Modelling and Enactment of Data-aware Processes

Diego Calvanese¹, Marco Montali¹, Fabio Patrizi², Andrey Rivkin¹

¹ Free University of Bozen-Bolzano, Piazza Domenicani 3, 39100 Bolzano, Italy
calvanese,montali,rivkin@inf.unibz.it
² Sapienza Università di Roma
patrizi@dis.uniroma1.it

Abstract. During the last two decades, increasing attention has been given to the challenging problem of resolving the dichotomy between business process management and master data management. Consequently, a substantial number of data-centric models of dynamic systems have been brought forward. However, the control-flow abstractions they adopt are ad-hoc, and so are the data models they use. At the same time, contemporary process management systems rely on well-established formalisms for representing the control-flow and typically employ full-fledged relational databases for storing master data. Nevertheless, they miss a conceptually clean representation of the task and condition logic, that is, of how data are queried and updated by the process. In this paper, we address such issues by proposing a general, pristine approach to model processes operating on top of the standard relational technology. Specifically, we propose a declarative language based on SQL that supports the conceptual modelling of control-flow conditions and of persistent data updates with external inputs. We show how this language can be automatically translated into a concrete procedural SQL dialect, consequently providing in-database process execution support. We then report on how we made the language operational into a concrete prototype, which provides a plethora of functionalities to specify and enact process models, inspect their execution state, and construct their state space. Notably, the proposed approach can be seen as the concrete counterpart of one of the most well-established formal frameworks for data-aware processes, thus enjoying all the formal properties and verifiability conditions studied therein.

1 Introduction

During the last two decades, increasing attention has been given to the challenging problem, still persisting in modern organizations [18], of resolving the dichotomy between business process management and master data management [8,17,3]. Devising integrated models and corresponding enactment platforms for processes and data is now acknowledged as a necessary step to tame a number of conceptual and enterprise engineering issues, which cannot be tackled by implementation solutions applied at the level of the enterprise IT infrastructure.

This triggered a flourishing line of research on concrete languages for data-aware processes, and on the development of tools to model and enact such processes. The main unifying theme for such approaches is a shift from standard activity-centric business process meta-models, to a data-centric paradigm that focuses first on the elicitation of business entities, and then on their behavioral aspects. Notable approaches in this line
are object-centric processes \cite{10} and artifact-centric models\cite{8}. In parallel to these new modeling paradigms, also business process management systems based on standard, activity-centric approaches à la BPMN, have increasingly incorporated data-related aspects in their tool support. Many modern BPM platforms provide (typically proprietary) data models, ad-hoc user interfaces to indicate how process tasks induce data updates, and query languages to express decisions based on data. This diversity creates the disadvantage that a data-aware process deployed in the existing tools cannot be understood in terms of more general principles, nor redeployed directly using other tools. This is witnessed by a number of ongoing proposals that advocate mappings for model-to-model transformation (see, e.g., \cite{21,9}).

In the database community, many foundational results have been produced towards the formalization of data-aware business processes and the identification of boundaries for their verifiability \cite{3}. The models studied in this line are typically more essential and succinct than their concrete counterparts stemming from the domains mentioned before. Yet, they have not made their way into actual modeling&enactment tools.

In this paper, we address such issues by proposing a general, pristine approach to model data-aware processes operating on top of the standard relational technology. Specifically, we propose a methodology based on SQL that allows for conceptual modeling of control-flow conditions and of persistent data updates with external inputs. We then show how this methodology can be automatically translated into a concrete procedural SQL dialect, consequently providing in-database process execution support. Specifically, we introduce DAPHNE, an engine that exploits standard relational technology and Java to provide, at once, the basis for data-aware process modeling and enactment. The DAPHNE execution engine comes with a relational back-end used to store relational data and apply the updates induced by the atomic tasks of the process. In addition, it is equipped with a Java front-end providing APIs and functionalities to inspect the current state of the process and its underlying data, as well as interact with different concrete systems for acquiring external data. We show that the internal functioning of DAPHNE seamlessly accounts for three key usage modalities: enactment with and without recall about historical data, and state space construction to support formal analysis.

\section{The DAPHNE Model}

DAPHNE relies on a declarative, SQL-based \textit{data-aware process specification (DAPS)} to capture processes operating over relational data. Methodologically, \textit{DAPS} can be seen as a guideline for business process programmers that have minimal knowledge of SQL and
aim at developing process-aware, data-intensive applications. Technically, DAPS can be seen as a SQL-based variant of data-centric dynamic systems (DCDS) [1], one of the most well-known formal models for data-aware processes.

A DAPS consists of two components: (i) a data layer, which accounts for the structural aspects of the domain, and maintains its corresponding extensional data; (ii) a control layer, which inspects and evolves the (extensional part of the) data layer.

We next delve into these two components in detail, illustrating the essential features of DAPS on the following running example, inspired by [6].

Example 1. We consider a travel reimbursement process, whose control flow is depicted in Figure 1. The process starts (StartWorkflow) by checking pending employee travel requests in the database. Then, after selecting a request, the system examines it (ReviewRequest), and decides whether to approve it or not. If approved, the process continues by calculating the maximum refundable amount, and the employee can go on her business trip. On arrival, she is asked to compile and submit a form with all the business trip expenses (FillReimb). The system analyzes the submitted form (ReviewReimb) and, if the estimated maximum has not been exceeded, approves the refunding. Otherwise the reimbursement is rejected.

Data layer. Essentially, the data layer is a full-fledged relational database, consisting of an intensional (schema) part, and an extensional (instance) part. The intensional part is a database schema, that is, a pair \( \langle R, E \rangle \), where \( R \) is a finite set of relation schemas, and \( E \) is a finite set of integrity constraints over \( R \). We adopt the named perspective: a relation schema is defined by a signature containing a relation name and a set of attribute names. In the following, we always implicitly assume that all attribute names are typed, and so are all the constitutive elements of a DAPS that insist on relation schemas. Type compatibility can be easily defined and checked, but we do not tackle it explicitly so as to maintain the presentation light.

The extensional part of the data layer is a database instance, consisting of a set of labelled tuples over the relation schemas in \( R \). Given a relation \( R \) in \( R \), a labelled tuple over \( R \) is a total function mapping the attribute names in the signature of \( R \) to corresponding values. We always assume that a database instance is consistent, that is, satisfies all constraints in \( E \). While the intensional part is fixed throughout the execution of a DAPS model, the extensional part starts from an initial database instance that is then iteratively updated through the control layer, as dictated below.

In the remainder of the paper, we consider three types of database constraints: primary keys, foreign keys, and domain constraints. A domain constraint is attached to a given relation attribute, and explicitly enumerates which values can be assigned to that attribute. To succintly refer to primary and foreign keys, we use the following shorthand notation. Given a relation \( R \) and a tuple \( A = \langle A_1, \ldots, A_m \rangle \) of attributes defined on \( R \), we use \( R[A] \) to denote the projection of \( R \) on such attributes. \( \text{PK}(R) \) indicates the set of attributes in \( R \) that forms its primary key (similarly for keys), whereas \( S[B] \rightarrow R[A] \) defines that projection \( S[B] \) is a foreign key referencing \( R[A] \) (where attributes in \( B \) and those in \( A \) are matched component-wise).

Example 2. The database schema that defines the data manipulated by the process of the DAPS informally described in Example 1 is depicted in Figure 1. We describe in detail some of the relations: (i) requests under process are stored in the relation CurrReq,
whose components are the request UID, which is the primary key, the employee requesting a reimbursement, the trip destination, and the status of the request, which ranges over a set of predefined values (i.e., obeys to a given domain constraint); (ii) maximum allowed trip budgets are stored in \texttt{TrvlMaxAmnt}, whose components are the identifier (the primary key), the request reference number (a foreign key), and the maximum amount assigned for the trip; (iii) \texttt{TrvlCost} stores the total amount spent, with the same components as \texttt{TrvlMaxAmnt}.

\textbf{Control layer.} While the data layer focuses on the static properties of the domain of interest, the control layer captures the dynamics within the same domain. More precisely, the control layer is a triple \( \langle F, A, \rho \rangle \), where \( F \) is a finite set of external services, \( A \) is a finite set of atomic tasks (or actions), and \( \rho \) is a process specification.

Each service is a black-box function that can bring input data into the process, and that in turn abstractly accounts for a variety of concrete data injection mechanisms such as user forms, third-party applications, web services, internal generation of primary keys, and so on. Each external service comes with a signature indicating the service name and its formal input parameters. To distinguish services, we use names starting with @.

Actions are the basic building blocks of the control layer, and represent transactional operations over the data layer. Each action comes with a distinguished name and a set of formal parameters, and consists of a set of parameterized SQL statements that inspect and update the the current state of the DAPS (i.e., the current database instance), possibly invoking services to incorporate external data into the update. The executability of an action, including how its formal parameters may be bound to corresponding values, is dictated by the process specification \( \rho \). This, in turn, is a set of condition-action (CA) rules, again grounded in SQL, and used to declaratively capture the DAPS control-flow.

Formally, an \textit{action} is an expression \( \alpha(p_1, \ldots, p_n) : \{e_1; \ldots; e_m\} \), where:

- \( \alpha(p_1, \ldots, p_n) \) is the action signature, constituted by the action name \( \alpha \) and the set \( \{p_1, \ldots, p_n\} \) of action formal parameters;
- \( \{e_1, \ldots, e_m\} \) is a set of (simultaneous) effect specifications.

We assume that no two actions in \( A \) share the same name. Consequently, we sometimes use the action name to refer to its corresponding action specification.

Each effect specification \( e_i \) modifies the current database instance using standard SQL, and is either a deletion or insertion.

An \textit{insertion effect specification} is a SQL statement of the form:

\[
\text{INSERT INTO} \quad R(A_1, \ldots, A_k) \ \text{VALUES} \quad (t_1, \ldots, t_k),
\]

where each \( t_j \) is either a value, an action formal parameter or a scalar function invocation. The latter amounts to the SQL representation of a service call. Given a service call \( @F \) with \( p \) parameters, a scalar function invocation for \( F \) is of the form \( @F(x_1, \ldots, x_p) \), where each \( x_j \) is either a value or an action formal parameter (i.e., functions are not nested). Notice that \texttt{VALUES} can be seamlessly substituted by a complex SQL selection inner query, which in turn allows for bulk insertions into \( R \), using all the answers obtained from the evaluation of the inner query.

A \textit{deletion effect specification} is a SQL statement of the form:

\[
\text{DELETE FROM} \quad R \ \text{WHERE} \quad \langle \text{condition} \rangle,
\]

where the \texttt{WHERE} SQL clause may internally refer to the action formal parameters. This specification captures the simultaneous deletion of all tuples returned by the evaluation
of condition on the current database instance. Consistently with classical conceptual modeling approaches to domain changes \[16\], we allow for overlapping deletion and insertion effect specifications, giving higher priority to deletions, that is, first all deletions and then all insertions are applied. This, in turn, allows to unambiguously capture update effects (by deleting certain tuples, and inserting back variants of those tuples). Introducing explicit SQL update statements would create ambiguities on how to prioritize updates w.r.t. potentially overlapping deletions and insertions.

For each action $\alpha$ in $A$ with $k$ parameters, $\rho$ contains a single CA rule determining the executability of $\alpha$. The CA rule is an expression of the form:

$$\text{SELECT } A_1, \ldots, A_s \text{ FROM } R_1, \ldots, R_m \text{ WHERE } \langle \text{condition} \rangle \text{ ENABLES } \alpha(A_{n_1}, \ldots, A_{n_k}),$$

where each $A_i$ represents an attribute, each $R_i$ is a relation, $\alpha \in A$, and $\{A_{n_1}, \ldots, A_{n_k}\} \subseteq \{A_1, \ldots, A_s\}$. Here, the SQL SELECT query represents the rule condition, and the results of the query provide alternative actual parameters that instantiate the formal parameters of $\alpha$. This grounding mechanism is applied on a per-answer basis, that is, to execute $\alpha$ one has to choose how to instantiate the formal parameters of $\alpha$ with one of the query answers returned by the SELECT query. Multiple answers consequently provide alternative instantiation choices. Notice that requiring each action to have only one CA rule is without loss of generality, as multiple CA rules for the same action can be compacted into a unique rule whose condition is the UNION of the condition queries in the original rules.

Example 3. We concentrate on three tasks of the process in Example 1 and show their DAPS representation. Task StartWorkflow creates a new travel reimbursement request by picking one of the pending requests from the current database instance. We represent this via a StartWorkflow DAPS action with three formal parameters, respectively denoting a pending request id, its responsible employee, and her intended destination:

$$\text{SELECT } \text{id, empl, dest FROM } \text{Pending ENABLES StartWorkflow(id, empl, dest)}$$

StartWorkflow(id, empl, dest): \{ 
  \text{DELETE FROM } \text{Pending WHERE } \text{Pending.id = id;} 
  \text{INSERT INTO } \text{CurrReq(id, empl, dest, status)} 
  \text{VALUES(@genpk(), empl, dest, submitd}) \}

Here, a new travel reimbursement request is generated by removing the entry of Pending matching the given id, and then inserting a new tuple into CurrReq by passing the empl and dest values of the deleted tuple, and by setting the status to 'submitd'. To get a unique identifier value for the newly inserted tuple, we invoke the nullary service call @genpk, which returns a fresh primary key value.

Task ReviewRequest examines an employee trip request and, if accepted, assigns the maximum reimbursable amount to it. The corresponding action can be executed only if the CurrReq table contains at least one submitted request:

$$\text{SELECT } \text{id, empl, dest FROM } \text{CurrReq WHERE } \text{CurrReq.status = 'submitd'} \text{ ENABLES RvwRequest(id, empl, dest)}$$

RvwRequest(id, empl, dest): \{ 
  \text{DELETE FROM } \text{CurrReq WHERE } \text{CurrReq.id = id;} 
  \text{INSERT INTO } \text{CurrReq(id, empl, dest, status)} \}
VALUES(id, empl, dest, @status(empl, dest))
;
INSERT INTO TrvlMaxAmnt(tid, tfid, tmaxAmnt)
VALUES(@genpk(), id, @maxAmnt(empl, dest))

The request status of CurrReq is updated by calling service @status, that takes as input an employee name and a trip destination, and returns a new status value. Also, a new tuple containing the maximum reimbursable amount is added to TrvlMaxAmnt. To get the maximum refundable amount for TrvlMaxAmnt, we employ service @maxAmnt with the same arguments as @status.

Task FillReimbursement updates the employee’s current request by adding a compiled form with all the business trip expenses. This can be done only when the request has been previously accepted. This translates into DAPS as follows:

SELECT id, empl, dest FROM CurrReq WHERE CurrReq.status = 'acceptd'
ENABLES FillReimb(id, empl, dest)

FillReimb(id, empl, dest): {INSERT INTO TrvlCost(id, fid, cost)
VALUES(@genpk(), id, @cost(empl, dest))}

Again, @genpk and @cost are used to obtain values externally upon insertion. ◄

Execution semantics. First of all, we define the execution semantics of DAPS actions. Let $\mathcal{I}$ be the current database instance for the data layer of the DAPS of interest. An action $\alpha$ is enabled in $\mathcal{I}$ if the evaluation of the SQL query constituting the condition in the CA rule of $\alpha$ returns a nonempty result set. This result set is then used to instantiate $\alpha$, by non-deterministically picking an answer tuple, and use it to bind the formal parameters of $\alpha$ to actual values. This produces a so-called ground action for $\alpha$.

The execution of a ground action amounts to simultaneous application of all its effect specifications, which requires to first manage the function invocations, and then apply the deletions and insertions. This is done as follows. First, function invocation in the ground action needs to be fully instantiated, by resolving the subqueries present in all those insertion effects whose values contain function invocations. Each function invocation then becomes a call to the corresponding service, passing the ground values as input. The result obtained from the call is then used to replace the function invocation itself, getting a fully instantiated VALUES clause for the insertion effect specification. Once this instantiation is in place, a transactional update is issued on top of $\mathcal{I}$, by first pushing all deletions, and then pushing all insertions. If the resulting database instance satisfies the constraints of the data layer, then the update is committed. If instead a constraint is violated, then the update is rolled back, maintaining $\mathcal{I}$ unaltered.

Connection with existing process modeling languages. As pointed out before, DAPS may be seen as a SQL-based variant of the DCDS formal framework. This has a twofold advantage. On the one hand, all the results on the boundaries of verifiability for DCDS directly transfer to DAPS as well. On the other hand, DCDS have been used to formalize a variety of more concrete process modeling languages, consequently showing that a declarative, rule-based mechanism for defining the process control-flow can be used to encode both data- and activity-centric approaches. In particular, DAPS can be readily used to capture: (i) data-centric process models supporting the explicit notion of process instance (i.e., case) [13]; (ii) several variants of Petri nets [2] without data; (iii) Petri nets equipped with resources and data-carrying tokens [14]; (iv) recent variants of (colored)
Fig. 2: Conceptual architecture of DAPHNE

Petri nets equipped with a relational database storage [6][15]; (v) artifact-centric process models specified using Guard-Stage-Milestone language by IBM [19].

3 The DAPHNE System

We discuss how the DAPS approach has been implemented in a concrete system that provides in-database process enactment, as well as the basis for formal analysis.

3.1 Internal Architecture

The core architecture of DAPHNE is depicted in Figure 2. The system takes as input a representation of a DAPS and uses a standard relational database management system (DBMS) to support the DAPS execution.

The DBMS takes care of storing the data relevant to the input DAPS and supports, through the DB Engine of the underlying RDBMS, the application of a set of operations that jointly realize the given DAPS actions. The Flow Engine constitutes the application layer of the system; it facilitates the execution of a DAPS by coordinating the activities that involve the user, the DBMS, and the services. Specifically, the Flow Engine issues queries to the DBMS, calls stored procedures, and handles, through a further module called Service Manager, the communication with external services, when needed.

Next we give a detailed representation of DAPHNE’s architecture by describing the stages of each execution step. For the moment we do not consider how the input DAPS is concretely encoded inside the DBMS. At each point in time, the DBMS stores the current state of the DAPS. We assume that, before the execution starts, the DBMS contains an initial database instance for the DAPS data layer. To start the execution, the Flow Engine queries the DBMS about the actions that are enabled in the current state; if one is found, the engine retrieves all possible parameter assignments that can be selected to ground the action, and returns them to the user (or the software module responsible for the process enactment). The user is then asked to choose one of such parameter assignments. At this point, the actual application of the ground action is triggered. The Flow Engine invokes a set of stored procedures from the DBMS that take care of evaluating and applying action effects. If needed by the action specification, the Flow Engine interacts with external services, through the Service Manager, to acquire new data via service calls. The tuples to be deleted and inserted in the various DAPS relations are then computed, and the consequent changes are pushed to the DBMS within a transaction, so that the underlying database instance is updated only if all constraints are satisfied. After the update is committed or rolled back, the action execution cycle can be repeated by selecting either a new parameter assignment or another action available in the newly generated state.

We now detail how a DAPS is effectively encoded by DAPHNE into the DBMS.
From now on, we consider a \( DAPS S = (\mathcal{L}, \mathcal{P}) \) with data layer \( \mathcal{L} = (\mathcal{R}, \mathcal{E}) \) and control layer \( \mathcal{P} = (\mathcal{F}, \mathcal{A}, \rho) \). Intuitively, DAPHNE represents \( \mathcal{L} \) as a set of tables, and \( \mathcal{P} \) as a set of stored procedures working over those tables and also over additional auxiliary tables. Such data structures and stored procedures are defined in terms of the native language of the chosen DBMS. These can be either created manually, or automatically instrumented by DAPHNE itself once the user communicates to DAPHNE the content of \( S \) using dedicated Java APIs. Specifically, we employ the jOOQ framework as the basis for the concrete input syntax of \( DAPS \) within DAPHNE. The interested reader may refer to Appendix A to have a glimpse about how jOOQ and the DAPHNE APIs work.

Before entering into the encoding details, it is important to stress that DAPHNE provides three main usage modalities. The first modality is enactment. Here DAPHNE supports users in the process execution, storing the current database instance, and suitably updating it in response to the application of actions. The second modality is enactment with historical recall. This is enactment where DAPHNE does not simply store the current state and evolves it, but also recall historical information about the previous state configurations, i.e., the previous database instances, together with information about the applied actions (action names, parameters, service calls, and timestamps). This provides full traceability about how the process execution evolved the initial state into the current one. The last modality is state space construction for formal analysis. In this modality, DAPHNE generates all possible “relevant” possible executions of the system, abstracting away from timestamps and consequently folding the so-obtained traces into a relational transition system that explicitly represents the execution semantics of \( S \). Differently from the previous modalities, in this case DAPHNE does not simply account for a system run, but for the branching behaviour of \( S \). Due to the presence of services and external input data, the resulting transition system contains in general infinitely many states. However, thanks to the correspondence between \( DAPS \) and the DCDS formal frameworks, the abstraction techniques studied for DCDS in \([1,4]\) can be seamlessly applied in DAPHNE to construct a finite, faithful representation of the transition system. These abstraction techniques have been actually implemented within DAPHNE, providing the basis for verification of general properties such as reachability, liveness, and deadlock freedom, as well as explicit temporal model checking (in the style of \([4]\)).

**Data layer.** DAPHNE does not internally store the data layer as it is specified in \( \mathcal{L} \), but adopts a more sophisticated schema. This is done to have a unique homogeneous approach that supports the three usage modalities mentioned before. In fact, instructing

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[3] https://www.jooq.org/
the DBMS to directly store the schema expressed in $L$ would suffice only in the enactment case, but not to store historical data about previous states, nor the state space with its branching nature. To accommodate all three usages at once, DAPHNE proceeds as follows. Each relation schema $R$ in $L$ becomes relativized to a state identifier, and decomposed into two interconnected relation schemas: (i) $R_{raw}$ (raw data storage), an inflationary table that incrementally stores all the tuples that have been ever inserted in $R$; (ii) $R_{log}$ (state log), which is responsible at once for maintaining the referential integrity of the data in a state, as well as for fully reconstructing the exact content of $R$ in a state. In details, $R_{raw}$ contains all the attributes $A$ of $R$ that are not part of primary keys nor sources of a foreign key, plus an additional surrogate identifier $RID$, so that $\text{PK}(R_{raw}) = \langle RID \rangle$. Each possible combination of values over $A$ is stored only once in $R_{raw}$ (i.e., $R_{raw}[A]$ is a key), thus maximizing compactness. At the same time, $R_{log}$ contains the following attributes: (i) an attribute $\text{state}$ representing the state identifier; (ii) the primary key of (the original relation) $R$; (iii) a reference to $R_{raw}$, i.e., an attribute $\text{RID}$ with $R_{log}[\text{RID}] \rightarrow R_{raw}[\text{RID}]$; (iv) all attributes of $R$ that are sources of a foreign key in $L$. To guarantee referential integrity, $R_{log}$ must ensure that (primary) keys and foreign keys are now relativized to a state. This is essential, as the same tuple of $R$ may evolve across states, consequently requiring to historically store its different versions, and suitably keep track of which version refers to which state. Also foreign keys have to be understood within the same state: if a reference tuple changes from one state to the other, all the other tuples referencing it need to update their references accordingly. To realize this, we set $\text{PK}(R_{log}) = \langle \text{PK}(R), \text{state} \rangle$. Similarly, for each foreign key $S[B] \rightarrow R[A]$ originally associated to relations $R$ and $S$ in $L$, we insert in the DBMS the foreign key $S_{log}[B, \text{state}] \rightarrow R_{log}[A, \text{state}]$ over their corresponding state log relations.

With this strategy, the “referential” part of $R$ is suitably relativized w.r.t. a state, while at the same time all the other attributes are compactly stored in $R_{raw}$, and referenced possibly multiple times from $R_{log}$. In addition, notice that, given a state identified by $s$, the full extension of relation $R$ in $s$ can be fully reconstructed by (i) selecting the tuples of $R_{log}$ where $\text{state} = s$; (ii) joining the obtained selection with $R_{raw}$ on $\text{RID}$; (iii) finally projecting the result on the original attributes of $R$. In general, this technique shows how an arbitrary SQL query over $L$ can be directly reformulated as a state-relativized query over the corresponding DAPHNE schema.

**Example 4.** Consider our running example, and in particular relations $\text{CurrReq}$ and $\text{TrvlMaxAmnt}$ shown in Figure 1. Figure 4 shows the representation of these relations inside DAPHNE, suitably pairing $\text{CurrReq}_{raw}$ with $\text{CurrReq}_{log}$, and $\text{TrvlMaxAmnt}_{raw}$ with $\text{TrvlMaxAmnt}_{log}$. Notice the presence of foreign keys: each state log table di-
Fig. 5: Action application with two partial database snapshots mentioning \( \text{Pending} \) and \( \text{CurrReq} \). Here, \( \text{StartWorkflow} \) is applied in state 1 with \( \{\text{id} = 2, \text{empl} = \text{Kriss}, \text{dest} = \text{Rome}\} \) as binding and, in turn, generates a new state 2.

Fig. 6: Action application with two partial database snapshots mentioning \( \text{CurrReq} \) and \( \text{TrvlMaxAmnt} \). Here, \( \text{RvwRequest} \) is applied in state 2 with \( \{\text{id} = 2, \text{empl} = \text{Kriss}, \text{dest} = \text{Rome}\} \) as binding and 900 resulting from the invocation to service \( \theta_{\text{maxAmnt}} \) that, in turn, generates a new state 3.

We now discuss updates over \( R \). As already pointed out, \( R_{\text{raw}} \) stores any tuple that occurs in some state, that is, tuples are never deleted from \( R_{\text{raw}} \). Deletions are simply obtained by not referencing the deleted tuple in the new state. For instance, in Figure 5 it can be seen that the first tuple of \( \text{Pending}_{\text{raw}} \) (properly extended with its ID, through \( \text{RID} \)) has been deleted from \( \text{Pending} \) in state 2: while being present in state 1 (cf. first tuple of \( \text{Pending}_{\log} \)), the tuple is not anymore in state 2 (cf. third tuple of \( \text{Pending}_{\log} \)).

As for additions, we proceed as follows. Before inserting a new tuple, we check whether it is already present in \( R_{\text{raw}} \). If so, we update only \( R_{\log} \) by copying the \( R_{\log} \) tuple referencing the corresponding \( \text{RID} \) in \( R_{\text{raw}} \). In the copied tuple, the value of attribute \( \text{state} \) is going to be the one of the newly generated state, while the values of \( \text{ID} \) and all foreign key attributes remain unchanged. If the tuple is not present in \( R_{\text{raw}} \), it is also added to \( R_{\log} \) together with a fresh \( \text{RID} \). Notice that in that case its \( \text{ID} \) and foreign key attributes are provided as input, and thus they are simply added, together with the value of \( \text{state} \), to \( R_{\log} \). In the actual implementation, \( R_{\text{raw}} \) features also a \( \text{hash} \) attribute, with the value of a hash function computed based on original \( R \) attributes (extracted from both \( R_{\text{raw}} \) and \( R_{\log} \)). This speeds up the search for identical tuples in \( R_{\text{raw}} \).

Finally, we consider the case of relation schemas whose content is not changed when transitioning from a state to a new state. Assume that relation schema \( S \) in \( \mathcal{L} \)
The cycle starts with the user choosing one of the available actions presented by the Flow Engine. The available actions are acquired by calling \( \alpha_{\text{ca}}(s) \), for each action \( \alpha \) in \( P \). (2) If any unmarked parameter is present in \( \alpha_{\text{params}} \), the user is asked to choose one of those (by selecting a binding identifier \( b \)); once chosen, the parameter is marked, and the Flow Engine proceeds to the evaluation of \( \alpha \) by calling \( \alpha_{\text{eff}}(s,b) \). If there are no such parameters, the user is asked to choose another available action, and the present step is repeated. (3) If \( \alpha_{\text{eff}}(s,b) \)
involves service calls, these are passed to the the Service Manager component, which fetches the corresponding results. If all constraints in $L$ are satisfied, the transaction is committed and a new iteration starts from step 1; otherwise, the transaction is aborted and the execution history is kept unaltered, and the execution continues from step 2.

3.3 Realization of the Three Usage Modalities

Let us now discuss how the three usage modalities are realized in DAPHNE. The simple enactment modality is realized by only recalling the current information about log relations. Enactment with history recall is instead handled as follows. First, the generation of a new state always comes with an additional update over an accessory 1-tuple relation schema indicating the timestamp of the actual update operation. The fact that timestamps always increase along the execution guarantees that each new state is genuinely different from previously encountered ones. Finally, an additional binary state transition table is employed, so as to keep track of the resulting total order over state identifiers. By considering our running example, in state 4 shown in Figure 7, the content of the transition table would consist of the three pairs $\langle 1, 2 \rangle$, $\langle 2, 3 \rangle$, and $\langle 3, 4 \rangle$.

State space construction is handled by executing the following iteration. A state $s$ is picked (at the beginning, only the initial state exists and can be picked). For each enabled ground action in $s$, and for all relevant possible results returned by service calls (where the notion of relevance is obtained from the abstraction techniques developed in [1,4]), the database instance corresponding to the update is generated. If such a database instance has been already encountered (i.e., is associated to an already existing state), then the corresponding state identifier $s'$ is fetched. If this is not the case, a new identifier $s'$ is created, inserting its content into the DBMS. In addition, the state transition table is updated by inserting the tuple $\langle s, s' \rangle$, which indeed witnesses that $s'$ is one of the successors of $s$. The cycle is then repeated until all states and all enabled ground actions therein are processed. Notice that, differently from the enactment with history recall modality, in this case the state transition table is graph-structured, and in fact reconstructs the transition system capturing the execution semantics of $S$.

4 Related work

It has been widely acknowledged that conventional business process modelling methodologies fall short when considering complex data objects as tantamount modelling elements. To answer the increasing demand of integrated models holistically tackling the dynamics of a complex domain and the manipulation of data, a plethora of approaches have been proposed in both academia and industry.

State-of-the-art business process management systems, along with clean conceptualizations for the process control flow, often provide more sophisticated, multi-layered conceptual abstractions for manipulated business data. Notable examples of such systems are Bizagi BPM Suite (bizagi.com), Bonita BPM (bonitasoft.com), Camunda (camunda.com), Activiti (activiti.org) and YAWL (yawlfoundation.org). Even though such tools slightly vary in their modelling choices (e.g., in the graphical modelling language) and advanced functionalities, they share two common
features: business processes definition languages are based on BPMN, and the business data accessibility is managed via typed variables assigned to the workflow. While many tools provide sophisticated data structures (e.g., tables for historical and runtime data) and storage (e.g., in-memory or shared) options, the way the data are modified is often hidden inside the task logic. The so-obtained models are thus activity-centric, but they do not conceptually reveal the task logic and how it impacts on the data, seeing it as a sort of “procedural attachment” \[3\]. The shortcomings of this have been extensively discussed in the literature \[18,7,17,3\].

Another series of more foundational approaches stemmed from the research area studying business artifacts. Artifacts are usually used to represent key business entities, including both their data and life-cycle, where the latter one specifies the ways an artifact might progress through the business while responding to events and invoking external services, including human activities. Interestingly, the artifact-centric approach inspired the creation of various modeling languages \[8,12\] and execution frameworks such as: (i) the declarative rule-based Guard-Stage-Milestone (GSM) language \[5\] and its BizArtifact (https://sourceforge.net/projects/bizartifact/) execution platform; (ii) the OMG CMMN standard; (iii) the object-aware business process management approach implemented by PHILharmonic Flows \[10\]; (iv) the extension of GSM called EZ-Flow \[21\], with SeGA as \[20\] an execution platform. While giving conceptual visibility to data objects and their manipulation, artifact-centric approaches do not come with well-established abstractions to capture the control-flow dimension, which tends in fact to stay implicit.

In this respect, DAPHNE plays the role of a fully operational framework for the enactment (and, in principle, the formal analysis) of integrated models for processes and data, while staying agnostic w.r.t. the preferred modeling language of choice. While DAPHNE makes the task logic fully transparent and declarative, it can in fact seamlessly integrate different data models (provided that a suitable encoding is defined to store their corresponding data in a standard relational database), as well as different control-flow abstractions (provided that they are encoded, in the back-end, using CA rules).

5 Conclusions

In this work, we have introduced a declarative, purely relational framework for data-aware processes, in which SQL is used as the core data inspection and manipulation language. We have reported on the implementation of this framework in DAPHNE, a system prototype grounded on standard relational technology and Java that at once accounts for modeling, enactment, and state space construction. In this light, DAPHNE can be seen as a sort of relational extension to enactment frameworks such as jBPM (https://www.jboss.org/).

As for modeling, we intend to interface DAPHNE with different concrete end user-oriented languages for the integrated modeling of processes and data, incorporating at once artifact- and activity-centric approaches. As for formal analysis, we plan to augment the state space construction with native verification capabilities to handle basic properties such as reachability and liveness, and even more sophisticated temporal logic model checking. At the moment, the development of verification tools for data-aware processes is at its infancy, with a few existing tools \[6,11\].
References

1. Bagheri Hariri, B., Calvanese, D., De Giacomo, G., Deutsch, A., Montali, M.: Verification of relational data-centric dynamic systems with external services. In: Proc. of PODS (2013)
2. Bagheri Hariri, B., Calvanese, D., Deutsch, A., Montali, M.: State-boundedness for decidability of verification in data-aware dynamic systems. In: Proc. of KR. AAAI Press (2014)
3. Calvanese, D., De Giacomo, G., Montali, M.: Foundations of data aware process analysis: A database theory perspective. In: Proc. of PODS (2013)
4. Calvanese, D., De Giacomo, G., Montali, M., Patrizi, F.: First-order mu-calculus over generic transition systems and applications to the situation calculus. Inf. and Comp. (2017)
5. Damaggio, E., Hull, R., Vaculín, R.: On the equivalence of incremental and fixpoint semantics for business artifacts with Guard-Stage-Milestone lifecycles. In: Proc. of BPM (2011)
6. De Masellis, R., Di Francescomarino, C., Ghidini, C., Montali, M., Tessaris, S.: Add data into business process verification: Bridging the gap between theory and practice. In: Proc. of AAAI. AAAI Press (2017)
7. Dumas, M.: On the convergence of data and process engineering. In: Proc. of ADBIS. LNCS, vol. 6909. Springer (2011)
8. Hull, R.: Artifact-centric business process models: Brief survey of research results and challenges. In: Proc. of OTM. LNCS, vol. 5332. Springer (2008)
9. Köpke, J., Su, J.: Towards quality-aware translations of activity-centric processes to guard stage milestone. In: Proc. of BPM. LNCS, vol. 9850. Springer (2016)
10. Künzle, V., Weber, B., Reichert, M.: Object-aware business processes: Fundamental requirements and their support in existing approaches. Int. J. of Information System Modeling and Design 2(2) (2011)
11. Li, Y., Deutsch, A., Vianu, V.: VERIFAS: A practical verifier for artifact systems. PVLDB 11(3) (2017)
12. Meyer, A., Smirnov, S., Weske, M.: Data in business processes. Tech. Rep. 50, Hasso-Plattner-Institut for IT Systems Engineering, Universität Potsdam (2011)
13. Montali, M., Calvanese, D.: Soundness of data-aware, case-centric processes. Int. J. on Software Tools for Technology Transfer 18(5), 535–558 (2016)
14. Montali, M., Rivkin, A.: Model checking Petri nets with names using data-centric dynamic systems. Formal Aspects of Computing (2016)
15. Montali, M., Rivkin, A.: DB-Nets: on the marriage of colored Petri Nets and relational databases. Trans. on Petri Nets and Other Models of Concurrency 28(4) (2017)
16. Olivé, A.: Conceptual modeling of information systems. Springer (2007)
17. Reichert, M.: Process and data: Two sides of the same coin? In: Proc. of OTM. LNCS, vol. 7565. Springer (2012)
18. Richardson, C.: Warning: Don’t assume your business processes use master data. In: Proc. of BPM. LNCS, vol. 6336. Springer (2010)
19. Solomakhin, D., Montali, M., Tessaris, S., De Masellis, R.: Verification of artifact-centric systems: Decidability and modeling issues. In: Proc. of ICSOC. LNCS, vol. 8274. Springer (2013)
20. Sun, Y., Su, J., Yang, J.: Universal artifacts: A new approach to business process management (BPM) systems. ACM TMIS 7(1) (2016)
21. Xu, W., Su, J., Yan, Z., Yang, J., Zhang, L.: An artifact-centric approach to dynamic modification of workflow execution. In: Proc. of CoopIS. vol. 7044. Springer (2011)
A Interacting with DAPHNE

DAPHNE comes with dedicated APIs to acquire a DAPS, injects it in the underlying DBMS, and interact with the execution engine, on the one hand inspect the state of the process and the current data, and on the other to enact its progression. In order to avoid redundant technicalities and still give a flavor of the way DAPHNE works, we show how to specify and enact DAPSs on top of it for the case when the history recall modality is chosen.

As a concrete specification language for DAPS, we are developing an extension of the standard SQL, mixed with few syntactic additions allowing to compactly define DAPS rules and actions. Concretely, such a language is directly embedded into Java using the jOOQ framework[4] which allows to create and manipulate relational tables, constraints, and SQL queries as Java objects. Building on top of the jOOQ APIs, we have realized an additional API layer that, given a jOOQ object describing a DAPS component (such as a relation, rule, or action), automatically transforms it into a corresponding SQL or PL/pgSQL code snippet following the strategy defined in Section 3.2. E.g., one could specify the CurrReq schema and its primary key using the following code:

```java
DSLContext create = DSL.using(SQLDialect.POSTGRES_9_4);
Field<Integer> id = DSL.field(DSL.name("CurrReq", "id"),
        SQLDataType.INTEGER.nullable(false).identity(true));
Field<String> empl = DSL.field(DSL.name("CurrReq", "empl"),
        SQLDataType.VARCHAR.length(40).nullable(false));
Field<String> dest = DSL.field(DSL.name("CurrReq", "dest"),
        SQLDataType.VARCHAR.length(40).nullable(false));
Field<String> status = DSL.field(DSL.name("CurrReq", "status"),
        SQLDataType.VARCHAR.length(40).nullable(false));
Schema currReq = new Schema("CurrReq", id, empl, dest, status);
PrimaryKey pkCurrReq = new PrimaryKey("pk_CurrReq", currReq,
        Arrays.asList(id));
currReq.addConstraint(pkCurrReq);
```

To generate the SQL code for that relation, which should account for creating the state log and raw data storage relations for CurrReq (and related constraints), one can then either rely on conventional JDBC methods, or directly invoke the DAPHNE API:

```java
String createCurrReq_script = currReq.getSQLTranslation(create);
```

The following snippet shows how to create a CA rule for action RvwRequest:

```java
Select query = create.select(id,empl, dest)
    .from(currReq.generateTable(), trvlCost.generateTable())
    .where(status.eq("submitted"));
Action rvwRequest = new Action("RvwRequest");
CARule rvwRequestCARule = new CARule(query, rvwRequest,
        Arrays.asList(id));
```

To generate a script that will instrument the necessary tables and stored procedures in the underlying DAPS, as stipulated in Section 3.2, the user just needs to call another dedicated DAPHNE API:

```java
String script = rvwRequestCARule.getSQLTranslation(create);
```

[4] https://www.jooq.org/
Let us now provide a flavour of the runtime API of DAPHNE, employed during the enactment of a system run. First, we need to obtain an instance of process engine, providing its corresponding database connection details:

```java
Connection con = DBTools.getConnection(...);
StatefulEngine dcds = StatefulEngine.getEngingeInstance(con);
```

The engine provides a plethora of state inspection and update functionalities. We show how to create an action provider object that provides metadata (such as action names and their params) about all actions that are enabled in the current state.

```java
State currState = dcds.getCurrentState();
ActionProvider provider = dcds.getActionProvider(currState);
List<Attributes> md = provider.getAvailableActionsMetaData();
```

Using one of the so-obtained metadata, we create an action and a binding provider, in turn used to obtain all the current legal parameter instantiations for such an action.

```java
Attributes att = md.get(0);
ImmutablePair<Action, BindingProvider> actionElements = provider.getAction(att);
```

Among the available bindings, we pick one, getting back a ground, “ready-to-fire” action that can then be transactionally applied by DAPHNE.

```java
List<Binding> bindings = actionElements.getRight().getAvailableBindings();
GroundAction groundAction = actionElements.getLeft().bind(bindings.get(0));
```

With this ground action at hand, we can check whether it involves service calls in its specification. Service calls are responsible for the communication with the outer world and might introduce some fresh data into the system. In the database, every service call invocation is represented as a textual signature. E.g., the service call @maxAmnt on employee Kriss with trip destination Rome is internally represented as a string `maxAmnt(Kriss, Rome)` in the database. DAPHNE knows about this internal representation and offers a special storage for all the service call invocations, i.e., a service call map list. This list keeps a map from services to all their invocations in the state. Each invocation also comes with the value type that the original service call returns.

```java
ServiceCallMapList aSCMList = groundAction.getServiceCallMapList();
```

If the evaluation of ground action effects yielded at least one service invocation, one has to instantiate it before updating the database. To do so we create a service manager instance that, given a service call map list, manages corresponding service objects by applying them to processed arguments (extracted from the signatures) and then collecting the results of the invocations. As soon as the service call map list is fully instantiated, one can finally proceed with executing the ground action

```java
ServiceManager sm = new ServiceManager(connection);
if (!aSCMList.equals(null)) {
    aSCMList = sm.getResults(aSCMList, currState.getStateID());}
groundAction.launch(aSCMList);
```