Reasoning about Time Constraints in a Mixed-Initiative Calendar Manager

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Abstract
Scheduling support is very important for calendar management in order to automatize the execution of possibly complex reasoning tasks. However, an interactive approach is desirable to enable the user to steer the allocation of events, which is a rather personal and critical kind of activity. This paper proposes a mixed-initiative scheduling model supporting user’s awareness during the exploration of the solution space. The paper describes the temporal reasoning techniques underlying MARA (Mixed-initiative calendarR mAnager), focusing on the generation of scheduling options and on the characterization of their properties, needed to present the pros and cons of each possible solution to the user.

Keywords: mixed-initiative scheduling, temporal reasoning, constraint satisfaction.

Introduction
Calendar management is burdensome and challenging when schedules are overconstrained or include items having multiple participants because it requires the verification of a possibly large number of temporal constraints. However, a fully automated scheduling support is considered as hardly acceptable for this type of activity because it fails to keep the user in control of the decisions to be taken; e.g., see (Berry et al. 2011).

In the attempt to address this issue, we propose a new, mixed-initiative scheduling model that enables the user to temporally allocate multi-user events and tasks in cooperation with the system. The paper also proposes a novel, conservative scheduling policy to suggest calendar revisions by modifying small portions of the schedules, leaving the rest as originally planned or with minor temporal shifts. The idea is that of keeping the changes to the user’s plans as local as possible in order to maintain stable daily plans.

Our scheduling model is applied in the MARA Mixed-initiative calendarR mAnager, which exploits Temporal Constraint Satisfaction Problem techniques for suggesting safe scheduling solutions across multiple calendars. The mixed-initiative interaction with the user is achieved by invoking the Interval-based TEmporal Reasoner (ITER) for computing a synthesis of the solutions to be proposed to the user, instead of presenting a possibly large number of alternative schedules to choose from. Such a synthesis is based on the specification of admissible intervals for the allocation of items and of the corresponding impact on the calendars of the involved people. In this way, the user can analyze the solution space at an abstract level and select the paths which are worth to be explored in an informed way.

In the following, we first describe the mixed-initiative scheduling support offered by MARA. Then, we discuss in detail the temporal reasoning techniques adopted in ITER. Finally, we present related research and conclusions.

Mixed-Initiative Scheduling in MARA
Calendar Management
MARA supports cross-calendar management providing the user with an overview of the impact of her/his actions on the schedules of all the involved actors. Figure 1 shows a portion of the User Interface of the system. The table in the upper right portion of the page shows the list of shared calendars and enables the user to select those to be jointly visualized. In order to let the user identify the actors involved in a calendar item (e.g., a meeting), each item has associated a number of vertical bars whose colors correspond to those of the respective calendars; e.g., the participants of event CDD in Figure 1 are Gianluca and Prof. Rossi.

While the user adds new items or revises the existing ones, the system checks whether the temporal constraints of the affected items are satisfied. If any conflicts occur, it notifies the user; moreover, it helps her/him to incrementally explore the solution space in order to quickly evaluate the available options. Specifically:

- The system offers a “Where can I place the task?” feature which helps the user to allocate calendar items. When the user asks for help regarding an item $M$, MARA presents in a calendar window an overview of the feasible time intervals in which $M$ could be allocated, possibly moving other existing items. Each interval $I$ provides the user with information useful to evaluate its convenience; i.e., (i) the names of the actors whose existing commitments have to be revised if $M$ is placed in $I$; (ii) the criticality of placing $M$ in $I$, given the existing commitments of the involved actors (e.g., the criticality is high if at least one high-priority commitment has to be shifted in order to allocate the item).
The user can select a specific interval for scheduling the item. At that point, the system further enables her/him to steer the scheduling activity by presenting a few alternative revision hypotheses for the calendar, e.g., alternative items might be shifted to allocate "M." The user can accept one of the suggestions, in which case the involved actors are informed and asked to confirm the change, or (s)he can go back to the available options and investigate further revision opportunities.

See (Ardissono, Segnan, and Torta 2013) for more information about MARA’s User Interface and functionality.

**System Architecture**

MARA stores the information about calendars, items and actors as lists of objects. While the user revises a calendar, the core of MARA invokes the following modules to check whether the user’s actions violate any temporal constraints and to suggest how such conflicts might be solved:

1. **Every time an item is manually added/moved, a consistency check module** checks the consistency of the temporal constraints associated to the item to verify whether they are satisfied or not.

2. **In case of inconsistency (or, more generally, when requested by the user), the Interval-based Temporal Reasoner (ITER) supports the addition/movement of an item by identifying the feasible intervals where it could be allocated and the consequent impact on the schedules of the involved actors.** Once the user chooses where to place the item, this module generates the corresponding conservative calendar revisions.

MARA is a Java Web application. The ITER module is developed in Perl using the Graph.pm extension module (Hiitaniemi 2010) for representing and manipulating STNs. The minimization of the STNs is performed by invoking the implementation of the Floyd-Warshall algorithm included in Graph.pm. The Java Web application invokes ITER as a local REST service via HTTP.

**Temporal Reasoning Underlying MARA**

Running example

In this section we will use the following scenario to illustrate the temporal reasoning performed by ITER. Our running example refers to the calendar displayed in Figure 1.

Gianluca is a University staff member and he collaborates with some colleagues (Liliana, Giovanna, Marino) and with the Head of Department, Prof. Rossi. Gianluca’s calendar includes teaching hours (e.g., Progr 1, SW), Department meetings (CDD, CCS), student support (Tutoring, Thesis Ugo / Idia), project meetings (e.g., Skype call PRIN, Meet Dr. Neri) and personal commitments (e.g., Baseball, Plumber, Attorney). Some activities have a fixed schedule; e.g., teaching hours and Department meetings. Others are flexible and could be moved to other times if needed; for instance, Gianluca is available for student support on Wednesday, Thursday and Friday.

Suppose that Gianluca has to schedule a 2-hours Staff meeting with Prof. Rossi on Thursday. The event can start at 8:00 and must finish by 10:00 (deadline). In order to accommodate this meeting, the current calendar has to be revised.

By analyzing Prof. Rossi’s constraints, it can be seen that he is available starting from 10:00 until 13:00. However, Gianluca is busy at that time because he teaches SW from 9:00 to 11:00 and then he meets two students (Thesis Ugo / Idia). The SW lesson cannot be moved. Thus, the only solution is to move Thesis Ugo and Thesis Idia to different times.

In a typical calendar manager this revision would imply that Gianluca first analyzes all the relevant commitments (including Prof. Rossi’s ones) in order to identify the items that can be moved and their alternative times; then, he manually moves the selected items; finally, he inserts the new item. Considering that calendar revision is a frequent daily activity, it is worth saving as much effort as possible in it. Thus,
an automatic support to its execution is crucial. Our work attempts to address this need.

**Representation of Calendars Items**

The ITER module exploits reasoning techniques based on Temporal Constraint Satisfaction Problems (TCSP) (Dechter, Meiri, and Pearl 1991). Specifically, ITER employs a subclass of TCSPs, the Simple Temporal Problems (STPs) (Dechter, Meiri, and Pearl 1991), where all of the constraints are binary and they do not contain any disjunctions, i.e., they have the following format:

\[ a \leq X_j - X_i \leq b \]

This class of problems can be represented as a graph named Simple Temporal Network (STN), whose consistency can be checked in polynomial time (Planken, de Weerdh, and van der Krogt 2011). Also the minimization of an STN (i.e., the computation, for each pair of variables \( X_i, X_j \), of an interval [\( a_{min}, b_{min} \)] which guarantees the existence of a global solution for the STN) can be done in polynomial time.

The scheduling of a set of calendars is done by reasoning on the joint set of constraints associated to their items. A calendar item is represented as an object having several features, among which the expected duration (number of hours devoted to the item), the earliest start time for scheduling it, the deadline for its completion, the schedule (current temporal allocation), the list of participants and a priority (low, medium, high) representing the importance of the commitment.

Given such information, each calendar item \( M \) is internally represented by means of:

- Two numeric variables \( M_s \) and \( M_e \), representing the start and end time of \( M \) in a given schedule. For simplicity, we assume that the value of a variable \( M_s \) (resp. \( M_e \)) is the number of one-hour slots between Monday 8.00 and the start (respectively the end) of \( M \). Note, however, that the TCSP techniques we use are able to deal with real numbers, so that we could easily deal with finer granularities of time.
- The temporal constraints on \( M_s \) and \( M_e \) needed to schedule \( M \) consistently with its earliest start time, duration and deadline.
- The temporal constraints on \( M_s \) and \( M_e \) needed to impose precedence relations with respect to other calendar items.

For instance, given an item Staff Meeting (SM in Figure 1):

- The earliest start time, Thursday at 8.00, is expressed as \( SM_s \geq 36 \) because in the calendar there are 36 one-hour slots between Monday 8.00 and Thursday 8.00.
- The deadline, Thursday 16.00, is expressed as \( SM_e \leq 44 \).
- The duration, 2 hours, is \( SM_e - SM_s = 2 \) as the item takes 2 time slots.
- A precedence relation among calendar items, e.g., the fact that \( SM \) must take place after another event \( E \), is expressed as \( SM_s - E_s \geq 0 \).

With slight abuse we use the term deadline also to indicate constraints on the exact end of a calendar item; e.g., the fact that an item \( P \) must end exactly on Wednesday at 13.00 is represented as \( P_e = 29 \) (i.e., \( 29 \leq P_e \leq 29 \)).

**ITER: Computing the Feasible Intervals**

Given the temporal constraints of the calendar and an item \( M \) to be added (or moved), ITER:

- Searches for feasible intervals for allocating \( M \). For each interval, it computes the criticity on the basis of the priorities of the existing items which should be moved to allocate \( M \) in the corresponding time window.
- Generates a schedule, given a (feasible) start time for \( M \) selected by the user.

**ALGORITHM 1**: Feasible intervals for starting a new calendar item \( M \) for a specific user \( U_i \).

**input**:

- new item \( M \)
- other \( U_i \) items in current schedule order \( (T_i, \ldots, T_{i,u}) \)
- STN \( N \) (temporal constraints for \( M, T_1, \ldots, T_{i,u} \))
- \( S_i \) current schedule for \( T_1, \ldots, T_{i,u} \)

**1 foreach** \( C \in \{ L, I, M, H \} \) **do**

**2 \( T^C_i \leftarrow \text{Intervals}(M, (T_i, \ldots, T_{i,u}), N, S_i, C) \)**

**3 end**

**4 return** \( T^L_i \)

Note that, different from a classic scheduler, ITER computes a set of intervals within which the item can be placed, instead of a set of specific places. In this way, ITER supports a compact and synthetic presentation of scheduling options, to be further refined. As we shall see, each interval corresponds to a different revision of the calendars, based on which time point within the interval will be chosen by the user, as well as additional user input.

The feasible intervals and the schedules that are computed by ITER are restricted by conservativeness criteria. In general, this means that placing \( M \) in a feasible interval does not require a heavy revision of the current schedule. In our current implementation, we adopt a simple conservativeness criterion, requiring that the relative order of existing items in the schedule can be maintained when \( M \) is added.

For simplicity, we will first consider feasible intervals which do not require to move any already scheduled items involving multiple users. The relaxation of this restriction will be discussed later in the section on handling existing items involving multiple actors.

We introduce a notation in order to tag feasible intervals with information about their criticity. Each computed interval \( I_{M,i} \) will have an associated label:

\[ H(I_{M,i}) = \{ U_1^{C_1}, \ldots, U_m^{C_m} \} \]

where \( U_1, \ldots, U_m \) are the users involved by \( M \) and the \( C_i \) superscripts denote the criticity of the interval for each actor \( U_i \); i.e., the impact on \( U_i \)'s calendar of allocating
\( M \) in the interval \( I_{M,i} \) in terms of revisions. Specifically, \( C_i \in \{L, M, H\} \), where:

- \( \bot \) means that the schedule of \( U_i \) is not affected by \( M \);
- \( L \): only low-importance commitments of \( U_i \) have to be shifted to allocate \( M \);
- \( M \): only medium- and low-importance commitments of \( U_i \) have to be shifted;
- \( H \): at least one high-importance commitment of \( U_i \) has to be shifted;

The computation of the set of feasible intervals \( I_M \) for \( M \) is split in two steps:

1. Computing the feasible intervals \( I_j = (I_{j,1}, \ldots, I_{j,N_j}) \) for each user \( U_j \). Each interval \( I_{j,k} \) is assigned a label \( l(I_{j,k}) = U^{(C_i)}_j \), with \( C_i \in \{L, M, H\} \); the label specifies how critical is to allocate \( M \) in that interval, given the temporal constraints of \( U_j \)'s commitments.

2. Computing the joint feasible intervals \( I_M \) and their labels from user intervals \( I_j \) in order to synthesize a limited number of options to be considered for scheduling \( M \) by its organizer.

### Computing the User Intervals

Algorithm \( A \) (on the previous page) concerns a single user \( U \) and implements the first step. It takes as inputs: (i) the new item \( M \) to be allocated; (ii) \( U \)'s other items \((T_{i,1}, \ldots, T_{i,N_i})\) in the order in which they appear in the current schedule; (iii) an STN \( N_i \) encoding the deadline, duration and precedence constraints for \((T_{i,1}, \ldots, T_{i,N_i})\) \( M \); and, (iv) the current scheduled times \( S_j \) for \((T_{i,1}, \ldots, T_{i,N_i})\).

In the loop starting at line 1, the algorithm computes four sequences of intervals \( I_j, I_j^2, I_j^3, I_j^4 \) by invoking procedure \( Intervals \), described below. Each sequence \( I_j^k \) contains \( k \) intervals, one for each position where \( M \) can be placed in the order of the existing items \((T_{i,1}, \ldots, T_{i,N_i})\). For each position \( j \), interval \( I_{j,k}^k \in I_j^k \) represents the set of time points \( l \) such that starting \( M \) at time \( l \) requires to modify \( U \)'s schedule by shifting items of importance \( C \) or lower.

The intervals in sequences \( I_j, I_j^2, I_j^3, I_j^4 \) can overlap both within the same sequence and between sequences. Thus, in line 4 the algorithm invokes procedure \( DComp \) to merge \( I_j^2, I_j^3, I_j^4 \) into a single sequence \( I_j \) of labeled and ordered disjoint intervals. Each overlapping portion is labeled with the lowest (i.e., best) criticality class to which it belongs.

#### Procedure Intervals

Procedure \( Intervals \) is called to generate a sequence of intervals of given criticality \( C \). Therefore, it immediately adds the scheduled times of tasks of classes \( C' > C \) to the temporal constraints encoded by STN \( N_i \), obtaining STN \( N_i^C \) (line 2). With these added constraints, \( N_i^C \) ensures that no task with criticality \( C' > C \) can be moved.

Then, \( Intervals \) considers each possible positioning of \( j \) of \( M \) in the sequence of existing items \((T_{i,1}, \ldots, T_{i,N_i})\) involving \( U \). In this way a total order \( \Pi \) is determined among all the items, including \( M \), and can be asserted as a set of precedence constraints into the STN. The resulting STN \( N_i^\Pi \) is then minimized, yielding a feasible interval \( I_{ij}^C = \) [\( \min, \max \)] for the start of \( M \). As said above, for each position \( j \) of \( M \), such an interval represents the set of time points \( t \) such that starting \( M \) at time \( t \) requires to shift items having importance \( C \) or lower in \( U \)'s schedule. Intervals \( I_{ij}^C \) are added to sequence \( I_j^C \) and, after all the positions have been considered, such a sequence is returned.

#### Example 1

Let us refer to the running example and consider the execution of Intervals when it is invoked on user Gianluca for adding the Staff meeting \( S \) on Thursday with the class parameter \( C \) set to \( H \). That day, the items already allocated for Gianluca include, in the order: Attorney (\( AT \)), SW3 (\( S3 \)), Thist Ugo (\( TU \)), Thist Ida (\( TI \)) and Plumber (\( PL \)).

Figure 2 shows a portion of the STN \( N_i^C \) computed by Intervals for user Gianluca. Such a network corresponds to the iteration of the Intervals procedure when the for loop has set position \( j = 2 \) (i.e., between \( S3 \) and \( TU \)).

The z time point represents Monday 8.00 and the boldface intervals on the arcs express the minimum and maximum
distance between the connected time points. For example, interval [36, 42] on the arc connecting z and SM, represents: 36 ≤ SM ≤ z ≤ 42; i.e., SM must start on Thursday between 8:00 and 14:00. The dashed arcs represent the precedence between two items T'. T'' in the current order P. Their associated intervals, omitted for readability, would be [0, +∞]; i.e., T'' must follow T' by at least 0 hours. Moreover each item is labeled with its importance; e.g., AT has low importance and TU has medium importance.

The intervals after the minimization of N^2 are shown in its intervals. The interval computed for SM, and are, respectively, [39, 41] (Thursday 11:00 to 13:00) and [41, 43] (13:00 to 15:00). Indeed, when SM is positioned between S3 and TU, it can start only after the end of S3 (11:00) and its latest event (15:00) must leave enough time for T U, T1 and PL to be completed by 20:00. The present example [39, 41] is added to the sequence T^0 of feasible intervals with class B for Gianluca.

Let us now consider the intervals for SM, when position is j = 2 but the class C is 2, i.e., scheduled items of importance 2, and it cannot be shifted. In such a case, the interval for SM is ∅ (it has medium importance); thus, SM cannot be moved between S3 and TU.

By repeating the process, it is easy to see that the non-empty intervals of class B for user Gianluca are: [39, 41] (j = 2); [40, 42] (j = 3); [41, 42] (j = 4). The B intervals are the same but the L and ∥ intervals are empty.

Procedure DComp receives sequences I^0, I^L, I^M, I^H and composes them into a single sequence I of ordered, labeled, disjoint intervals. In line 1, it orders the start and ends of each interval of both the input and output intervals and stores them in a list T. This operation consists of two steps:

1. Flatten each input list of intervals I^g = (I^g_1, ..., I^g_k) into an ordered list of start and end time points (s(I^g_1), ..., s(I^g_k));
2. Merge such ordered lists into list T. In case of ties, put start time points before end time points, and further order start (resp., end) points in increasing (resp., decreasing) order of their criticality classes (⊥, ⊥, ∥, ⊥). In other words, if several intervals start at the same time, the start of the best (i.e., lowest class) is the first one in the order. Moreover, if several intervals end at the same time, the end of the best interval is the last one.

In the procedure, line 2 initializes the output sequence I of the empty list. Moreover it sets to 0 the counter n_c of input intervals and the counter n_c of input intervals of class C to which the elements of T belong. The loop starting at line 3 considers each t ∈ T. If t is the start point of an input interval I^g (line 4), n_c and n_c (intervals to which t belongs) are incremented. Then:

- If n_c is equal to 1, t corresponds to the start s(I) of a new output interval I whose label is set to U^g_1, because the input interval has class C.
- If n_c > 1 but the class C of the input interval is lower than the label l of the current output interval, a new output interval has to be created after closing and adding to the output sequence I the current output interval (line 10).

If t is the end point of an input interval I^g (line 17), n_c and n_c are decremented.

- If n_c is equal to 0, t is the end s(I) of the current output interval I (line 20), which has to be closed and added to sequence I.
- If n_c > 1 but the class C of the input interval is equal to the label l of the current output interval and n_c = 0, a new output interval has to be created after closing and adding to the output sequence I the current output interval (line 23). In line 27 the label of the new output interval is set to the minimum (best) class C associated with at least one input interval which includes t, i.e. such that n_c > 0.
Example 2 As shown in example 1, the \( \Xi \) and \( \Theta \) sequences for Gianluca contain the following intervals: \([39, 41]\) (\( j = 2 \)); \([40, 42]\) (\( j = 3 \)); \([41, 42]\) (\( j = 4 \)). The sequence \( T \) of time points considered by DComp is therefore:

\[
T = (30^6, 30^6, 40^6, 41^6, 41^6, 41^6, 41^6, 42^6, 42^6, 42^6)
\]

where we have marked each \( t \in T \) with the class of its interval and its role (start/end). When \( t = 30^6 \) is considered, a new output interval \( I \) is started with \( I_t = 30 \) and label \( G^\Theta \) (for Gianluca). Time point \( t = 30^6 \) is skipped because its class is higher than the current output class (line 10 of DComp). For the same reason, time points 40^6, 40^6, 41^6, 41^6 are skipped. Note that meanwhile the number \( n_u \) of feasible input intervals has grown to 6, with \( n_u = 3 \) and \( n_u = 3 \). For this reason also ending time points 41^6, 41^6, 42^6 (\( 42^6 \) is considered, \( n_u \) drops to 0 and the only output interval \([39, 42]\) with label \( G^\Theta \) is returned in the sequence \( I_i \) for Gianluca.

Computing the Joint Intervals. For each user \( U_i \) involved in \( M \), Algorithm 1 computes a sequence of ordered, disjoint intervals \( I_i \) such that each interval \( I_{i,j} \) has a label \( I(I_{i,j}) \) which takes values in \( \Xi' \cup C \). C is \( \{L, L, R, R\} \).

Given that the involved users are \( \{U_1, \ldots, U_m\} \), ITER computes a single sequence of ordered, disjoint intervals \( I_M = \{I_{i,j}, \ldots, I_{M,j}\} \) such that each element \( I_{M,j} \) of \( I_M \) represents a jointly feasible interval for starting \( M \). Interval \( I_{M,j} \) is labeled based on the labels of the user intervals from which it is derived. Given \( I_{i,j}, \ldots, I_{M,j} \), the sequence of jointly feasible intervals \( I_M \) satisfies the following conditions:

- Two time points \( t, t' \) belong to an interval \( I_{M,j} \) iff for each involved user \( U_i \) they belong to the same user interval \( I_{i,j} \).
- The label \( I(I_{M,j}) \) associated with interval \( I_{M,j} \) is given by \( \bigcup I(I_{i,j}) \).

The computation of \( I_M \) is performed by a procedure \( JComp \) (joint composition) analogous to \( DComp \). The procedure receives the sequences of intervals \( I_i \) for all users \( U_i \) and produces the single sequence \( I_M \) of jointly feasible intervals.

Example 3 As shown in Example 2, the only interval for user Gianluca is \([39, 42]\) with label \( G^\Theta \). Let us assume that Prof. Rossi’s BUSY3 cannot be moved and that BUSY4 could be postponed at 14:00. Then, for Prof. Rossi there are two feasible intervals: \([38, 39]\) with label \( Ro^R \) (i.e., his schedule has not to be modified) and \([39, 40]\) with label \( Ro^B \) (medium importance task BUSY4 has to be moved). The invocation of \( JComp \) on the sequences of intervals for Gianluca and Prof. Rossi returns a single interval \([39, 40]\) with label \( \{Ro^B, G^\Theta\} \). Indeed, \([39, 40]\) is the only feasible time window for both Prof. Rossi and Gianluca; moreover the interval has impact on both actors. Therefore, SM must start at 11:00 or later and end by 14:00.

ITER: Computing Revisions to a Calendar

We briefly describe the computation of revisions to shared calendars because it only requires to run again the \( Interval \) procedure used for computing the feasible intervals.

Let us consider the feasible interval \([39, 40]\) with label \( \{Ro^P, G^B\} \) computed for \( SM \), and let us suppose that Gianluca places \( SM \) at time point 40 (12.00 pm). In order to compute the alternative revisions, \( Interval \) has to be invoked with the additional constraints that \( SM \) starts at time point 40 and that this allocation has impact on Gianluca and Prof. Rossi’s calendars. For Gianluca, \( SM \) can be placed between \( S3 \) and \( TU \), or between \( TU \) and \( TF \); for Prof. Rossi, between \( BUSY3 \) and \( BUSY4 \).

The first revision of Gianluca’s calendar is obtained by considering the minimized STN computed by placing \( SM \) between items \( S3 \) and \( TU \), which also contains feasible intervals for the other items in the calendar. For each such item we choose a start time point as close as possible to its current schedule, which results in pushing \( TU \) at 14.00, \( TI \) at 15.00, and \( PL \) at 16.00. The second revision of Gianluca’s calendar and the only available revision of Prof. Rossi’s calendar are computed in a similar way.

Handling existing items involving multiple actors

The results presented in the previous section hold when existing items which involve multiple actors (henceforth, meetings) cannot be anticipated nor postponed. However, when looking for the feasible intervals for a new item \( M \), it is desirable to consider re-scheduling such items. Let us assume that \( M \) involves a set of actors \( U = \{U_1, \ldots, U_m\} \).

The previous meetings of actors \( U \) can be of two kinds:

1. They involve only some of the members of \( U \).
2. They have additional participants \( U' \) which are not involved in \( M \).

Re-scheduling calendar items of the second kind can result in a domino effect: actors in \( U' \) may have existing meetings with yet other users \( U'' \), and so forth. Thus, adding \( M \) may lead to revise schedules of people having an indirect connection with users \( U \). While we believe this is an interesting problem, that may likely involve some forms of automatic negotiation, such propagations are out of the scope of this paper. Thus, we add the following restriction: if an existing calendar item which involves actors \( U \) also involves actors \( U' \), it can be only moved to time slots where the members of \( U' \) are available.

In the following we discuss how to handle the items involving subsets of \( U \). Handling additional users with the above stated restriction trivially consists in pruning some of the solutions computed for users \( U \), based on the free time slots of users \( U' \). Therefore, we do not discuss it.

In order to handle existing meetings among users \( U \), we first partition them in families \( U_1, \ldots, U_k \), such that:

- Users \( U, U' \) should be in the same family \( U \) if there is a meeting involving \( U, U' \).
- Families should be disjoint, i.e., if two families \( U', U'' \) share at least one user, they are replaced by a new family \( U = U' \cup U'' \).

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The previously described techniques can be applied to this case by computing the sequences of intervals $I_i$ for each family instead of for each user. Indeed, if users $U_1, \ldots, U_q$ in a family have an existing shared meeting $M^t$, each of them has an item $M^t_i$ in their calendar representing $M^t$ and the start/end times of items $M^t_i$, $i = 1, \ldots, q$ must be equal. For this reason, we have to build and use an STN that encodes the calendar constraints of all the users in the family. After the sequences for each family have been computed, they can be merged with the previously described XComp procedure for computing jointly feasible intervals.

We now explain how Algorithm 1. Intervals and DComp are adapted to operate on families of users.

Let us start by considering the changes to Algorithm 1. Instead of receiving a single sequence of items $(I_i, \ldots, I_{i+1})$ and a single schedule $S_i$ associated with a user $U_i$, the algorithm must receive a sequence $(I_i, \ldots, I_{i+1})$ and a schedule $S_i$ for each user $U_i$ in a family $U = \{U_1, \ldots, U_q\}$. Moreover, instead of an STN $N_e$, encoding the basic constraints for the items of an individual user, it must receive an STN $N_{e'}$, encoding the basic constraints for the items of all of the users in family $U$.

Procedure Intervals returns a set of $4^q$ sequences, each one associating a class to a user in the family. For example, if $U = \{U_1, U_2\}$, Intervals must return a sequence $T_{I_1, I_2}$, a sequence $T_{I_1, I_2}$, and so forth. Moreover, the number of positions to be considered by Intervals for placing the new meeting $M$ (line 3) is now:

$$(k_1 + 1) \times \ldots (k_q + 1)$$

For example, if the existing tasks of $U_1$ are $(T_{1,1}, T_{1,2})$ ($k_1 = 2$) and the existing tasks of $U_2$ are $(T_{2,1}, T_{2,2}, T_{2,3})$ ($k_2 = 3$), we must consider scheduling $M$ at position “0” for $U_1$ and 0 for $T_{2,3}$ (i.e., before both $T_{1,1}$ and $T_{2,1}$), at position “1” for $U_1$ and 1 for $T_{2,2}$ (i.e., before $T_{1,1}$ and between $T_{2,1}$ and $T_{2,2}$), and so on.

Therefore, Intervals computes $4^q$ sequences of size $(k_1 + 1) \times \ldots (k_q + 1)$, and such sequences are passed as inputs to DComp. DComp is almost unchanged but there is an important point to make about the labels. While for the intervals of a single user labels are totally ordered (as $\perp \leq \ldots \leq M < \infty$), this is no longer true for the intervals of a family. For example, labels $U_1 T_{2,1}$ (i.e., some low-importance tasks of $U_2$ have to be shifted) and $U_1 T_{2,1}$ (i.e., some low-importance tasks of $U_1$ have to be shifted) are not ordered. As a consequence, the if starting at line 7 of DComp should have one additional branch, covering the case when the class $C$ of the starting input interval is not comparable with the label $I$ of the current output interval. In such a case, a new output interval should be started with label $(C; I)$.

**Related Work**

The importance of a mixed-initiative approach to scheduling calendars was recognized in previous works, such as (Cesta, D’alòisi, and Brancalion 1996) and (Berry et al. 2011). However, relatively little work has been done on this topic so far.

Some recent calendar managers (e.g., Google Calendar Smart Rescheduling (Marramay 2010)) analyze the estimated duration and temporal constraints of the items to be scheduled in order to identify the available time slots where they could be allocated. However, they cannot suggest any schedule revisions for addressing temporal conflicts.

Many task managers such as Things (Cultural Code 2011) and Standaq Smart Schedules for Outlook (Standaq 2012) manage tasks and deadlines but they have no scheduling capabilities. Other ones are very powerful but they require too much information from the user for everyday activity management, and/or they only handle single-user tasks; e.g., see (Refanidis and Yorke-Smith 2010).

Opportunistic schedulers synchronously guide the user in the execution of activities; e.g., see (Horvitz and Subramani 2007). However, they cannot present an overview of long-term schedules.

PTIME (Berry et al. 2011) adopts a mixed-initiative approach and generates personalized scheduling options by learning the user’s preferences. A major difference with respect to MARA is the fact that it proposes complete solutions to choose from, instead of interacting with the user during the exploration of the solution space, represented as a set of feasible intervals for adding/moving a task.

The TCSP-based classic techniques used in the paper (Dechter, Mei, and Pearl 1991) have been extensively studied and extended in the temporal reasoning and planning/ scheduling communities. Of particular interest for extensions of this paper are, among others, improved efficiency of STN consistency check (Planken, de Weerdt, and van der Krogt 2011), consistency check of distributed STNs (Boerkoel and Durfee 2010), incremental consistency checks (Planken, de Weerdt, and Yorke-Smith 2011) and temporal preferences (Peitner and Pollack 2004). While these techniques could definitely improve the efficiency and scalability of our approach, we are not aware of any existing work which exploits them in the way proposed in this paper for improving the mixed-initiative user experience in calendar management.

Finally, it is worth mentioning the works by Bresina et al. on mixed-initiative planning of Mars rover missions (Bresina and Morris 2005; 2007). In such works, however, the role of the automated reasoner is that of helping the human to plan the daily activity for the rover by detecting (temporal) inconsistencies and trying to explain them in terms of previous commitments made by the user.

**Conclusions**

We presented the temporal reasoning support underlying the Mixed-initiative cAlendAr mAnager. MARA exploits Temporal Constraint Satisfaction techniques to generate safe schedules across multiple calendars; it adopts a mixed-initiative interaction model to guide the user in the exploration of the solution space, providing her/him with information about the available options and their impact on the existing commitments of the involved actors. In this way, it helps the user to quickly solve calendar management problems, leaving her/him in control of the scheduling activity.
A preliminary test with users provided encouraging results on the efficacy and usefulness of MARA’s calendar management features: users particularly appreciated its awareness support because it enabled them to easily find the allocation options for events and to select the most convenient ones by previewing their impact on people’s commitments, without analyzing all the possible solutions in detail.

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