Exploring the Power of Triple Crown Process Modeling in Healthcare: Sepsis Case

Camelia Maleki[a] and Frederik Gailly[b]
Faculty of Economics and Business Administration, Ghent University, Tweekerkenstraat 2, Gent, Belgium

Keywords: Patient Care Process, Triple Crown Modeling Approach, Process Improvement.

Abstract: Effective process modeling plays a pivotal role in optimizing patient care processes within the continually evolving healthcare landscape. This paper focuses on the application of the Triple Crown standard, which encompasses the Business Process Model and Notation (BPMN), Case Management Model and Notation (CMMN), and Decision Model and Notation (DMN), within the context of the sepsis diagnosis process. Through an in-depth exploration of this case study, the paper uncovers the immense potential of these standards in empowering healthcare practitioners to streamline workflows, enhance decision-making at critical junctures, and ensure the delivery of the highest quality care despite the diverse challenges inherent in patient care processes. By dissecting key dimensions such as flexibility, data and information flow, complexity management, and decision points, this study provides valuable insights into how the Triple Crown approach can significantly enhance patient care process models.

1 INTRODUCTION

In today's intricate healthcare landscape, healthcare process modeling plays a pivotal role in efficiently managing the flexibility and complexity inherent in these processes. It not only aids in identifying and eliminating inefficiencies, and addressing bottlenecks but also allows for dynamic adaptation to the ever-evolving nature of healthcare procedures. Process models empower healthcare providers and policymakers with the ability to make well-informed decisions, thereby providing a framework for understanding and responding to fluctuations caused by emerging medical technologies, shifting patient needs, evolving regulatory requirements, and other factors. This enables healthcare professionals to stay agile, predict potential challenges and opportunities, and make adjustments to ensure optimal patient care(Pufahl et al., 2022).

Healthcare organizations are responsible for carrying out a variety of processes that vary in their characteristics and needs, ranging from clinical procedures like diagnosis and treatment to organizational and administrative tasks such as scheduling appointments and registering patients. These processes are not isolated from one another, but rather interconnected and dependent. Patient care processes have become particularly important in recent years as they consider both organizational requirements and clinical tasks(Mans et al., 2015). In the patient care processes, many sections require healthcare providers to make decisions based on their knowledge and expertise (Di Ciccio et al., 2015). These parts are dynamic, flexible, and often referred to as ”knowledge-intensive”. However, some tasks follow a specific workflow or set of instructions, such as regular assessments or performing a specific protocol(Rojo et al., 2008).

To effectively model a process, it is imperative to first grasp its priorities and challenges. Lenz et al (Lenz and Reichert, 2007) conducted an investigation into the primary challenges associated with supporting and representing care processes, taking into account their unique characteristics. One major issue arises from the restricted process flexibility inherent in existing traditional languages. This limitation entails the ability of the implemented process to execute based on a loosely or partially specified model that is completed at runtime. (Lenz et al., 2012). Another concern relates to complexity management. Since the primary goal of business process diagrams is to enhance communication among process-related stakeholders, overly complex diagrams can hinder

[a] https://orcid.org/0000-0002-7818-2559
[b] https://orcid.org/0000-0003-0481-9745

Maleki, C. and Gailly, F.
Exploring the Power of Triple Crown Process Modeling in Healthcare: Sepsis Case.
DOI: 10.5220/0012394000003657

In *Proceedings of the 17th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2024) - Volume 2*, pages 516-528
ISBN: 978-989-758-688-0; ISSN: 2184-4305

their correctness and comprehension. Improper use of a modeling language regardless of the characteristics and requirements of a process can result in reduced clarity and increased complexity in model.(Jošt et al., 2019). Moreover, patient care processes depend on medical knowledge and case-specific decisions. This entails that healthcare professionals depend on the amalgamation of the finest accessible evidence, clinical expertise, and patient preferences to arrive at well-informed decisions. To proficiently maneuver through these processes, it becomes crucial to establish streamlined information exchange and a comprehensive depiction of the decision-making aspect within process models (Pufahl et al., 2022). In light of these challenges and requirements, it becomes evident that relying exclusively on a single modeling language may fall short of creating a comprehensive model, as different aspects of patient care processes possess distinct characteristics and priorities. Therefore, it may be essential to employ a combination of modeling languages to comprehensively capture the patient care process and represent all its dimensions.(Pufahl et al., 2022; Mulyar et al., 2008a). One choice for this is the Triple Crown of OMG, which combines the BPMN (Activity-centric language), CMMN (Artifact-centric language), and DMN (Decision-centric language). The Triple Crown approach is a popular choice due to its comprehensive nature, adaptability, and standardization. It allows healthcare providers to model both the workflow-oriented and knowledge-intensive aspects of a process and offers flexibility by allowing organizations to choose one or more of the standards based on their specific needs(OMG Healthcare Domain Taskforce, 2020).

This paper aims to shed light on the substantial potential inherent in the Triple Crown standard. By evaluating the synergistic capabilities of BPMN, CMMN, and DMN in enhancing critical aspects of patient care process models. In our pursuit of evaluating the modeling languages within the healthcare landscape, we deliberately chose to examine four critical dimensions: flexibility, complexity management, information flow, and decision-making due to their fundamental significance in providing a comprehensive representation of patient care processes. These four dimensions are intricately interconnected and collectively underpin the success of healthcare process modeling. By focusing our research on these dimensions, we aim to provide a comprehensive assessment of the Triple Crown standard's applicability and effectiveness in the patient care processes. Ultimately, our goal is to empower healthcare practitioners with the tools they need to navigate the complex and ever-changing landscape of patient care, thereby enhancing the quality of care delivered to patients.

2 BACKGROUND

The "OMG Triple Crown" refers to the three major standards developed by the Object Management Group (OMG) for business process management (BPM), decision management (DM), and case management (CM). These three standards are the Business Process Model and Notation (BPMN)(OMG, 2011), the Decision Model and Notation (DMN), and the Case Management Model and Notation (CMMN) (OMG, 2016). Together, they provide a comprehensive framework for modeling, analyzing, and managing complex business processes, decisions, and cases (OMG Healthcare Domain Taskforce, 2020)

2.0.1 BPMN in Healthcare

Several studies have concentrated on the analysis of BPMN's benefits within the healthcare sector, with a focus on its application in specific medical scenarios, as discussed below. Rolon et al. (Rolón et al., 2008) employed BPMN to visualize and enhance programmed surgical patient processes. Rojo et al. (Rojo et al., 2008) conducted an examination of the utility of BPMN in modeling anatomic pathology processes. In a separate study (Barbagallo et al., 2015), BPMN is used to model standard operating pathways, to analyze the challenges related to operating room planning and scheduling.

2.0.2 CMMN in Healthcare

In the work of (Herzberg et al., 2015), they present an approach aimed at addressing the requirements of a flexible healthcare process through the utilization of CMMN. Additionally, they explore the establishment of case monitoring and analysis by combining event processing and case management. Another relevant study, as proposed in (Mei et al., 2014), introduces a CMMN-based model for care pathways in CHF (congestive heart failure) processes.

2.0.3 Combination of BPMN, CMMN, and DMN in Healthcare

In this section, we highlight studies that have leveraged a combination of OMG standards to model healthcare processes. It's important to note that DMN cannot function independently and is typically employed in conjunction with other modeling languages. For example, Wiemuth et al. (Wiemuth et al., 2017) demonstrated the utilization of a combination of BPMN, CMMN, and DMN to model non-deterministic medical processes. Likewise, Junger et al. [2] conducted a comparative analysis of the capabilities of BPMN, CMMN, and a combination of both notations in representing adaptable surgical procedures. The evidence-based decision-making is explored in (Combi et al., 2016). This study serves as the foundation for the methodology discussed in (Combi et al., 2017), which recommends the combination of BPMN and DMN to depict decision-intensive healthcare processes(particularly chronic care processes).

Despite prior research on the utilization of BPMN, CMMN, and DMN in the healthcare domain, a void persists in the literature when it comes to applying all three notations (the Triple Crown approach) within healthcare processes and assessing its efficacy. This paper endeavors to bridge this gap by investigating the Triple Crown approach within the realm of healthcare process modeling. Through a detailed analysis of critical facets and an assessment of its capacity to optimize workflows and elevate decision-making, this study contributes to the growing body of literature on healthcare process modeling.

3 METHODOLOGY

In this section, we have outlined a methodology that facilitates the creation of a healthcare process model utilizing the triple crown standard.

1. Define the scope of the process
   (a) What is the goal of the process?
   (b) What is the start and end point?
2. Define the key performance indicators. they should reflect the critical success factors and the value proposition of your process.
3. Define the process
   (a) List of Activity groups, Artifacts, Events, and Goals that are used in the Model
   (b) Identify the relationship between elements
4. Choose the appropriate modeling language for each part of the process, taking into consideration the content captured and the key performance indicators (KPIs)
5. Create the first draft of the models
6. Continuously refine and validate the model until it is functional. Some techniques are listed below:
   (a) Expert Review: Engage healthcare professionals and experts
   (b) Comparative Analysis: Compare the model with existing documentation and guidelines.
   (c) Regulatory Compliance: Ensure that the model complies with relevant healthcare regulations and standards
   (d) Audit Trails and Documentation: Maintain thorough documentation of the model's development and validation process
   (e) Simulation: If possible use simulation software to execute the process model under different scenarios

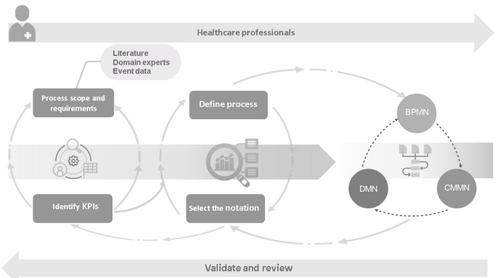


Figure 1: Main steps of the proposed design methodology.

4 SEPSIS CASE STUDY

In many situations, including the sepsis diagnosing process, there are no documented procedures that dictate the way in which the care process is undertaken. Consequently, there is a need to discover the process from first principles. During this phase of the methodology, the aim is to gain a thorough understanding of the current healthcare process.

The study aimed to comprehensively understand the sepsis diagnosing process in healthcare by gathering data from various sources. Three primary methods were employed: event logs from a reputable Dutch hospital, clinical guidelines, and interviews with healthcare professionals. The event logs, consisting of 15,214 recorded events related to 1,050 sepsis cases, were obtained from the hospital's enterprise resource planning (ERP) system. While valuable, these event logs did not cover all aspects of the sepsis process. To address this limitation and obtain a more holistic perspective, interviews with healthcare professionals and relevant clinical guidelines were utilized. This combined approach provided nuanced details that enhanced the analysis, resulting in a rich dataset for a thorough exploration of the sepsis process. The diverse data sources enabled the researchers to model and evaluate different aspects of the sepsis process, highlighting the strengths and limitations of various modeling languages.

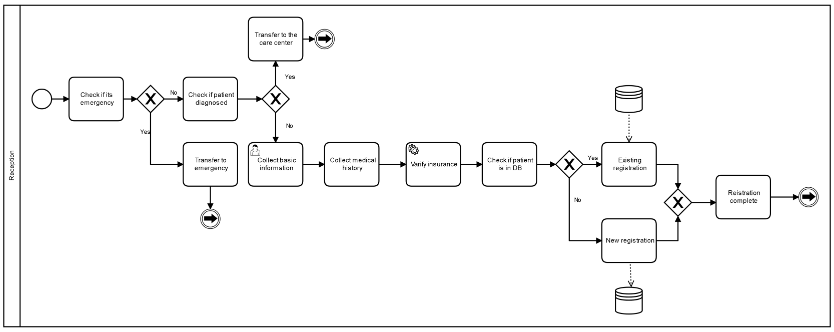


Figure 2: Patient administration process with BPMN.

4.1 Patient Administration

Patient administration is the functional, structural consolidation of patient registration, admitting, and other patient-generated activities in the hospital. It is a simple and concise process (Table 2) requiring no specific knowledge and low levels of flexibility. This part of the process begins when a patient arrives through the acceptance process in the Entrance Room and ends with sending the patient for sepsis triage (Figure 2).

The choice to implement BPMN for the patient registration process was based on its ability to effectively capture structured, sequential, and task-centric processes. BPMN aligns well with the distinct activity groups in patient registration, offering a straightforward representation of tasks. In contrast, CMMN introduces additional elements like cases, stages, and milestones, leading to unnecessary complexity for a simple patient registration process. BPMN's flexibility patterns, incorporating gateways and subprocesses, make it more suitable for handling variations in patient registration, whereas CMMN requires navigating multiple paths and outcomes, making the process more challenging to understand.

4.2 Patient Diagnostic Exams

Upon patient registration, the nurse prioritizes patients by severity, entering triage information into the electronic health record (EHR). If sepsis is suspected, the nurse initiates the formal sepsis pathway, documenting the start in a clinical note in the EHR, and promptly communicates with the first available physician. This process primarily involves documenting patient situations, categorized as a structured and routine process with low flexibility and complexity. Consequently, the decision was made to model this part using BPMN.

In the second and main part of the diagnosis process, the physician assesses the patient's condition,

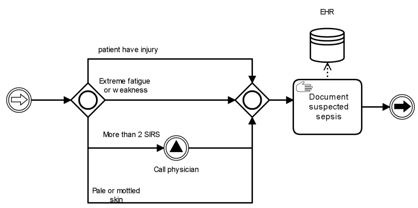


Figure 3: First part of diagnose process with BPMN.

drawing on clinical skills, patient information, and diagnostic testing to ensure an accurate evaluation. The diagnosis process involves gathering information and employing clinical reasoning to identify the patient's health problem. This process, as highlighted by Rzepinski et al. (Rzepiński, 2007), is not entirely predictable and demands flexible execution. It commences with initial examinations and patient interviews, concluding with the documentation of the diagnostic report.

The issue here is that the specific sequence and set of activities in the patient examination process do not follow a particular script and order, but rather are based on a diagnostic procedure (e.g., information discovered in one step can drastically alter the next set of steps). In BPMN, we can represent this process as an "ad hoc subprocess" which is a group of tasks designed for handling a specific case and can be executed in any order (Ye et al., 2008). While both BPMN ad hoc sub-processes and CMMN tasks can involve tasks without a predefined order, There are some limitations of BPMN ad hoc sub-processes in comparison with CMMN tasks. Here are some limitations of BPMN ad hoc sub-processes:

- **Unpredictable Flow:** In an ad hoc sub-process, the exact sequence of activities is not predefined. This can make it challenging to grasp the overall process flow, as the order of activities might vary from instance to instance.
- **Variability:** With the possibility of repeated activities and different ordering, the number of potential paths through the process can grow signifi-

Table 1: Events and response activities after evaluating the results.

ID	Event description	Response
T0	10 minutes timer event	notify the care staff to evaluate the patient's status
T1	Alert for respiratory symptoms	Doing Chest X-ray and/or CT scan
T2	Request culture	Culture from a specific site
T3	Alert: Cardiovascular instability	Echo exam
T4	High risk: Brain infection	CFS analysis
T5	High risk: Request for Dialysis	Dialysis
T6	surgical intervention is a consideration	evaluation by a surgical team to assess the need for surgery
T7	Alert: presence of infection	Prescribe Antibiotics
T8	Alert: have hypertension	Administrator IVF
T9	Alert: renal failure	BUN exam
T10	Alert: decreased oxygen saturation	ABg, Pulse oximetry

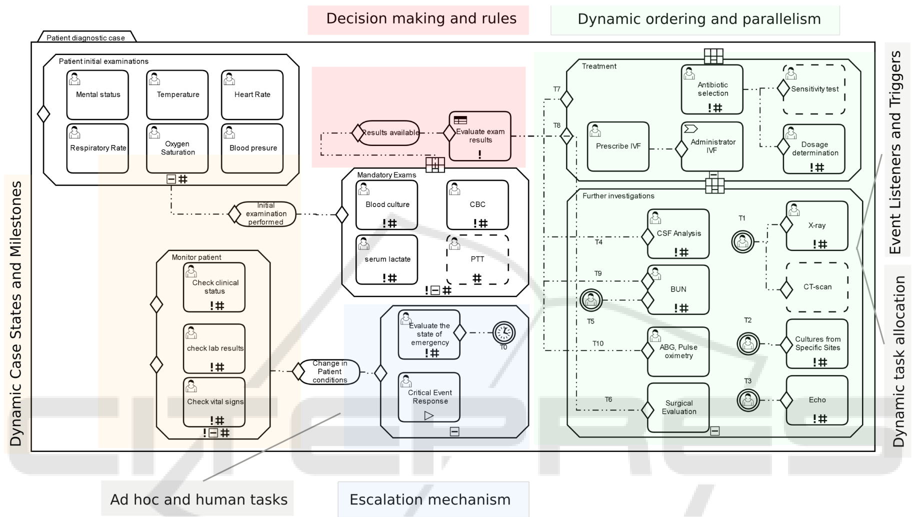


Figure 4: Patient exam sub-process with CMMN.

cantly, making it more difficult to understand and analyze the process as a whole.

- **Diagram Clutter:** When activities are not constrained to a predefined sequence, the diagram can become cluttered with various arrows indicating conditional flows and potential transitions between activities, making the visual representation more complex.
- **Loss of Structure:** Traditional BPMN diagrams have a clear structure with defined start and end points. Ad hoc sub-processes introduce a level of non-linearity that might blur the structure, especially when used extensively.
- **Cognitive Load:** Readers of the diagram need to mentally keep track of potential sequences and conditional flows, which increases the cognitive load required to understand the process.
- **Limited Standardization:** Ad hoc sub-processes can be interpreted and modeled differently by different people, leading to inconsistencies in understanding

We will investigate how CMMN can address BPMN limitations. As depicted in Figure 4, we modeled investigations that are performed for sepsis exams in CMMN. The model includes four main stages: Mandatory exams, patient initial exams, treatment, and further investigation. All stages are initiated according to the triggering event that represents the incident escalation. The first stage in the model is to ”perform an initial exam” which is depicted as 6 human tasks. The purpose of these tasks is to gather real-time information about patient vital signs. Based on the collected information from this stage and performing the exams in the ”mandatory exams” stage, the patient's situation is evaluated through a Decision-Task called ”evaluate exam results”. This task can be modeled with a DMN decision table. This task contains the events and their corresponding decisions (response activity) based on the patient exam results (T4, T5, T9, etc.) (Table 3). For example, the T7. The presence of infection initiates the treatment stage, which includes a Human Task called ”antibiotic selection” and ”dosage determination”. The next stage

Table 2: Comparing the data modeling capabilities languages.

Measures	BPMN	CMMN
collections	Data Object with a ”Collection” property	CaseFileItem used to represent collections
Relationships	By Data Associations	Elements like association, dependency, required rule, and onPart condition
Meta data	Can be represented by annotations	CaseFileItemDefinition can be used to represent metadata
Hierarchical data	BPMN can not represent hierarchical data	By using Case File Items
Object oriented data structure	BPMN is not designed to model object-oriented data structures	using Case File object that is a container to hold data and other objects related to a particular case instance
Complex data structures	BPMN is not well-suited for complex data structures that involve multiple data types	using caseFileItem and PlanItem
lifecycle	BPMN does not have a specific notation to represent lifecycles	CMMN can manage various states a case file item goes through, like ”update”, ”replace”, ”add”

```
<cmmn:caseFileModel id="patient_model">
  <cmmn:caseFileItem id="patient" definitionRef="patient_def">
    <cmmn:children>
      <cmmn:caseFileItem id="patient_history" definitionRef="history_def">
        <cmmn:children>
          <caseFileItem id="condition1" definitionRef="conditionDef" value="Asthma" />
            <cmmn:children>
              <cmmn:caseFileItem id="pollen" definitionRef="pollen_def" />
              <cmmn:caseFileItem id="dust" definitionRef="dust_def" />
            </cmmn:children>
          </cmmn:caseFileItem>
        </cmmn:children>
      </cmmn:caseFileItem>
    </cmmn:children>
```

```
<caseFileItem id="patientInfo" definitionRef="patientInformationType">
    <properties>
        <property name="name" value="John Doe"/>
        <property name="age" value="35"/>
        <property name="gender" value="Male"/>
    </properties>
    <caseFileItem id="address" definitionRef="addressType">
        <properties>
            <property name="street" value="123 Main St"/>
            <property name="city" value="Anytown"/>
            <property name="state" value="CA"/>
            <property name="zip" value="12345"/>
        </properties>
    </caseFileItem>
    <caseFileItem id="medicalHistory" definitionRef="medicalHistoryType">
        <properties>
            <property name="conditions" value="Diabetes, Hypertension"/>
            <property name="allergies" value="Penicillin"/>
        </properties>
    </caseFileItem>
</caseFileItem>
```

Figure 5: Simple example of hierarchical and nested data using casefileitem.

of our investigation involves addressing various scenarios where patients may require additional examinations triggered by different event escalations. For instance, in the case of T4 (high risk: Brain infection), a critical Human Task must be executed: CPS analysis.

The inherent flexibility mechanisms of CMMN, exemplified in Figure 4, serve as valuable tools for accommodating diverse scenarios and variations within a process model. The escalation mechanism allows the process to adapt by escalating tasks or cases when predefined conditions are met, ensuring timely resolution. Ordering and parallelism offer agility to manage tasks sequentially or concurrently. Ad hoc and human tasks permit the on-the-fly inclusion of tasks as needed, while dynamic task allocation ensures dynamic assignment of the right resources based on changing requirements. Conditional expressions in ”ifparts” provide dynamic control over case element activation and completion. Milestones facilitate progress tracking and action triggering, and discretionary tasks offer optional activities that adapt to case-specific requirements.(Routis et al., 2020; Zensen and Kuster, 2018). These mechanisms collectively eliminate the need to create multiple process models, streamline processes, and enhance the adaptability of a process(Andree et al., 2022; Routis et al., 2023; Kurz et al., 2015).

This example demonstrates how CMMN successfully addresses the mentioned issues. for example, CMMN leverages a combination of case context management, case stages, milestones, event listeners, dynamic task allocation, and flexible dependencies, to effectively manage maintenance challenges and address the unpredictable flow within case management scenarios.

One more challenge during the triage and diagnostic process is ensuring the quality of the data and information during the process(Albahri et al., 2018). Representing complex data structures, such as hierarchical or nested data structures like trees or graphs, with BPMN data objects can be difficult. The patient exam results, for example, contain essential details about different exams, and other nested elements that are critical for healthcare staff to access with the highest level of accuracy and completeness. We presented a comparison of the data modeling capabilities of both CMMN and BPMN This example demonstrates how CMMN successfully addresses the mentioned issues. for example, CMMN leverages a combination of case context management, case stages, milestones, event listeners, dynamic task allocation, case plans, ad hoc tasks, and flexible dependencies, to effectively manage maintenance challenges and address the unpredictable flow within case management scenarios. or for managing diagram clutter the notation includes features like stages and plans that help organize and structure tasks within a case.

An additional challenge during the triage and diagnostic process is ensuring the quality of data and information (Albahri et al., 2018). Representing complex data structures, such as hierarchical or nested data structures like trees or graphs, with BPMN data objects can be challenging. For instance, patient exam results contain crucial details about various exams and other nested elements critical for healthcare staff to access with the highest level of accuracy and completeness. We provided a comparison of the data modeling capabilities of both CMMN and BPMN.(Gagne, 2016; Von Rosing et al., 2014; Neskovic and Kirchner, 2016). As shown in the table although both BPMN and CMMN offer data modeling capabilities, CMMN is particularly suited for handling intricate data structures in case management procedures and offers more sophisticated elements for modeling complex care process data. In addition, CMMN comes with built-in access control capabilities and audit trails including user roles and permissions, case and task ownership, and user-defined access control rules. Consequently, CMMN offers a range of features that can aid in preserving the integrity, and accessibility of patient data.

4.3 Diagnose Process

The final diagnostic step involves determining sepsis severity, a task heavily reliant on physician expertise and intricate decision-making. While CMMN is versatile for various processes, it may have limitations in modeling complex decision scenarios. Though it supports simple decision-making with sentry and event elements, CMMN might not be optimal for intricate decision-making with multiple conditions and rules.

In this phase, models are created using standard BPMN and DMN. Executable standard BPMN elements are employed, with decision-making rules translated into first-order logic (FO(·)). The challenge encountered during this part is the difficulty in modeling certain rules using standard BPMN constructs due to their complex logical conditions which cannot be easily represented through a sequence of tasks and gateways. While it may be possible to model these rules using more advanced BPMN constructs, such as nested subprocesses or complex gateways, it would likely result in a highly complex and difficult-to-understand diagram that may not be practical for a real-world scenario. As an example, consider the following rule:

$$\left[\begin{array}{l}\forall x[patient](Fever(x)\wedge WBC(x)\wedge Confirmedinfection(x)\\ \wedge(SBP(x)<90\wedge(HoTN(x)\vee Lac>4))\wedge(\exists y[labtest]\\ (orderedafter(y,x)\wedge\Delta Lac(y,x)\geq 0.5\wedge\Delta SBP(y,x)\leq 20)\vee\\ (\exists z[medication](orderedafter(z,x)\wedge Vasopressor(z)\wedge\\ \Delta Dose(z,x)\geq 0.5\wedge\Delta SBP(z,x)\leq 20)))\\ \rightarrow\ Refractorysepticshock(x)\end{array}\right]$$

This rule states that if a patient has a fever, positive blood cultures, and a confirmed infection, and their systolic blood pressure is below 90 mmHg, and either they have evidence of tissue hypoperfusion (HoTN) or lactate levels above 4 mmol/L, and they have either experienced a significant increase in lactate levels or a decrease in systolic blood pressure by 20 mmHg or more after receiving vasopressor medication, then they should be diagnosed with refractory septic shock. There are a few technical issues with modeling this rule in BPMN:

- **Expressing Temporal Relationships:** BPMN can express temporal relationships between activities using gateways and events, but it can be difficult to represent complex temporal relationships, such as ”orderedafter” in the rule.
- **Expressing Logical Conditions:** BPMN can express simple logical conditions using gateways and events, but more complex logical conditions in the rule, can be difficult to represent (e.g., the change in lactate levels (ΔLac) between ”y” and ”x” is greater than or equal to 0.5, and the change in systolic blood pressure (ΔSBP) between ”y” and ”x” is less than or equal to 20).
- **Expressing Quantitative Conditions:** BPMN is not designed to represent quantitative conditions, such as $\Delta Lac(y,x) \geq 0.5$. While it may be possible to use data objects or variables to represent these values, it can be less intuitive than expressing them in a decision table.
- **Handling Nested Expressions:** The rule contains nested expressions, such as the combination of ”OR” and ”AND” operators within parentheses. While it is possible to represent nested expressions in BPMN, it can make the diagram more complex and harder to read.

However, this rule can be represented clearly and concisely in a DMN decision table by breaking it down into smaller logical expressions and assigning them to decision inputs and outputs (Figure 6).

To compare BPMN and DMN in decision modeling, we have decided to limit our scope to a set of rules for the sepsis severity diagnostic process that

Fever	Positive blood cultures	Confirmed infection	SBP < 90 mmHg	HoTN or lactate > 4 mmol/L	ΔLactate ≥ 0.5 mmol/L	ΔSBP ≤ -20 mmHg	Vasopressor dose Δ ≥ 0.5	Diagnosis
TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	Refractorysepticshock

Figure 6: Decision table with the rule for refractory septic shock.

can be modeled by both languages, excluding very complex rules that BPMN may not be capable of modeling. We have defined specific rules for diagnosing the severity of sepsis based on clinical guidelines, sepsis protocols, and insights gathered from interviews with healthcare experts (Dugar et al., 2020; Taj et al., 2022). These rules serve as a framework to assess the severity of sepsis cases and guide the decision-making process in our model. Below is a list of some examples of these rules:

$$\begin{bmatrix} \forall x[patient](Fever(x) \wedge WBC(x) \wedge SBP(x) > 90 \rightarrow \ SIRS(x)) \\ \forall x[patient](Fever(x) \wedge WBC(x) \wedge Confirmedinfection(x) \\ \wedge SBP(x) > 90 \wedge Lac < 2 \rightarrow \ Sepsis(x)) \\ \forall x[patient](Fever(x) \wedge WBC(x) \wedge Confirmedinfection(x) \\ \wedge SBP(x) < 90 \wedge Lac > 4 \rightarrow \ Septicshock(x)) \\ \forall x[patient](Fever(x) \wedge WBC(x) \wedge Confirmedinfection(x) \\ \wedge SBP(x) < 90 \wedge HoTN(x) \wedge Lac > 4 \rightarrow \ Septicshock(x)) \\ \forall x[patient](Fever(x) \wedge WBC(x) \wedge Confirmedinfection(x) \\ \wedge SBP(x) < 90 \wedge 2 < Lac < 4 \rightarrow \ Seversepsis(x)) \\ \forall x[patient](Fever(x) \wedge WBC(x) \wedge Confirmedinfection(x) \\ \wedge SBP(x) < 90 \wedge 2 < Lac < 4 \wedge OD(x) \rightarrow \ Septicshock(x)) \end{bmatrix}$$

BPMN allows representing decisions and their impact or consequence respectively. However, BPMN is not meant to represent the detailed decision logic since modeling the decision logic often results in an Intricate mess of nodes and connections (see Figure 8). According to integrated BPMN and DMN modeling, decisions are not mapped to control flow elements. Rather, decisions are externalized into a separate DMN decision model that can be invoked by the process.

To calculate decision table values, it is essential to outline the requirements for decision-making, graphically represented in a Decision Requirements Diagram (DRD). The DRD comprises four element types: decision, input data, business knowledge model, and knowledge source. Oval shapes like "Patient history" represent input data, while "evaluate patient result" and "identify sepsis severeness" are decision nodes. Process resources, such as physicians and guidelines, are considered knowledge sources, directly influencing decision-making. Text annotations can serve as knowledge sources or input data, depending on their information content.

Figure 7 provides an overview of decision model execution. In the table's upper left corner, "unique" signifies the defined hit policy for the decision table, indicating that only one of the rows below can be true when a decision is required.

5 DISCUSSION

In this section, we will explore our approaches in terms of their capacity to handle complexity and flexibility.

5.1 Complexity Management

Analyzing BPMN, CMMN, and DMN reveals the potential for a more comprehensive model through their integration. However, our focus here is to assess whether the combined model is more complex than the standalone BPMN model. Currently, no widely accepted unified complexity metric exists due to the distinct purposes, elements, and scenarios these notations involve in business process management and decision modeling. Each notation has unique elements and objectives, making a universally applicable complexity metric challenging. One potential solution is adapting existing complexity metrics like nesting depth and control flow complexity (CFC) to consistently assess the impact of using these languages together.(Kluza and Nalepa, 2012). Table 3 summarizes metrics used for complexity measurement.

Table 3: Process model complexity metrics.

metrics	Focus
NOA, NOAC	Measure the activity complexity
CFC	Measure the control-flow complexity
Depth	Evaluate the nesting of the process

The NOA metric calculates activity complexity and was inspired by lines of code (LOC) metric. NOAC metric considers both activities and control-flow elements for well-structured models. The formula of CFC that captures the complexity of XOR-split, OR-split, and AND-split constructs is as follows:

$$CFC_{XOR-split}(a) = fan-out^{a} \quad (1)$$

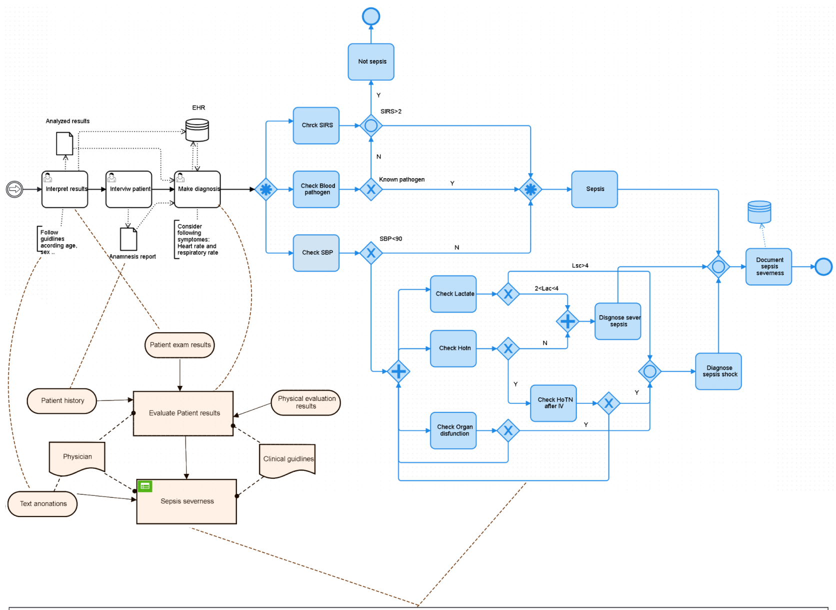
XOR-split CFC is determined by the number of induced states introduced with the split. For XOR splits, the complexity corresponds to the fan-out of the split.

$$CFC_{OR-split}(a) = 2^{fan-out(a)} - 1 \quad (2)$$

OR-split CFC is also determined by the number of induced states introduced with the split.

$$CFC_{AND-split}(a) = 1 \quad (3)$$

For AND splits, the complexity is simply 1. Lastly, Depth is defined as the nesting of the process model. If there is a split gateway, the depth is increased with one. If there is a join gateway, the depth is decreased with one. The cumulative sum is taken and the maximum of the cumulative sum is calculated for each



Sepsis severness | Hit Policy: Unique

	When SIRS>2 (boolean)	And Known/Suspected pathogen (boolean)	And Systolic blood presure (SBP) (double)	And Hypotensi on (HoTN) (boolean)	And Hypotensi on after IVF (boolean)	And Lactate (double)	And Organ dysfunction (boolean)	Then Patient situation (string)	Annotations
1	True	True	<90	True	True	-	-	IC	Sepsis shock
2	True	True	<90	False	False	4<Lac	-	IC	Sepsis shock
3	True	True	<90	True	False	4<Lac	-	IC	Sepsis shock
4	True	True	<90	False	False	2<LAc<4	-	NC	Sever Sepsis
5	True	True	<90	False	False	2<LAc<4	True	IC	Sepsis shock
6	True	False	>90	False	False	-	-	NC	SIRS
7	True	True	>90	False	False	-	-	NC	Sepsis

Figure 7: Transform a BPMN model into DMN.

Table 4: Complexity metrics comparison.

Complexity metrics	BPMN	BPMN+DMN
NOA, NOAC	27, 56	14, 30
CFC XOR-Split	19	7
CFC OR-split	15	9
CFC And gateway	2	0
Total CFC	36	16
Depth	5	3

path. The nesting depth is the maximum of each path value.

Table 4 shows that combining BPMN and DMN reduces process model complexity. According to (Sánchez-González et al., 2011), a process model with CFC OR-split decision nodes exceeding a value of 14 can be incomprehensible; our BPMN process had a value of 15. After integrating DMN, the value decreased to 9, making it understandable. In summary, the BPMN-DMN combination streamlines process model complexity by reducing gateways and flows. However, it introduces new intricacies related to additional decision models. Despite this, the added complexity shifts from the process model to the decision model. DMN decision tables facilitate the identification of overlapping and missing rules, allowing for rule reordering and consolidation, leading to a more concise decision-making process in the workflow, unlike situations with complex sequential structures.

To perform a meaningful comparison of complexity between BPMN and CMMN, it's crucial to ensure that we have an identical process model represented in both notations. While we already have the patient registration process represented in both languages as a structured process, to assess the complexity of a flexible process model, we need to recreate what we've modeled in CMMN using BPMN. However, modeling the entire CMMN model within BPMN poses a formidable challenge, as certain elements are inherently unsuitable for representation in BPMN. As a result, we have opted to narrow our focus to a specific part of the CMMN model depicted in Figure 5, which we will then represent using BPMN notation. (Figure 8).

Given these fundamental distinctions between BPMN and CMMN, many established complexity metrics may not be directly applicable to CMMN. For example, one common metric is Activity Complexity (AC), which quantifies the nodes within a process

Table 5: Complexity metrics comparision.

	Flexible		Structured	
Complexity metrics	BPMN	CMMN	BPMN	CMMN
AC	66	5	16	14
CNC	1.28	0.83	1	1.07

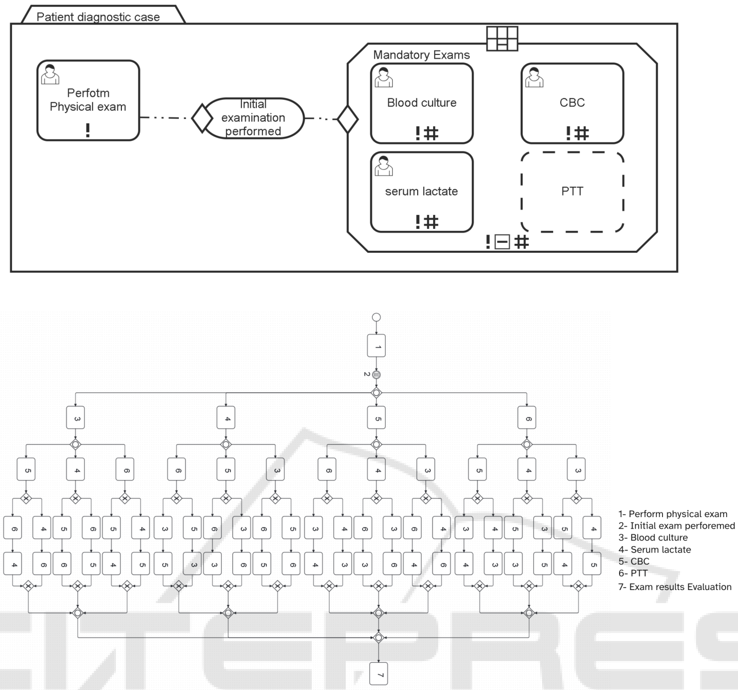


Figure 8: Comparison of BPMN and CMMN complexity in a flexible process.

graph. Assuming that all elements in a CMMN model can be considered as nodes, AC can be calculated for both BPMN and CMMN models (Marin,). However, certain complexity metrics, like Control Flow Complexity (CFC), do not find relevance in CMMN. This is because CMMN lacks equivalents to the AND, OR, or XOR nodes present in BPMN. Therefore, for complexity measurement, we utilize Activity Complexity (AC) to count the activities. Additionally, we employ a complexity metric known as the Coefficient of Network Connectivity (CNC) exploits the notion of connectivity between elements to quantify structural complexity. Inspired by Graph theory, the given metric explores the relation of the number of Arcs to the number of Nodes. Higher values of it reveal a dense model, which is more likely to contain errors since the modeler has to perceive more connections between nodes than in a model that is less dense. In this metric, all activity elements are counted as nodes, and all connectors are counted as arcs.

$$CNC = Arcs \div Nodes \quad (4)$$

In CMMN, we assume elements that represent various types of relationships in CMMN, including Entry Criteria, Exit Criteria, On-Part Relationships, and sentries, as connectors.

Figure 11 illustrates that even a small segment of a CMMN model can become intricately complex when translated into the context of BPMN, resulting in 4! different execution sequences for each sequential ordering of activities. This unnecessary complexity, combined with potential limitations in expressiveness, can hinder process model maintainability, requiring multiple adjustments. While modeling flexible processes in CMMN may reduce the number of activities and overall process model density, a comparison of CMMN and BPMN complexity in a structured process reveals no notable difference in AC and CNC metrics between the two models. Consequently, CMMN not only fails to reduce complexity in structured processes but also introduces additional complexities to the model.

It is undeniably true that CMMN and DMN introduce additional layers of complexity to the overall model. Nevertheless, when dealing with knowledge-intensive or decision-centric processes, attempting to replicate the quality of CMMN or DMN using BPMN invariably results in heightened complexity, and a di-

Table 6: Catalog of flexibility patterns.

Flexibility pattern	CMMN	BPMN	Flexibility pattern	CMMN	BPMN
Flexible initiation			**Flexible reordering**		
Alternative entry-points	+	+	Interleaving	+	+
Entrance skip	+	-	Swap	-	-
Undefined entry	+	-	Momentary reordering	-	-
Momentary entry change	-	-	Permanent reordering	+ \ -	-
Permanent entry change	-	-	**Flexible elimination**		
Flexible termination			Task skip	+ \ -	-
Alternative exit points	+	+	Foreseen bypass	+	+
Termination skip	+	+ \ -	Momentary task elimination	-	-
Undefined exit	+	-	Permanent task elimination	-	-
Momentary exit change	-	-	**Flexible extension**		
Permanent exit change	-	-	Task invocation	+	-
Flexible selection			Late creation	+ \ -	-
Choice	+	+	Momentary task insertion	+ \-	-
Task substitution	-	-	Permanent task insertion	-	-
Late selection	+	-	**Flexible Repetition**		
Permanent choice insertion	+ \ -	-	Redo	+ \ -	-
Momentary choice insertion	+ \ -	-	Momentary loop insertion	+ \ -	-
Flexible Concurrency			Iteration	+	+
Parallelism	+	+	Permanent loop insertion	-	-
Momentary Task Parallelization	-	-			
Parmanent Task Parallelization	-	-			

minished level of overall quality. In some cases, it may even fall short of the comprehensiveness offered by CMMN or DMN models. Therefore, it is imperative that we exercise caution and judiciously employ these modeling approaches only in situations where they can yield optimal efficiency and performance.

5.2 Flexibility

Flexibility, particularly in the context of processes, has undergone extensive exploration in academic research, leading to the introduction of numerous taxonomies. One of the most comprehensive taxonomies is presented by Mulyar et al. (Mulyar et al., 2008b). This taxonomy delineates two types of process flexibility: flexibility during design time, which addresses foreseeable changes accommodated in modeled process schemas, and flexibility during runtime, allowing alterations to the process instance after initiation. Organized based on this taxonomy, patterns are grouped into eight distinct categories (Table 6). These patterns facilitate high-level structural changes in process models, encompassing actions such as adding, deleting, selecting, or relocating activities and process fragments.

BPMN, in its traditional form, is a static modeling language that defines processes at design time. It is not inherently designed to handle dynamic or runtime changes to process structures. So it can just handle patterns like ”choice” by using gateways to allow the selection of one of several alternative tasks at design time. CMMN offers a robust framework for modeling and adapting knowledge-intensive processes, providing flexibility patterns for managing dynamic processes. It allows for adding, deleting, moving, and adapting activities and process fragments at a high level of abstraction. However, there are scenarios where CMMN may not fully capture the dynamic and unpredictable nature of certain processes. It is not designed to provide a high level of flexibility in modifying the case model at runtime. CMMN introduces discretionary elements, allowing tasks and stages to be manually activated during case execution, enabling execution-time planning for handling unpredictability. These mechanisms offer some runtime adaptability like ”late selection”, ”late creation” or ”momentary choice insertion”. However, their application relies on predictions made during the design phase, making CMMN most suitable for scenarios requiring flexibility within the originally designed case structure. For extensive runtime changes or situations involving unpredictable events, extreme variability, emergent behaviors, and rapid changes, alternative workflow or process management systems may be more appropriate

The sepsis diagnosis process, unlike emergency room processes, is not entirely unstructured. Many potential variations and changes in these processes can be predicted during the design phase, based on clinical guidelines and insights from domain experts. Here are key flexibility patterns crucial to this process:

- Late Selection: Essential when test results or patient conditions evolve over time, late selection is crucial for adapting the care plan accordingly.

- Late Creation: When there's a need to create new tasks in response to unexpected patient developments or additional requirements during the diagnosis.
- Parallelism: Sepsis exams often involve multiple concurrent tasks, such as laboratory tests, patient assessment, and treatment initiation. The parallelism pattern allows for handling these tasks simultaneously.
- Iteration and Momentary Loop Insertion: Sepsis exams might involve iterative processes, such as repeated assessments or treatments at specific intervals. Using these patterns allows modeling of recurring activities.

As shown in Table 6 CMMN is a well-suited modeling approach to efficiently accommodate the flexibility patterns mentioned. Therefore, CMMN can be a suitable choice for modeling and managing the flexible parts of these processes.

6 CONCLUSION

In conclusion, this paper has illuminated the potential of the Triple Crown standard, comprising BPMN, CMMN, and DMN, in effectively representing patient care processes. Our exploration has delved into critical dimensions, including flexibility, data and information flow, complexity management, and decision points, vividly demonstrating how the Triple Crown approach can substantially enhance patient care process models. We have shown that, based on selected KPIs, we can harness the combination of these languages to unlock their potential for creating more comprehensive models. In this paper, we tackled three challenges in patient care process modeling:

- Patients exhibit a variety of conditions and unique needs that must be taken into account when modeling a care process: Utilized CMMN to establish distinct abstraction levels for representing process variants and diverse paths, effectively capturing various aspects of flexibility while mitigating complexity
- Complex decisions for diagnosing and treatment of patients: DMN offers a modular decision requirements hierarchy which allows for the decomposition of complex decision logic into smaller, more manageable components
- In patient care processes, achieving evidence-based decision making requires a high-quality flow of information : CMMN excels in its capacity to model a wide range of data structures, making it a versatile choice for representing the diverse and complex information inherent in patient care processes

Nevertheless, it is imperative to acknowledge the challenges associated with CMMN and DMN, including complexity, limited tool support, and integration issues. To ensure the successful implementation of these modeling languages, stakeholders must invest time and resources in learning and addressing these challenges.

To enhance the applicability of our findings, future research endeavors should encompass evaluations and analyses in our work, with a dedicated focus on validating the conclusions drawn in this paper.

REFERENCES

Albahri, O. S., Albahri, A. S., Mohammed, K., Zaidan, A., Zaidan, B., Hashim, M., and Salman, O. H. (2018). Systematic review of real-time remote health monitoring system in triage and priority-based sensor technology: Taxonomy, open challenges, motivation and recommendations. *Journal of medical systems*, 42:1–27.

Andree, K., Ihde, S., Weske, M., and Pufahl, L. (2022). An exception handling framework for case management. *Software and Systems Modeling*, 21(3):939–962.

Barbagallo, S., Corradi, L., De Ville de Goyet, J., Iannucci, M., Porro, I., Rosso, N., Tanfani, E., and Testi, A. (2015). Optimization and planning of operating theatre activities: an original definition of pathways and process modeling. *BMC medical informatics and decision making*, 15:1–16.

Combi, C., Oliboni, B., Zardini, A., and Zerbato, F. (2017). A Methodological Framework for the Integrated Design of Decision-Intensive Care Pathways—an Application to the Management of COPD Patients. *Journal of Healthcare Informatics Research*, 1(2):157–217.

Combi, C., Oliboni, B., Zardiniy, A., and Zerbato, F. (2016). Seamless design of decision-intensive care pathways. In *2016 IEEE International Conference on Healthcare Informatics (ICHI)*, pages 35–45. IEEE.

Di Ciccio, C., Marrella, A., and Russo, A. (2015). Knowledge-Intensive Processes: Characteristics, Requirements and Analysis of Contemporary Approaches. *Journal on Data Semantics*, 4(1):29–57.

Dugar, S., Choudhary, C., and Duggal, A. (2020). Sepsis and septic shock: Guideline-based management.

Gagne, D. (2016). Case Management Model and Notation (CMMN): An Introduction. (December).

Herzberg, N., Kirchner, K., and Weske, M. (2015). Modeling and monitoring variability in hospital treatments: a scenario using cmmn. In *Business Process Management Workshops: BPM 2014 International Work-*

shops, Eindhoven, The Netherlands, September 7-8, 2014, Revised Papers 12, pages 3–15. Springer.

Jošt, G., Heričko, M., and Polančič, G. (2019). Theoretical foundations and implementation of business process diagrams' complexity management technique based on highlights. *Software & Systems Modeling*, 18:1079–1095.

Kluza, K. and Nalepa, G. J. (2012). Proposal of square metrics for measuring business process model complexity. In *2012 Federated Conference on Computer Science and Information Systems (FedCSIS)*, pages 919–922. IEEE.

Kurz, M., Schmidt, W., Fleischmann, A., and Lederer, M. (2015). Leveraging cmmn for acm: examining the applicability of a new omg standard for adaptive case management. In *Proceedings of the 7th international conference on subject-oriented business process management*, pages 1–9.

Lenz, R., Peleg, M., and Reichert, M. (2012). Healthcare process support: achievements, challenges, current research. *International Journal of Knowledge-Based Organizations (IJKBO)*, 2(4).

Lenz, R. and Reichert, M. (2007). It support for healthcare processes–premises, challenges, perspectives. *Data & Knowledge Engineering*, 61(1):39–58.

Mans, R. S., Van der Aalst, W. M., and Vanwersch, R. J. (2015). *Process mining in healthcare: evaluating and exploiting operational healthcare processes*. Springer.

Marin, M. A. Complexity metrics for the case management modeling notation (cmmn).

Mei, J., Li, J., Yu, Y., Li, X., Liu, H., and Xie, G. (2014). Embracing case management for computerization of care pathways. In *MIE*, pages 3–7.

Mulyar, N., Pesic, M., Van Der Aalst, W. M., and Peleg, M. (2008a). Declarative and procedural approaches for modelling clinical guidelines: addressing flexibility issues. In *Business Process Management Workshops: BPM 2007 International Workshops, BPI, BPD, CBP, ProHealth, RefMod, semantics4ws, Brisbane, Australia, September 24, 2007, Revised Selected Papers 5*, pages 335–346. Springer.

Mulyar, N., van der Aalst, W. M., and Russell, N. (2008b). Process flexibility patterns.

Neskovic, S. and Kirchner, K. (2016). Using context information and cmmn to model knowledge-. pages 17–21.

OMG (2011). Business Process Model and Notation . (January):538.

OMG (2016). Case Management Model and Notation 1.1 Beta. (March):124.

OMG Healthcare Domain Taskforce (2020). The BPM+ Field Guide to Shareable Clinical Pathways. page 125.

Pufahl, L., Zerbato, F., Weber, B., and Weber, I. (2022). Bpmn in healthcare: Challenges and best practices. *Information Systems*, 107:102013.

Rojo, M. G., Rolón, E., Calahorra, L., García, F. Ó., Sánchez, R. P., Ruiz, F., Ballester, N., Armenteros, M., Rodríguez, T., and Espartero, R. M. (2008). Implementation of the business process modelling notation (bpmn) in the modelling of anatomic pathology processes. In *Diagnostic pathology*, volume 3, pages 1–4. BioMed Central.

Rolón, E., Aguilar, E., García, F., Ruiz, F., Piattini, M., Calahorra, L., et al. (2008). Process modeling of the health sector using bpmn: a case study. In *Proceedings of First International Conference on Health Informatics, HEALTHINF 2008*, volume 2, pages 173–8.

Routis, I., Bardaki, C., Nikolaidou, M., Dede, G., and Anagnostopoulos, D. (2023). Exploring cmmn applicability to knowledge-intensive process modeling: An empirical evaluation by modelers. *Knowledge and Process Management*, 30(1):33–54.

Routis, I., Nikolaidou, M., and Anagnostopoulos, D. (2020). Empirical evaluation of CMMN models: a collaborative process case study. *Software and Systems Modeling*, 19(6):1395–1413.

Rzepiński, T. M. (2007). The structure of diagnosis in medicine: Introduction to interrogative characteristics. *Theoretical Medicine and Bioethics*, 28:63–81.

Sánchez-González, L., Ruiz, F., García, F., and Cardoso, J. (2011). Towards thresholds of control flow complexity measures for bpmn models. In *Proceedings of the 2011 ACM symposium on Applied computing*, pages 1445–1450.

Taj, M., Brenner, M., Sulaiman, Z., and Pandian, V. (2022). Sepsis protocols to reduce mortality in resource-restricted settings: A systematic review. *Intensive and Critical Care Nursing*, page 103255.

Von Rosing, M., White, S. A., Cummins, F., and De Man, H. (2014). Business process model and notation-BPMN. *The Complete Business Process Handbook: Body of Knowledge from Process Modeling to BPM*, 1(January):429–453.

Wiemuth, M., Junger, D., Leitritz, M., Neumann, J., Neumuth, T., and Burgert, O. (2017). Application fields for the new object management group (omg) standards case management model and notation (cmmn) and decision management notation (dmn) in the perioperative field. *International journal of computer assisted radiology and surgery*, 12:1439–1449.

Ye, J., Sun, S., Song, W., and Wen, L. (2008). Formal semantics of bpmn process models using yawl. In *2008 Second International Symposium on Intelligent Information Technology Application*, volume 2, pages 70–74. IEEE.

Zensen, A. and Kuster, J. (2018). A comparison of flexible BPMN and CMMN in practice: A case study on component release processes. *Proceedings - 2018 IEEE 22nd International Enterprise Distributed Object Computing Conference, EDOC 2018*, pages 105–114.