for evidence-based decision-making (C4), which included DMN concepts that were not introduced, made evident that the modeling concepts have to be clear to a process designer to apply the proposed best practices successfully. Still, several participants with basic BPMN understanding used the best practices as a way to improve their understanding of BPMN, both in general (e.g., for understanding the semantics of boundary events) and in the context of healthcare. Some of the interviewees claimed that the best practices helped them to become more acquainted with some BPMN constructs and to learn how to use them to capture similar concepts (e.g., “I focused on time constraints and I found it helpful to see that timer events can be used to avoid loops” or “the modeling was easier with the best practices, as I knew which constructs were needed for capturing which aspects”). A few participants complained that they found it hard to go through all the best practices during the modeling task and preferred not to use them as they felt under time pressure.

Thus, we learned that it is essential to have enough time available to use the best practices effectively.

Involving graduate students with different backgrounds in the study allowed us to gain insights into how domain knowledge is used during process modeling, bringing both advantages and disadvantages. Participants familiar with the healthcare domain could relate more to certain clinical aspects described in the text and considered their representation in the process model essential: For example, a participant with a medicine background modeled the monitoring activity without the best practices in a way similar to our solution. However, domain knowledge also led to models with unnecessary details (e.g., differentiating all kinds of samples collected for the analysis), which often made the process complicated even with the help of the best practices. This happened more for participants with a healthcare background but less experience with BPMN.

From our first evaluation, we can evince that the process modelers with relatively good experience of the used BPMN modeling constructs and domain-knowledge can benefit most from the presented best practices.

### 7.2. Limitations and threads to validity

The main limitation of this work is that the identified list of challenges and best practices might not be comprehensive. Nevertheless, we identified them from a diverse set of healthcare modeling initiatives from different countries and compared them to existing related work to confirm our findings. No additional relevant challenges were identified besides communication challenges arising in cross-organizational healthcare processes. However, since in this paper we focused on healthcare processes within one organization, we did not discuss challenges related to cross-organizational healthcare processes. Besides, we built upon our experience and the reviewed literature to derive the proposed best practices, but we do not exclude that there may be other BPMN solutions equivalent to those we have presented. Last but not least, the focus of this study was on supporting process modeling challenges by providing a set of BPMN fragments, the industry-standard. The available concepts of BPMN and the notation's limitation might have led to a bias in the creation of the fragments. We tried to minimize the impact of such bias by taking solutions from literature and from the modeling projects, and by discussing them again in the group of co-authors. The fragments could be additionally complemented with other types of models for capturing additional process-related aspects, e.g., UML models [61] for representing the interaction with healthcare IT systems or Asbru [38] for specifying and handling advanced temporal aspects. However, since the presented best practices are

grounded on practical evidence and include several concrete examples taken from clinical practice, they have the potential of reaching out to a broad audience, including academics but also healthcare practitioners and digital health students.

The results of our exploratory study should also be seen in light of some limitations. First, the final results could be influenced by the different expertise of the participants in BPMN and their domain knowledge. Indeed, although all the participants were attending the same BPMN course and were randomly divided into two groups, we could not control the differences in healthcare and process modeling expertise acquired during their undergraduate studies. Indeed, prior BPMN and DMN knowledge positively impacted the quality of the obtained process models, including those modeled without the help of best practices. Speaking of domain knowledge, none of the participants reported working with the healthcare processes chosen for the modeling task. We noticed that a few participants with a clinical background relied on their general clinical knowledge and modeled details not specified in the process description. Nevertheless, we could not notice significant differences in the quality of the results based on the background of the participants. Second, we acknowledge that time constraints imposed on the modeling task may have affected the quality of the obtained models. Indeed, a few participants reported not having enough time to complete the task and did not accurately model some of the challenges at the end of the process description. However, in the final questionnaire, we asked participants to report if they have had enough time for modeling and, if not, to specify the aspects they could not model. Thus, in our findings, we could distinguish actual modeling challenges from issues caused by the lack of time. Third, our study was conducted with a rather limited sample size of 28 participants. Thus, we acknowledge that additional studies are needed to generalize our results to a broader group of subjects. Still, the obtained process models combined with the qualitative feedback from our participants provided insights into the practical use of the best practices, including suggestions for improving them. Finally, we chose to evaluate best practices with graduate students instead of healthcare and IT professionals. The participants in our study were representative of junior healthcare and IT experts since most of them also had prior professional experience in their respective fields of study. Thus, we acknowledge that more studies are needed to generalize our results to experienced process modelers and real clinical contexts. However, the healthcare concepts captured by the best practices are quite complex, and seeing that students with a background in medicine were able to understand and use them reasonably well is promising for future developments, especially since healthcare process modeling initiatives are becoming more and more multidisciplinary.

## 8. Conclusion and outlook

In this paper, we have presented a set of BPMN best practices for supporting process modeling in healthcare, tackling some critical modeling challenges typical of this domain. We identified nine challenges which we categorized into three main categories, namely (1) patient-related, i.e., challenges considering the active role and needs of the patient throughout the healthcare process, (2) medical practice-specific, i.e., related to the knowledge-intensive character of healthcare activities, and (3) medical-resource specific, dealing with dynamic and multidisciplinary working behavior of health workers. For each challenge, we developed a list of best practices with different modeling options and abstraction levels and provided concrete examples showing the suitability of a particular option over others given specific modeling goals. The presented list might not necessarily

be complete but provides a set of best practices grounded in empirical evidence that can encourage the uptake of BPMN for healthcare process modeling.

A first evaluation of the best practices through a process modeling study with graduate students in Digital Health showed that these domain-specific best practices could help to streamline the task of healthcare process modeling and improve the general understanding of BPMN. Besides, the participants in our study perceived them as useful to speed up the modeling and improve the visual appearance of the BPMN diagram. We observed that participants with a basic knowledge of BPMN and an understanding of healthcare domains benefited more from the best practices than those with limited process modeling expertise and with no expertise in healthcare. Thus, we assume that the proposed BPMN best practices for healthcare are most beneficial for process designers with a basic understanding of BPMN and the healthcare domain.

In the future, we plan to test the best practices in real-world healthcare modeling initiatives, also involving (senior) expert process modelers. Furthermore, we want to evaluate their usefulness for the representation of clinical practice guidelines and aim to extend the list of best practices by addressing the typical challenges of inter-organizational healthcare processes. The best practices presented in this work focus specifically on modeling challenges observed in the healthcare environment. Some of the challenges and best practices might also be relevant to other domains; however, this needs to be more systematically explored in the future.

## Declaration of competing interest

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

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