Weak Controllability of multi-agent plans with uncertainty: towards temporal flexibility negotiation

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Résumé

Dans les réseaux logistiques de santé, les hôpitaux doivent s'occuper efficacement de leurs patients tout en respectant leur planning journalier et en se coordonnant les uns avec les autres. Par exemple, en cas de saturation, les hôpitaux peuvent avoir besoin de transférer des patients. Plus généralement, ils ont à faire face à de nombreuses imprécisions, notamment en termes de durées effectives de leurs opérations. Lorsque ces imprécisions proviennent des autres agents hospitaliers, elles deviennent des sources d'incertitude pouvant perturber le plan journalier en raison de leur caractère incontrôlable. Ainsi, lorsqu'un plan journalier est irréalisable, un moyen de le reconstruire est de négocier ces opérations contrôlées par d'autres. Tout cela peut être formalisé comme un problème multi-agents, où chaque plan est représenté par un Simple Temporal Network with Uncertainty (STNU), dont nous proposons de vérifier la propriéte de Contrôlabilité Faible par un nouvel algorithme identifiant le cycle fautif, et où les ontologies sont appliquées pour améliorer l'interopérabilité entre agents hétérogènes.

Mots-clés

Planification d'activités hospitalières. Contrôlabilité Faible. Négociation multi-agent. Raisonnement ontologique.

Abstract

In health services networks, hospitals must take care of their patients while satisfying their daily plan and coordinating with other services. For instance, in an overcrowded situation, hospitals may transfer patients to another one. More generally speaking, they need to face temporal imprecisions, in terms of effective durations of their operations. When such imprecisions come from the other agents, they become a source of uncertainty possibly disrupting the local plan as they are uncontrollable. Thus, when a daily plan is no longer feasible, one way to rebuild it is to negotiate around these operations controlled by others. Such a problem can be formalised as a multi-agent problem, where Simple Temporal Network with Uncertainty (STNU), which so-called Weak Controllability can be checked through some new algorithm that isolates the faulty cycle, and where ontologies are applied to enhance interoperability among heteregeneous agents.

Keywords

Hospital activity planning. Weak controllability. Multi-agent negotiation. Ontological reasoning.

1 Introduction

Nowadays, hospitals act in their own way to try to take care of their patient in the most efficient way depending on their own capabilities. Even through hospitals belong to an healthcare system there are few interaction between hospitals and thus few coordination among hospitals. As an example, such case is visible in the French healthcare system but also in other countries. However, the covid-19 pandemic highlighted the importance of coordination within a hospital system to respond more effectively to save more lives in extreme situations. In France, since the covid19 pandemic, more and more exchanges between hospitals have taken place through patient transfers.

In a more technical sense, hospitals needs, on a daily basis, to plan their activities according to their own goals while allocating shared resources to each task and considering potential uncertainty (patients arrival, loss of human resources, etc.). Such a plan should answer the patient needs, mainly operating, bed assignment and management, and nurse scheduling during a clinical routine but also in times of crisis. Delivering healthcare services during an emergency or a crisis is very challenging. Scaling such a problem in a multi hospital system, as a multi-agent problem, is more challenging because for one hospital other hospitals can be source of uncertainty. For example, for a daily plan, a patient transfer is an uncertain activity for the hospital that receive the patient because it does not have any control over the activity. Hence, considering such a scenario, hospitals must ensure the reliability of their plans on an ongoing basis, which can be done by inserting or at least checking the existence of some flexibility in the plan (e.g., temporal slack, or availability of alternate resources). But then such a flexibility is not always fairly distributed and it might be appropriate for the agents to share the flexibility among their plans.

Checking a plan consistency facing temporal uncertainties on dates and durations can be done by using the *Simple Temporal Network under Uncertainty (STNU)* model which can check weak, dynamic and strong controllability of a plan [11]. These three level of controllability refers to how strong a plan is against temporal uncertainties. However,

existing algorithms for weak, dynamic and strong controllability do not identify the causes of inconsistency in a plan.; i.e., the temporal constraints that make the plan unfeasible. Therefore, such model does not propose any "repair strategy" which would be needed in a multi-agent context : usually the contingent duration that makes the plan uncontrollable is actually controlled by another agent with which one could try to negotiate. Such model, can be applied in a multi-agent context where each agent own an STNU.
In addition, in a multi-agent context, agents need a high level of interoperability during negotiation process. This can be obtained by using semantic ontology which as been proven to enhance interoperability among different stakeholders. Thus, using an ontological approach can help to formalize better the information that the agents will have to exchange and reinforce the interpretation capacities of the agents to produce consistent reasoning [1] [3].
Consequently, our work aims to provide a generic approach of negotiation between agent's STNU to share temporal flexibility among agents which can be applied to a multi hospitals context with uncertain patient transfer. More precisely, it aims at extending the STNU model to implement informed algorithms for consistency checking that locate the causes of inconsistency. Then, a negotiation process must be done by the agents to repair their STNU by sharing their flexibility among them. The negotiation process is not the subject of this paper which is to present an inform algorithm for the weak controllability problem. However, we will discuss about the planning ontology (PO) which aims to enhance interoperability among agents.

2 Background

We will review the definitions of Simple Temporal Networks (STN) [2] and Simple Temporal Networks under Uncertainty (STNU)[6]. Then we will review in details the definitions of *Strong Controllability* (SC), *Dynamic Controllability* (DC) and *Weak Controllability* (WC).

2.1 STN and STNU

An STN is a pair, (V, E), where V= $[v_1, v_2, v_3, ..., v_n]$ is a set of time-points representing event occurrence times, and E a set of temporal constraints between these time-points. A constraint $C_{ij} \in$ E is defined as follows : C_{ij} = $[L_{ij}, U_{ij}]$ where $L_{ij} \in \mathbb{R}$ and $U_{ij} \in \mathbb{R}$, respectively specify a minimum and a maximum temporal distance between v_i and v_j. A reference time-point $v_0 \in V$ defines the initial point in time (e.g. 0 :00 am of the current day, or week). A STN as another graphical representation called distance graph : for any constraint C_{ij}, there is one constraint from i to j with a weight U_{ij} and one from j to i with a weight -L_{ij}. The STN is inconsistent if there is a negative cycle in the distance graph.
An STNU is an extension of a STN in order to represent uncertain durations. Therefore a STNU is a triple (V, E, C) where (V, E) is a STN and where C = $[c_1, c_2, ..., c_n]$ is a set of uncontrollable constraints. In a STNU, a constraint e in E is called requirement constraint or controllable constraint and an uncontrollable constraint is called a contingent constraint. It is the same for time-points and their possible dates : a time-point ending a contingent constraint is said to be contingent, others are controllable. Each constraint is defined as in a STN with the interval $L_{ij}, U_{ij}]$ and time-points (v_i, v_j).
The distance graph of an STNU is identical to the distance graph of a STN, except for contingents, where 2 additional labeled constraints are added, with inverse weights to those of an STN. They represent the 2 worst cases of the contingent, either taking its minimum or its maximum. An STNU is inconsistent there exist at least one contingent that is too restrictive on controllable constraints and make a negative cycle in the STNU's distance graph.

2.2 Three levels of controllability

Definition 1 (Strong Controllability) : A STNU is *strongly controllable* iff there exists at least one 'universal' solution that fits any situation; i.e., an assignment of values to the controllable time-points that makes the STNU consistent whatever the uncontrollable constraints values are.

Definition 2 (Dynamic Controllability) : A STNU is *dynamically controllable* iff, at any time t, there exists an assignment of values to the next controllable time-points that makes the STNU consistent whatever the remaining uncontrollable constraints values will be.

Definition 3 (Weak Controllability) : A STNU is *weakly controllable* iff for each combination of values to the contingent constraints, there exists at least one assignment of values to the controllable time-points that makes the STNU consistent regardless of the uncontrollable constraints values.

Despite the existence of three levels of controllability, only the DC was supposed to be relevant in real world contexts. Indeed, SC is too demanding, since it is usually not necessary to fix in advance the times of each activity start time, and it is actually almost never possible, such decisions often depending on the durations of preceding contingent constraints; while WC is not realistic as it means one would decide some activity start time based on some kind of oracle of the durations of future contingent durations. Thus, mainly DC was considered. However, in multi-agent contexts WC often reveals to be relevant. For instance in our multi-hospital context with the patient transfer activity involving two hospital, the decision will be known just before the coordinated execution. Thus, the contingents duration will be known by the agents. Hence, the agents only need to verify if there exist an execution strategy that satisfy their STNU. In this case, the WC fit perfectly.

3 Weak controllability

The WC is a problem which has been supposed to be co-NP-complete by [11] which still need to be proven. In addition, algorithms for WC exist that are exponential but none

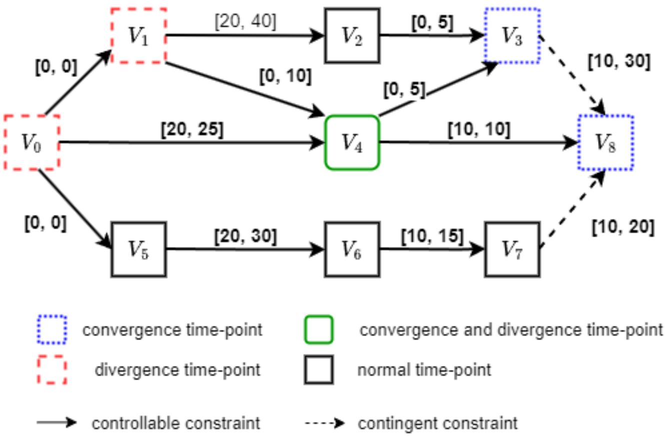

FIGURE 1 – An STNU revisited

of them are informed of the origin of the non-WC. A starting point for resolving the issue of WC being not informed is to change our view of an STNU graphical representation (see Figure 1). We simple distinct time-points of a classical STNU as divergence and convergence time-points. A convergence time-point has at least two incoming edges while the opposite for a divergence time-point. It is possible for a single time-point to be at the same time a convergent and a divergent time-point.
From this distinction, any cycle in the graph starts from a divergent time-point and ends on a convergent time-point. Therefore, in an STNU, a cycle is the divergence of a route r at a time-point s in two routes r_i and r_j, and the convergence of the two routes r_i and r_j into a single one at time-point t. It is explained by the graphical representation of an STNU, which is the same as a tree with v_0 as the root. Our methodology consists in checking the controllability of each cycle of an STNU. Consequently, we determine the WC of an STNU by locally determining the WC of its cycles. In this way, a cycle which is not weakly controllable means that it contains at least one uncontrollable constraint in r_i and/or r_j that needs to be negotiated. Such approach is inform because it return the negative cycles of an STNU. Hence, it is possible to find the contingents contained in each negative cycle.

3.1 Local checking

To verify if a cycle is weakly controllable, we need to ensure that there exists at least one sequence of values that satisfies the cycle, regardless of the uncontrollable constraints values in the cycle. The idea is to compare the worst case scenario of r_i and r_j such as : the minimal duration of r_i where its uncontrollable constraints take their maximum value, with the maximal duration of r_j where its uncontrollable constraints take their minimal value ; and vice versa. Thus, if the minimal duration of r_i is higher than the maximum value of r_j and vice versa ; then the cycle is not weakly controllable because there is no value of r_j where r_i = r_i holds. Hence, we know from this cycle that the STNU is not weakly controllable because the cycle is a negative cycle.

3.2 Global checking

To verify the WC of an STNU, we check the WC of all its cycles. It is done by :

- reducing the constraints value to their minimum by using the pseudo-controllabilty of Morris [7] : *an STNU is pseudo-controllable if it is consistent in the STN sense and none of the contingent links are squeezed.*
- considering uncontrollable constraints in both directions in the graph to get all possible cycles. Indeed, if contingents are not considers in both direction then the algorithm cannot cover all possible path present in the STNU's distance graph. There is no need to consider controllable constraint in both direction cause only contingents are source of the non consistency of an STNU.
- combining a backward search with a forward search : for each divergent time-point from last to first (backward search) get all of its cycles (forward search).

Algorithme 1 : WC-Checking algorithm

```
Input : X : STNU(V,E,C)
Output : Boolean
G = PseudoControllability(STNU)
divergents = getDivergents(G)
for each divergent in divergents) do
    cycles = getCycles(G, divergent)
    for each cycle in cycles do
        if checkCycleWC(cycle) == False then
            return False
return True
```

Algorithm 1 summarize the new algorithm to check WC (it can be modified to return any inconsistent cycle).

3.3 Experiments

We compared our algorithm with the existing (exponential) one on a very large scale number of arbitrary STNUs with different numbers of nodes and different sizes of contingent durations. Results are that both algorithms provide the same answer, which shows our algorithm works. Compared to the other one, our algorithm is informed and can also return all cycle that are not weakly controllable, which can be negotiate. Regarding time complexity, our algorithm depends on the graph density. Thus, in realistic graph, the number of cycle is should be more polynomial than exponential but its still need to be tested.

4 Ontology

Another problem arises when agents are heterogeneous with respect to notions such as urgency, flexibility or criticity, to cite a few. A 'high-level' of flexibility may not mean the same thing for two distinct agents. Negotiating then becomes harder, as it requires some level of semantic interoperabiility.

Ontologies have been identified as an effective means to implement semantic integration and to achieve information interoperability. They offer the richest representations of machine-interpretable semantics for systems and database. They serve as both knowledge representation and as a mediation to enhance interoperability in heterogeneous systems. Three main levels of abstraction of knowledge representation exist :

- The Upper-level ontology (ULO), which describes general concepts across all domains by providing a hierarchy and rules. In fact, such ontology represents the highest level of abstraction to describe the world.
- The middle-level ontology (MLO) is the bridge between the abstract concepts and the detailed one from specific domains. Generally, such ontology provides more description about the abstract concepts such as time, space and relation between entities.
- The domain-level ontology (DLO) which describes concepts from a specific domain. Such definition is the one with the lowest abstraction.

Regarding upper-level ontology, we based our work on BFO (Basic Formal Ontology) [9] a realistic, formal and domain-neutral upper-level ontology. BFO is designed to represent at a very high level of generality the types of entities that exist in the world and the relations that hold between them. Such a choice of ULO is explained by the need of a realistic representation of the world as it is and that the descriptions are universal, i.e., concepts are defined in a natural way that abstracts or generalizes over similar particular things such as : person, material entities, process, etc. Thus the BFO approach that focuses on what is universal in the reality is the best choice. Then as a MLO, the IOF-core ontology [4] [5] from the Industrial Ontologies Foundry is chosen. Based on BFO, it contains universal definitions of the industrial domain, which is similar to the healthcare domain. In addition, our ontology must incorporate concepts from planning and scheduling domain, which IOF-core already has a first version of. Thus, it needs to be extended to have a full version of a planning and scheduling ontology. Table 1 provides some terms of planning and scheduling aligned under IOF-core.

5 Conclusion and future work

This paper considers the problem of patient care in a multiple hospital architecture where hospitals share resources and negotiate their flexibility to ensure the validity of their daily plan. STNU is an efficient way of representing a daily plan of an hospital and checking its consistency. However, current algorithms for controllability checking (WC, DC and SC) are not suitable in providing repair strategies. Considering only WC, we presented a more efficient algorithm for checking WC by arguing its relevance in a multi-agent context where some shared events may be controllable by some agent and uncontrollable for the others. The proposed algorithm is informed, which is suitable for providing repair strategies for STNU.

On the other hand, some work in progress for modeling an ontology joining planing and scheduling domain with healthcare domain under the BFO upper-level ontology is proposed. The ontology aims to enhance interoperability among hospitals during the negotiation process.

Regarding future work, we aim to provide an efficient repair strategy by negotiating flexibility on contingent activities. Several ideas need to be studied such as : finding a Nash equilibrium strategy to satisfy agents involved in the negotiation, a contract net protocol for a centralized negotiation where the agent owning the non-controllable STNU acts as the manager during the negotiation ; and the work of Posenato et al that adds flexibility on contingent constraints to facilitate negotiation of flexibility [8]. Moreover, the negotiation approach must incorporate the ontology as its core for interoperability. Thus, some work must be done in combining both the ontology and a negotiation method to provide a semantic negotiation approach [10].

Références

[1] Thomas BITTNER, Maureen DONNELLY et Stephan WINTER. “Ontology and semantic interoperability”. In : *Large-scale 3D data integration*. CRC Press, 2005, p. 139-160.

[2] Rina DECHTER, Itay MEIRI et Judea PEARL. “Temporal constraint networks”. In : *Artificial intelligence* 49.1-3 (1991), p. 61-95.

[3] R GAYATHRI et V UMA. “Ontology based knowledge representation technique, domain modeling languages and planners for robotic path planning : A survey”. In : *ICT Express* 4.2 (2018), p. 69-74.

[4] Mohamed KARRAY et al. “The industrial ontologies foundry (IOF) perspectives”. In : (2021).

[5] Boonserm KULVATUNYOU et al. “The industrial ontologies foundry proof-of-concept project”. In : *Advances in Production Management Systems. Smart Manufacturing for Industry 4.0 : IFIP WG 5.7 International Conference, APMS 2018, Seoul, Korea, August 26-30, 2018, Proceedings, Part II*. Springer. 2018, p. 402-409.

[6] Paul MORRIS, Nicola MUSCETTOLA et Thierry VIDAL. “Dynamic control of plans with temporal uncertainty”. In : (2001).

[7] Paul H MORRIS et Nicola MUSCETTOLA. “Temporal dynamic controllability revisited”. In : *Aaai*. 2005, p. 1193-1198.

[8] Roberto POSENATO et Carlo COMBI. “Adding flexibility to uncertainty : Flexible simple temporal networks with uncertainty (FTNU)”. In : *Information Sciences* 584 (2022), p. 784-807.

[9] Barry SMITH, Anand KUMAR et Thomas BITTNER. “Basic formal ontology for bioinformatics”. In : (2005).

Class	Definition
IOF : resource	A material entity which has the material resource role that can be either borrowed or consumed.
IOF : reusable resource	A resource that is only borrowed.
IOF : consumable resource	A resource that is only consumed.
IOF : action	A BFO process p that has some temporal proper part and for some time t, p has some material entity as participant at t.
IOF : preemptive action	An action that can be interrupted.
IOF : nonpreemptive action	An action that cannot be interrupted and therefore is continuous.
IOF : plan specification	A directive information content entity that prescribe a process
IOF : schedule specification	A plan specification that prescribes a process with some temporal specification.

TABLE 1 – Planning and Scheduling terms under IOF-core ontology

[10] Jurriaan VAN DIGGELEN et al. "Ontology negotiation : Goals, requirements and implementation". In : *International Journal of Agent-Oriented Software Engineering* 1.1 (2007), p. 63-90.

[11] Thierry VIDAL. "Handling contingency in temporal constraint networks : from consistency to controllabilities". In : *Journal of Experimental & Theoretical Artificial Intelligence* 11.1 (1999), p. 23-45.