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Specification and automated verification of atomic concurrent real-time transactions

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Abstract

Many database management systems (DBMS) need to ensure atomicity and isolation of transactions for logical data consistency, as well as to guarantee temporal correctness of the executed transactions. Since the mechanisms for atomicity and isolation may lead to breaching temporal correctness, trade-offs between these properties are often required during the DBMS design. To be able to address this concern, we have previously proposed the pattern-based UPPCART framework, which models the transactions and the DBMS mechanisms as timed automata, and verifies the trade-offs with provable guarantee. However, the manual construction of UPPCART models can require considerable effort and is prone to errors. In this paper, we advance the formal analysis of atomic concurrent real-time transactions with tool-automated construction of UPPCART models. The latter are generated automatically from our previously proposed UTRAN specifications, which are high-level UML-based specifications familiar to designers. To achieve this, we first propose formal definitions for the modeling patterns in UPPCART, as well as for the pattern-based construction of DBMS models, respectively. Based on this, we establish a translational semantics from UTRAN specifications to UPPCART models, to provide the former with a formal semantics relying on timed automata, and develop a tool that implements the automated transformation. We also extend the expressiveness of UTRAN and UPPCART, to incorporate transaction sequences and their timing properties. We demonstrate the specification in UTRAN, automated transformation to UPPCART, and verification of the traded-off properties, via an industrial use case.

Keywords Transaction · Atomicity · Isolation · Temporal correctness · Unified modeling language · Model checking

1 Introduction

Many modern computer systems rely on database management systems (DBMS) to maintain the logical consistency of critical data, such as to ensure the correct balance of bank accounts during a bank transfer. By employing a variety of transaction management mechanisms, DBMS ensures logical data consistency under complex data management scenarios, such as transaction abortions and concurrent access of data. Among these mechanisms, abort recovery (AR) restores the consistent state of a database when a transaction is aborted due to errors and thus achieves *atomicity* [1]. Rollback, for instance, is a common AR technique that undoes all changes of an aborted transaction [1]. Concurrency control (CC) regulates concurrent access to data from different transactions, which prevents inconsistent data due to interference, and ensures *isolation* [1]. A widely adopted CC technique is to apply locks on the data such that arbitrary access is prevented [2]. Together, AR and CC ensure the logical consistency of critical data that the applications rely on, hence contributing to the dependability of the overall systems.

In addition to logical data consistency, another important factor to the dependability of many database-centric systems is the *temporal correctness* of transactions. Examples of systems where the temporal property is crucial include industrial control systems [3] and automotive systems [4], whose configurations and states can be stored in databases. Reading an

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outdated sensor value or calibration parameter could result in catastrophic consequences such as loss of lives. Finishing a transaction too late could cause the production process to fall behind schedule and lead to economic loss. In such real-time database systems, transactions must be temporally correct, meaning that they must be scheduled to use fresh data, and have to meet specified deadlines [5].

The assurance of atomicity and isolation, however, may stand at odds with enforcing temporal correctness, because CC may cause a transaction to be blocked for a long time, and AR often introduces extra workload when performing recovery. To make matters worse, some CC algorithms may directly abort transactions, while the recovery may again lock the data and block other transactions further, which entails complex behaviors in time and could lead to deadline misses. Therefore, designing a real-time DBMS (RTDBMS) requires careful trade-offs in transaction management [6], with respect to deciding on proper “variants” [7] of atomicity and isolation, as well as selecting proper AR and CC mechanisms. To achieve an appropriate trade-off, it is helpful to specify all three properties explicitly, together with their supporting AR, CC, and scheduling mechanisms, in a high-level language if possible familiar to system designers. To ensure the correctness of the trade-off, one should be able to analyze such specifications, and reason about whether the properties can be satisfied with the selected mechanisms.

This paper builds on top of our previous work [8], in which we took an initial step to specify and verify atomicity, isolation and temporal correctness in a unified framework. We proposed a Unified Modeling Language (UML) [9] profile called UML for TRANsactions (UTRAN), for the specification of transactions with atomicity, isolation and temporal correctness properties. UTRAN models a transaction as an activity, and includes explicit modeling elements to express atomicity and isolation variants, as well as the AR, CC and scheduling mechanisms. We also proposed a formal framework, called UPPAAL for Concurrent Atomic Real-time Transactions (UPPCART) [8], which models real-time transactions, together with the selected AR, CC and scheduling mechanisms in the RTDBMS, as a network of UPPAAL timed automata (TA) [10]. Constituents of the UPPCART models are formulated as automata patterns, such that the complexity of the models is tamed, and reuse of repeatable modeling pieces is enabled. The transactional properties can then be formalized, and verified rigorously using the state-of-the-art UPPAAL model checker [10]. The connection between UTRAN and UPPCART, however, is still not formally defined, which prohibits automated transformation for practices in complex systems. As a result, the current construction of UPPCART models requires considerable manual efforts and is prone to error.

In this paper, we contribute to the specification and verification of atomic concurrent real-time transactions in several aspects. We extend UTRAN and UPPCART to support sequences of transactions, and their end-to-end deadlines. Many real-time system designs contain invocation dependencies between transactions, that is, one transaction is started only after the termination of another. For instance, an update transaction executed by a sensor may trigger another transaction that updates the speed of the vehicle. In such cases, it is the end-to-end execution of the entire sequence that matters to the system validation. Therefore, we extend our UTRAN and UPPCART so as to cater for the specification and analysis of transaction sequences.

In order to help system designers to create well-formed UTRAN specifications, we enhance the UTRAN definition with static semantics constraints, defined in the Object Constraint Language (OCL) [11]. Specification errors violating the OCL constraints can be directly spotted by common UML editors, such as Eclipse Papyrus [1] and IBM Rational Software Architect (RSA) [2].

We bridge the gap between UTRAN and UPPCART in this paper, such that automated transformation is facilitated. To achieve this, we first propose formal definitions of UPPCART patterns and connectors, in terms of UPPAAL TA, based on which we are able to define the pattern-based construction for UPPCART models. This formalism enables us to create a translational semantics that maps the syntactic structures in UTRAN with the UPPCART patterns, which provides UTRAN with a formal semantics relying on timed automata. The translation process is implemented in our tool $U^2Transformer$ [12], which transforms high-level UTRAN specifications, into verifiable UPPCART models.

We also present an industrial use case to demonstrate the specification, transformation, and verification of transactions using the extended UTRAN and UPPCART. The use case involves multiple construction vehicles working autonomously in a quarry, with requirements on collision avoidance and mission efficiency. To achieve this, we design a two-layer collision avoidance system to moderate the behaviors of the vehicles. Among them, the global collision avoidance layer is backed by an RTDBMS that stores the map of the quarry, and prevent vehicles colliding into each other via concurrency control. The local layer utilizes a local RTDBMS for ambient data that are used for obstacle avoidance by individual vehicles. We use UTRAN to specify the transaction sequences and transactions in both layers, as well as the properties to be ensured. We then transform these specifications into UPPCART models with U^2Transformer, and verify the correctness of our design.

In brief, our contributions in this paper are listed as follows:

[1] https://www.eclipse.org/papyrus/.

[2] https://www.ibm.com/developerworks/downloads/r/architect.

- extensions of UTRAN and UPPCART for transaction sequences;
- OCL constraints for UTRAN;
- a formal definition of pattern-based construction for UPPCART;
- a translational semantics from UTRAN to UPPCART, and tool-supported transformations based on this;
- a use case that demonstrates UTRAN, UPPCART, the transformation, and the verification.

The remainder of the paper is organized as follows. In Sect. 2, we present the preliminaries of the paper. In Sect. 3, we recall and extend the UTRAN profile. Section 4 introduces the formal definition of pattern-based construction, as well as the extended UPPCART framework. We propose the translational semantics of UTRAN to UPPCART, as well as our automated transformation, in Sect. 5, followed by our use case in Sect. 6. We discuss the related work in Sect. 7, after which we conclude the paper and outline future work in Sect. 8.

2 Preliminaries

In this section, we present the preliminaries of this paper, including the concepts of transactions, atomicity, isolation and temporal correctness (Sect. 2.1), UML profiles (Sect. 2.2), and UPPAAL timed automata (Sect. 2.3).

2.1 Real-time transactions

A DBMS models read and write operations of data as transactions, and handles data consistency via transaction management. Traditionally, a *transaction* is a partially ordered set of logically-related operations that as a whole ensures the *ACID* properties [1]: *atomicity* (a transaction either runs completely or makes no changes at all), *consistency* (transactions executed alone must ensure logical constraints), *isolation* (concurrent transactions do not interfere with each other), and *durability* (committed changes are made permanent). The set of operations is called a *work unit* (WU). The scope of a transaction is usually defined by the following operations: *begin* (start a transaction), *commit* (terminate a transaction and make its changes permanent and visible), and *abort* (terminate a transaction and recover from its changes). We consider two types of aborts in a database system: *system aborts* are caused by system errors or data contentions and thus are issued by the DBMS. *User aborts* are started by clients to stop the transaction on the purpose of fulfilling application semantics.

As complements to the classical transaction model with full ACID assurance, a number of other transaction models that define different variants of transaction properties have been proposed, as well as the mechanisms to realize them [7]. In this paper, we focus on the variants of atomicity, isolation, and temporal correctness.

2.1.1 Atomicity

Full atomicity achieves an “all-or-nothing” semantics, in which “commit” means completing “all” changes included in the transaction, while “abort” means that “nothing” is changed at all. In this paper, we particularly emphasize the recovery of transactions terminated by errors, and focus on the variants of atomicity upon transaction abortions.

We refer to the “nothing” semantics of full atomicity as *failure atomicity*, which is achieved by *rollback*, a recovery mechanism that restores database consistency by undoing all changes made by the to-be-aborted transaction [1]. Let us use w_i^j to denote that transaction T_i writes data D_j. The sequence $< w_1^0, w_1^1 >$ denotes that transaction T_1 writes D_0 and D_1 in order. If T_1 gets aborted right after w_1^1, its rollback sequence is $< w_1^1, w_1^0 >$. Due to the performance and functionality restrictions of failure atomicity, a number of *relaxed atomicity* variants as options have been proposed, which allow changes to be partially undone, or recover inconsistency semantically using compensating operations [7,13]. We consider the following abort recovery mechanisms for relaxed atomicity in this paper. *Immediate compensation* executes a sequence of operations immediately upon abortion, in order to update the database into a consistent state. For instance, the compensation for the aforementioned aborted transaction T_1 may be $< w_1^2 >$, that is, to update D_2 immediately instead of rollback. *Deferred compensation*, in contrast to the immediate execution of compensation, executes the compensating operations to restore consistency as a normal transaction, scheduled with other transactions. The deferred compensation for the previous example could be, for instance, that the update of D_2 is scheduled to take place after the termination of other transactions rather than immediately. In both variants, designers can decide the operations flexibly depending on the application semantics. An atomicity manager with the knowledge of the atomicity variants then performs the designed recovery at runtime.

2.1.2 Isolation

Isolation variants have been proposed as a series of levels [7,14], for instance, the read uncommitted, read committed, repeatable read and serializable levels in the SQL-92 standard [15]. An *isolation level* is defined as the property to preclude a particular set of *phenomena*, which are interleaved transaction executions that can lead to inconsistent data. Let us use r_i^j to denote that transaction T_i reads data D_j. The following sequence $< r_0^0, w_1^0, w_1^1, r_0^1 >$ represents the execution “T_0 reads D_0, T_1 writes D_0, T_1 writes D_1, T_0

reads D_1". In this execution, T_0 reads an old version of D_0 before the change of T_1, but a new version of D_1 after the change of T_1. Considering that D_0 and D_1 are a pair of configuration parameters that are required to always be updated together, the values read by T_0 become inconsistent in this sequence, which may break the safety requirements. Therefore, the example execution is considered as an isolation phenomenon, and should be avoided by the required isolation level, such as the serializable level [15]. By adjusting the precluded phenomena, isolation levels provide a flexible way to relax isolation according to the particular semantics.

DBMS ensures isolation by applying concurrency control on the access of data, which regulates the interleaved transaction executions according to a selected CC algorithm [2]. We consider a family of commonly applied CC algorithms in this paper, called *pessimistic concurrency control (PCC)* algorithms[2]. PCC exploits locking techniques to prevent unwanted interleavings. Depending on the algorithm, a transaction needs to acquire a specific type of lock at a certain time point before accessing the data, and releases the lock at a certain time point after the usage of the data. Upon receiving requests, the CC manager decides which transactions should obtain the lock, wait for the lock, or even be aborted, according to the resolution policy of the selected algorithm. In case a transaction gets aborted by CC, the atomicity manager may perform the abort and recovery of the transaction.

2.1.3 Temporal correctness

In a real-time database system, *temporal correctness* consists of transaction *timeliness*, and *temporal data consistency* [5]. Timeliness means that transactions should meet their deadlines [5]. Temporal data consistency includes two aspects. *Absolute validity* requires that data read by a transaction must not be older than a specified validity interval. *Relative validity* requires that, if a transaction reads a group of data, these data must be generated within a specified interval so that the results are temporally correct. RTDBMS may employ various scheduling policies to schedule the transaction operations, in order to achieve better temporal correctness. Commonly applied scheduling policies include first-in-first-out (FIFO), round robin, or policies based on the priorities of the transactions [2]. In addition to deadlines and validity intervals, other important time-related information includes execution times of the operations, and the arrival patterns of transactions (whether a transaction is started with a period, with a bounded inter-arrival interval, or randomly) [5].

Since temporal correctness is often crucial to the safety of the system, full ACID assurance often needs to be relaxed such that the former can be guaranteed [6]. For instance, relaxed atomicity with compensation can be adopted, instead of failure atomicity with rollback [16]. Real-time CC algorithms often incorporate time-related information of the transactions to achieve better timeliness. For instance, a widely applied real-time PCC, *Two-Phase locking - High Priority (2PL-HP)* [17], takes priorities and abortion into consideration of its resolution policy. In this algorithm, a transaction acquires a readlock (writelock) on data before it performs a read (write) operation, and releases all locks during commitment. A CC conflict occurs when two transactions try to writelock the same data. In this situation, the transaction with higher priority will be granted with the lock, while the transaction with lower priority will be aborted by the RTDBMS. As a result, transactions with higher priorities are more likely to meet their deadlines.

2.2 UML Profiles and MARTE

UML is one of the most widely accepted modeling language in software development, and has been extended for various application domains [9]. A common way to extend UML is through *profiles*. A profile defines a package of stereotypes, which are domain-specific concepts that extend existing UML metaclasses, as well as dependencies between the defined stereotypes. Properties that are specific to these concepts are defined as tagged values associated to the stereotypes. When a stereotype is applied to a UML modeling element, the instance of this element becomes an instance of the domain-specific concept represented by the stereotype, and extended with its properties.

In addition to developing specification languages for particular domains, profiles may also be adopted to add supplementary information for the purpose of analysis or code generation. Modeling and analysis of real-time embedded systems (MARTE) [18] is a profile that defines the basic concepts to support the modeling of real-time and embedded applications, as well as to provide time-related information for performance and schedulability analysis. As timing information is essential for our analysis and thus needs to be supported in the specifications, we reuse the relevant concepts from MARTE in this paper. The following MARTE concepts are reused: (i) MARTE::NFP_Duration, a data type for time intervals; (ii) MARTE::ArrivalPattern, a data type for arrival patterns, such as periodic, sporadic and aperiodic patterns.

2.3 UPPAAL timed automata and UPPAAL model checker

An UPPAAL Timed Automaton (TA)[10] is defined as a tuple $A ::= (L, l_0, X, V, I, Act, E)$, in which:

- L is a finite set of locations,
- l_0 is the initial location,
- X is a finite set of clock variables,
- V is a finite set of discrete variables,

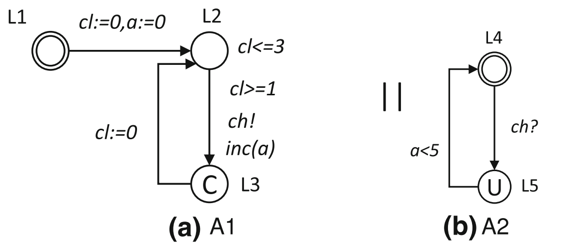


Fig. 1 A network of timed automata

- $I : L \to B(X)$ assigns invariants to locations, where $B(X)$ denotes the set of clock constraints,
- Act is a set of synchronization channels,
- $E \subset L \times B(X, V) \times Act \times R \times L$ is a finite set of edges, where $B(X, V)$ denotes the set of guards, R denotes the set of assignments.

The state of a TA consists of the values of its clock variables, together with the current location. Multiple TA can form a network of timed automata (NTA) via parallel composition ("||") [19], by which individual TA are allowed to carry out internal actions (i.e., interleaving), while pairs of TA can perform hand-shake synchronization via channels (see below). The state of an NTA then consists of the values of all variables in the NTA, together with the currently visited locations of each TA, respectively.

As an example, Fig. 1 shows an NTA modeling a simple concurrent real-time system, in which automaton A1 sporadically increments a variable *a* and synchronizes with automaton A2. A1 consists of a set of locations (L1, L2 and L3), and edges connecting them. A clock variable *cl* is defined in A1 to measure the elapse of time, and progresses continuously at rate 1. A discrete variable *a* is defined globally, and shared by A1 and A2. At each location, an automaton may stay at the location, as long as the **invariant**, which is a conjunction of clock constraints associated with the location, is satisfied. Alternatively and non-deterministically, the automaton may take a transition along an edge, if the **guard**, which is a conjunction of constraints on discrete or clock variables associated with the edge, is satisfied. In Fig. 1, A1 may delay in L2 as long as cl $\leq$ 3, or follow the edge to L3 when cl $\geq$ 1. Each edge may have an associated action, which is the synchronization with other automata via a **channel**. Binary channels are used to synchronize one sender (indicated by a mark "!") with a single receiver (indicated by a mark "?"). In Fig. 1, A1 sends a message to A2 via binary channel *ch*, while taking the edge from L2 to L3. The synchronization can take place only if both the sender and the receiver are ready to traverse the edge. A broadcast channel is used to pass messages between one sender and an arbitrary number of receivers. When using broadcast channels, the sender does not block even if some of the receivers are not ready. An edge may have an *assignment*, which resets the clocks or updates discrete variables when the edge is traversed. In UPPAAL TA, both guards and assignments can be encoded as functions in a subset of the C language, which brings high flexibility and expressiveness to modeling. In our example, when A1 moves from L2 to L3, *a* is incremented using the function *inc(a)*.

A location marked as "U" is an urgent location, meaning that the automaton must leave the location without delay in time. Another automaton may fire transitions as long as time does not progress. A location marked as "C" is a committed location, which indicates no delay in time, and immediate transition. Another automaton may *not* fire any transitions, unless it is also at a committed location.

The UPPAAL model checker can verify properties specified as UPPAAL queries, in UPPAAL's property specification language [10] that is a decidable subset of Computation Tree Logic (CTL) [20], possibly extended with clock constraints. For instance, the invariance property "A1 never reaches location L3" can be specified as "$A[\,]\ not\ A1.L3$", in which "A" is a path quantifier and reads "for all paths", whereas "[ ]" is the "always" temporal operator and specifies that ($not\ A1.L3$) is satisfied in all states of a path. If an invariance property is not satisfied, the model checker will provide a counterexample. The liveness property "If A1 reaches L2, it will eventually reach L3" can be specified, using the "leads-to ($\rightarrow$)" operator, as "$A1.L2 \rightarrow A1.L3$", which is equivalent to "$A[\,](A1.L2\ imply\ A <> A1.L3)$", where "<>" is the "eventually" temporal operator and specifies that $A1.L3$ is satisfied in finite time in at least one state of a path.

3 UTRAN

In this section, we recall the UTRAN profile firstly proposed in our previous work [8], and present its extension for transaction sequences, as well as the OCL constraints for creating consistent UTRAN specifications. We first present the domain model of real-time transactions in Section 3.1, after which we introduce the UML profile diagram in Section 3.2, including the OCL constraints.

3.1 Domain view

The domain model of real-time transactions is presented in Fig. 2. A RTDBMS manages a set of transactions. A transaction can be conceptually modeled as an activity in the UML activity diagram, which consists of a set of partially-ordered operations, represented as UML actions in the containing activity. Two types of operations are considered explicitly in a transaction: *DBOperations* and *TMOperations*. DBOperations directly perform read and write access to the data. Such read and write operations, denoted as *ReadOP* and *WriteOP*

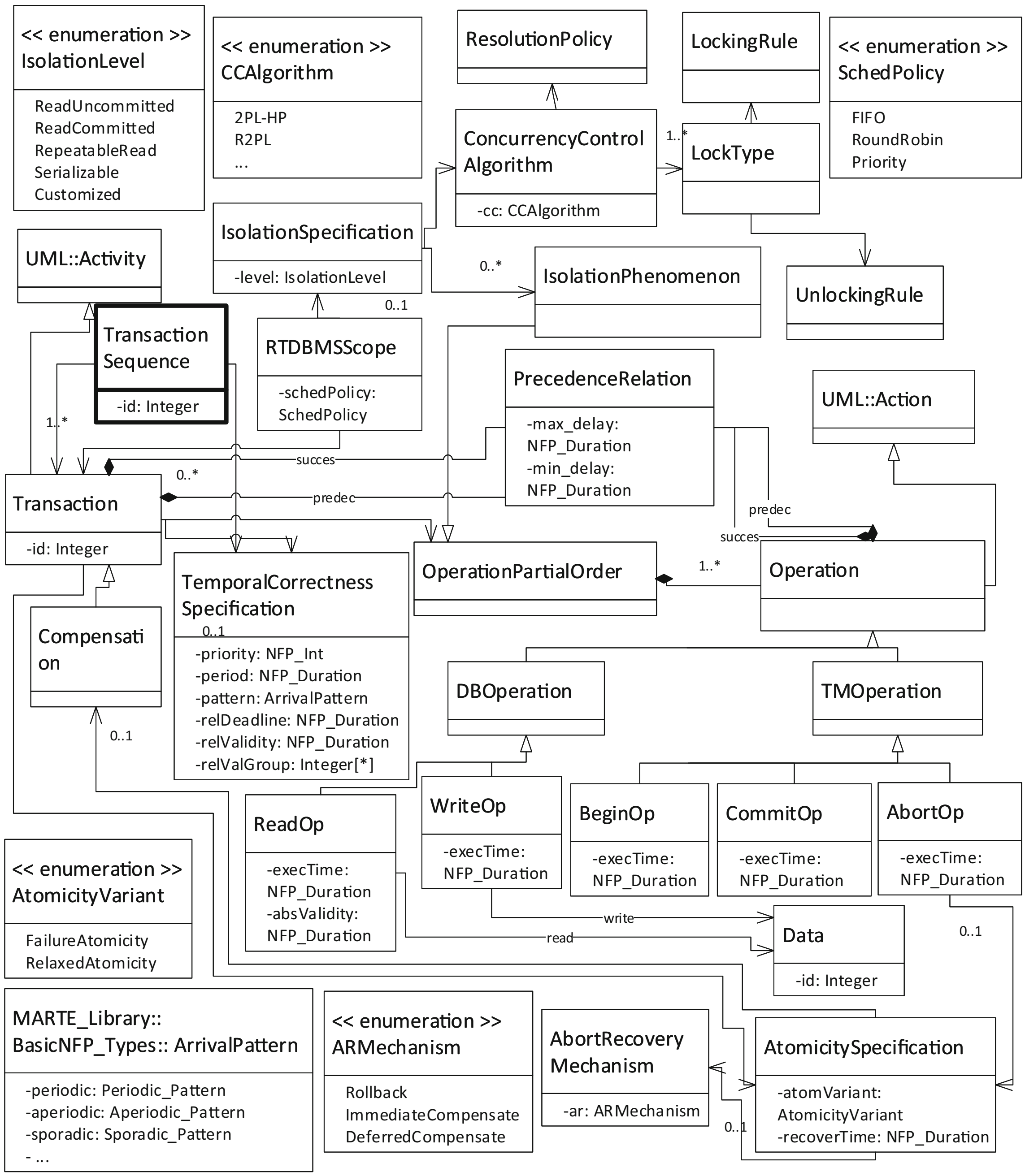


Fig. 2 Domain model of real-time transactions, extended from [8]. New concept marked with darker frame

respectively, are atomic, and their *worst-case execution times* are known a priori (assuming a given hardware platform). A ReadOP may be assigned with an *absolute validity interval* for the data it reads. TMOperations are the operations that *begin*, *commit* and *abort* transactions. The times for the RTDBMS to execute such TMOperations are also known a priori. A *precedence relation* describes the order of the operations, as well as the maximal and minimal *delays* between the operations. Such delays may include, not only the communication overhead, but also the response times of the client computations that do not interact with the database.

A transaction may be assigned with a *TemporalCorrectnessSpecification* for time-related properties, including the *priority*, the *relative deadline*, and the *period* (or minimum inter-arrival time) of the transaction, if applicable. A transaction may also have a specified *relative validity interval*, for the validity of a group of data read by the transaction, and the arrival *pattern* of the transaction, such as periodic, sporadic and aperiodic.

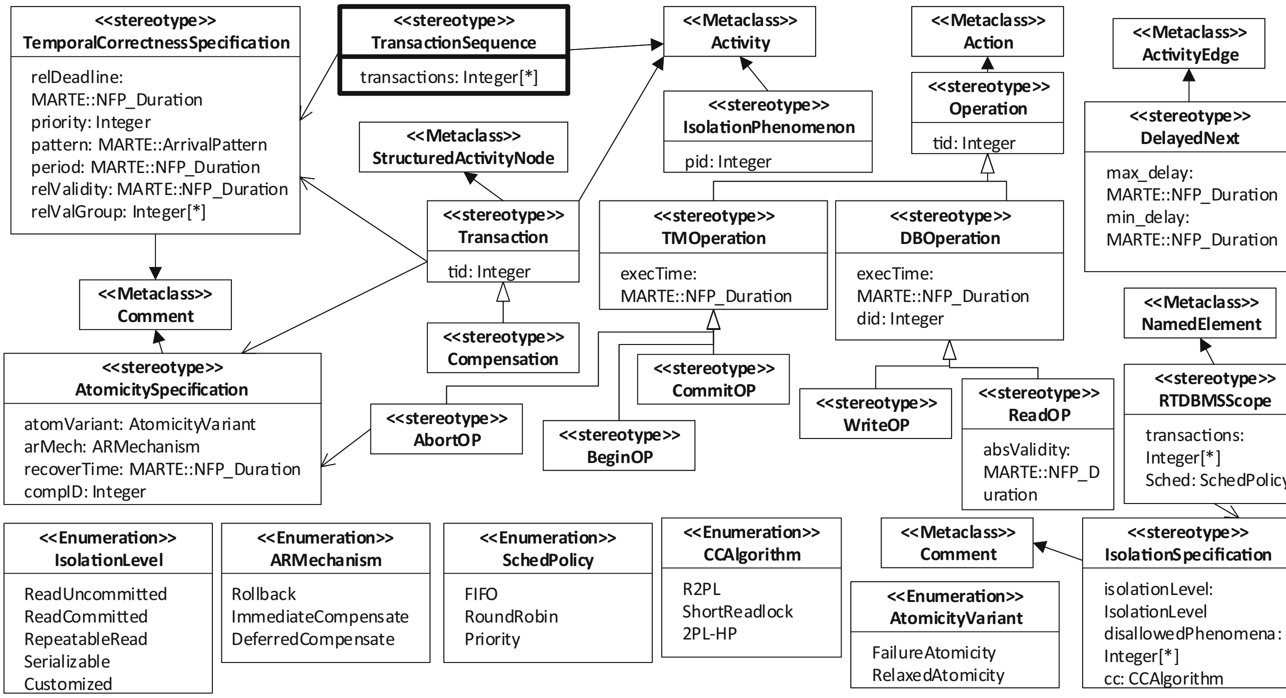


Fig. 3 UTRAN profile for real-time transactions, extended from [8]. New structure marked with darker frame

Atomicity and isolation of transactions are also included in the domain model. Multiple transactions managed by the same RTDBMS are related to an *RTDBMSScope*, which employs a *scheduling policy*, selected from FIFO, round robin, and priority based. An *IsolationSpecification* is associated with the RTDBMSScope, with an *IsolationLevel* indicating the variant of isolation that should be provided for the set of transactions. The IsolationSpecification is associated with a set of *IsolationPhenomena*, which are OperationPartialOrders that represent the illegal sequences of operations.

A *ConcurrencyControlAlgorithm* defines a set of *lock types* to be applied in the lock-based concurrency control. The rules for obtaining and releasing locks are specified as *LockingRule* and *UnlockingRule*. A *resolution policy* describes the resolution of lock conflicts on the shared data.

An *AtomicitySpecification* specifies the atomicity variant and the desired *recovery time*. An AtomicitySpecification can be attached to a transaction, or to an abort operation. In the former case, the AtomicitySpecification specifies the atomicity handling of system abortion by the RTDBMS, while in the latter, it specifies the handling of user abortion via abort operations. An AtomicitySpecification contains an *AtomicityVariant* and its corresponding *AbortRecoveryMechanism*. An AtomicityVariant is an enumeration of the supported atomicity variants, which includes *FailureAtomicity* and *RelaxedAtomicity*. An AbortRecoveryMechanism can be selected from *rollback*, *immediateCompensate*, and *deferredCompensate*. Without any AtomicitySpecification specified, atomicity is totally relaxed, and the partially changed data will not be recovered or compensated at all.

In this paper, we also consider transactions with invocation dependencies, modeled as a *TransactionSequence*. Its time-related constraints can be specified in the associated *TemporalCorrectnessSpecification*. A transaction in a TransactionSequence can be started only if its prior one has terminated (committed or aborted).

3.2 Profile

This subsection describes our previous UTRAN profile [8], as well as the extensions to model the TransactionSequence in the extended domain model. The profile diagram is presented in Fig. 3, with the new structure marked with darker frame.

In the existing UTRAN profile, the stereotype <<Transaction>> extends the UML Activity metaclass, and is mapped to the Transaction domain element. Each <<Transaction>> may be associated with a <<TemporalCorrectnessSpecification>>, and an <<AtomicitySpecification>>, both extending the UML Comment metaclass. A <<TemporalCorrectnessSpecification>> contains values of deadline, priority, arrival pattern, period, and relative validity of the transaction. An <<AtomicitySpecification>> specifies the selected AtomicityVariant and Abort-RecoveryMechanism, as well as the recovery time, and the reference to the compensation transaction, which is stereotyped with <<Compensation>> that inherits <<Transaction>>.

Each action in a <<Transaction>> is a stereotyped <<Operation>>. <<DBOperation>>, <<TMOperation >> and <<ClientOperation>> map the DBOperation, TMOperation and ClientOperation, respectively. A <<DBOp eration>> contains tagged values that specify the execution time for this operation, and the reference to the data it accesses. <<ReadOP>> and <<WriteOP>> map the ReadOP and WriteOP, respectively, and both extend <<DBOperation>>. A <<TMOperation>> is associated with the execution time for the transaction management operation, which can be <<BeginOP>>, <<CommitOP>>, or <<AbortOP>>. The PrecedenceRelation in the domain view is mapped by the stereotype <<DelayedNext>>, which extends the UML metaclass ActivityEdge with delays between operations, and delays between sub-transactions.

The stereotype <<RTDBMSScope>> maps the RTDB MSScope concept, which contains the transactions managed by the RTDBMS. The stereotype also specifies the scheduling policy, selected from the enumeration of SchedPolicy. The stereotype <<IsolationSpecification>> maps IsolationSpecation in the domain view, and specifies the isolation level, the CC algorithm selected from the enumeration of CCAlgorithm, as well as the disallowed phenomena explicitly. Each phenomenon is modeled as an activity stereotyped as <<IsolationPhenomenon>>, which contains a sequence of actions stereotyped as <<Operation>>.

TransactionSequence domain element, which contains the id's of the transactions in the sequence. The invocation order and the delays between invocations are specified via <<DelayedNext>> associated to <<Transaction>>.

3.2.1 Static semantics constraints for UTRAN

We present a set of static semantics constraints for correct specifications in UTRAN. These constraints are formulated in the Object Constraint Language (OCL) [11], as follows.

1. A <<Transaction>> must have one <<BeginOP>>, one <<CommitOP>>, and at least one <<DBOperati on>>.

```
Context Transaction
inv: self.operations->
 select(DBOperation)->size()>=1
inv: self.operations->
 select(BeginOP)->size()=1
inv: self.operations->
 select(CommitOP)->size()=1
```

2. <<BeginOP>> marks the start of the transaction. <<CommitOP>> and <<AbortOP>> mark the end of the transaction. No <<Operation>> occurs before a <<BeginOP>>, or after a <<CommitOP>> or an <<AbortOP>>.

```
Context Operation
def: precedingOPs() : Set(Action)
 =self.incoming.source
def: succeedingOPs() : Set(Action)
 =self.outgoing.target

inv: self->oclIsTypeOf(BeginOP) implies
  (not self->closure(precedingOPs)->
  exits(Operation))
inv: (self->oclIsTypeOf(CommitOP) or
  self->oclIsTypeOf(AbortOP)) implies
  (not self->closure(succeedingOPs)->
  exits(Operation))
```

3. If ImmediateCompensate is selected as the AR, the compensate transaction is executed by the DBMS with no delays between its operations. Therefore, in this case, the *max_delay* and *min_delay* values of every <<DelayedNext>> edge in the <<Compensation>> transaction are 0.

```
Context AtomicitySpecification
inv: (self.arMech=ARMechanism::
 ImmediateCompensate)
       implies (self.compensation.
       delayednexts->
       forall(max_delay=0
       and min_delay=0))
```

4. Immediate compensation transactions are always executed immediately by the DBMS after abortion. Therefore, they do not have <<TemporalCorrectnessSpecification>>.

```
Context Compensation
inv: (self.atomspec.arMech=
      ARMechanism::ImmediateCompensate)
      implies (self.tcspec->size()=0)
```

5. For deferred compensation transactions, the only meaningful value in its <<TemporalCorrectnessSpecification>> is *priority*.

```
Context Compensation
inv: (self.atomspec.arMech=
 ARMechanism::DeferredCompensate)
 implies
 (self.tcspec.relDeadline=null and
 self.tcspec.pattern=null and
 self.tcspec.period=null
 and self.tcspec.relValidity=null and
 self.tcspec.relValGroup=null)
```

6. Since cascade abortion introduces high unpredictability and is hence not desired in real-time systems, we assume that compensation transactions do not have user abort operations, and do not get recovered after system abortion. Therefore, a <<Compensation>> does not have <<AbortOp>>, <<AtomicitySpecification>>, or <<TemporalCorrectnessSpecification>>.

```
Context Compensation
inv: self.tcspec=null
inv: self.atomspec=null
inv: not (self.operations->exists(AbortOp))
```

7. The *execTime* and *absValidity* values of every <<Operation>> in the <<IsolationPhenomenon>> are set to 0.

```
Context IsolationPhenomenon
inv: self.operations->forall(execTime=0)
inv: self.operations->select(ReadOP)->
       forall(absValidity=0)
```

8. Since the start of the first sub-transaction also marks the start of its containing transaction sequence, the first <<Transaction>> has the same pattern and period attributes as its corresponding <<TransactionSequence>>. Since the other sub-transactions are started by the termination of their previous counterparts, their patterns and periods may remain unspecified and can be derived later. If the <<TransactionSequence>>'s priority is specified, all <<Transactions>> inherit this priority value. The sum of the relative deadlines of all <<Transactions>> must be smaller than or equal to the relative deadline of the <<TransactionSequence>>.

```
Context TransactionSequence
inv: self.transactions->
first().tcspec.pattern=self.
tcspec.pattern
inv: self.transactions->
first().tcspec.period=
self.tcspec.period
inv: self.tcspec.priority<>
null implies
     (self.transactions->
     forall(tcspec.priority=
     self.tcspec.priority))
inv: self.transactions->
     collect(tcspec.relDeadline)->
      sum<=self.tcspec.relDeadline
```

9. For a periodic or sporadic <<Transaction>> or <<TransactionSequence>>, its period value should be no smaller than its relative deadline. This rule eliminates the following non-schedulable and undesirable execution from early design: A transaction instance is started even before a previous instance, which is known likely to still be in execution.

```
Context TemporalCorrectness
 Specification
inv: (self.pattern=periodic
       or self.pattern=sporadic)
       implies self.period>=
       self.relDeadline
```

4 UPPCART framework

In this section, we extend our UPPCART (UPPaal for Concurrent Atomic Real-time Transactions) framework, for pattern-based formal modeling of real-time transactions with concurrency control and abort recovery in UPPAAL TA.

Our UPPCART framework, first proposed in our previous work [8], models the transactions, together with the CC algorithm and the AR mechanisms, as a network of UPPAAL TA. Denoted as N, the NTA of the modeled real-time transactions is defined as follows:

$$N ::= W_1 \,||\, ... \,||\, W_n \,||\, A_{CCManager} \,||\, A_{ATManager} \\ \,||\, O_1 \,||\, ... \,||\, O_k \,||\, D_1 \,||\, ... \,||\, D_m, \,||\, S_1 \,||\, ... \,||\, S_l, \quad (1)$$

where W_1, ..., W_n are work unit automata of transactions T_1, ..., T_n, respectively. They also model the work unit's interaction with the transaction manager with respect to concurrency control and abort recovery. $A_{CCManager}$ is the CCManager automaton that models the CC algorithm, and interacts with the work unit TA. $A_{ATManager}$ is the ATManager automaton that models the atomicity controller of recovery mechanisms upon abort of transactions. O_1, ..., O_k are IsolationObserver automata that observe the phenomena to be precluded by isolation, by monitoring the behaviors of the work unit automata. When a work unit automaton performs a particular sequence of transitions representing a phenomenon, the corresponding IsolationObserver is notified and moves to a state indicating this occurrence. D_1, ..., D_m are data automata for the data with temporal validity constraints. S_1, ..., S_l are automata for transaction sequences.

For each type of the aforementioned TA in N, we propose a set of parameterized *patterns* and *connectors* for the pattern-based construction. In the following, we propose a definition of pattern-based construction, followed by the detailed patterns for UPPCART in the next subsections.

A *parameterized pattern (PP)* of TA is a reusable structure that models a repetitive behavior or property. Formally, we defined a parameterized pattern as follows:

$$PP(\mathbf{P}) ::= (L_{pp}, L_{pinit}, X_{pp}, V_{pp}, I_{pp}, Act_{pp}, E_{pp}) \\ \cup \mathbf{F}, \quad (2)$$

where $\mathbf{P}$ is a set of parameters $(p1,\ p2,\ ...)$ that appear in the tuple $(L_{pp}, L_{pinit}, X_{pp}, V_{pp}, I_{pp}, Act_{pp}, E_{pp})$, and $\mathbf{F}$ is a set of function signatures that appear in E_{pp}.

A *parameterized connector (PCon)* is a structure that connects two parameterized patterns. Formally, a parameterized connector connecting parameterized patterns PP_i and PP_j is defined as follows:

$$PCon(PP_i, PP_j, \mathbf{P}) ::= (L_{pp\_i} \times B(X_{pcon}, V_{pcon})$$

$$\times Act_{pcon} \times L_{pp\_j}) \cup \mathbf{F}. \quad (3)$$

A parameterized pattern can be constructed from sub-patterns and the connectors connecting them, as the unions of their locations, variables, invariants, edges, actions, and parameters.

The instantiation of PP assigns the parameters in $\mathbf{P}$ with actual values, and provides the functions in $\mathbf{F}$ with implementations. Using "$p = v$" to denote the assignment of parameter p with value v, we define the instantiated pattern as:

$$PI_i(p1{=}v1, p2{=}v2, ...): := (L_{pi\_i}, L_{init\_i}, X_{pi\_i}, V_{pi\_i}, I_{pi\_i}, Act_{pi\_i}, E_{pi\_i}). \quad (4)$$

Similarly, the instantiation of $Con_{i,j}$ assigns the parameters in $\mathbf{P}$ with actual values:

$$Con_{i,j}(PI_i, PI_j, p1 = v1, p2 = v2, ...): := (L_{pi\_i} \times B(X_{con\_ij}, V_{con\_ij}) \times Act_{con\_ij} \times L_{pi\_j}), \quad (5)$$

which is a set of edges of a TA.

Given a TA $A = (L, l_0, X, V, I, Act, E)$, a set of instantiated patterns **PI**, and a set of instantiated connectors **CON**, A is a *pattern-based construction* from **PI** and **CON**, *iff*:

- $L = \bigcup_{PI_i \in \mathbf{PI}} L_{pi\_i}$,
- $\bigcup_{PI_i \in \mathbf{PI}} L_{init\_i} = \{l_0\}$,
- $X = \bigcup_{PI_i \in \mathbf{PI}} X_{pi\_i} \bigcup_{Con_j \in \mathbf{CON}} X_{con\_j}$,
- $V = \bigcup_{PI_i \in \mathbf{PI}} V_{pi\_i} \bigcup_{Con_j \in \mathbf{CON}} V_{con\_j}$,
- $Act = \bigcup_{PI_i \in \mathbf{PI}} Act_{pi\_i} \bigcup_{Con_j \in \mathbf{CON}} Act_{con\_j}$,
- $E = \bigcup_{PI_i \in \mathbf{PI}} E_{pi\_i} \bigcup \mathbf{CON}$,

which means that the locations, variables, actions and edges of A are the unions of the respective counterparts in the component instantiated patterns and connectors. We denote it as $A = \dot{\bigcup}(\mathbf{PI}, \mathbf{CON})$.

For the convenience of later presentations, we call a pattern a *skeleton* of TA A, if $L_{init} \neq \emptyset$.

4.1 Patterns and connectors for modeling work units

In the following subsections, we introduce the UPPCART patterns and connectors for each automaton within the parallel composition in Eq. 1, in the order of the work unit automaton W, the transaction sequence automaton S, CCManager automaton $A_{CCManager}$, ATManager automaton $A_{ATManager}$, IsolationObserver O, and data automaton D.

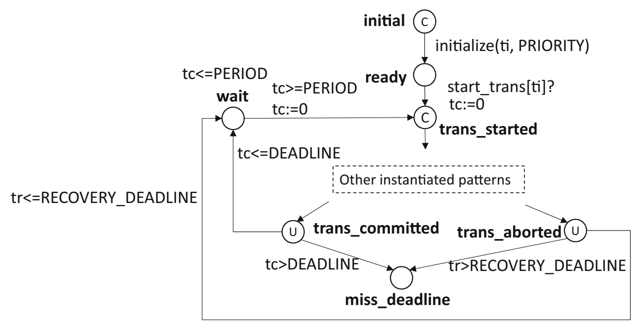


Fig. 4 Work unit skeleton (WUS) for a generic transaction T_i [8]

4.1.1 Work unit skeleton (WUS)

A work unit (WU) automaton models the work unit of a transaction and its interaction with the CC and atomicity managers. A *WU skeleton (WUS)*, as shown in Fig. 4, is a parameterized pattern that consists of the common variables, locations and edges of a WU automaton. Formally, WUS is defined as follows:

$$WUS(\mathbf{P}_{wus}): :=(L_{wus}, L_{wusinit}, X_{wus}, V_{wus}, I_{wus}, Act_{wus}, E_{wus}) \cup \mathbf{F}_{wus}, \quad (6)$$

The locations L_{wus} and edges E_{wus} are shown in Fig. 4, in which $L_{wusinit}$ is the location *initial*. The parameters $\mathbf{P}_{wus}$, clock variables X_{wus}, discrete variables V_{wus}, as well as functions $\mathbf{F}_{wus}$, are listed in Table 1. In Fig. 4, the automaton starts from the *initial* location, initializes the transaction with the specified id *ti* and priority *p* using function *initialize(ti, p)*, and moves to the location *ready*. Upon receiving the *start_trans[ti]* message, it moves to the location *trans_started*, which represents the begin of the transaction, and resets clock variable *tc*. The location *trans_committed* indicates the committed state of the transaction. Between *trans_started* and *trans_committed* are a set of connected instantiated patterns that model the database and transaction management operations, and delays between the operations. If the value of *tc* is greater than the specified *DEADLINE*, the automaton moves to the location *miss_deadline*, indicating a deadline miss. Otherwise, it waits until the specified *PERIOD* has been reached, and moves to *begin* for the next activation. The location *trans_aborted* represents the aborted state of the transaction. If the value of *tr* is greater than the specified *RECOVERY_DEADLINE*, timeliness is breached, and the WU automaton moves to *miss_deadline*.

Table 1 Modeling elements of the work unit skeleton

Element	Type	Explanation
ti	Parameter	Id of the modeled transaction
PRIORITY	Parameter	Priority of transaction ti
PERIOD	Parameter	Period/minimal inter-arrival time of the transaction ti
DEADLINE	Parameter	Deadline of transaction ti's commitment
RECOVERY_ DEADLINE	Parameter	Deadline of transaction ti's recovery
tc	Clock variable	Tracking the elapsed time of transaction ti
tr	Clock variable	Tracking the elapsed time of the abort recovery of ti
start_trans[ti]	Channel	Message to start the transaction ti
initialize(ti, p)	Function	Initialization of the transaction ti with priority p

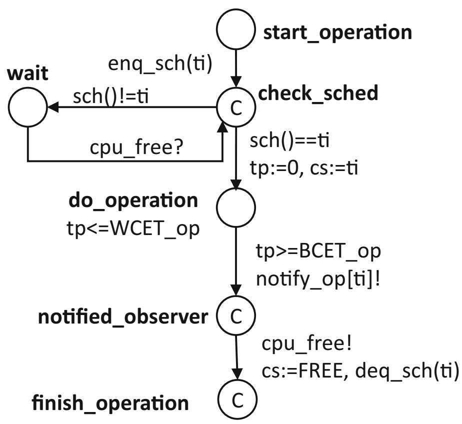


Fig. 5 Operation Pattern (OP)[8]

4.1.2 Operation-CC, Locking and Unlocking Patterns, and their Connectors

We define patterns to model the begin, commit, read and write operations in each work unit. Since a transaction may interact with the CC manager according to the specific CC algorithm during the operations, our operation patterns also comprises CC-related activities such as the locking and unlocking activities. The pattern for modeling basic operations, the **operation pattern (OP)**, is presented in Fig. 5. The modeling elements are listed in Table 2. In OP, we model the scheduling policy using three functions, namely, *enq_sch(ti)*, *deq_sch(ti)* and *sch()*. After the *start_operation* location, the *enq_sch(ti)* function is called, which pushes the transaction into the scheduling queue. On the edges from the location *check_sched*, the function *sch()* checks whether the transaction is the next one to be executed. If yes, the automaton moves to *do_operation*, representing the execution of the operation; otherwise, the automaton waits at location *wait*, until the CPU is released by the occupying transaction or the RTDBMS, indicated via the signal in the *cpu_free* channel. The automaton may stay at *do_operation* for at most *WCRT_op* time units, and at least *BCRT_op* time units, which represent the longest and shortest time to complete the operation. Upon the completion of the operation, a signal is sent to the IsolationObservers via channel *notify_op[ti]*. Before reaching *finish_operation*, the CPU is set to be free, and the transaction is removed from the scheduling queue by the function *deq_sch(ti)*. As an example, the corresponding functions for a priority-based scheduling policy is listed in Listing 1.

Listing 1 Functions for priority-based scheduling

```
//Push ti to the queue, sorted by priority
void enq_sch(ti) {
    ...
    for(i=0;i<queue.size;i++) {
        if(ti.priority < queue[i].priority) {
            queue[i+1] = queue[i];
            queue[i] = ti;
        ...} }
}

//Delete ti from the queue, and sort the rest
void deq_sch(ti) {
    ...
    for(i=0;i<queue.size;i++) {
        if(ti == queue[i]) {
            queue[i] = queue[i+1];
        ...} }
}

//Return the first ready transaction in the queue,
//and the CPU is not occupied by others
int sch() {
    ...
    for(i=0;i<queue.size;i++) {
        if((cs==i||cs==FREE) && queue[i].state==READY) {
          return i;  }}
}
```

According to the selected CC algorithm, the transaction needs to lock and unlock data, before or after the operations. This is modeled by the **Locking Pattern** (**LP**, Fig. 6) and **Unlocking Pattern** (**UP**, Fig. 7), which are composed with the operation patterns. The locations and edges are presented in the figures, while the parameters, variables and functions are listed in Table 2. In the locking pattern, the automaton sends a request to the CCManager via channel *locktype[ti][di]*, in which "locktype" is parameterized for the particular type of lock, such as a readlock, specified by the CC algorithm. The automaton then either moves to location *finish_locking*, if it is granted by CCManager via channel *grant[ti][di]*; or releases CPU and gets blocked at location *wait_for_lock*, until CCManager grants it later. In the Unlocking pattern, the automaton sends the request via channel *unlock[ti][di]*, which is received and processed by the CCManager. A database operation may lock (or unlock) several data items altogether, depending on the CC algorithm. The combination of multiple lock/unlocks are modeled by the connectors. The connector connecting two Locking patterns is defined as $Con(LP_i, LP_j)$ in Table 3, and the connector connecting two unlocking patterns is defined as $Con(UP_i, UP_j)$ in Table 3.

The composition of LP and UP with OP is illustrated in Fig. 8, which forms the **Operation-CC Pattern (OCCP)**. Formally, OCCP is defined as follows:

$$OCCP ::= \dot{\bigcup}(\mathbf{LP} \cup \mathbf{OP} \cup \mathbf{UP},\ \mathbf{CON}_{occp}), \tag{7}$$

in which **LP**, **OP** and **UP** are previously defined sets of locking, operation and unlocking patterns, respectively. The set of connectors is defined as:

$$\begin{aligned}\mathbf{CON}_{occp} := &\mathbf{Con}(OP, LP') \cup \mathbf{Con}(OP, UP') \\ &\cup \{Con(Begin, WUS)\} \\ &\cup \{Con(Commit, WUS)\}. \end{aligned} \tag{8}$$

$Con(OP, LP')$ is a connector that connects an OP with a group of LP, as defined in Table 3, in which LP' is a pattern composed of a set of LP, starting with LP_i and ending with

Table 2 Modeling elements of the operationand locking and unlocking patterns

Element	Type	Explanation
ti	Parameter	Id of the modeled transaction
di	Parameter	Id of the data to be accessed
op	Parameter	Name of the operation
locktype	Parameter	The type of lock according to the selected CC
BCRT_op (WCRT_op)	Parameter	Best (worst) case response time of the operation
tp	Clock variable	Temporary variable for tracking the time of individual operations
cs	Integer variable	Indicating the possession of the CPU
FREE	Constant	Indicating that the CPU is free
cpu_free	Broadcast channel	Release of CPU
locktype[ti][di]	Channel	Request sent by ti to the CCManager for a "locktype" of lock on data di
grant[ti][di]	Channel	Grant of lock on data di for ti from CCManager
wait[ti][di]	Channel	Reject of ti's lock request on data di from CCManager
unlock[ti][di]	Channel	ti unlocking data di
notify_op[ti]	Broadcast channel	Notification of completion of ti's operation
enq_sch(ti)	Function	Adding transaction ti in the scheduling queue
sch()	function	Returning the next transaction from the scheduling queue according to the selected policy
deq_sch(ti)	Function	Removing transaction ti from the scheduling queue

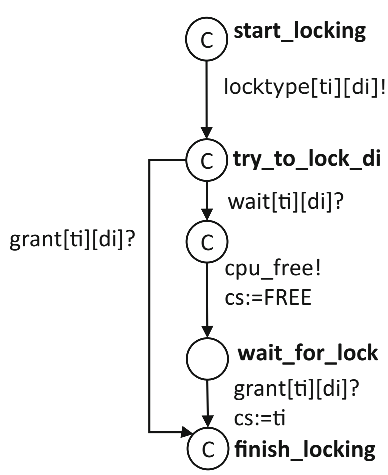


Fig. 6 Locking Pattern (LP)[8]

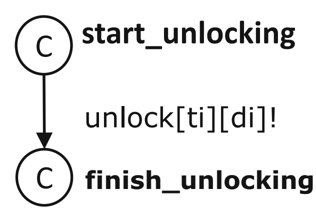


Fig. 7 Unlocking Pattern (UP)[8]

LP_j. $Con(OP, UP')$ is a connector that connects an OP with a group of UP, as defined in Table 3, in which UP' is a pattern composed of a set of UP, starting with UP_i and ending with UP_j. $Con(Begin, WUS)$ and $Con(Commit, WUS)$ are connectors that connect the begin OP and commit OP to the work unit skeleton WUS, also defined in Table 3.

4.1.3 Delay Pattern and its Connector

The delay pattern (DP) in Fig 9 models the delays between operations, formally defined as follows:

$$DP(\mathbf{P}_{dp}) ::= (L_{dp}, \emptyset, X_{dp}, \emptyset, I_{dp}, \emptyset, \emptyset) \cup \emptyset, \quad (9)$$

which contains one location and its invariant as shown in Fig 9, and a parameter *MAX_delay*. The automaton may stay at location *delay* for at most *MAX_delay* time units.

Assuming that OP_i and OP_j model the operations before and after a delay modeled by DP, respectively, the connectors to connect OP_i and DP is defined as $Con(OP_i, DP)$ in Table 3. The connector for connecting DP with OP_j is defined as $Con(DP, OP_j)$ in Table 3, in which *MIN_delay* is a parameter and denotes the lower bound of the delay.

4.1.4 Abort and Recovery Patterns, and their Connectors

The abort recovery mechanisms are modeled by the **RollbackImComp Pattern** (**RIP**, Fig. 10), and the **DeferredComp Pattern** (**DCP**, Fig. 11), respectively, which are composed into the work unit automata. The former (RIP) models the rollback and immediate compensation mechanisms, which are executions of series of operations by the

Table 3 Definitions of connectors in UPPCART

Connector Identifier	Definition
$Con(LP_i, LP_j)$	$\{finish\_locking\_i \rightarrow start\_locking\_j\}$
$Con(UP_i, UP_j)$	$\{finish\_unlocking\_i \rightarrow start\_unlocking\_j\}$
$Con(OP, LP')$	$\{check\_sched \xrightarrow[cs:=ti]{sch()==ti} start\_locking\_i,\ finish\_locking\_j \xrightarrow{tp:=0} do\_operation\}$
$Con(OP, UP')$	$\{notified\_observer \rightarrow start\_unlocking\_i,$ $finish\_unlocking\_j \xrightarrow[cs:=FREE, deq\_sch(ti)]{cpu\_free!} finish\_operation\}$
$Con(Begin, WUS)$	$\{trans\_started \rightarrow start\_operation\}$
$Con(Commit, WUS)$	$\{finish\_operation \rightarrow trans\_committed\}$
$Con(OP_i, DP)$	$\{finish\_operation\_i \xrightarrow{tp:=0} delay\}$
$Con(DP, OP_j)$	$\{delay \xrightarrow{tp \geq MIN\_delay} start\_operation\_j\}$
$Con(DP, UAP)$	$\{delay \xrightarrow{tp \geq MIN\_delay} start\_user\_abort\}$
$Con(UAP, WUS)$	$\{finish\_user\_abort \rightarrow trans\_aborted\}$
$Con(UAO, RIP)$	$\{wait1 \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_rollback,\ wait2 \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_rollback,$ $abort\_notified \xrightarrow[cs:=FREE]{cpu\_free!} finish\_user\_abort\}$
$Con(UAO, DCP)$	$\{wait1 \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_deferred\_op,\ wait2 \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_deferred\_op,$ $abort\_notified \xrightarrow[cs:=FREE]{cpu\_free!} finish\_user\_abort\}$
$Con(OCCP, RIP)$	$\{wait \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_rollback,\ do\_operation \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_rollback,$ $wait\_for\_lock \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_rollback\}$
$Con(OCCP, DCP)$	$\{wait \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_deferred\_op,\ do\_operation \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_deferred\_op,$ $wait\_for\_lock \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_deferred\_op\}$
$Con(DP, RIP)$	$\{delay \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_rollback\}$
$Con(DP, DCP)$	$\{delay \xrightarrow[tr:=0]{abort\_trans[ti]?} start\_deferred\_op\}$
$Con(RIP, WUS)$	$\{abort\_notified \rightarrow trans\_aborted\}$
$Con(DCP, WUS)$	$\{abort\_notified \rightarrow trans\_aborted\}$
$Con(TSS, SSP_i)$	$\{seq\_started \rightarrow start\_sub\_i\}$
$Con(SSP_j, TSS)$	$\{sub\_j\_terminated \rightarrow seq\_terminated\}$
$Con(SSP_i, DP)$	$\{sub\_i\_terminated \xrightarrow{tp:=0} delay\}$
$Con(DP, SSP_j)$	$\{delay \xrightarrow{tp \geq MIN\_delay} start\_sub\_j\}$

DBMS immediately after the abort. In case of rollback, the recovery operations redo the write operations that have been completed by the aborted transaction. In case of immediate compensation, the operations are specified for the transaction explicitly. The latter (DCP) models the deferred compensation mechanism, which executes a separate transaction for compensation. The locations and edges are shown in the figures, while parameters, variables and functions are listed in Table 4.

In the RIP pattern (Fig. 10), each operation is represented by a location *op_n*, at which the automaton may stay for at most (least) *WCRT_opn* (*BCRT_opn*) time units. When all operations are completed, the completion of recovery is reported to the ATManager via channel *report_abort[ti]*, removes the transaction from the scheduling queue by function *deq_sch(ti)*, and notifies the IsolationObserver via channel *notify_abort[ti]*.

In case of deferred compensation, a compensating transaction is modeled as a separate work unit, using the work

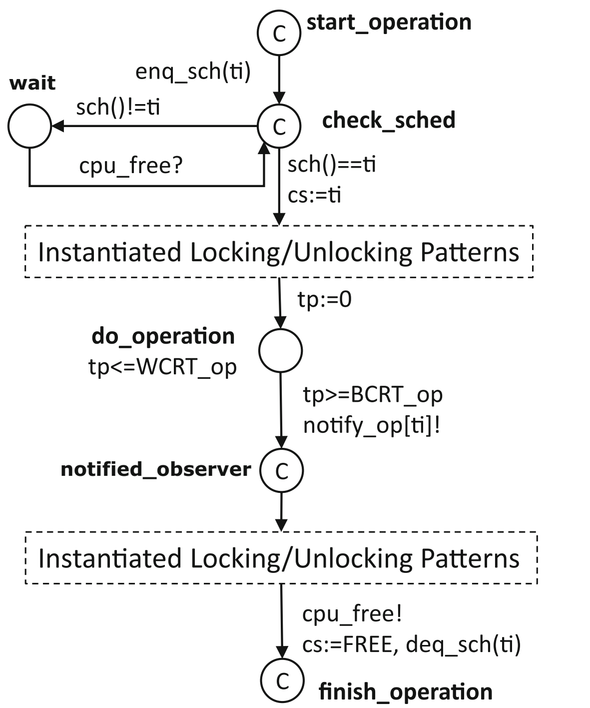
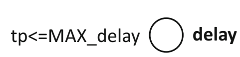


Fig. 8 Operation-CC Pattern (OCCP)[8]

Fig. 9 Delay Pattern (DP)[8]



unit skeleton and the operation patterns. The DeferredComp pattern (Fig. 11) starts the compensation transaction via the channel *start_trans[ci]*, where *ci* is the id of the compensating transaction. The work unit automaton then immediately reports to ATManager and removes the transaction from the scheduling queue. When the compensating transaction *ci* has committed, the work unit automaton receives the notification of *ci*, and notifies that transaction is aborted and recovered via channel *notify_abort[ti]*.

The above two recovery patterns are composed into a work unit skeleton via the **UserAbort Pattern**, if they model the recovery for user abort; or via the **System Abort Connectors**, if the recovery is performed for system abort.

4.1.5 UserAbort Pattern (UAP)

This pattern is defined as a composition of a recovery pattern (RIP or DCP) with a UserAbortOp (UAO) pattern as shown in Fig. 12. When the work unit is scheduled as the next one to be executed, according to function *sch(ti)*, it issues the abort request to ATManager via channel *user_abort[ti]*. After it gets the permission from ATManager via channel *abort_trans[ti]*, the automaton proceeds to the corresponding abort recovery pattern. When the recovery is completed, the automaton sets the CPU to be free. Formally, UAP is defined as follows:

$$UAP ::= \dot{\bigcup}((\{RIP\} \mid\mid \{DCP\}) \cup \{UAO\},\ \mathbf{CON}_{uap}), \tag{10}$$

Here, the locations and edges of UAO are defined in Fig. 12, while the parameters, variables and functions are listed in Table 4. $\mathbf{CON}_{uap}$ contains connectors $Con(UAO, RIP)$ and $Con(UAO, DCP)$, as defined in Table 3.

The UAP can be composed with the delay pattern representing the delay before the user abort operation, using the connector $Con(DP, UAP)$ in Table 3. The UAP is composed with the work unit skeleton using the connector $Con(UAP, WUS)$ in Table 3.

4.1.6 System Abort Connectors

System abort and its consequent recovery activities may take place either during one operation, or between the execution of two operations. We define the following connectors to model both behaviors. For the system abortion that occurs within one operation, we define $Con(OCCP, RIP)$ and $Con(OCCP, DCP)$ that compose an instantiated Operation-CC pattern with a RollbackImComp pattern or a DeferredComp pattern, respectively, as illustrated in Fig. 13. When the OCCP receives a signal via channel *abort_trans[ti]* from the ATManager, it moves to the corresponding abort recovery patterns. The connectors are defined as $Con(OCCP, RIP)$ and $Con(OCCP, DCP)$, respectively, in Table 3.

Fig. 10 RollbackImComp Pattern (RIP)[8]

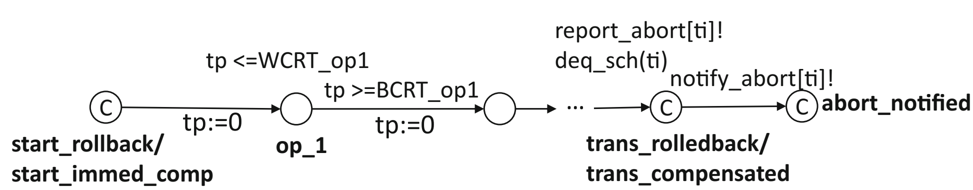


Fig. 11 DeferredComp Pattern (DCP)[8]

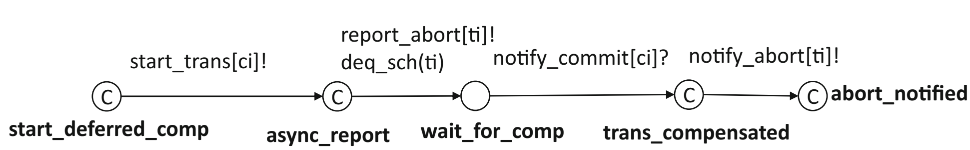


Table 4 Modeling elements of the abort and recovery patterns

Element	Type	Explanation
ti	Parameter	Id of the modeled transaction
ci	Parameter	Id of compensation transaction
op	Parameter	Name of the operation
BCRT_op (WCRT_op)	Parameter	Best (worst) case response time of the operation
tp	Clock variable	Temporary variable for tracking the time of individual operations
tr	Clock variable	Tracking the recovery time
cs	Integer variable	Indicating the possession of the CPU
FREE	Constant	Indicating that the CPU is free
report_abort[ti]	Channel	Message that reports to the ATManager that the abortion of ti is done
abort_trans[ti]	Channel	Message from the ATManager that starts the abortion of ti
user_abort[ti]	Channel	Message that notifies to the ATManager that a user abort operation of ti is issued
start_trans[ci]	Channel	Message that starts the compensation transaction ci
notify_abort[ti]	Broadcast channel	Notification of abortion of the transaction ti
notify_commit [ci]	Broadcast channel	Notification of commitment of the transaction ci
cpu_free	Broadcast channel	Release of CPU
enq_sch(ti)	Function	Adding transaction ti in the scheduling queue
sch()	function	Returning the next transaction from the scheduling queue according to the selected policy
deq_sch(ti)	Function	Removing transaction ti from the scheduling queue

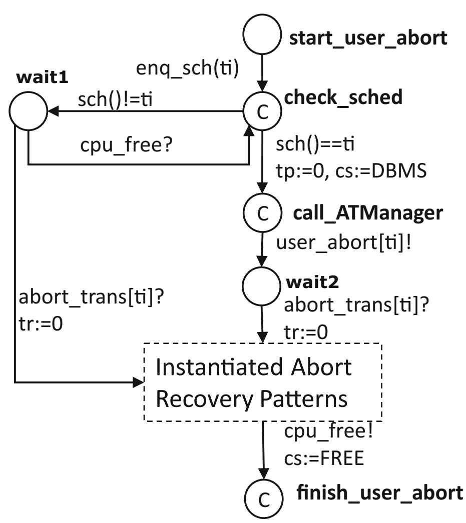


Fig. 12 UserAbort Pattern (UAP)[8]

For system aborts that occur between operations, we define the following connectors $Con(DP, RIP)$ and $Con(DP, DCP)$ in Table 3, which connect a Delay pattern with a RollbackImComp pattern or a DeferredComp pattern respectively.

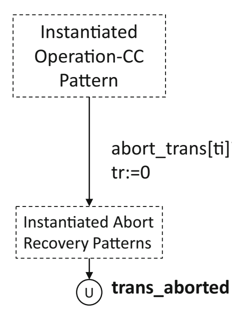


Fig. 13 System Abort Connector $Con(OCCP, RIP)$ and $Con(OCCP, DCP)$[8]

In addition, to connect the recovery patterns with the work unit skeleton, we define connectors $Con(RIP, WUS)$, and $Con(DCP, WUS)$, respectively, in Table 3.

4.1.7 Pattern-based Construction of a WU Automaton

With these definitions of patterns and connectors, a work unit automaton W is a pattern-based construction, as follows:

$$W ::= \dot{\bigcup}(\{WUS\} \bigcup \mathbf{OCCP} \bigcup \mathbf{UAP} \bigcup \mathbf{DP}, \mathbf{CON}), \quad (11)$$

in which,

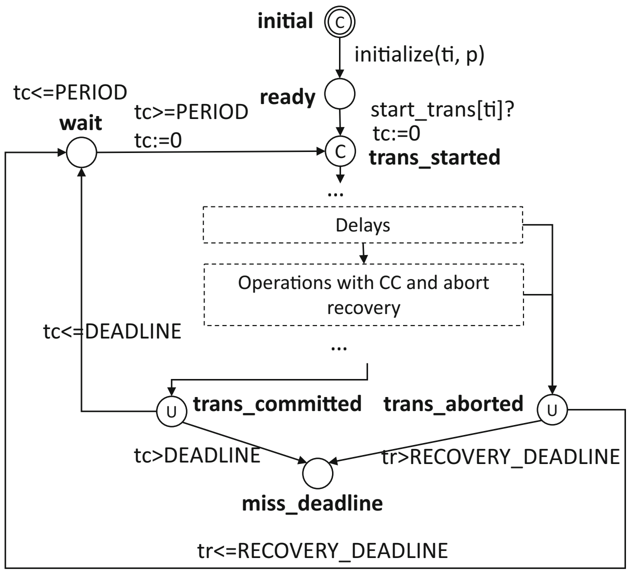


Fig. 14 Illustration of pattern-based construction of a WU automaton

- WUS is an instantiated WUS for the basic structure of W, defined in Equation 6;
- **OCCP** is a set of instantiated OCCP, defined in Equation 7, each representing a begin, commit, read or write operation;
- **UAP** is a set of instantiated UAP, defined in Equation 10, each representing a user abort operation;
- **DP** is a set of instantiated DP, defined in Equation 9, each representing a delay between two operations;
- **CON** is a set of instantiated connectors defined in Table 3: $Con(Begin, WUS)$, $Con(Commit, WUS)$, $Con(UAP, WUS)$, $Con(DP, OCCP)$, $Con(OCCP, DP)$, for each OCCP, DP and UAP.

The pattern-based construction of a WU automaton is illustrated in Fig. 14.

4.2 Patterns and Connectors for Modeling TransactionSequence

The modeling units in this subsection model the basic structure of a TransactionSequence, as well as the interactions between the TransactionSequence and its sub-transactions.

4.2.1 TransactionSequence Skeleton (TSS)

The skeleton of a TransactionSequence, presented in Fig. 15, resembles the work unit skeleton of a transaction, in which its basic locations represent the ready, start, termination and deadline-missing states, respectively. Formally, TSS is defined as follows:

$$TSS(\mathbf{P}_{tss}) ::=(L_{tss}, L_{tssinit}, X_{tss}, V_{tss}, I_{tss}, Act_{tss}, E_{tss}) \cup \mathbf{F}_{tss}, \quad (12)$$

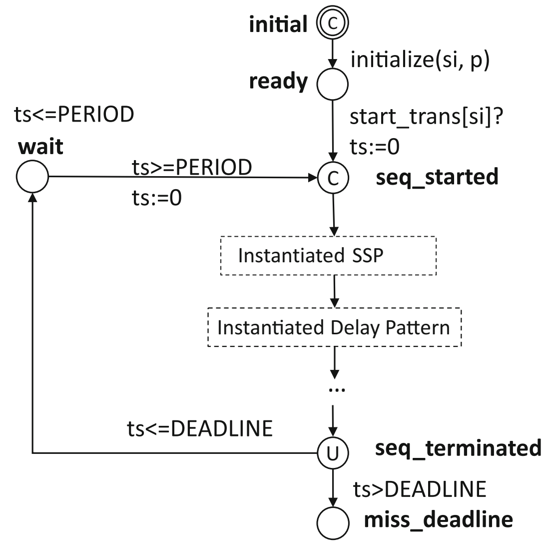


Fig. 15 TransactionSequence Skeleton (TSS)

Table 5 Modeling elements of the TransactionSequence skeleton

Element	Type	Explanation
si	Parameter	Id of the modeled transaction sequence
p	Parameter	Priority of transaction sequence si
PERIOD	Parameter	Period/minimal inter-arrival time of the transaction sequence si
DEADLINE	Parameter	Deadline of transaction sequence si's commitment
ts	Clock variable	Tracking the elapsed time of transaction sequence si
start_trans[si]	Channel	Message to start the transaction sequence si
initialize(si, p)	Function	Initialization of the transaction sequence si with priority p

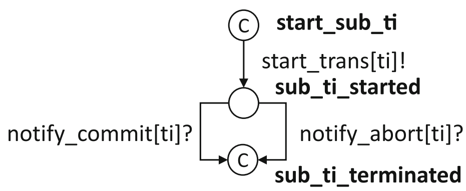


Fig. 16 Sequence Sub-transaction Pattern (SSP)

in which the parameters, variables and functions are defined in Table 5. A clock variable *ts* keeps track of the time spent by the sequence. If the value of *ts* exceeds the specified deadline, the automaton will reach the *miss_deadline* location.

4.2.2 Sequence Sub-transaction Pattern (SSP)

A TransactionSequence skeleton incorporates a series of instantiated Sequence Sub-transaction Patterns (SSP), shown in Fig. 16, which models the behavior of starting a sub-transaction and waiting for its termination. SSP is formally defined as follows:

$$SSP(\mathbf{P}_{ssp}) ::= (L_{ssp}, \emptyset, \emptyset, \emptyset, I_{ssp}, Act_{ssp}, E_{ssp}) \cup \emptyset, \quad (13)$$

where the locations and edges are defined as shown in Fig. 16, and $\mathbf{P}_{ssp}$ contains a parameter *ti* that represents a sub-transaction. The TransactionSequence automaton starts a sub-transaction *ti* by sending a message via the *start_trans[ti]* channel, which is received by the WU automaton of transaction *ti*. Then the TransactionSequence automaton waits for the broadcast signals of either commitment or abortion of *ti*.

4.2.3 TransactionSequence Connectors

To connect a TransactionSequence with its sub-transactions, we define the following connectors in Table 3: $Con(TSS, SSP_i)$, and $Con(SSP_j, TSS)$.

We also define the following connectors to connect two sub-transaction with delay between them: $Con(SSP_i, DP)$ and $Con(DP, SSP_j)$ in Table 3 in which DP is a delay pattern.

With these definitions of patterns and connectors, we define a TransactionSequence automaton S as the following pattern-based construction:

$$S ::= \dot{\bigcup}(\{TSS\} \bigcup \mathbf{SSP} \bigcup \mathbf{DP}, \mathbf{CON}), \quad (14)$$

in which,

- TSS is an instantiated TSS, defined in Equation 12, for the basic structure of the sequence automaton;
- **SSP** a set of instantiated SSP, defined in Equation 13, each representing the control of a sub-transaction;
- **DP** is a set of instantiated DP, defined in Equation 9, each representing a delay between two sub-transactions;
- **CON** is a set of the following instantiated connectors defined in Table 3: $Con(TSS, SSP)$, $Con(SSP, TSS)$, $Con(DP, SSP)$, $Con(SSP, DP)$, for each SSP and DP.

4.3 CCManager Skeleton (CCS)

The CCManager skeleton, presented in Fig. 17, provides a common structure for modeling various CC algorithms, and the interaction with the transactions and the atomicity manager. Formally, CCS is defined as follows:

$$CCS(\mathbf{P}_{ccs}) ::= (L_{ccs}, L_{ccsinit}, X_{ccs}, V_{ccs}, I_{ccs}, Act_{ccs}, E_{ccs}) \cup \mathbf{F}_{ccs}, \quad (15)$$

in which the locations and edges are defined as shown in Fig. 17. Table 6 lists the parameters and variables, as well as functions to encode the resolution policy of a CC algorithm. In this skeleton, the CCManager calls *satisfyPolicy()* when it receives a locking request, in order to decide whether the requester should be granted with the lock. If the function returns true, and no other transactions should be aborted, as suggested by *needAbort()*, the requester is granted with the lock. If any transactions need to be aborted due to concurrency conflicts, CCManager sends a signal to ATManager via channel *cc_conf*, and waits until all abort and recovery have been processed, before it grants the lock to the requester. On the other hand, if *satisfyPolicy()* returns false, the requester either gets aborted, decided by *needAbort()* according to the CC algorithm, or gets blocked and has to wait.

In case the CCManager receives an unlocking request, it updates the status of the transaction and the locks, and grants locks to all legitimated blocked transactions, decided by the *getNext()* function.

Automaton $A_{CCManager}$ is then constructed by instantiating the CCManager skeleton, according to the selected CC algorithm. For instance, Listing 2 shows the function *satisfy-*

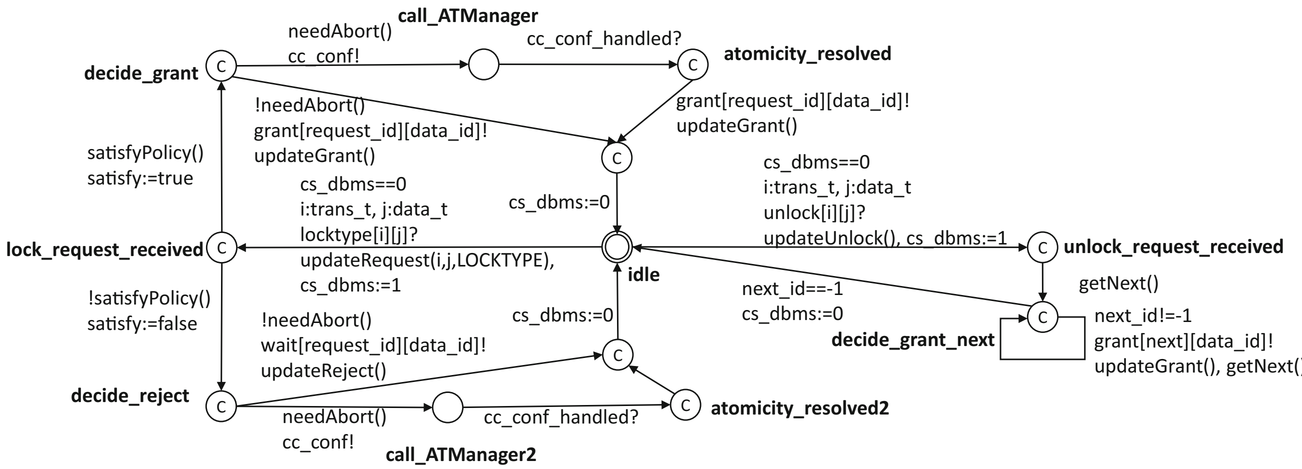


Fig. 17 CCManager Skeleton (CCS) [8]

Table 6 Modeling elements of the CCManager skeleton

Element	Type	Explanation
LOCKTYPE	Parameter	Type of the lock
request_id	Integer variable	Id of the requesting transaction
data_id	Integer variable	Id of the requested data
next_id	Integer variable	Id of the next transaction to be granted with locks
cs_dbms	Integer variable	Indicating critical section for handling request atomically
satisfy	Boolean variable	Indicating whether the requester request_id should be granted with the lock
cc_conf	Channel	Notification of CC conflict to ATManager
cc_conf_handled	Channel	Resolution of CC conflict by ATManager
satisfy Policy()	Function	Checking if the requester request_id should be granted with the lock according to the selected CC algorithm
needAbort()	Function	Checking if any transaction should be aborted due to CC
getNext()	Function	Getting the next transaction to be granted with locks
update Request()	Function	Updating status of transaction request_id and data data_id on request
update Grant()	Function	Updating status of transaction request_id and data data_id after grant
update Reject()	Function	Updating status of transaction request_id and data data_id after reject
update Unlock()	Function	Updating status of transaction request_id and data data_id after unlock

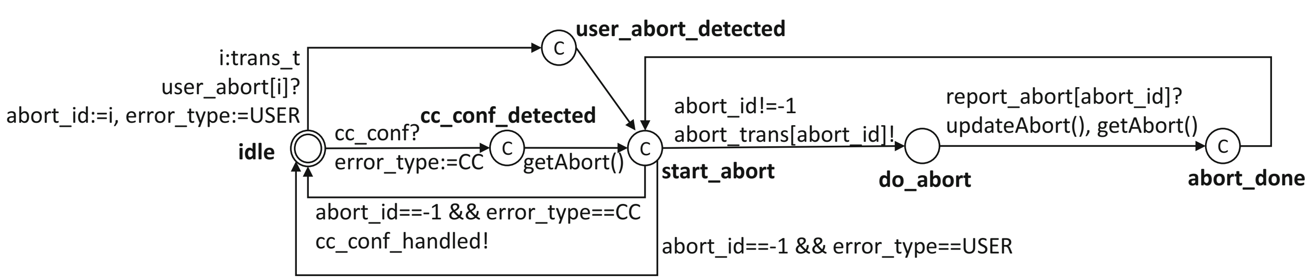


Fig. 18 ATManager Skeleton (ATS)[8]

Policy() of the CCManager that models the conflict detection of the 2PL-HP algorithm.

Listing 2 Functions for 2PL-HP CCManager

```
//Check if the requester should be granted with the lock
bool satisfyPolicy() {
    ...
    if(data_id not locked) return true;
    else if(data_id is readlocked) {
        if(locktype == readlock) return true;
        if(locker has lower priority) return true;
        else return false;
    } else {
        if(locker has lower priority) return true;
        else return false;  }
}
```

4.4 ATManager Skeleton (ATS)

We separate the atomicity control model into an ATManager automaton, and the abort recovery parts in work unit automata. The ATManager models the decisions on aborted transactions upon errors, conflicts or user's instructions. The work unit automata include the instantiated abort recovery patterns that model the selected mechanisms for the specific transactions. We distinguish two types of abort, which are user abort that is issued by a client using an abort operation deliberately, and system abort that occurs due to internal conflicts and system failures, such as CC conflicts.

Our ATManager skeleton provides a common structure for modeling the atomicity manager. Formally, ATS is defined as follows:

$$ATS(\mathbf{P}_{ats}) ::= (L_{ats}, L_{atsinit}, X_{ats}, V_{ats}, I_{ats}, Act_{ats}, E_{ats}) \cup \mathbf{F}_{ats}, \tag{16}$$

in which the locations and edges are defined in Fig. 18, while the parameters, variables and functions are listed in Table 7. The ATManager may receive user abort requests via *user_abort[i]* channel, or system abort due to CC via *cc_conf* channel from CCManager. Other types of errors, such as communication errors, can be modeled in a similar way. The function *getAbort()* specifies the logic to decide the transaction to be aborted. The automaton then sends the abort signal to the corresponding work unit automaton via channel *abort_trans[abort_id]*, and waits until the abort is done by the work unit automaton. ATManager then updates the status and locks of transactions and data using the function *updateAbort()*, and checks if more transactions need to be aborted. The construction of automaton $A_{ATManager}$ is achieved by instantiating this ATManager Skeleton.

4.5 IsolationObserver Skeleton (IOS)

The skeleton for an IsolationObserver is shown in Fig. 19. Formally, IOS is defined as follows:

$$IOS(\mathbf{P}_{ios}) ::= (L_{ios}, L_{iosinit}, X_{ios}, V_{ios}, I_{ios}, Act_{ios}, E_{ios}) \cup \emptyset, \tag{17}$$

in which the locations and edges are defined in Fig. 19. The parameters include transaction ids *ti* and *tm*, as well as data ids *dj* and *dn*. Each IsolationObserver observes a specified sequence of operations, by accepting the corresponding notification messages from the work unit automata via the *notify_op[ti][di]* channel when an operation is completed. If the monitored sequence indicating the phenomenon occurs, the automaton moves to the *isolation_phenomenon* location.

4.6 Data Skeleton (DS)

Fig. 20 presents the skeleton of data. Formally, DS is defined as follows:

$$DS(\mathbf{P}_{ds}) ::= (L_{ds}, L_{dsinit}, X_{ds}, V_{ds}, I_{ds}, Act_{ds}, E_{ds}) \cup \emptyset, \tag{18}$$

in which the locations and edges are defined in Fig. 20. The parameters include a list of transaction ids *trans_t*, as well as data id *di*. The clock variable *age* is reset every time a write

Table 7 Modeling elements of the ATManager skeleton

Element	Type	Explanation
abort_id	Integer variable	Id of the aborting transaction
error_type	Integer variable	Type of error that causes abortion
CC	Constant	Indicating the abortion caused by CC
USER	Constant	Indicating the abortion caused by user abort operation
cc_conf	Channel	Notification of CC conflict to ATManager
cc_conf_handled	Channel	Resolution of CC conflict by ATManager
report_abort[ti]	Channel	Message that reports to the ATManager that the abortion of ti is done
abort_trans[ti]	Channel	Message from the ATManager that starts the abortion of ti
user_abort[ti]	Channel	Message that notifies to the ATManager that a user abort operation for ti is issued
getAbort()	Function	Getting the transaction to be aborted
updateAbort()	Function	Updating status of transaction and data after transaction ti gets aborted

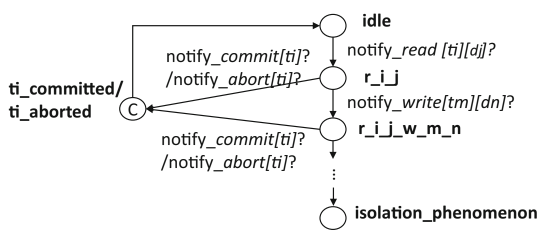


Fig. 19 IsolationObserver Skeleton (IOS)[8]

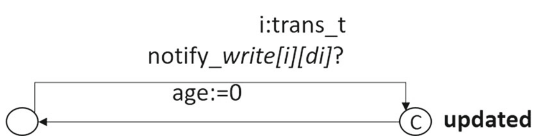


Fig. 20 Data Skeleton (DS)[8]

operation is performed on the data. The value of *age* hence represents how old the data is since the last update.

4.7 Summary of Modeling

Given a set of transactions and the selected CC and AR mechanisms, the UPPCART model of the RTDBMS can be created by the parallel composition of its component TA, which are constructed via the pattern-based construction by instantiating our proposed patterns and connectors. Formally, the pattern-based construction of the RTDBMS is defined as follows:

$$N ::= W_1 \,||\, ... \,||\, W_n \,||\, A_{CCManager} \,||\, A_{ATManager} \\ ||\, O_1 \,||\, ... \,||\, O_k \,||\, D_1 \,||\, ... \,||\, D_m, \,||\, S_1 \,||\, ... \,||\, S_l,$$

in which:

- $W_i ::= \dot{\bigcup}(\{WUS_i\} \bigcup \mathbf{OCCP}_i \bigcup \mathbf{UAP}_i \bigcup \mathbf{DP}_i, \mathbf{CON}_i)$,
- $A_{CCManager} ::= \dot{\bigcup}(\{CCS\}, \emptyset)$,
- $A_{ATManager} ::= \dot{\bigcup}(\{ATS\}, \emptyset)$,
- $O_i ::= \dot{\bigcup}(\{IOS_i\}, \emptyset)$,
- $D_i ::= \dot{\bigcup}(\{DS_i\}, \emptyset)$,
- $S_i ::= \dot{\bigcup}(\{TSS_i\} \bigcup \mathbf{SSP}_i \bigcup \mathbf{DP}_i, \mathbf{CON}_i)$.

The pattern-based construction allows large parts of existing models to be reused, in case a different CC or AR is selected, and the models need to be updated. An example is presented in our previous work [21], which demonstrates the easy adjustments when different CC algorithms are selected for the same sets of transactions and data.

It is possible to extend UPPCART to model more varieties of transaction management and behaviors. For instance, one can also add a TA to the parallel composition, to model the dispatching pattern of transactions from the clients. This TA sends signals via the *start_trans[i]* channel to each W_i, with a specific order and predefined intervals. It may even receive the *notify_commit[i]* signals from W_i, such that the end-to-end deadline of a sequence of transactions can be monitored.

4.8 Verification

With the transactions as well as the atomicity and concurrency control mechanisms modeled in UPPAAL TA, we are able to formally verify the atomicity, isolation and temporal correctness properties using UPPAAL Model Checker.

Table 8 lists the patterns to formalize the properties in UPPAAL queries. Among them, atomicity is formalized as a liveness property, that the automaton A_i representing transaction T_i eventually reaches the dedicated *trans_rollback* or *trans_compensated* location if the *abort_id* equals *i*. Isolation and temporal correctness are formalized as invariance properties. The isolation property is specified as the *isolation_phenomenon* locations are not reachable. The timeliness property is formalized as the *miss_deadline* location of the analyzed T_i is not reachable, while temporal validity proper-

Table 8 UPPAAL query patterns for verifying transactional properties[8]

Property Type	Property Description	UPPAAL Query Pattern
Atomicity	T_i aborted due to ERRORTYPE is eventually rolled back (compensated)	$(ATManager.abort\_id == i \;\&\& \; ATManager.error\_type == ERRORTYPE) \rightarrow Ai.trans\_rolledback\;(Ai.trans\_compensated)$
Isolation	The specified isolation phenomena never occur	$A\,[\,]\; not\; (O_1.isolation\_phenomenon \,\|\| \ldots \|\| \, O_n.isolation\_phenomenon)$
Timeliness	T_i never misses its deadline	$A\,[\,]\; not\; Ai.miss\_deadline$
Absolute Validity	When read by T_i, D_j is never older than the absolute validity interval AVI(j)	$A\,[\,]\,(Ai.read\_di\_done\; imply\;\; Dj.age <= AVI(j))$
Relative Validity	Whenever T_i reads D_j or D_l, the age differences of D_j and D_l is smaller than or equal to the relative validity interval RVI(j,l)	$A[\,]\,((Ai.read\_dj\_done \,\|\|\, Ai.read\_dl\_done)\; imply\; ((Dj.age - Dl.age <= RVI(j,l)) \;\&\&\; (Dl.age - Dj.age <= RVI(j,l))))$

ties are formalized as the states where the ages of data exceed their thresholds are never reachable.

5 From UTRAN to UPPCART

We provide a translational semantics from UTRAN to UPPCART, in order to bridge the gap between the high-level description of transactions and the verifiable models for reasoning about the transaction properties. In this way, the formal semantics of UTRAN is defined using UPPAAL TA, which also lays the foundation of automated transformation from UTRAN to UPPCART models. In this section, we first introduce the semantic definitions of UTRAN (Section 5.1), followed by the tool automation for the transformation (Section 5.2).

5.1 Translational Semantics of UTRAN

We encode the formal semantics of UTRAN in terms of UPPCART as follows:

Definition 1 [Semantics of <<RTDBMSScope>>] An <<RTDBMSScope>> in UTRAN is formally defined as an UPPCART NTA N_{RTDBMS}, whose definition is given in Equation 1.

Definition 2 [Semantics of <<IsolationSpecification>>] An <<IsolationSpecification>> in the <<RTDBMSScope>> is formally defined as $A_{CCManager}$ and a set of IsolationObservers in N_{RTDBMS}. The $A_{CCManager}$ is an instantiation of the CCManager skeleton with the selected CC algorithm, that is, the value of $CCAlgorithm$ in the <<IsolationSpecification>>. An <<IsolationPhenomenon>> specified in the <<IsolationSpecification>> is defined as an instantiated IsolationObserver skeleton.

Definition 3 [Semantics of <<Transaction>>] A <<Transaction>> T_i in the <<RTDBMSScope>> is formally defined as a work unit TA W_i, according to Equation 11, in the parallel composition of N_{RTDBMS}.

The <<Operations>> within a <<Transaction>> are defined as follows:

Definition 4 [Semantics of <<BeginOp>>, <<CommitOp>>, <<ReadOp>> and <<WriteOp>>] A <<BeginOp>>, <<CommitOp>>, <<ReadOp>> or <<WriteOp>> is formally defined as an instantiated OCCP. The data j read by <<ReadOP>> r, with $r.did == j$ and $r.absValidity > 0$, is defined as a Data automaton D_{ij} by instantiating the Data skeleton.

Depending on the value of $CCAlgorithm$ in the <<IsolationSpecification>>, the OCCP is defined by composing an OP (operation), with zero or more LP (locking) or UP (unlocking).

For instance, if $CCAlgorithm \in \{2PL\text{-}HP, R2PL\}$, the operations with CC are defined as follows:

- For the <<BeginOP>>, $OCCP_{begin} ::= \dot{\bigcup}(\{OP_{begin}\}, \emptyset)$.
- For each <<ReadOP>> r, with $r.tid == i$ and $r.did == j$, $OCCP_i ::= \dot{\bigcup}(\{OP_i, LP_i\}, \{Con(OP_i, LP_i)\})$, in which the parameter *locktype* in LP_i is *readlock*.
- For each <<WriteOP>> w, with $w.tid == i$ and $w.did == j$, $OCCP_i ::= \dot{\bigcup}(\{OP_i, LP_i\}, \{Con(OP_i, LP_i)\})$, in which the parameter *locktype* in LP_i is *writelock*.
- For the <<CommitOP>>, $OCCP_{commit} ::= \dot{\bigcup}(\{OP_{commit}\} \bigcup UP', \{Con(OP_{commit}, UP')\})$, in which UP' is a pattern composed of a set of unlocking patterns for all data read or written by the transaction.

If $CCAlgorithm \in \{ShortReadlock\}$, the operations with CC are defined as follows:

- For the <<BeginOP>>, $OCCP_{begin} ::= \dot{\bigcup}(\{OP_{begin}\}, \emptyset)$.
- For each <<ReadOP>> r, with $r.tid == i$ and $r.did == j$, $OCCP_i ::= \dot{\bigcup}(\{OP_i, LP_i, UP_i\}, \{Con(OP_i, LP_i), Con(OP_i, UP_i)\})$, in which the parameter *locktype* in LP_i is *readlock*.
- For each <<WriteOP>> w, with $w.tid == i$ and $w.did == j$, $OCCP_i ::= \dot{\bigcup}(\{OP_i, LP_i\}, \{Con(OP_i, LP_i)\})$, in which the parameter *locktype* in LP_i is *writelock*.
- For the <<CommitOP>>, $OCCP_{commit} ::= \dot{\bigcup}(\{OP_{commit}\} \bigcup UP', \{Con(OP_{commit}, UP')\})$, in which UP' is a pattern composed of a set of unlocking patterns for all data writen by the transaction.

Definition 5 [Semantics of <<DelayedNext>>] A <<DelayedNext>> edge is formally defined as an instantiated DP, together with connectors $Con(OCCP_i, DP)$ and $Con(DP, OCCP_j)$, where $OCCP_i$ and $OCCP_j$ are the source and target <<Operation>> of the <<DelayedNext>>, respectively.

Definition 6 [Semantics of <<AtomicitySpecification>>] An <<AtomicitySpecification>> associated with the <<Transaction>> is formally defined as a construction of patterns and connectors, depending on the values in the specification. We define a $Con(OCCP, RIP)$ for each OCCP, if $arMech \in \{Rollback, ImmediateCompensate\}$; or a $Con(OCCP, DCP)$ for each OCCP, if $arMech \in \{DeferredCompen\text{-}sate\}$. For each DP, we define a $Con(DP, RIP)$ or a $Con(DP, DCP)$.

Definition 7 [Semantics of <<AbortOp>>] Each <<AbortOp>> is formally defined as an instantiated UAP, which is composed with a $Con(OCCP, RIP)$ or a $Con(OCCP, DCP)$, depending on the value of attribute $arMech$ in the associated <<AtomicitySpecification>>.

Definition 8 [Semantics of <<TransactionSequence>>] A <<TransactionSequence>> Seq_i is formally defined as a TA S_i, according to Equation 14, whose construction elements are defined by the following:

1. Each <<Transaction>> in the sequence is defined as an instantiated Sequence Sub-transaction Pattern (SSP), together with the connectors $Con(TSS, SSP)$ and $Con(SSP, TSS)$.
2. Each <<DelayedNext>> between the <<Transactions>> is defined as an instantiated DP, as well as instantiated connectors $Con(DP, SSP)$ and $Con(SSP, DP)$.

5.2 Automated Transformation

Automated transformation from UTRAN specifications to UPPCART models can reduce the efforts of system designers by shielding them from the under-the-hood formalism. In this section, we developed a Java-based tool prototype, called $U^2 - Transformer$ [12], which provides automated transformation based on the previously mentioned mapping.

U^2Transformer accepts a system model defined in UML with the UTRAN profile, created in common UML editors including Eclipse Papyrus modeling environment [3] and IBM Rational Software Architect (RSA) environment [4], in their respective XML format. The tool parses the UTRAN specifications and returns the XML-format UPPCART models for the UPPAAL tool. More implementation details of the tool can be referred to in our extended report [22].

5.3 Validation of U^2Transformer

As the first step of validation, we create a series of unit test cases to test the individual mappings in Section 5.1. They generate pieces of UPPCART models corresponding to the selected subsets of UTRAN concepts. These cases include transformation of single transactions with only one type of the properties, as well as sequences of transactions with multiple properties. The generated models are manually checked for their correctness. The test units are written using the JUnit framework, and are included in the source files of the tool.

We also apply a common approach to test model transformation, that is, to compare the automatically generated model with an expected output model [23]. We use the example UTRAN specification and its manually-generated corresponding UPPCART model from our previous work [8] as a reference for the validation.

The UTRAN example in [8] specifies the transactions managing the configuration data and mission status of an autonomous wheel loader. It involves three ordinary transactions, one compensation transaction, five data objects, as well as the atomicity, isolation and temporal correctness specifications. The UPPCART model is created manually by the authors, which is a network of UPPAAL TA that conforms to Equation 1. We use the same UTRAN specification as the input of U^2Transformer, and run the translation. The generated UPPCART model contains the same elements (e.g., individual automata and global variables) as the manually created model, and satisfy the same atomicity, isolation and temporal correctness properties.

6 Case Study

In this section, we demonstrate UTRAN, UPPCART and the tool-supported transformation, via the specification and verification of a transaction-based system.

[3] https://www.eclipse.org/papyrus/.

[4] https://www.ibm.com/developerworks/downloads/r/architect.

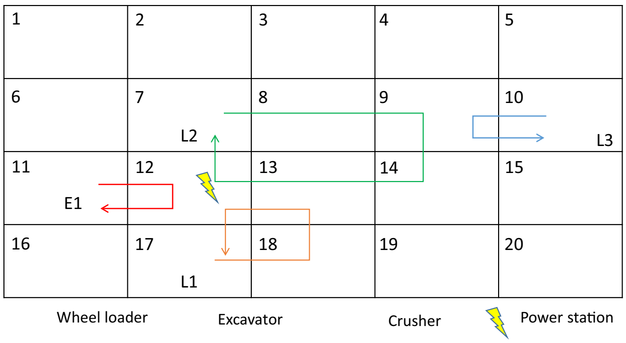


Fig. 21 Map and paths of vehicles in our case study

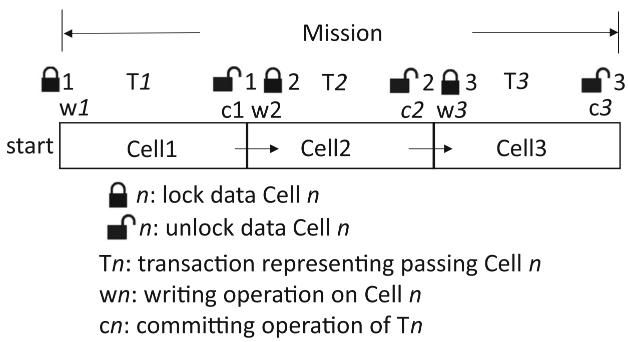


Fig. 22 Illustration of collision avoidance through transactions and CC

Autonomous construction vehicles such as wheel loaders and excavators are considered as a promising trend to reduce costs and avoid safety hazards in construction and mining sites. In this case study, we consider a quarry where raw materials (e.g., iron ores) are mined by excavators, and transported by a group of wheel loaders to crushers deployed on the site. A mission is decided for each wheel loader and excavator, which follows a designed path in order to complete its job, such as transportation of materials, and maintenance activities, such as charging the battery. In order to ensure safety while maintaining productivity, we design a two-layer collision avoidance system to prevent collisions between vehicles achieved by the global collision avoidance layer, as well as with obstacles such as rocks and holes, achieved by the local collision avoidance layer. The functionalities of both layers rely on the data management and transaction control provided by their DBMS. In the following subsections, we present the design of the DBMS in these two layers, as well as the verification of the crucial temporal and logical properties using our proposed framework and tool, respectively.

6.1 Global Collision Avoidance Layer

The center of the global collision avoidance layer is a global DBMS that stores the map of the quarry, which is divided into smaller cells of a grid. The mission of a vehicle is represented as a sequence of cells that it should visit. Fig. 21 presents the map of the quarry in our case study. Three wheel loaders are deployed at Cells 7, 10 and 17, whose plans are determined to carry materials to the crushers at Cells 9 and 18, respectively. On the way back from the crushers, some of the wheel loaders are scheduled to refuel at the charging stations at Cell 12, as shown in their paths respectively. An excavator digs the ores at Cell 11. From time to time, the excavator also needs to charge at Cell 12. As illustrated in the figure, the vehicles not only share the crushers and the power stations, but their paths also overlap in multiple cells.

In order to avoid collision with each other, the vehicles are not allowed to operate in the same cell simultaneously. To achieve optimal productivity, each wheel loader is scheduled to operate its mission with a specific period, and is expected to finish by a given deadline. In addition, since there are more wheel loaders than excavators, it is further required to allow the excavator to be charged whenever necessary for better productivity. In other words, the excavator should be prioritized to use the charging station.

We achieve global collision avoidance by leveraging concurrency control of the DBMS to prevent multiple vehicles operating in the same cell simultaneously. The key idea is to let a vehicle lock the cell before entering it, and unlock it when the vehicle is about to leave the cell. As illustrated in Fig. 22, the entire path of a vehicle is modeled as transaction sequence, while the activity of passing an individual cell, including the performed job in it, is modeled as a transaction. Before entering a cell, a vehicle starts a transaction and performs a write operation on the cell data, which results in a lock on the cell. Before the vehicle leaves the cell, it commits the transaction, which releases the lock and allows other vehicles to enter this cell. We assume the committing vehicle is in full stop before entering the next cell. Therefore, even if another vehicle may enter the unlocked cell before the committing vehicle leaves, these two are not operating their tasks simultaneously, and hence are considered safe. To ensure immediate access of the high-priority vehicle, we apply a priority-based CC (2PL-HP [17]), which aborts the low-priority transaction when two transactions try to lock the same data.

Based on this, we identify 4 transaction sequences in the global layer, each for one vehicle in Fig. 21; with a total number of 18 transactions, each controlling one vehicle passing one cell, and 2 compensation transactions re-entering the charging stations. The sequences and transactions are listed in Table 9. For temporal correctness, in this case study we focus on the end-to-end deadlines of the sequences. The isolation constraint imposed by safety requires that two vehicles should not use the same cell, especially the power station, that is, no simultaneous access to Cell 12. In addition, since the excavator has a higher priority, the wheel loaders L1 and L2 may be aborted when they are using the power station. We

Table 9 Transactions in the global collision avoidance layer

Vehicle	Transaction sequence	Contained transactions	Sequence deadline	Atomicity	Isolation
L1	S1L1	G17, G18, G13, G12, G17	2000 s	When G12 (charging) gets aborted, redo G12	Vehicles should not access the power station simultaneously. That is, transactions do not access Cell 12 simultaneously.
L2	S2L2	G7, G8, G9, G14, G13, G12, G7	2100 s	When G12 (charging) gets aborted, redo G12	
L3	S3L3	G1, G9, G10	2500 s		
E1	S4E1	G11, G12, G11	2400 s		

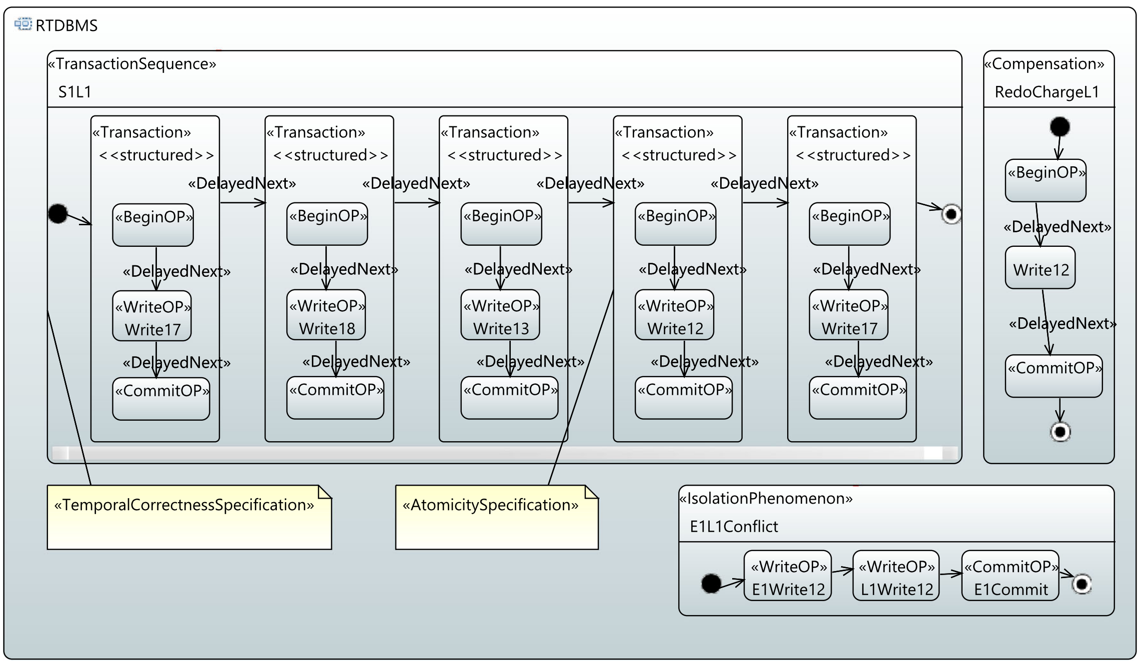


Fig. 23 Excerpt of the UTRAN specification for the global layer using the Papyrus tool

hence add the atomicity requirement that when charging gets aborted, the vehicle should redo the charging later when the station is free.

6.1.1 Specification in UTRAN

Fig. 23 presents an excerpt from the Eclipse Papyrus tool that exhibits the specification of transaction sequence S1L1. The sequence contains five <<Transactions>>. Each <<Transaction>> includes three <<Operations>>: one <<BeginOP>>, one <<WriteOP>> that writes the cell data, and one <<CommitOP>>. The time to perform the operation in the cell (e.g., digging, cruising, crushing, or charging) is specified as the delay in the <<DelayedNext>> edge between the <<WriteOP>> and the <<CommitOP>>. The timing properties of S1L1 are specified in its attached <<TemporalCorrectnessSpecification>>. <<Transaction>> G12 is associated with an <<AtomicitySpecification>>, which refers to <<Compensation>> RedoCharge1 as its deferred compensating transaction. An <<IsolationPhenomenon>>, E1- L1Conflict, specifies the interleavings that results in the simultaneous access of Cell 12, which should be prevented by the CC. The complete specification can be found in our online repository [12].

6.1.2 Construction of UPPCART models

We applied U^2Transformer to generate UPPCART models. As shown in Fig. 24, we used the command-line interface to specify the Eclipse Papyrus format, the path to the input

Fig. 24 Transformation of the UTRAN specification using U^{2}Transformer

```
C:\tool>java -jar u2transformer.jar -p -e AutoQuarry.uml AutoQuarryUPPAAL.xml
Generating UPPAAL models for UTRAN specifications in Papyrus format...
Completed! Time spent on transformation: 4 s 97 ms.
```

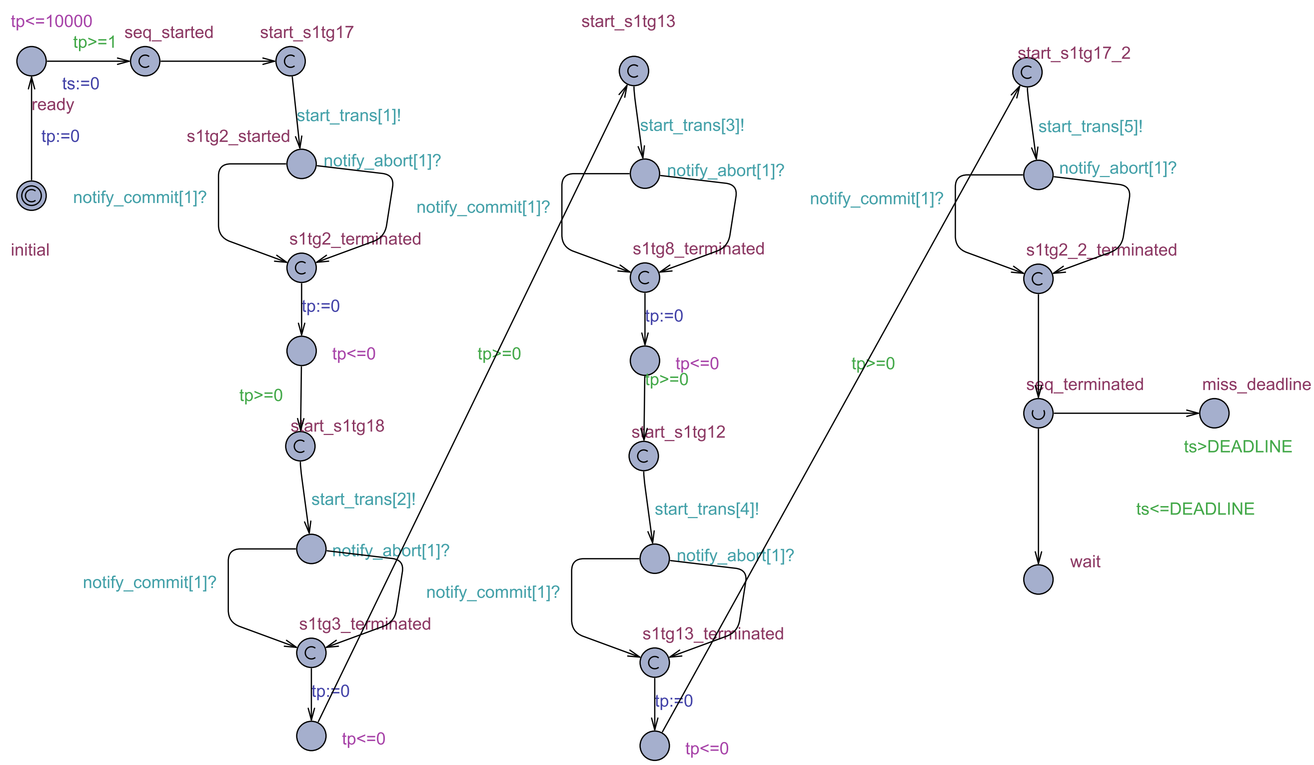


Fig. 25 Excerpt of the UPPCART models for S1L1 from the UPPAAL tool

UTRAN file, and the output path for the generated UPPAAL model. The transformation took 4.097 s.

Figure 25 shows an example of the generated UPPCART model for S1L1, which corresponds to the <<TransactionSequence>> S1L1 in Fig. 23. The main structure of this TA is an instantiation of the TransactionSequence Skeleton and represents the basic structure of the sequence S1L1. Its sub-transactions, including G17, G18, G13, G12, and G17_2, are modeled by instantiation of the sub-transaction patterns, respectively.

6.1.3 Optimization

During the simulation and verification of the generated models, we realize that the number of channels is large, which causes very long time for UPPAAL to reach a conclusion. For instance, we have a matrix of channels for write locks, whose number is a multiplication of the number of transactions and the number of data. This contributes greatly to the state space, which results in extremely long verification time. Therefore, we have performed a few optimizations in the TA models. First, we merge the begin operation with the write operation in each sub-transaction. This is because the delays between these two operations are negligible (in milliseconds) compared with the mission time (in hundreds or thousands of seconds). This way, we can reduce the channels related to the begin operations. Second, since within each sequence, only one sub-transaction can be executed at any time, we therefore use the sequence ID to identify its sub-transactions in the channels. This considerably reduces the number of channels without changing the semantics of the models. For instance, the number of channels for write locks is now a multiplication of the number of sequences and the number of data, which is significantly smaller than using separate transaction ID's. Both the original and the optimized UPPCART models are presented in our online repository [12].

6.1.4 Verification of the global layer

We verify the optimized models against the requirements using the UPPAAL model checker (version 4.1.19). The verification PC is equipped with an Intel i7-4800MQ CPU (2.70 GHz, 8 cores), 16 GB memory, and Ubuntu 16.04 (64-bit).

Table 10 Verification results of the global collision avoidance layer

Property type	UPPAAL query pattern	Explored states	Memory consumption	Verification time	Result
Timeliness	$A[\,]\ not\ S1L1.miss\_deadline$	40950261	3054896 KB	6161 s	Satisfied
Timeliness	$A[\,]\ not\ S2L2.miss\_deadline$	40950261	3054944 KB	6208 s	Satisfied
Timeliness	$A[\,]\ not\ S3L3.miss\_deadline$	40950261	3054888 KB	6229 s	Satisfied
Timeliness	$A[\,]\ not\ S4E1.miss\_deadline$	40950261	3054968 KB	6178 s	Satisfied
Atomicity	$E<>\ (ATManager.abort\_id == 1\ \&\&\ ATManager.error\_type == CC)$	36840129	2988620KB	5687s	Satisfied
	$(ATManager.abort\_id == 1\ \&\&\ ATManager.error\_type == CC) \rightarrow S1G12.trans\_def\_compensated$	40467738	3083780KB	6444s	Satisfied
Atomicity	$E<>\ (ATManager.abort\_id == 2\ \&\&\ ATManager.error\_type == CC)$	36839868	2988480KB	5613s	Satisfied
	$(ATManager.abort\_id == 2\ \&\&\ ATManager.error\_type == CC) \rightarrow S2G12.trans\_def\_compensated$	40470864	3083812KB	6452s	Satisfied
Isolation	$A[\,]\ not\ (IsolationObserver1.isolation\_phenomenon \Vert IsolationObserver1.isolation\_phenomenon \Vert IsolationObserver1.isolation\_phenomenon \Vert IsolationObserver1.isolation\_phenomenon \Vert IsolationObserver1.isolation\_phenomenon \Vert IsolationObserver1.isolation\_phenomenon)$	40950261	3057276KB	6165s	Satisfied

The verification results, presented in Table 10, show that the current design satisfies all imposed requirements.

6.2 Local collision avoidance layer

The local collision avoidance layer allows a vehicle to move around an obstacle in its way, by monitoring the surroundings using a camera, a sensor and a lidar. Timely update and access of the surrounding data, as well as correct reaction to the detection of obstacles, are crucial to the safety of the vehicle. The data and all related transactions are listed in Table 11. In our case, these data are stored in the vehicle's local DBMS, and updated periodically by transactions UpdateCamera, UpdateSensor, and UpdateLidar respectively. Another transaction MoveVehicle reads these data, and checks if any obstacle occurs. If the path is clear, the vehicle moves forward for a period of time, and commits the transaction. If an obstacle occurs, the MoveVehicle transaction is aborted, after which a compensation AvoidObstacle is started to move around the obstacle, and updates a log with the obstacle position for the future updates of vehicle paths.

Similar to the design of the global layer, we specify the local layer in UTRAN, as presented in Fig. 26. Each transaction in Table 11 is specified as an activity stereotyped with <<Transaction>> (or <<Compensation>> for AvoidObstacle), with their properties specified in the attached <<TemporalCorrectnessSpecification>> and <<AtomicitySpecification>>. We generate the UPPAAL models from this UTRAN specification using our tool. The complete specifications and the TA models are presented in our online repository [12].

The verification results of the local collision avoidance layer are listed in Table 12. The desired atomicity and temporal correctness properties are satisfied by the current design, according to the verification results.

Since all desired requirements have been satisfied, no trade-offs among the properties are necessary in our current design. However, in case any violation was detected by the verification, indicating conflicts among the properties, the designer would need to revise the design with trade-off decisions. Such trade-offs may involve adjustments in the selected CC, AR and scheduling mechanisms, as well as in the variants of the properties. The revised specifications are then formalized and checked as mentioned above. Such revising-and-model-checking iterations continue until we reach a design that satisfies all desired properties.

7 Related work

Researchers have made a number of efforts in the specification of transaction-based systems and their properties. Among them, ASSET [24] and KALA [25] specify flexible transaction models with procedural languages, in which operations and AR mechanisms are specified using primitives provided by the languages. ReflecTS [26] allows specification of various ACID properties of flexible transaction models. Compared to these works, our supports specification of temporal correctness for transactions and transaction sequences, and the selection of CC algorithms. Several high-level description languages opt for extending UML with elements related to the topic. In the real-database profile proposed by Marouane et al. [27], the authors extend MARTE for real-time database systems and incorporate timing properties such as transaction timeliness. However, neither transaction sequence nor atomicity or isolation are their focus. Unified transaction modeling language (UTML) [28] and its extension [29] extend UML for transactions with various selection of the ACID properties. In these works, atomicity and isolation are treated as monolithic properties respectively, rather than a spectrum of variants. Temporal correctness of transactions and transaction sequences is not addressed.

Some influential work include the Business Process Execution Language (BPEL) [30], the Business Process Model and Notation (BPMN) [31], and their extensions. Both BPEL and BPMN are XML-based, high-level description languages for specifying business processes, which can be considered as a flexible transaction model with various atomicity options. Rollback and compensation can be specified at transaction level and for internal activities. Invocation dependencies between transactions are also supported by these languages. Charfi et al. [32] and Sun et al. [33] introduce extra concepts for transactions to BPEL, which allow explicit specification of atomicity policies. Compared with their work, our proposed profile can specify variants of isolation for a group of transactions, as well as timing properties for transactions and transaction sequences. Watahiki et al. [34] propose to strengthen BPMN with temporal constraints, and generate UPPAAL models for verification. Isolation and CC are out of the scope of this framework.

As for formal modeling and analysis of transaction properties, the ACTA framework [35] specifies transaction models in first order logic and allows for formal reasoning. Derks et al. [13] propose to model and verify transactions with atomicity variants in Petri nets. Gallina [7] uses higher-order logic to specify transaction properties, which can be formally analyzed by the Alloy tool. A number of formal languages for transaction models have been discussed by Gallina [7]. However, these frameworks are restricted in the formal specification and analysis of ACID, while timeliness, especially the impact of CC and abort recovery mechanisms on the time, are not included. In a more recent work, Liu et al. [36] model a transaction model using Maude, and analyze only properties regarding logical consistency. Lanotte et al. [37] propose a timed-automata-based language for long running transactions with timing constraints. Committing protocols for

Table 11 Transactions in the local collision avoidance layer

Transaction	Description	Period	Deadline	Atomicity	Temporal correctness
UpdateCamera	Write *camera*	200 ms	150 ms	When MoveVehicle is aborted, execute AvoidObstacle for compensation immediately.	The absolute validity intervals of *camera*, *sensor* and *lidar* are 400 ms. The relative validity interval of the group {*camera*, *sensor*, *lidar*} read by MoveVehicle is 400 ms.
UpdateSensor	Write *sensor*	200 ms	150 ms		
UpdateLidar	Write *lidar*	200 ms	150 ms		
MoveVehicle	Read *camera*, *snesor* and *lidar*, If no obstacles, move forward 1200 ms. Otherwise, abort.	2000 ms	2000 ms		
AvoidObstacle	Move around the obstacle. Write *log*.				

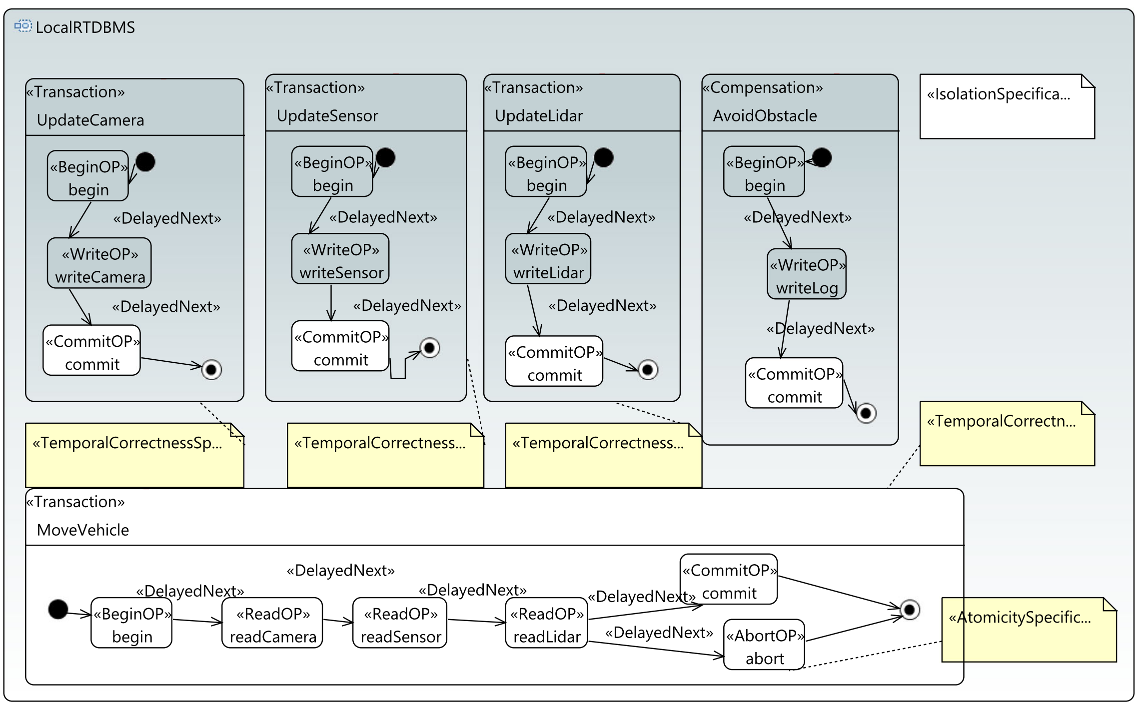


Fig. 26 Excerpt of the UTRAN specification for the local layer using the Papyrus tool

atomicity variants can be modeled and analyzed. In contrast to these works, our work provides a formal framework for modeling transactions together with abort recovery and CC mechanisms, in which atomicity, isolation, temporal correctness, as well as their impacts on each other, can be analyzed in a unified framework. Our recent work [38] proposes the UPPCART-SMC framework, which models the transaction system as stochastic timed automata, and applies statistical model checking [39] to analyze the same properties as we do in this paper. Although UPPCART-SMC avoids the state explosion problem and thus can analyze large systems, it only provides probabilistic assurance of the properties. On the contrary, UPPCART in this paper applies exhaustive model checking and provides a formal guarantee of the properties.

Pattern-based techniques have been considered useful in modeling real-time systems with timed automata. Dong et al. [40] propose a set of TA patterns for common timing constraints, such as delay and deadline. Mekki et al. [41] introduce TA observer patterns for time-related requirement in UML statecharts. Étienne André [42] proposes a set of TA observer patterns for timing constraints and behaviors of real-time systems. In our work, we also apply pattern-

Table 12 Verification results of the local collision avoidance layer

Property type	UPPAAL query pattern	Explored states	Memory consumption	Verification time	Result
Timeliness	$A[\,]\ not\ UpdateCamera.miss\_deadline$	6752	45872 KB	0.13 s	Satisfied
Timeliness	$A[\,]\ not\ UpdateSensor.miss\_deadline$	6752	45872 KB	0.14 s	Satisfied
Timeliness	$A[\,]\ not\ UpdateLidar.miss\_deadline$	6752	45872 KB	0.14 s	Satisfied
Timeliness	$A[\,]\ not\ MoveVehicle.miss\_deadline$	6752	45872 KB	0.13 s	Satisfied
Absolute Validity	$A[\,]\ (camera.age \leq 40)$	6821	45872 KB	0.2 s	Satisfied
Absolute Validity	$A[\,]\ (sensor.age \leq 40)$	6821	45872 KB	0.19 s	Satisfied
Absolute Validity	$A[\,]\ (lidar.age \leq 40)$	6821	45872 KB	0.2 s	Satisfied
Relative Validity	$A[\,]\ ((MoveVehicle.finish\_readCamera \Vert MoveVehicle.finish\_readSensor \Vert MoveVehicle.finish\_readLidar)\ imply\ (camera.age - sensor.age \leq 40\ \&\&\ camera.age - lidar.age \leq 40\ \&\&\ sensor.age - lidar.age \leq 40\ \&\&\ sensor.age - camera.age \leq 40\ \&\&\ lidar.age - sensor.age \leq 40\ \&\&\ lidar.age - camera.age \leq 40))$	39804	45872 KB	1.62 s	Satisfied
Atomicity	$E <> (ATManager.abort\_id == 4\ \&\&\ ATManager.error\_type == USER)$	3675	28976 KB	0.03 s	Satisfied
	$(ATManager.abort\_id == 4\ \&\&\ ATManager.error\_type == USER) \rightarrow MoveVehicle.trans\_imme\_compensated$	25,008	43,084 KB	0.16s	Satisfied

based techniques to model real-time transactions. We provide a formal definition of patterns and pattern-based modeling in our context. Our patterns are not only used to model time-related behaviors and observe timing properties, but also used to specify transaction management mechanisms and capture data inconsistency.

Researchers have proposed many tool chains for modeling and analyzing various aspects of critical systems, within the model-driven engineering paradigm. Examples include the work of Biehl et al. [43], ViTAL [44] and CHESS [45]. In these tool chains, domain-specific languages are implemented to be applied by users to create system specifications, which are then transformed into formal models for rigorous analysis. Our work shares the same model-driven engineering approach, facilitated with our own language, formal semantics, and transformation.

8 Conclusions and future work

In this paper, we have presented a high-level specification language that extends our previously proposed UTRAN profile. In addition to the specification of transactions with atomicity, isolation and temporal correctness properties, the extended UTRAN profile also supports specification of transaction sequences and their timing constraints. We have also extended our previously proposed UPPCART framework, a pattern-based formal framework that models transactions in UPPAAL timed automata, with counterparts for transaction sequences.

We have proposed a formal definition of pattern-based construction of UPPCART models, based on which we are able to provide a mapping between the UTRAN elements and UPPCART patterns, and automate the transformation from UTRAN to UPPCART. Designers can specify the transactions in UML diagrams with UTRAN using existing UML editors, and transform them into formal models that can be rigorously analyzed by UPPAAL. The automated transformation is supported by our tool U^{2}Transformer.

We also have performed an industrial use case that involves collision avoidance of autonomous vehicles via transaction management. In the case study, we applied UTRAN to specify the transactions in the system, and transformed them into UPPCART models using U^{2}Transformer. The desired atomicity, isolation and temporal correctness properties were successfully verified by UPPAAL model checker. A lesson learned from the use case is that, the automatically generated models can be further optimized according to the application semantics. By reducing, for instance, the number of channels, the models may achieve much smaller state space and result in much shorter verification time and lower memory consumption. This is important for large systems since we use exhaustive model checking for the analysis. Such optimization, admittedly, requires knowledge in formal modeling with UPPAAL. Nevertheless, our proposed tool automation greatly reduces the efforts to construct the formal models.

Although only a set of property variants and mechanisms are selected and presented in this paper, our work can be used as a general framework for creating formally assured designs for a wider variety of transaction models applied in data and process management. Both transaction properties, and transaction management mechanisms, can be traded-off in the development process, guided by formal verification. Support for advanced transaction models such as nested transactions [46] and SAGAs [47] can be easily added, as we have done for transaction sequences in this paper. Other CC, AR and scheduling mechanisms can also be modeled and checked in our framework following the same principles.

As we have learned from the use case, automatically generated formal models may not be optimal in terms of verification performance. Manual optimization of the models can help to reduce verification time, and sometimes is even necessary for the verification process to reach a conclusion. However, this introduces extra development costs since domain knowledge is often required, risks of errors arise during manual optimization. A solution to this, as a future work, is to devise “optimization patterns” with domain expertise that are formally proven and integrated as part of the formal transformation process.

Our other future work includes to develop a better tool chain, based on best practices in model-driven engineering, that integrates specification, model generation and verification. A more thorough validation of the model transformation, including more evidences from mathematical reasoning and testing, should be considered in the future tool chain development. Selection between UPPCART and UPPCART-SMC, based on heuristics such as verification time or memory consumption, may also be supported by tool automation in the future. Another future work is to incorporate the verification of the user-defined functions for different transaction management mechanisms, which are encoded in C, and can be verified using existing program verifiers.

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