Customizing BPMN Diagrams Using Timelines

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Abstract

BPMN (Business Process Model and Notation) is widely used standard modeling technique for representing Business Processes by using diagrams, but lacks in some aspects. Representing execution-dependent and time-dependent decisions in BPMN Diagrams may be a daunting challenge [11]. In many cases such constraints are omitted in order to preserve the simplicity and the readability of the process model. However, for purposes such as compliance checking, process mining, and verification, formalizing such constraints could be very useful. In this paper, we propose a novel approach for annotating BPMN Diagrams with *Temporal Synchronization Rules* borrowed from the timeline-based planning field. We discuss the expressivity of the proposed approach and show that it is able to capture a lot of complex temporally-related constraints without affecting the structure of BPMN diagrams. Finally, we provide a mapping from annotated BPMN diagrams to timeline-based planning problems that allows one to take advantage of the last twenty years of theoretical and practical developments in the field.

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1 Introduction

Nowadays Process-Aware Information Systems (PAISs) have become the cornerstone for organizing activities in most realities, ranging from large private companies (operating in logistics, manufactoring, avionics, and so on) to healthcare institutions [26]. Business Process Management deals with many important aspects such as analysis, modeling, execution, and monitoring of Business Processes [21].

In this context, BPMN (Business Process Model and Notation) [28] is the standard for representing and managing business processes, but it lacks in some aspects such as the specification of (i) temporal constraints [11, 29], (ii) resources availability [12], and (iii) external data affecting decisions [31].

As pointed out by many applications, time-awareness is a crucial property of business processes in most domains and especially in the healthcare one [20, 29]. However, BPMN does not directly allow the specification of time constraints in process diagrams, despite the fact that they affect the real process flow in many aspects such as choices to be made at given

decision points, event handling, task durations, resource allocation and so on. This limitation has been considered in the literature in different ways. A possible approach is to extend BPMN with constructs borrowed from workflows and simple temporal networks fields [11, 29]. Another approach consists of translating BPMN diagrams into logical or automata-based formalisms [13, 22] and then expressing constraints by means of the considered formalisms.

Moreover, BPMN does not allow the representation of resource availability and external data affecting decisions, even if these aspects are crucial in managing process execution and outcome [11]. A further issue to be considered is that resources and data values change over time. As an example, in the healthcare domain, resource availability with respect to blood analysis may be affected by the time of the day (i.e., morning, afternoon, evening, and night) and the current load of the lab (i.e., the number of undergoing analyses). Time of the day and current load may influence the whole time required for getting results of blood tests. An example taking into account external data affecting decisions is related to shifts in the systolic blood pressure values of a patient undergoing a surgical procedure. Significant differences in pressure values in last 5 hours may force the anaesthetist to administer a local sedation in place of a total one for safety reasons [12].

For the sake of clarity and conciseness of BPMN diagrams, often the formal specification of these aspects are intentionally neglected and left to the following implementation by specific software tools.

In this paper, we propose an approach, residing in between the two aforementioned ones, that allows the annotation of BPMN diagrams based on *Temporal Synchronization Rules* of *Timeline-based planning* [27]. We also show that this simple language may naturally express the specification of (i) temporal constraints, (ii) resource availability, and (iii) external data affecting decisions. Moreover, the proposed approach allows one to constrain the execution of the process (e.g., a decision in an exclusive-gateway) according to the aforementioned specifications. Then, another contribution of this work is a complete mapping of our timeline-annotated BPMN diagrams into a timeline-based planning problem, that is, given a set of state variables and a set of synchronization rules on them, find a consistent execution where all the synchronization rules are satisfied [27]. The translation step suffices for our verification purpose, since various tools for satisfiability of timeline-based planning have been proposed in the last decade [2, 5, 6].

The advantages of our proposal are manyfold:

1. The proposed approach allows us to express complex temporal constraints even if they involve some external data or resources.
2. The temporal behaviour of data and resources may be regulated with the same machinery (i.e., state variables).
3. Our approach allows composability. As a matter of fact, resources/data may be updated/removed/inserted, as well as temporal constraints on the execution of the business process, by simply modifying the relative temporal synchronization rules/state variables.
4. The process diagram is not affected at all and it may be seen through a layered perspective: (a) at the highest level, the original BPMN diagram provides a general idea of how activities are organized; (b) at an intermediate level, temporal synchronization rules, possibly involving one or more external entities, detail how the execution is temporally constrained and how some decision points are affected by (the temporal evolution of) data/resources and/or by some previous temporal behavior of the process; (c) finally, at the lowest level, the state variables regulate the evolutions of the involved data/resources.

The power and generality of this approach come at the price that the definition of a set of temporal constraints in the form of temporal synchronization rules and state variables could be inconsistent (i.e., every possible execution of the diagram combined with every possible consistent evolution of data/resources violates at least one temporal synchronization rule).

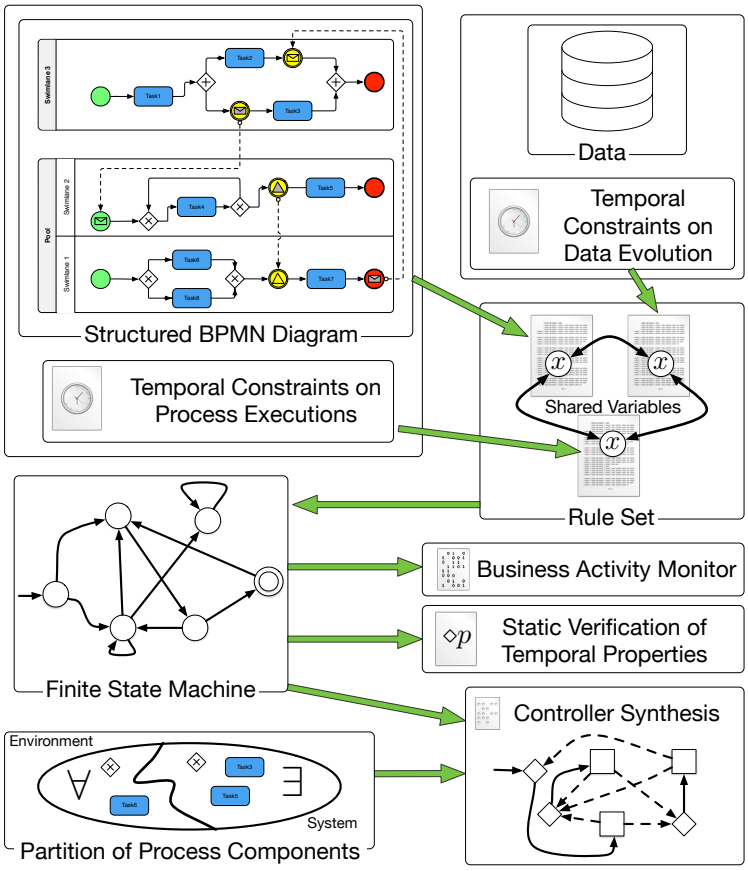

Figure 1 A pipeline for integrating timeline-based planning and BPMN diagrams.

In this paper, we will focus only on structured BPMN diagrams, and thus from now on we will call them just diagrams. A diagram is said to be well-structured if every node with multiple outgoing edges, i.e., a split node, has a corresponding node with multiple incoming edges, i.e., a join node, such that the set of nodes delimited by the split and the join nodes form a Single-Entry-Single-Exit (SESE) region, and these regions within the process are properly nested [15, 19]. In this way a SESE region is any area within a process delimited by a single entry edge and a single exit edge.

The paper is organized as follows. Sec. 2 gives an overall description of the proposed approach. Sec. 3 provides an example of a real-world process in the healthcare domain, which features non-trivial temporal constraints. Sec. 4 recalls the basic concepts and notation of timelines and timeline-based planning, together with some recent results in the field. Sec. 5 shows some meaningful temporal constraints that may be enforced by means of timeline annotations in BPMN diagrams in a straightforward way, without compromising the overall readability of the diagram. Sec. 6 describes how the proposed approach allows the specification of constraints involving data, resources, and decisions. Sec. 7 summarizes the contribution of the paper and sketches some lines for future work.

2 Enriching BPMN with Timelines: the Big Picture

In this section we give an overview of the proposed approach, which is graphically summarized in Fig. 1. BPMN diagrams are often used for modelling business processes, where there are often time-critical, resource-critical, and data-critical situations. Usually business processes

are underspecified w.r.t. such requirements for preserving their readability and conciseness. In this simplified form they cannot be directly managed by a suitable algorithm for controlling the whole process at runtime and/or for performing qualitative/quantitative static analysis. On the other hand, forcing the representation of such requirements by enriching the diagram will compromise the readability of the diagram itself.

In order to overcome such trade-off, our proposal consists of keeping the original diagram and annotating it by using a set of constraints, namely *temporal synchronization rules*, borrowed from the timeline-based planning domain. As we will detail in Sec. 5, such rules are able to express in a concise and clear way temporal constraints that would otherwise be captured by a complex combination of throw/catch events and event-based gateways [11]. In [9], we will provide a way to translate structured BPMN processes into a set of rules representing all and only the possible correct executions of the process. Such mapping is crucial because, as shown in Fig. 1, it allows the representation of both requirements and process as a set of rules.

In Fig. 1, we suppose to have a process that makes use of some data, and constraints on such data must be taken into account. For instance, let us assume that the diagram represents a medical guideline in which the decision on the exclusive gateway is driven by the value of the patient blood pressure. It is straightforward to see that such value cannot increase/decrease too fast in a short amount of time and it would be desirable to force such constraint in order to prune irrealistic behaviors of the process in subsequent analysis. In this paper, we assume that constraints on data may be captured by a suitable set of temporal synchronization rules. As shown in Fig. 1, as a first step, the diagram, temporal constraints, and data constraints are translated into sets of rules in an independent manner. The union of such obtained rules (the Rule Set in Fig. 1) represents the whole description of the considered process. As mentioned before, the translations are pairwise independent but, as we will observe in Sec. 6, rules in different sets may "communicate" via shared variables. For instance, rules representing the diagram may involve the variable representing the pressure, whose behaviour is encoded by other rules coming from data constraints. Another example may be represented by the fact that a given temporal constraint imposes that the execution of two specific tasks must be non-overlapping (since they use the same shared resource), no matter how they are arranged in the diagram (e.g., they may appear in parallel branches). It is easy to see that such approach fosters modularity in the design of every component. As a matter of fact, we may change constraints on the behavior of data, without affecting the diagram, or we may change the diagram without impacting on related temporal constraints.

As depicted in Fig. 1, the whole set of rules is translated into a Finite State Machine (FSM), whose language represents all the possible correct executions of the considered diagram w.r.t. to temporal/data constraints. The FSM may be used for performing a plethora of process-related analyses. In Fig. 1, we just provide three of them. (i) FSM may be translated into an algorithm that may be used at runtime for monitoring the correct execution of the process by means of alerts/execeptions pointing out the violation of a given constraint [16]. (ii) On the FSM we may perform static verification of qualitative/quantitative properties, expressed in temporal logics such as LTL or CTL [18], by using one of the many well-established tools available [8, 17]. (iii) Supposing to be in a scenario where some process elements are under the control of the environment (e.g., medical guidelines). By means of the FSM we may synthesize, if it exists, a controller that "drives" the system-controlled elements (i.e., the process elements which are not controlled by the environment) in a way that the correct termination of the process is ensured, no matter how the environment behaves on its set of elements [25, 30].

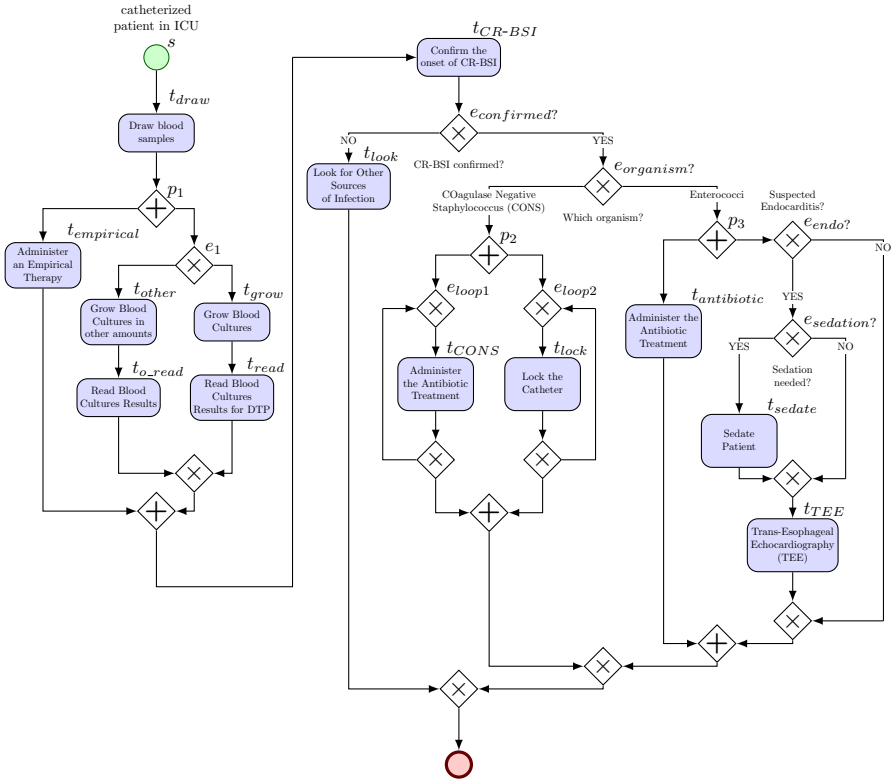

Figure 2 A BPMN Diagram representing CR-BSIs treatment.

3 A motivating example

In this section, we introduce a clinical process model and describe some time-related decisions and constrains that can be considered. The Business Process model, represented in Fig. 2 as a BPMN Diagram, is a process for the treatment of Catheter-Related Bloodstream Infections (CR-BSIs). Vascular catheters are vital for treating ill patients in critical situations. Their main drawback is represented by the concrete possibility of a patogens colonization of their injection site. This may lead patients to develop severe bloodstream infections.

Clinical guidelines for preventing such infections have been proposed and applied. Most of them usually rely on temporal constraints for their applicability [4]. The BPMN diagram in Fig. 2 shows the process for detecting and treating CR-BSIs according to the well-known Infectious Diseases Society of America (IDSA) practice guideline [23]. The guideline includes blood and/or catheter cultures activities for supporting the diagnosis of CR-BSI. In particular, clinicians first draw *simultaneously* two blood samples to be cultured, one from the catheter suspected to be the source of the infection and, the other, from a peripheral vein. We call the first sample LS (local sample) and the second one PS (peripheral sample), respectively. These operations are included in the first process activity of Fig. 2, i.e. *Draw blood samples*. The considered activity takes a t_{draw} time to be completed.

After the first activity, physicians *Administer an empirical therapy* to the patient until the diagnosis of CR-BSI is confirmed. Among the criteria for confirming or not a CR-BSI, we considered the Differential Time to Positivity (DTP), which measures the difference between the time when LS becomes positive w.r.t. a certain micro-organism, and the time when PS becomes positive for the same micro-organism. If such difference exceeds a certain threshold (DTP), then the CR-BSI is confirmed.

In the process of Fig. 2, we considered only two of the possible micro-organisms that may be detected in a CR-BSI infection: Coagulase-negative Staphylococci and Enterococcus spp.

- In case of *Coagulase-negative Staphylococci (CONS)*, the patient is treated with antibiotic or heparin lock therapy. Such therapy consists of alternating between catheter locks and an antimicrobial therapy. In general, such phases have equal duration in order to prevent clot formations. These activities are represented in Fig. 2 by means of the process region related to gateway *p2*, composed of *Administer Antibiotic Treatment* and *Lock Catheter* activities.
- In case of *Enterococcus spp*, the patient is treated by administering Vancomycin. Unfortunately this case is often associated with endocarditis. This means that physicians may choose to perform a Trans-Esophageal Echocardiography (TEE) for detecting the issue. TEE must be performed not before five and up to seven days from the time when CR-BSI has been confirmed. These activities are represented in Fig. 2 by means of the process region related to gateway *p3*.

Summing up, even in this over-simplified representation of a real-world clinical scenario, we need to specify time-related constraints, which cannot be captured by using BPMN without compromising the process model readability. Examples of these time-related constraints are:

- Duration-Induced-Decision (*DID*). Durations and interleaving of given events/tasks preceding a decision point (i.e., an exclusive gateway), determine the choice to be made, and thus the path to follow. In process of Fig. 2, time durations *LS* and *PS* and their related DTP determine which branch of *CR-BSI confirmed?* will be taken.
- Disjoint-Parallel-Tasks (*DPT*). In this case, we consider tasks which may be executed without a given order, but their execution needs to be disjoint for some reasons (e.g., the preemption of a mutually exclusive resource). In the treatment of CONS, *Administer Antibiotic Treatement* and *Lock Catheter* must be executed in a non-overlapping way. Moreover, since in Fig. 2 both activities belong to a loop, they may be executed multiple times.
- Relative-Time-Constraint (*RTC*). Time durations of two given tasks, or the difference between their endpoints are constrained by specified bounds. In process of Fig. 2, the difference between the beginning of the *TEE* activity, and the end of the *CR-BSI* activity must be between five and seven days.

4 A formal account of Timelines

In this section we introduce the basic concepts of timelines and of timelines-based planning [27]. In [9] it is provided an informal explanation, together with a small example, of how the whole timelines-based machinery works. In the following, we use the notation introduced in [7]. We start by introducing the notion of *state variable*.

▶ **Definition 1** (state variable). *A state variable sv is a triple* $sv = (\mathbf{V}_{sv}, \mathbf{\Delta}_{sv}, \mathbf{D}_{sv})$ *where:*

- $\mathbf{V}_{sv}$ *is the finite domain of the state variable sv;*
- $\mathbf{\Delta}_{sv} : \mathbf{V}_{sv} \to 2^{\mathbf{V}_{sv}}$ *is the transition function, which maps each value* $v \in \mathbf{V}_{sv}$ *to the set of values that may be taken by sv immediately after sv has taken value v;*
- $\mathbf{D}_{sv} : \mathbf{V}_{sv} \to \mathbb{N} \times \mathbb{N} \cup \{+\infty\}$ *is a function that maps each* $v \in \mathbf{V}_{sv}$ *to an interval, i.e., a pair of values* $[d^{sv=v}_{\min}, d^{sv=v}_{\max}]$ *with* $0 < d^{sv=v}_{\min} \leq d^{sv=v}_{\max}$*, which represent respectively the minimum and the maximum duration of an interval over which sv takes value v.*

Table 1 A set of useful atoms conjunctions and their interval based interpretation.

shorthand	meaning	translation
$x\langle M\rangle y$	x **meets** y	$x \leq^{e,s}_{[0,0]} y$
$x\langle B\rangle y$	x **begins** y	$x \leq^{s,s}_{[0,0]} y \wedge x \leq^{e,e}_{[1,+\infty)} y$
$x\langle D\rangle y$	x **during** y	$y \leq^{s,s}_{[1,+\infty)} x \wedge x \leq^{e,e}_{[1,+\infty)} y$
$x\langle F\rangle y$	x **finishes** y	$y \leq^{s,s}_{[1,+\infty)} x \wedge x \leq^{e,e}_{[0,0]} y$
$x\langle O\rangle y$	x **overlaps** y	$x \leq^{s,s}_{[1,+\infty)} y \wedge x \leq^{e,e}_{[1,+\infty)} y \wedge y \leq^{s,e}_{[1,+\infty)} x$
$x \subset_{BD} y$	(x **begins** y) $\vee$ (x **during** y)	$y \leq^{s,s}_{[0,+\infty)} x \wedge x \leq^{e,e}_{[1,+\infty)} y$
$x \subseteq y$	(x **begins** y) $\vee$ (x **finishes** y) $\vee$(x **during** y) $\vee$ ($x = y$)	$y \leq^{s,s}_{[0,+\infty)} x \wedge x \leq^{e,e}_{[0,+\infty)} y$
$x \cap_{BMO} y$	(x **begins** y) $\vee$ (x **meets** y) $\vee$(x **overlaps** y)	$x \leq^{s,s}_{[0,+\infty)} y \wedge y \leq^{s,e}_{[0,+\infty)} x \wedge x \leq^{e,e}_{[1,+\infty)} y$
$x = y$	$x = y$	$x \leq^{s,s}_{[0,0]} y \wedge x \leq^{e,e}_{[0,0]} y$

Given a state variable sv, a *timeline for* sv is a sequence $\mathbf{T}_{sv}$ of pairs called *tokens* which consider functions $\mathbf{\Delta}_{sv}$ and $\mathbf{D}_{sv}$. Formally:

▶ **Definition 2** (token). *A token for a state variable* $sv = (\mathbf{V}_{sv}, \mathbf{\Delta}_{sv}, \mathbf{D}_{sv})$ *is a tuple* $\tau = \langle v, d\rangle$ *where* $v \in \mathbf{V}_{sv}$ *and* $d \in \mathbf{D}_{sv}(v)$.

It is worth noticing that in a token the duration d belongs to the allowed durations for the value v.

▶ **Definition 3** (timeline). *A timeline for a state variable* $sv = (\mathbf{V}_{sv}, \mathbf{\Delta}_{sv}, \mathbf{D}_{sv})$ *is a finite sequence* $\mathbf{T}_{sv} = \langle \tau_1, \ldots \tau_k\rangle$ *of tokens for* sv *such that for every* $1 \leq i < k$ *we have* $v_{i+1} \in \mathbf{\Delta}_{sv}(v_i)$.

Given a token $\tau = \langle v, d\rangle$, we denote with $value(\tau)$ its value (i.e., $value(\tau) = v$). Notice that the value of sv in two consecutive tokens within a timeline do not need to be different as it depends on how $\mathbf{\Delta}_{sv}$ is defined. Given a timeline $\mathbf{T}_{sv}$, we denote with $|\mathbf{T}_{sv}|$ its length. Moreover we will use an array-like notation for specific tokens in the sequence. Formally, if $\mathbf{T}_{sv} = \langle \tau_1, \ldots \tau_k\rangle$ we have $\mathbf{T}_{sv}[i] = \tau_i$ for every $1 \leq i \leq k$. In a timeline $\mathbf{T}_{sv} = \langle \tau_1, \ldots \tau_k\rangle$ for sv for every $1 \leq i \leq k$ we define $\mathbf{s}\_time(\mathbf{T}_{sv}, i)$ as $\mathbf{s}\_time(\mathbf{T}_{sv}, i) = \sum_{1 \leq j < i} d_j$ and $\mathbf{e}\_time(\mathbf{T}_{sv}, i)$ as $\mathbf{e}\_time(\mathbf{T}_{sv}, i) = \sum_{1 \leq j \leq i} d_j$. In the following we will often refer to specific sets of timelines instead of single ones. To this purpose, given a set of timelines $\Gamma = \{\mathbf{T}_{sv_1}, \ldots, \mathbf{T}_{sv_n}\}$, we will say that Γ is *repetition-free* if and only if $sv_i \neq sv_j$ for every $1 \leq i \neq j \leq n$. From now on we will assume every set of timelines to be repetition-free. Synchronization among timelines in the same set is given by means of a set of *Temporal Synchronization Rules*, TS-RULES for short. TS-RULES relate tokens, possibly belonging to different timelines, through temporal relations among intervals called *atoms*. Let $\Sigma = \{x, y, z, \ldots\}$ a set of *token names* (i.e., variables ranging over tokens):

▶ **Definition 4** (atom). *An atom is a clause of the form* $x \leq^{\circ,\bullet}_{I} y$ *where* $\circ, \bullet \in \{\mathbf{s}, \mathbf{e}\}$ *and* $I \in \{[l, u], [l, +\infty) : l, u \in \mathbb{N}, l \leq u\}$.

In the above definition **s** (resp., **e**) refers to the start (resp., end) time of tokens x and/or y. By means of *conjuctions* of atoms we may express all the possible Allen's interval relations [1] between two tokens, and some disjunctions of them. In particular, we will use the shorthands reported in Table 1. Tokens appear in conjunctions which are existentially closed for all but one distinguished variable.

▶ **Definition 5** (existential x-free conjunction). *Given a token name x, an existential x-free conjunction is a formula $\mathcal{E}$ of the form*

$$\mathcal{E} = \exists x_1[sv_1 = v_1] \dots \exists x_h[sv_h = v_h](A_1 \wedge \dots \wedge A_m)$$

where for every $1 \leq i \leq h$ we have $v_i \in \mathbf{V}_{sv_i}$ and $x_i \neq x$, moreover for every $1 \leq j \leq m$ A_j is an atom of the form $\overline{x}^1_j \leq^{\circ_j,\bullet_j}_{I_j} \overline{x}^2_j$ where $\overline{x}^1_j, \overline{x}^2_j \in \{x_1, \dots, x_h\} \cup \{x\}$.

Informally, in an existential x-free conjunction, a variable in the atom is existentially closed or equal to the unique free variable x. Moreover, we will say that an existential x-free conjunction $\mathcal{E}$ is an *existentially closed conjunction* if and only if for every $1 \leq j \leq m$, A_j is an atom of the form $\overline{x}^1_j \leq^{\circ_j,\bullet_j}_{I_j} \overline{x}^2_j$ where $\overline{x}^1_j, \overline{x}^2_j \in \{x_1, \dots, x_h\}$ (i.e., $\mathcal{E}$ does not feature any free-variable). From now on we will treat the case of x-free conjunction which are not existentially closed. Existentially closed conjunctions may be seen as a special case of x-free ones and thus we will omit them for the sake of brevity. Moreover, given an x-free conjunction $\mathcal{E} = \exists x_1[sv_1 = v_1] \dots \exists x_h[sv_h = v_h](A_1 \wedge \dots \wedge A_m)$ we define $SVar(\mathcal{E}) = \{sv_1, \dots, sv_h\}$ as the set of state variables in its existential preamble. Analogously, we define $TNames(\mathcal{E}) = \{x_1, \dots, x_h, x_{h+1}\}$ assuming without loss of generality that x_{h+1} is the free variable x.

Since the token names $TNames(\mathcal{E})$ are exactly $h+1$ (all the existentially quantified ones plus the free one x), we may have that $SVar(\mathcal{E}) \leq h$ because it is absolutely allowed that two distinct token names are bound to the same state variable.

Semantics for x-free conjunctions $\mathcal{E} = \exists x_1[sv_1 = v_1] \dots \exists x_h[sv_h = v_h](A_1 \wedge \dots \wedge A_m)$ is given in terms of a set of timelines $\Gamma = \{\mathbf{T}_{\overline{sv}_1}, \dots, \mathbf{T}_{\overline{sv}_n}\}$ such that $SVar(\mathcal{E}) \subseteq \{\overline{sv}_1, \dots, \overline{sv}_n\}$, a state variable sv_{h+1} in $\{\overline{sv}_1, \dots, \overline{sv}_n\}$ (i.e, $\mathbf{T}_{sv_{h+1}}$ is the timeline that will be associated to x), and a function $f : TNames(\mathcal{E}) \to \mathbb{N}$. In such setting we will have that $\Gamma, sv_{h+1}, f \models \mathcal{E}$ if and only if the following conditions hold:

- for every $1 \leq i \leq h+1$ we have $|\mathbf{T}_{sv_i}| \geq f(x_i)$;
- for every $1 \leq i \leq h$ we have $value(\mathbf{T}_{sv_i}[f(x_i)]) = v_i$
- for every $1 \leq j \leq m$ let $A_j = x_{i_j} \leq^{\circ_j,\bullet_j}_{[l_j,u_j]} x_{i'_j}$ (resp., $A_j = x_{i_j} \leq^{\circ_j,\bullet_j}_{[l_j,+\infty)} x_{i'_j}$) for some $1 \leq i_j, i'_j \leq h+1$, then

$$l_j \leq \bullet_j\_time(\mathbf{T}_{i'_j}, f(x_{i'_j})) - \circ_j\_time(\mathbf{T}_{i_j}, f(x_{i_j})) \leq u_j$$

(resp., $l_j \leq \bullet_j\_time(\mathbf{T}_{i'_j}, f(x_{i'_j})) - \circ_j\_time(\mathbf{T}_{i_j}, f(x_{i_j}))$).

Now we are ready to introduce TS-RULES.

▶ **Definition 6** (temporal synchronization rule). *A temporal synchronization rule $\mathcal{R}$ is a formula which has one of the following two forms:*

- *(trigger rule) $\mathcal{R} = x[sv = v] \to \mathcal{E}_1 \vee \dots \vee \mathcal{E}_n$, where for every $1 \leq i \leq n$ we have that $\mathcal{E}_i$ is an existential x-free conjunction;*
- *(triggerless rule) $\mathcal{R} = \mathcal{E}_1 \vee \dots \vee \mathcal{E}_n$ where for every $1 \leq i \leq n$ we have that $\mathcal{E}_i$ is an existentially closed conjunction.*

For the sake of clarity we will provide only the semantics of trigger rules, since triggerless ones are a simplified version of them. Given a trigger rule $\mathcal{R} = x[sv = v] \to \mathcal{E}_1 \vee \dots \vee \mathcal{E}_h$, its semantics is given by means of a set of timelines $\Gamma = \{\mathbf{T}_{sv_1}, \dots, \mathbf{T}_{sv_n}\}$, such that $\{sv_1, \dots, sv_n\} \supseteq \bigcup_{i=1}^{h} SVar(\mathcal{E}_i) \cup \{sv\}$ in such a case we say that Γ is a *candidate* for $\mathcal{R}$.

▶ **Definition 7** (semantics of trigger rules). *Given a trigger rule* $\mathcal{R} = x[sv = v] \rightarrow \mathcal{E}_1 \vee \ldots \vee \mathcal{E}_h$ *and a candidate* $\Gamma = \{\mathbf{T}_{sv_1}, \ldots, \mathbf{T}_{sv_n}\}$ *for it,* Γ *satisfies* $\mathcal{R}$*, written* $\Gamma \models \mathcal{R}$*, if and only if for every* $1 \leq i \leq |\mathbf{T}_{sv}|$*, if* $\mathbf{T}_{sv}[i] = v$ *then there exists* $1 \leq j \leq h$ *and a function* $f : TNames(\mathcal{E}_j) \rightarrow \mathbb{N}$*, for which* $f(x) = i$ *and* $\Gamma, sv, f \models \mathcal{E}_j$*.*

The timelines-based planning problem is defined as follows.

▶ **Definition 8** (timelines-based planning problem). *Given a set of TS-RULES* $\mathbf{R} = \{\mathcal{R}_1, \ldots, \mathcal{R}_p\}$ *the timelines-based planning problem, TPP for short, for* $\mathbf{R}$ *consists of determining whether or not there exists a set of timelines* $\Gamma = \{\mathbf{T}_{sv_1}, \ldots, \mathbf{T}_{sv_n}\}$ *such that* $\Gamma \models \mathcal{R}_i$ *for every* $1 \leq i \leq p$*.*

5 Annotating BPMN Diagrams with Timelines

In this section we describe in more details our approach, which consists of annotating BPMN diagrams with temporal synchronization rules. The proposed annotation is able to enrich the description of process execution by maintaining the diagram as simple as possible. In our proposal, we use a synchronization rule based notation, which allows us to easily handle temporal constraints represented by means of timelines. We would like to point out that in our approach each set Γ is associated with a possible instance of the process (i.e., Γ may be seen as the whole process log for a given process instance), while state variables together with TS-RULES abstract away from single instances and represent constraints on such instances exactly as the corresponding BPMN process diagram does.

As an example, we consider the BPMN diagram reported in Fig. 2, which has been annotated by means of timelines. In [9] it is provided a formal mapping from diagrams to timelines-based planning problems. It is easy to prove that such mapping guarantees the existence of a bijection between the solutions of the target planning problem and the correct executions of the related process model. In Fig. 3 we show an instance (i.e., an execution) of the considered process. The execution is represented as a set of timelines, one for each BPMN element. In this example tasks and gateway blocks are correctly interleaved.

Tokens on timelines may take two values, *active*, denoted by $\top$, and *not active*, denoted by $\bot$. It means that each token can be seen as an on/off switch. The meaning of these two values is straightforward: *active* means that the process element is currently executed and its duration is represented by means of the duration of the token, and *not active* means that the process element is not executed in the interval of time corresponding to the token. In Fig. 3, when a token is active, it is represented by using the BPMN notation related to the considered element. Otherwise, when the token is not active, it is represented by means of a dashed line. For example, the execution of task *Administer an Empirical Therapy* has a duration of 4 hours and half, as represented in Fig. 3 by using a task-like shape on the $t_{empirical}$ line from 19.00 to 23.30. The execution of task *Administer the Antibiotic Therapy* related to line t_{CONS} is not executed in the 1-hour interval starting at 10 *Jan* 2018 4:00.

In our proposal, we take advantage from the fact that the BPMN diagram is structured, and associate a timeline to each SESE region. The beginning of an active token represents the entry node (gateway) of the SESE region associated to the timeline, and the ending of such token represents its exit gateway. For instance, in Fig. 3 the two executions related to gateway e_{loop2} are represented by the active tokens [10 *Jan* 2018 2:00, 10 *Jan* 2018 5:00] and [10 *Jan* 2018 5:00, 10 *Jan* 2018 9:00] on the relative timeline.

In [9], more details are given about the way the described tokens can be properly constrained for representing correct executions of gateways and tasks, and about the way interleaving may be forced by means of suitable synchronization rules.

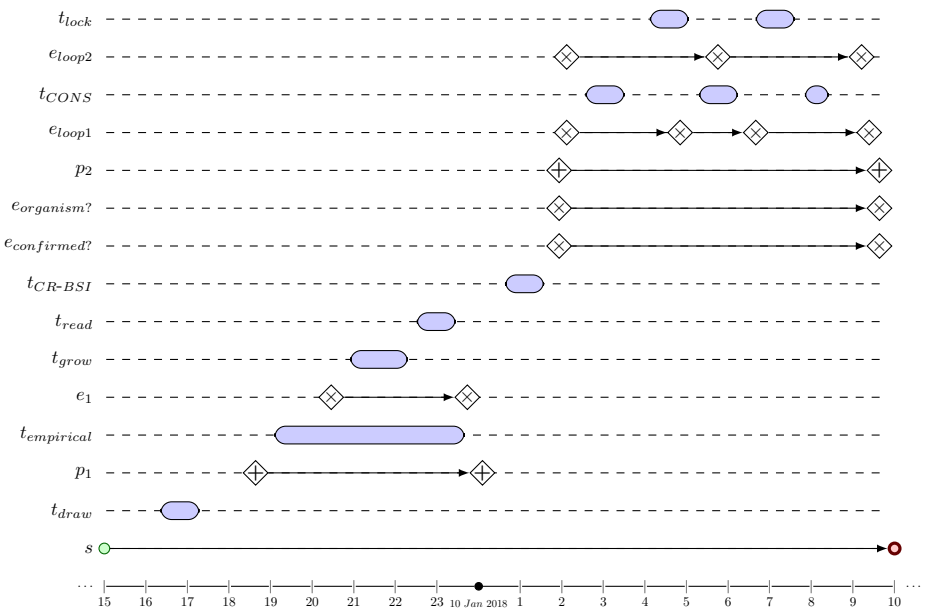

Figure 3 Example of an execution of the business process of Fig. 2, represented as timeline (for the sake of brevity only timelines related to elements involved in the considered execution are shown).

In the following examples we will assume that the presented scenario is taken from timelines representing correct executions of the considered BPMN process. For the process in Fig. 2, a timeline having a token t_{look}, which is active before an active token t_{grow}, is not allowed since the correct execution of the process requires that the execution of task *Look for Other Sources of Infection* related to t_{look} is after the execution of task *Grow Blood Culture* related to t_{grow}. Before providing the rules for the constraints related to the example of Sec. 3, we introduce a (more human-readable) variation on the syntax for TS-RULES. Such syntax seems more suitable for annotating BPMN diagrams. First, instead of anonymous state variable names like $x, y, \ldots$ we will use the element type associated to the state variable and thus we will write something like $task, task', \ldots$ when the state variable is associated to a task, $exclusive, exclusive', \ldots$ when the state variable is associated to a region delimited by an exclusive gateway, and so on. Moreover, we replace $state\text{-}variable = token\text{-}value$ in the quantifications with either $element\text{-}name$ or its overlined version $\overline{element\text{-}name}$ where $element\text{-}name$ is the subscript of the BPMN element associated to state-variable. We will write $element\text{-}name$ if $token\text{-}value = \top$ and $\overline{element\text{-}name}$ if $token\text{-}value = \bot$, respectively. For instance, rule $x[t_{CONS} = \top] \rightarrow \exists y[t_{lock} = \bot](x \subseteq y)$ turns out to be rule $task[CONS] \rightarrow \exists task'[\overline{lock}](task \subseteq task')$ in the new syntax. The DID, DPT and RTC constraints related to the example of Sec. 3 may be expressed as follows.

- Duration-Induced-Decision (DID):

$$\text{C1)}\quad task[grow] \rightarrow \exists exclusive[organism?] \left(\begin{array}{c} task \leq^{s,e}_{[2\ hours, +\infty)} task \wedge \\ task \leq^{s,s}_{[0,+\infty]} exclusive \end{array} \right) \vee (task \leq^{s,e}_{[0,2\ hours]} task)$$

Fig. 4 shows examples of four partial evolutions of timelines $t_{grow}, e_{organism?}$ and t_{look}. These considered scenarios are triggered by the presence of the execution of the task related to t_{grow} (i.e., the rounded rectangle on the bottom dashed line).

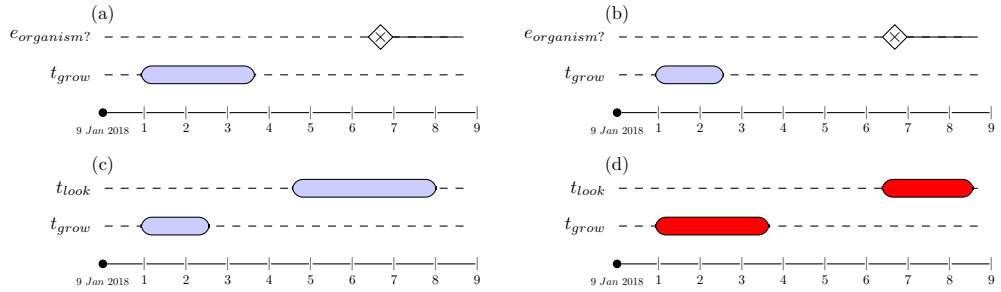

Figure 4 (a), (b), and (c) are examples of executions that fulfill the Duration Induced Decision constraint C1. (d) does not fulfill C1.

Fig. 4(a) represents the case in which the duration of t_{grow} is more than two hours and thus, according to the specified constraint, the YES branch of $e_{confirmed?}$, and the block $e_{organism?}$, must be executed. In this scenario the first disjunction in C1 is fulfilled. When the duration of t_{grow} is less than 2 hours, either YES branch or NO branch of $e_{confirmed?}$ is executed, as depicted in Fig. 4(b) and Fig. 4(c), respectively. In the latter case task related to t_{look} must be executed as correctly depicted in Fig. 4(c).
Example in Fig. 4(d) represents a way to violate constraint C1. In this case, the duration of t_{grow} is greater than 2 hours and the branch NO of $e_{confirmed?}$ is taken by executing t_{look}. This situation violates both disjunctions of C1.

- Disjoint-Parallel-Tasks (DPT):

$$\text{C2)}\quad task[CONS] \rightarrow \exists task'[\overline{lock}](task \subseteq task')$$

Fig. 5 reports examples of two partial evolutions of t_{lock} and t_{CONS} timelines. The intuition behind rule C2 is that if a token on the timeline t_{CONS} is active, then it is contained in a not active token on the timeline t_{lock}.

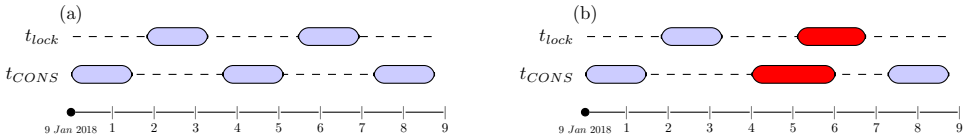

Figure 5 (a) is an example of execution that fulfills the Disjoint-Parallel-Tasks constraint C2. (b) does not fulfill C2.

In Fig. 5(a) an interleaving of tokens in t_{lock} and t_{CONS} that satisfies rule C2 is depicted. In Fig. 5(b) a scenario that violates rule C2 is reported. In this latter case, token [9 *Jan* 2018 4:00, 9 *Jan* 2018 6:00] on timeline t_{CONS} contains the overlap of tokens [9 *Jan* 2018 3:30, 9 *Jan* 2018 5:00] and [9 *Jan* 2018 5:00, 9 *Jan* 2018 6:30] on t_{lock}, and thus it cannot be contained in any token on timeline t_{lock}.

- Relative-Time-Constraint (RTC):

$$\begin{aligned}\text{C3)}\ task[\text{CR-BSI}] \rightarrow\ & \exists task'[\overline{TEE}]\exists task''[TEE](task \subseteq task' \\ & \wedge task'\langle M\rangle task'' \wedge task \leq^{e,s}_{[5\ days, 7\ days]} task'') \\ & \vee \exists task'[\overline{TEE}](task\langle M\rangle task' \wedge task' \leq^{s,e}_{(+\infty,+\infty)} task')\end{aligned}$$

Fig. 6 shows examples of three partial evolutions involving t_{TEE}, $t_{\text{CR-BSI}}$ and t_{CONS} timelines. The scenario reported in Fig. 6(a) fulfills rule C3 since an active token on timeline $t_{\text{CR-BSI}}$ is present, and the next active token on t_{TEE} happens after 6 days.

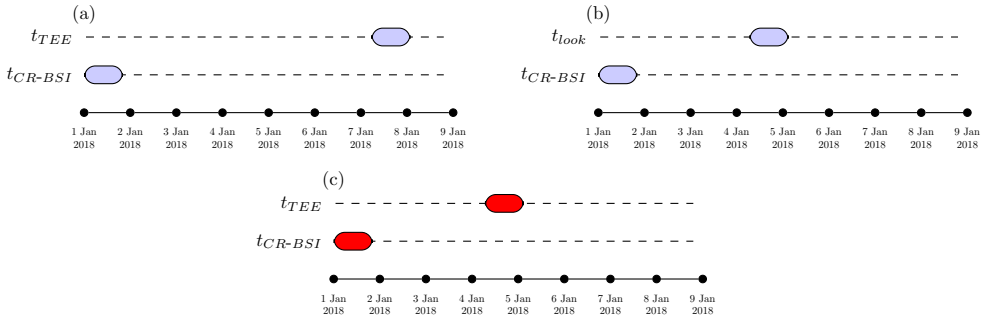

Figure 6 (a) and (b) are examples of executions that fulfill the Relative-Time-Constraint C3. (c) does not fulfill C3.

Also Fig. 6(b) represents a scenario satisfying C3. Assuming that timelines satisfy the correct execution of the process diagram, in this case there is an active token on the timeline t_{look} and thus the NO branch of $e_{confirmed?}$ has been chosen and there are no active tokens on timeline t_{TEE}. This means that the second conjunction of $C3$ is fulfilled. Finally, Fig. 6(c) shows a scenario violating rule C3, since there exists an active token τ on t_{TEE}, which happens after an active token τ' on $t_{CR\text{-}BSI}$, but the distance between the end of τ' and the beginning of τ is less than five days.

TS-RULES allow us to capture different kind of constraints For example, the described temporal constraints may be achieved by suitably adding throw/catch events and event-based gateways to the diagram. However, there are two main drawbacks in this approach:
(i) enforcing such constraints in the diagram may easily make it difficult to read (e.g., see [11] for an example); (ii) modularity is lost forever since some changes in the diagram may change how the constraints are enforced in it.

Moreover, some constraints expressible via TS-RULES may be defined by using *Decision Model and Notation* (DMN) [24]. DMN is a standard notation for modeling decisions, and it is complementary to BPMN. DMN is able to specify conditions on the elements that may change the flow of execution (e.g., exclusive gateways). Our approach can capture DMN sematics in a natural way by introducing additional state variables for data affecting the choice (more on that in Sec. 6) and the related TS-RULES, thus providing a way to check consistency properties between the DMN logic and the process. However, if the choices are inherently depending from the evolution of the data and/or of the flow of the process, TS-RULES explicit such dependence in a more direct and concise way. Finally, TS-RULES are more general since they constrain the flow of execution without the need to be bound to some element in the diagram. For instance, they can force parallel tasks to follow specific patterns as shown by rule C2.

6 Data, Resources, and History-driven gateways

In this section, we illustrate how the proposed approach can be used for expressing data and resource synchronization constraints. Moreover, we introduce a *decision* gateway, based on timelines, for specifying the decision rule about the branch to execute.

In Fig. 7, we report an example of a healthcare process for taking care of severely injured patients [12]. The process of Fig. 7 involves three actors: *paramedics*, *nurses*, and *operating room staff*. Each actor is represented as a swimlane within the pool. *Paramedics* reach the patient and provide transport for her. *Nurses* take care of the patient when she arrives at the hospital, and *operating room staff* (i.e., surgeon and anesthetist), alerted in critical situations, provide emergency surgery.

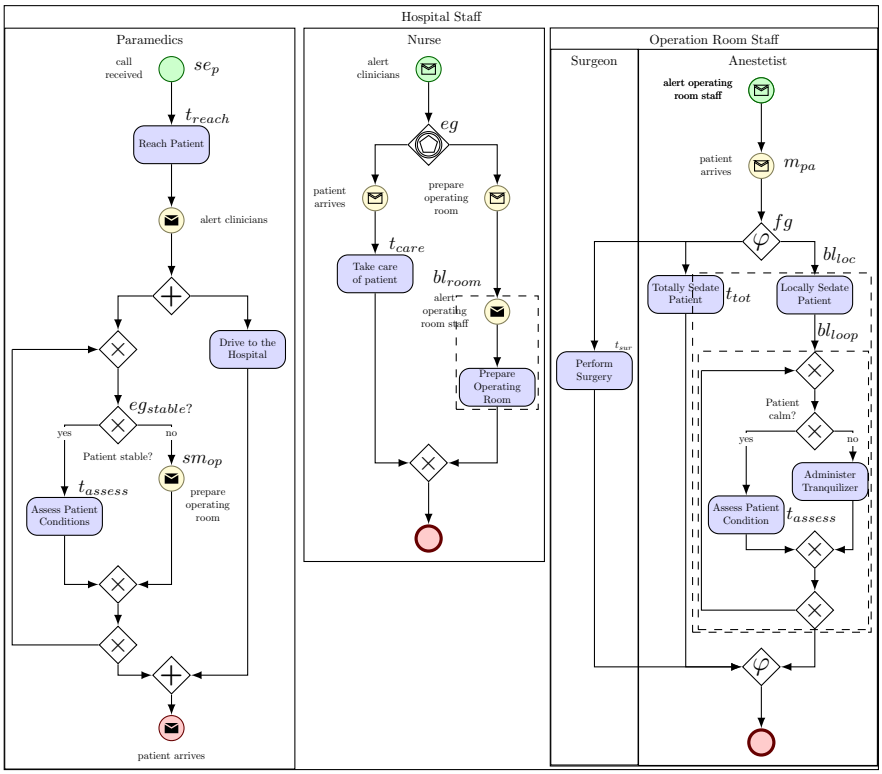

Figure 7 An example of History-driven gateway.

This simple example allows us to introduce the following constraints on data, resources and decisions that may be naturally captured by means of timelines.

- *Enforce parallelization:* this constraint allows us to enforce the simultaneosly execution of two activities beloging to a parallel block. As an example, for specifying that if block bl_{loc} is chosen, then the execution of its internal loop bl_{calm} must be performed for the whole duration of the surgery, we can use the rule: $x[bl_{calm} = \top] \rightarrow \exists y[t_{sur} = \top](y \subseteq x)$. This kind of constraint is symmetrical with respect to the Disjoint Parallel Task constraint described in Sec. 5.
- *Message passing:* BPMN elements like messages, with their possible different semantics, may be easily integrated in our formalism. In this paper, for the sake of space, we only sketch an idea of this kind of constraints, without giving a detailed description and analysis. As an example, during the transport of the patient, paramedics may alert the operation room staff in case the patient situation is getting worse. The aim of the notification alert is requiring the preparation of the operating room. This mechanism is managed by the event-based gateway eg in Fig. 7 in the following way (notice that we consider the messages attached to the gateway as part of it).

$$x[eg = \top] \rightarrow \begin{array}{l} \exists z[se_p = \top]\exists \overline{z}[sm_{op} = \bot]\exists y[t_{care} = \top]\exists \hat{y}[t_{care} = \bot]\exists \check{y}[t_{care} = \bot]\exists \overline{y}[bl_{room} = \bot] \\ \left(z \cap_{BMO} x \wedge \overline{z} \leq^{s,s}_{[0,+\infty)} x \wedge z \leq^{e,e}_{[0,+\infty)} \overline{z} \wedge \hat{y}\langle M\rangle y \wedge y\langle M\rangle \check{y} \wedge \hat{y} \cap_{BMO} x \wedge x \cap_{BMO} \check{y} \wedge y \subseteq x \wedge x \subseteq \overline{y} \right) \vee \\ \exists z[sm_{op} = \top]\exists \overline{z}[se_p = \top]\exists y[bl_{room} = \top]\exists \hat{y}[bl_{room} = \bot]\exists \check{y}[bl_{room} = \bot]\exists \overline{y}[t_{care} = \bot] \\ \left(z \subseteq x \wedge \overline{z} \leq^{s,s}_{[0,+\infty)} x \wedge z \leq^{e,e}_{[0,+\infty)} \overline{z} \wedge \hat{y}\langle M\rangle y \wedge y\langle M\rangle \check{y} \wedge \hat{y} \cap_{BMO} x \wedge x \cap_{BMO} \check{y} \wedge y \subseteq x \wedge x \subseteq \overline{y} \right) \end{array}$$

This proposal is similar to an exclusive gateway with the addition, by means of the $z/\overline{z}$ variables, of a constraint regarding the preemptiveness of messages determining which block will be executed. Managing end events and intermediate message events is slightly

different, since the former can be seen as the end of the related block. For example, in Fig. 7, *patient arrives* is the end of the block se_p. The duration of sm_{op} must be constrained to 1 unit, in order to make it istantaneous by means of rule $x[sm_{op} = \top] \rightarrow x \leq^{s,e}_{[1,1]} x$. Finally, when an intermediate message does not appear as a successor of an event-based gateway, its semantics must be explicitly encoded. This is the case of m_{pa} in Fig. 7, which is mapped to rule $x[m_{pa} = \top] \rightarrow \exists y[se_p = \top](x \leq^{e,e}_{[0,0]} y)$.

- *Resources and roles management:* a very important aspect to consider in managing business processes is related to the definition of roles that are involved in the process execution. BPMN provides swimlanes (within pools) for representing roles (within organizations).
  In the process of Fig. 7 tasks must be performed by the related roles (represented by means of swimlanes), this means that a paramedic cannot perform the surgery, and an anesthetist cannot drive the ambulance. However both a paramedic and an anesthetist may perform task t_{assess}. To force such constraint the rule $x[t_{assess} = \top] \rightarrow \exists y[Paramedic = \top](x = y) \vee \exists y[Anesthetist = \top](x = y)$ can be specified. In this case paramedics and anesthetists represent sets of timelines, one for each resource available in the considered instance. Each of such timelines represents how the specific resource is allocated to each task. The mutual exclusion in the use of resources is guaranteed by the non-overlapping nature of the intervals on the same timeline. The described notation allows us to abstract the number of available resources, since corresponding numbers are inserted at verification time. For example, by instantiating the above rule by using 2 paramedics and 3 anesthetists, we obtain $x[t_{assess} = \top] \rightarrow \exists y[paramedic_1 = \top](x = y) \vee \exists y[paramedic_2 = \top](x = y) \vee \exists y[anesthetist_1 = \top](x = y) \vee \exists y[anesthetist_2 = \top](x = y) \vee \exists y[anesthetist_3 = \top](x = y)$. This allows us to verify quantitative properties related to durations even in presence of multiple instances of the same process, that access the same resources [12].
- *Data driven decisions:* the described timeline-based approach is able to provide a preliminary integration of processes and data. Other proposals presented in literature [10, 14] are more focused on integrating existing formalisms (e.g., Entity-Relation data model), for representing data in BPMN process models.
  The timeline-based approach should not be considered as an alternative for such approaches, but as an annotation working well along with them, by helping in clarifying and verifying properties of data at the time execution of processes.
  As an example, let us suppose that the decision about which branch of $eg_{stable?}$ has to be chosen, is determined by both patient blood pressure (pBP), and patient body temperature (pBT). Let us assume that pBP and pBT are represented by means of the different timelines $(\mathbf{V}_{pBP}, \mathbf{\Delta}_{pBP}, \mathbf{D}_{pBP})$ and $(\mathbf{V}_{pBT}, \mathbf{\Delta}_{pBT}, \mathbf{D}_{pBT})$, respectively. More precisely, $\mathbf{V}_{pBP} = \{70, \ldots, 190, \perp\}$, i.e., on the timeline pBP all the possible ranges of blood pressures plus a disabled value when the pressure is not measured, are represented. The same holds for the body temperature, i.e., $\mathbf{V}_{pBT} = \{29, \ldots 41, \perp\}$. In this case, data may be available only when task t_{assess} is performed, thus the rules $x[t_{assess} = \perp] \rightarrow \exists y[pBP = \perp](y = x)$, $x[t_{assess} = \top] \rightarrow \bigvee_{v \in \{70,\ldots,190\}} \exists y[pBP = v](x = y)$ model this constraint. Similar rules can be specified for constraining pBT.
  Finally, for constraining the gateway sm_{op} to be executed whenever the values of BT and BP exceed certain thresholds, this set of rules can be specified:

$$y[BP = v] \rightarrow \exists x[eg_{stable?} = \top]\exists z[sm_{op} = \top](y \subseteq x \wedge z \subseteq x) \vee \exists x[eg_{stable?} = \perp](y \subseteq x), \text{ with } v > 150$$
$$y[BT = v] \rightarrow \exists x[eg_{stable?} = \top]\exists z[sm_{op} = \top](y \subseteq x \wedge z \subseteq x) \vee \exists x[eg_{stable?} = \perp](y \subseteq x), \text{ with } v > 39$$

  The described example is able to represent the way in which, by means of timeline-based annotation, it is possible to enrich processes with constraints on temporal aspects, roles

and data. Process models are equipped both with the constraints on their execution and with requirements about decisions and durations, without burden the process model.

- *Special behaviors for gateways:* in this work we show how to express BPMN diagram semantics and complex temporal constraints that would involve, if integrated directly in the diagram, complex patterns of throw/catch events as well as event-based gateways. We intentionally did not extend BPMN with some new element, in order to stay within the boundaries of BPMN semantics. However, it is possible to use TS-RULES for extending the standard BPMN notation, by expressing the behavior of complex new elements in a straightforward way. As an example, let us consider gateway fg in Fig. 7. If it is the case that an instance of the process reaches fg, we expect that the patient has to be sedated, either totally or locally, while surgery has to be performed. Thus, in this case, we expect that branch t_{sur} is anyway executed, while choosing exactly one between the branches t_{tot} and bl_{loc}. Moreover, the choice between t_{tot} and bl_{loc} will be dictated by recent results of measurements related to the patient condition. For example, in case that $pBP > 150$ at some time point between 3 hours and the beginning of the surgery, a partial sedation has to be administered, otherwise it is possible to administer the total one. Rules for specifying these expectations are the following:

$$x[fg = \top] \rightarrow \begin{array}{l} \exists y[t_{sur} = \top]\exists z[t_{tot} = \top]\exists w[bl_{loc} = \bot](y \subseteq x \wedge z \subseteq x \wedge x \subseteq w) \vee \\ \exists y[t_{sur} = \top]\exists z[bl_{loc} = \top]\exists w[t_{tot} = \bot](y \subseteq x \wedge z \subseteq x \wedge x \subseteq w) \end{array}$$

$$x[pBP = v] \rightarrow \begin{array}{l} \exists y[fg = \top]\exists z[bl_{loc} = \top](x \leq^{e,s}_{[0,3\ hours]} y \wedge z \subseteq y) \vee \\ \exists y[fg = \bot](x \leq^{e,e}_{[3\ hours,+\infty)} y \wedge y \leq^{s,s}_{[0,+\infty)} x) \end{array} \text{, with } v > 150$$

Summing up, by means of timelines we are able to introduce a BPMN element that behaves like a *conditional parallel* gateway, that is, a parallel gateway which runs all and only the branches that satisfy a certain condition at the precise moment of its execution.

7 Conclusions

In this paper we dealt with issues related to the specification of different kinds of constraints on process models represented by means of BPMN diagrams. We provided a timelines-based approach for expressing admissible executions of a process. Timelines allow us to specify complex constraints possibly related to time, data, and resources, by annotating the BPMN process diagram, without overburden the process diagram itself. Some of the advantages of our proposal are (i) providing a means for specifying complex constraints without extending BPMN; (ii) applying the existing tools for timeline-based planning [2, 5, 6] for verifying *qualitative properties* at design time; (iii) supporting resources optimization in the style of [12], and (iv) checking *quantitative properties* such as the interplay between the number of mutually exclusive resources and the number of process instances that may be completed in a given amount of time. For future work, we plan to apply synchronization rules for querying running processes and monitoring business process activities (Business Activity Monitoring (BAM[3]).

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