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Temporal Networks with Alternatives: Complexity and Model

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Abstract

Temporal Networks play an important role in solving planning problems and they are also used, though not as frequently, when solving scheduling problems. In this paper we propose an extension of temporal networks by parallel and alternative branching. This extension supports modelling of alternative paths in the network; in particular, it is motivated by modelling alternative process routes in manufacturing scheduling. We show that deciding which nodes can be consistently included in this extended temporal network is an NP-complete problem. The ideas are presented using precedence networks, but we also show how they can be extended to simple temporal networks.

Introduction

Scheduling problems typically deal with allocating known activities to available resources and time. Real-life problems are usually more complex than existing theoretical models and, for example, they also require selection among alternative process routes or alternative resources in complex manufacturing enterprises. Due to efficiency issues, selection of alternative processes and resource allocation are frequently done separately from scheduling. However, this also has several drawbacks. First, if the selected route or resource allocation cannot be scheduled, it is necessary to backtrack from the scheduling module to resource allocation and process selection modules. Second, even if the resource allocation and selected routes are feasible, separating the allocation and process selection algorithms from the scheduling algorithm may ruin the quality of the solution. Hence, a better result will be obtained when process selection and resource allocation is done within scheduling. While resource allocation is now an accepted part of scheduling problems and there exist approaches for doing resource allocation within scheduling, for example (Focacci, Laborie, and Nuijten 2000), process selection is still treated separately.

In this paper we propose an extension of temporal networks that can model alternative process routes. We describe the main ideas using networks with only

precedence relations, but at the end of the paper we also show how these ideas can be extended to simple temporal networks. To model selection of alternatives, we assign a validity variable to each node in the network. This validity variable indicates whether the node is selected or not to be in the final solution plan. The decision about validity/invalidity of the node is done by the solver. We also augment the precedence network by a description of splitting and joining operations that implicitly define dependencies between nodes in the network. The dependency relations specify which nodes must/cannot be valid in relation to the validity status of other nodes. The main motivation for these operations goes from modelling manufacturing processes. The nodes correspond to activities (or more precisely start times of activities) and the arcs describe flow of products between the activities. In some nodes the manufacturing process can split into two or more parallel sub-processes that can join back to a single process. For example, a piece of wood is cut in parts that are processed in parallel and then assembled together to a final product. This is called *parallel branching*. Another form of branching is *alternative branching* when the process also splits in sub-processes, but these sub-processes are treated as alternatives so exactly one of them is used. The alternative sub-processes can also join back to a single process (Figure 1).

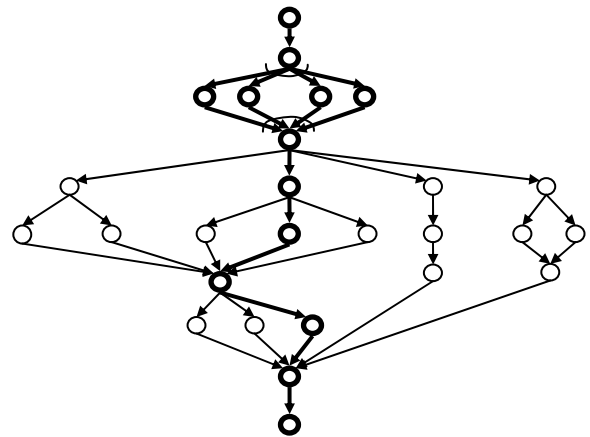


Figure 1. Graph of parallel (top) and alternative processes with a selected process.

In the paper we formally define the above-described precedence graph with parallel and alternative branching that we call a *P/A graph*. We generalise the P/A graph to a simple temporal network with alternatives and we demonstrate that this network can model temporal constraint satisfaction problems. We also show that the problem whether there exists an assignment of validity variables consistent with the specified branching is NP-complete. Hence there is a little hope for a fast solving algorithm so we propose a constraint model to describe the problem. We conclude the paper by comparing our proposal with existing works on temporal networks.

P/A Graphs

Let G be an acyclic graph. A subgraph of G is called a *fan-out subgraph* if it consists of nodes x, y_1, \dots, y_k (for some k) such that each (x, y_i) , $1 \leq i \leq k$, is an arc in G . Similarly, a subgraph of G is called a *fan-in subgraph* if it consists of nodes x, y_1, \dots, y_k (for some k) such that each (y_i, x) , $1 \leq i \leq k$, is an arc in G . In both cases x is called a *principal node* and all y_1, \dots, y_k are called *branching nodes*. G is called a *P/A graph* if the description of the graph (list of nodes and arcs) is accompanied by a list of pairwise edge-disjoint fan-out and fan-in subgraphs, where each subgraph on the list is marked either as a *parallel* subgraph or an *alternative* subgraph. An *assignment* of 0/1 (false/true) values to nodes of a given P/A graph is called *feasible* if

- in every parallel subgraph all nodes are assigned the same value (both the principal node and all branching nodes are 0 or both the principal node and all branching nodes are 1),
- in every alternative subgraph either all nodes (both the principal node and all branching nodes) are 0 or the principal node and exactly one branching node are 1 while all other branching nodes are 0.

It can be easily noticed that given an arbitrary P/A graph the assignment of the value 0 to all nodes is always feasible. On the other hand, if some of the nodes are required to take value 1 (as we shall see later, this requirement is a very natural one if the P/A graph is used to model a real-life problem), then the existence of a feasible assignment is by no means obvious. Let us now formulate this decision problem formally.

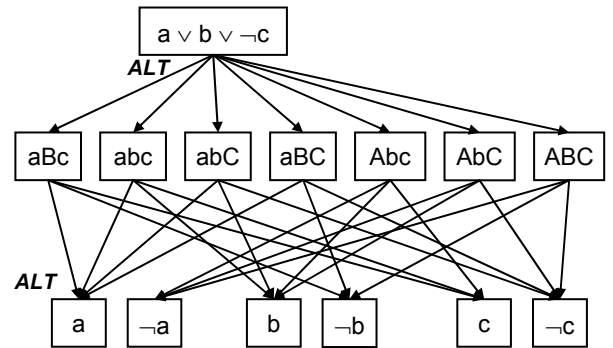
Definition: *P/A graph assignment problem* is given by a P/A graph G and a list of nodes of G which are assigned value 1. The question is whether there exist a feasible assignment of 0/1 values to all nodes of G which extends the prescribed partial assignment.

Remark: The above problem remains the same if we allow forcing the value 1 for just a single vertex. To see this, observe that the general case can be reduced to this special one by adding an extra vertex, forcing it to 1 and connecting it by a fan-in (or fan-out) parallel subgraph to all nodes that were forced to 1 originally. Moreover, if the original graph was acyclic, then so is the new one.

Proposition 1: The P/A graph assignment problem is NP-complete.

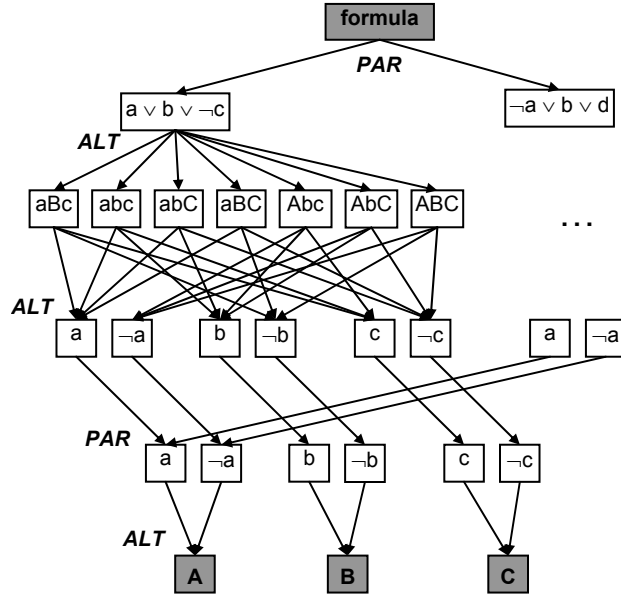
Proof: The problem is obviously in NP, because it suffices to guess the assignment and test its feasibility, which can be done in linear time in the number of parallel and alternative subgraphs (and hence in the number of edges). For the NP-hardness, we shall show that the 3SAT problem, which is known to be NP-complete, can be reduced (in a polynomial time) to the P/A graph assignment problem. Recall that the 3SAT problem is a problem of deciding whether there exists a model (a satisfying assignment of truth values to propositional variables) for a given formula in a conjunctive normal form, where each clause in the formula consists of exactly three literals. Moreover we may assume that no variable appears twice in a single clause, i.e. each clause consists of literals of three distinct variables.

Now we shall describe how to construct, for a given CNF (an instance of 3SAT), an instance of the P/A graph assignment problem. Consider e.g. a clause $(a \vee b \vee \neg c)$. There exist seven mutually exclusive assignments of truth values to variables a, b , and c satisfying this clause (each assignment except of $a=\text{false}, b=\text{false}, c=\text{true}$ is a satisfying one). We can model this clause using a “clause subgraph” which consists of a node for the clause, seven nodes for the mutually exclusive satisfying assignments, and six nodes for the values of propositional variables (three for positive values and three for negative values, i.e. one for each literal). The clause node is connected to all assignment nodes by a fan-out alternative subgraph and each value node is connected to appropriate assignment nodes (those assignment nodes containing the literal which corresponds to the given value node) by a fan-in alternative subgraph. The following figure shows the clause subgraph for the clause $(a \vee b \vee \neg c)$, where capital letters in the assignment nodes represent value false (so e.g. aBc corresponds to $a=\text{true}, b=\text{false}, c=\text{true}$).



Each clause from the input CNF will be modelled using a clause graph with the above-described structure. To connect the clause graphs, we introduce a formula node and connect it with all clause nodes by a fan-out parallel subgraph. The formula node is forced to take the value 1 (because we need the formula to be satisfied). A variable which is used in more than one clause will have value nodes in all clause graphs where it appears. To

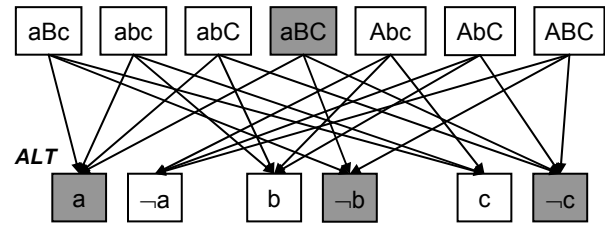
interconnect these value nodes we introduce for each variable in the formula a variable node, which is forced to take the value 1, and two literal nodes connected to the variable node by a fan-in alternative subgraph. Finally, each literal node is connected by a fan-in parallel subgraph to all value nodes in clause graphs which correspond to the given literal. The following figure shows these additional nodes and connections (the shaded nodes are the nodes that are forced to take the value 1).



First let us observe that the number of nodes in the constructed P/A graph is linear in the size of the input CNF formula. Namely, if there are M clauses and N variables (and hence $L = 3M$ literals) in the input CNF, then we get a graph with $(14M + 3N + 1)$ nodes. Because $14M + 1 \leq 5L$ and $N \leq L$ (assuming each variable appears at least once in the formula) we get that there are at most $8L$ nodes in the constructed P/A graph.

Now let us assume that the input CNF has a satisfying assignment. We shall construct a feasible assignment of the constructed P/A graph as follows. All clause nodes will get the value 1 to satisfy the parallel fan-out from the formula node. The literal nodes of each variable will get the 0 and 1 values as defined by the satisfying assignment of the input CNF (e.g. if variable b is false in the satisfying assignment, then the node b gets the value 0 and the node $\neg b$ gets the value 1). This satisfies the alternative fan-in into the variable nodes, and moreover it defines the 0 and 1 values for all value nodes via the parallel fan-ins that replicate the literal values into all clause subgraphs. Finally, for each clause exactly one assignment node is made valid, namely the one in which all three literals are valid, which satisfies the alternative fan-out from the clause nodes. It remains to show that also all alternative fan-ins into value nodes are satisfied. So let us consider an arbitrary value node. If it corresponds to a valid literal then it is connected to exactly one valid assignment node (the one where also the other

two literals are valid), and if it corresponds to an invalid literal then it is connected only to invalid assignment nodes (see figure below). In both cases this is exactly what we need and hence the constructed assignment of 0/1 values to all nodes is feasible.



To complete the proof let us assume that there exists a feasible assignment of 0/1 values to all nodes of the constructed P/A graph. In this assignment:

- All clause nodes have value 1 to satisfy the parallel fan-out from the formula node.
- For each clause exactly one assignment node has value 1 to satisfy the alternative fan-out from the clause nodes.
- For each variable one literal node has value 1 and the other has value 0 to satisfy the alternative fan-ins into the variable nodes. The literal values are replicated into the value nodes by the parallel fan-ins into the literal nodes.

Now let us check that the truth assignment defined by the values assigned to the literal nodes satisfies the input CNF. To this end let us pick an arbitrary clause and assume by contradiction that it is falsified. That means that the three valid value nodes correspond to the only missing combination among the assignment nodes, or in other words, that the valid assignment node must be connected to an invalid value node. However, this is a contradiction, because the corresponding fan-in subgraph into this value node spoils the feasibility of the assignment (the principal node is 0 while one of its branching nodes is 1). Hence, the input CNF has a satisfying assignment if and only if the constructed P/A graph has a feasible assignment.

Q.E.D.

Temporal Networks with Alternatives

So far we assumed acyclic graphs describing precedence relations between nodes and we focused on the logical aspects of the network, namely selecting the nodes to satisfy parallel and alternative branching. Nevertheless, in real-life problems we usually need a finer time resolution so we can extend precedence relations to simple temporal relations. It means that each arc (X, Y) in a P/A graph is annotated by a pair of numbers $[a, b]$ where a describes the minimal distance between nodes X and Y and b describes the maximal distance, formally, $a \leq Y - X \leq b$. We call the resulting graph a *simple temporal network with alternatives (STNA)*. Now the problem is to decide validity of nodes satisfying parallel and alternative branching and to assign

time (number) to each valid node in such a way that all simple temporal relations between valid nodes are satisfied. We call the problem of deciding whether a feasible assignment of validity and time variables exists a *STNA assignment problem*. Again, we assume that validity of some nodes is set to 1 (otherwise, there is a trivial solution where all nodes are invalid). This is a typical situation when the proposed temporal network is used to model real-life problems. The last nodes in the structure of alternative process routes typically describe delivery to a customer. Because the delivery must be fulfilled and we can just select alternative ways how to do it, these nodes must be valid.

Recall, that there exist polynomial algorithms for checking consistency of simple temporal networks (Dechter, Meiri, and Pearl 1991) so solving simple temporal problems is “easy”. However, as we showed above adding parallel and alternative branching makes the problem hard.

Proposition 2: The STNA assignment problem is NP-complete.

Proof: The problem is obviously in NP, because it suffices to guess the assignment and test its feasibility, which can be done in linear time in the number of arcs. The STNA is a generalisation of P/A graph in the following sense. For any P/A graph we can construct a simple temporal network with alternatives where all temporal constraints are in the form $[0, \infty]$. Now, there exists a feasible assignment to the P/A graph if and only if there exists a feasible assignment to the corresponding STNA. Moreover, if we assume that all time variables are set to 0, which trivially satisfies all temporal constraints, we get one-to-one mapping between assignments. Hence, the STNA assignment problem is NP-complete.

Q.E.D.

It may seem that we can further generalise the framework by using a disjunction of simple temporal relations. Formally, each arc (X, Y) is annotated by a set of number pairs $[a_i, b_i]$ for $i = 1, \dots, n$ with the following meaning $\forall_{i=1, \dots, n} a_i \leq Y - X \leq b_i$. Nevertheless, this generalisation does not increase the expressive power of the framework because we already have alternatives there. In fact, arc (X, Y) with a disjunctive constraint $\forall_{i=1, \dots, n} a_i \leq Y - X \leq b_i$ can be substituted by a sub-network with simple temporal constraints as Figure 2 shows.

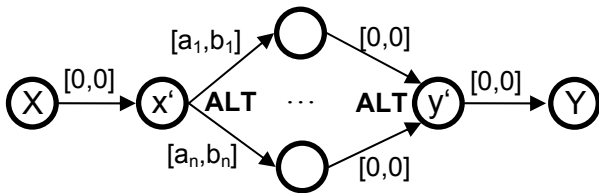


Figure 2. Modelling disjunctions of temporal constraints.

Note that auxiliary nodes x' and y' are necessary to keep fan-out subgraph with principal node X or fan-in subgraph with principal node Y (if such subgraphs exists) “isolated” from the newly added fan-out and fan-in subgraphs (otherwise we may have more than one fan-out or fan-in subgraph branching out of or in the same node, namely X or Y).

Because our framework covers SAT problems, we believe that it should be possible to model arbitrary temporal disjunctions as specified in disjunctive temporal networks (Stergiou and Koubarakis 1998). Nevertheless, we did no formal analysis in this direction yet because our application area (manufacturing scheduling) assumes only specific temporal disjunctions describing disjunctive resources. To handle these disjunctions, we plan to use existing constraints for disjunctive resources. For example the paper (Barták 2006) presents such a constraint that can handle activities with the validity status.

Example

So far we have discussed mainly the theoretical background of our proposal, so let us now present an example showing how the proposed framework can model a real-world problem. Consider the manufacturing of pistons where each piston consists of a rod and a tube that need to be assembled together to form the piston. Each rod consists of the main body and a special kit that is welded to the rod (the kit needs to be collected from warehouse and then assembled). The rod body is sawn from a large metal stick. The tube can also be sawn from a larger tube. Both rod body and tube must be collected together from the warehouse to ensure that their diameters fit. If the tube is not available, it can be bought from an external supplier. In any case some welding is necessary to be done on the tube before it can be assembled with the rod. Finally, between sawing and welding, both rod and tube must be cleared of metal cuts produced by sawing. Assume that welding and sawing operations require ten time units, assembly operation requires five time units, clearing can be done in two time units, and the material is collected from warehouse in one time unit. If the tube is bought from an external supplier then it takes fifty time units to get it. Moreover, tube and rod must cool-down after welding which takes five time units.

The above problem could be easily modelled using a simple temporal network if there is no alternative whether to produce the tube in-house or to buy it. Our proposal is focused exactly on this type of problems where (exclusive) alternatives must be modelled. Figure 3 shows a simple temporal network with alternatives modelling the problem. Each operation is modelled using a single node in the network indicating the start time of the operation. Note that neither disjunctive temporal networks nor other existing extensions of temporal networks can model this problem.

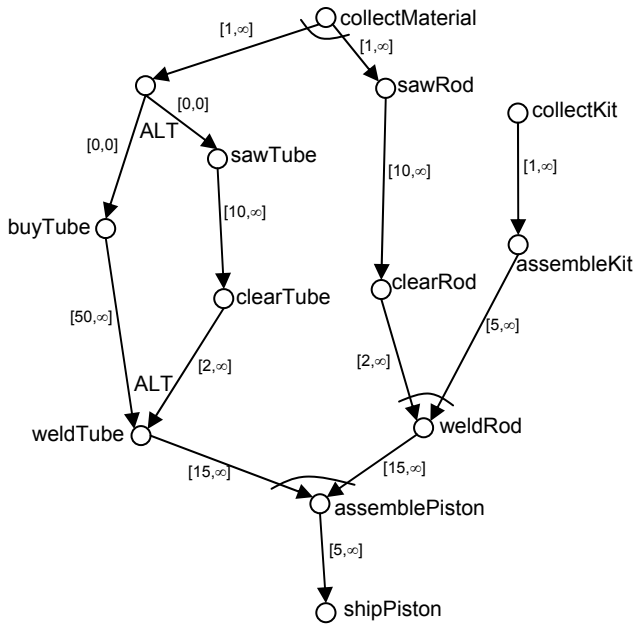


Figure 3. Example of manufacturing process with alternatives.

Constraint Model

We showed that solving STNA assignment problem is NP-complete so there is a little hope for a polynomial solving algorithm. Hence, we propose to use constraint satisfaction technology which is flexible enough to describe the problem and, moreover, it can easily integrate other constraints such as the resource constraints. The STNA assignment problem contains two types of decision variables: validity variables V_i and time variables T_i with a straightforward meaning. The domain for validity variables is $\{0,1\}$, the domain for time variables depends on possible time points, for simplicity reasons we assume the interval $(0, MaxTime)$ of integers, where $MaxTime$ is a constant. Assume that the temporal relation between nodes x_i and x_j is described by a pair $[a_{ij}, b_{ij}]$. This relation can be naturally represented using the following constraint:

$$V_i * V_j * (T_i + a_{ij}) \leq T_j \wedge V_i * V_j * (T_j - b_{ij}) \leq T_i.$$

If $b_{ij} = \infty$ then the second part of conjunction is omitted and similarly if $a_{ij} = -\infty$ then the first part of conjunction is omitted. Notice that if any V_i or V_j equals zero, i.e., some involved node is invalid, then the constraint is trivially satisfied (we get $0 \leq T_j \wedge 0 \leq T_i$). If both V_i and V_j equal 1 then we get $(T_i + a_{ij} \leq T_j \wedge T_j - b_{ij} \leq T_i)$, which is exactly the simple temporal relation between nodes x_i and x_j .

To complete the model, we need to describe the logical relations defined by alternative and parallel branching. If the arc between nodes x_i and x_j is a part of some parallel sub-graph then we define the following constraint:

$$V_i = V_j.$$

Notice that all nodes in parallel sub-graphs have the same validity status so the equality constraint fully defines this relation.

Finally, assume that x_i is a principal node and x_{i_1}, \dots, x_{i_k} for some k are all branching nodes in some alternative sub-graph. Then the logical relation defining the alternative branching can be described using the following constraint:

$$V_i = \sum_{j=i_1, \dots, i_k} V_j.$$

Again, notice that V_i equals one if and only if exactly one V_j equals one.

Figure 4 shows how the domains from the previous example (Figure 3) will look after filtering out the infeasible values by making the above constraint model arc consistent. We assume that shipPiston (the bottom node) is a valid node and $MaxTime = 70$. Black nodes are valid; validity of white nodes is not decided yet. Notice weak domain pruning of time variables in the white nodes caused by a disjunctive character of the problem. Actually, the left most path (with buyTube) cannot be selected due to time constraints but this is not discovered by making the constraints arc consistent. This can be improved by using stronger techniques like constructive disjunction; we are currently working on appropriate filtering rules.

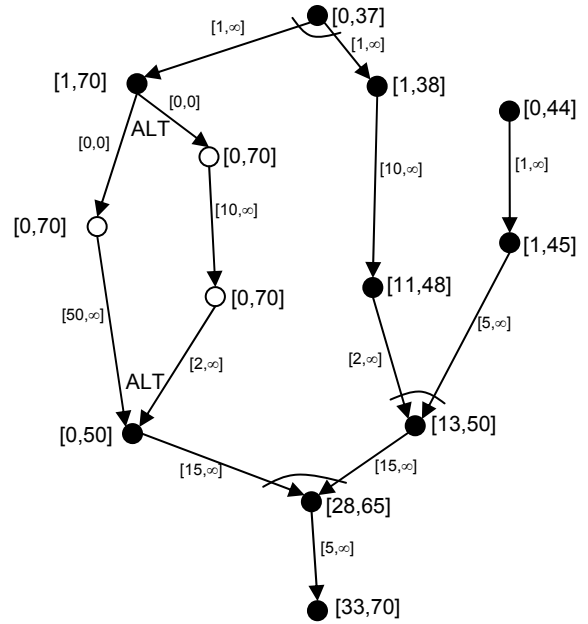


Figure 4. Domain filtering using the proposed constraint model.

Related Works

The intended application area for the proposed framework is manufacturing scheduling. There exists a benchmark set MaScLib by ILOG (Nuijten et al. 2003) which contains a formal description of real-life manufacturing scheduling problems. This description includes the concept of validity variables and logical dependencies between them. Temporal and logical relations are modelled separately there and various binary logical relations can be defined between the validity variables. Our framework defines the logical dependencies via branching in the temporal graph.

According to our experience this is satisfactory for modelling manufacturing (and other) processes. Moreover, we believe that the coupled definition will lead to more efficient filtering algorithms that use together temporal and logical information. In (Barták and Čepék, 2006) we already showed that integrated filtering of precedence and dependency constraints significantly reduces solving time.

We are not aware about another approach that can handle alternative process routes in the same generality as the proposed simple temporal networks with alternatives. The paper (Focacci, Laborie, and Nuijten 2000) describes a graph concept for modelling alternative resources, but it cannot be used for alternative routes because all activities must be present. Probably the closest approach to our proposal is the work by Beck and Fox (1999) on modelling alternative processes using PEX (probability of existence) variables. In our framework we focus on logical validity variables (PEX uses an interval of real numbers $\langle 0,1 \rangle$) but the main ideas of propagation are very similar. Using validity variables instead of PEX values simplifies integration to existing constraint solvers and we believe that using logical deduction during pre-processing can generate additional input to the filtering algorithm.

Our work is naturally related to temporal networks as we proposed an extension of simple temporal networks. We already showed that the proposed framework covers Temporal Constraint Satisfaction Problems (Dechter, Meiri, and Pearl 1991). Disjunctive Temporal Network (Stergiou and Koubarakis 1998) is another approach to handling temporal alternatives. We have no formal comparison to our P/A simple temporal network yet, but our ambition is slightly different from DTN – we model alternative routes rather than any temporal disjunction.

Recently several other extensions of temporal networks appeared such as resource temporal networks (Laborie 2003) or disjunctive temporal networks with finite domain constraints (Moffitt, Peintner, and Pollack 2005). These extensions integrate temporal reasoning with reasoning on non-temporal information, such as fluent resources. Our ambition is to extend existing constraint-based scheduling by some planning decisions, namely selection of alternative processes. So we extended temporal reasoning by logical reasoning on existence of nodes in the network. Actually, the possibility to decide about validity/invalidity of the node is the main difference of our approach from the above mentioned works on temporal networks where all nodes must always be present.

There exists Conditional Temporal Planning (Tsamardinos, Vidal, and Pollack 2003) where existence of node in the network depends on some condition. Though there is some similarity in modelling alternative processes/plans, satisfaction of condition in CTP depends on external forces – Nature – rather than being an internal relation between the nodes. In our approach, decision of validity of the node is done internally based on logical relations between the nodes.

Conclusions

The paper reports a work in progress on extension of simple temporal networks for handling alternative process routes. We focused on formalization of this new modelling framework, showing its hardness, and proposing a constraint model. We are currently working on stronger filtering algorithms for removing inconsistencies from the network based on ideas of constructive disjunction and on studying tractable subclasses of simple temporal networks with alternatives.

Acknowledgements

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