Soft Scheduling

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Abstract Classical notions of disjunctive and cumulative scheduling are studied from the point of view of soft constraint satisfaction. Soft disjunctive scheduling is introduced as an instance of soft CSP and preferences included in this problem are applied to generate a lower bound based on existing discrete capacity resource. Timetabling problems at Purdue University and Faculty of Informatics at Masaryk University considering individual course requirements of students demonstrate practical problems which are solved via proposed methods. Implementation of general preference constraint solver is discussed and first computational results for timetabling problem are presented.

1 Introduction

Practical solutions of timetabling problems at the Faculty of Informatics and at Purdue University suggest a general scheduling problem which may be regarded as a special type of soft constraint satisfaction problem [2,10]. Both of the solved problems are characterized by individual requirements of students for a set of courses they would like to attend. This type of problem includes a large number of constraints due to the diversity of requirements. Straightforward application of methods from disjunctive and cumulative scheduling [1,9] entails an over-constrained problem.

Let us consider a basic timetabling problem which is often solved via the constraint programming approach [8,7,6,10] to demonstrate where possible directions of solution for our problem may lead. The timetabling problem is represented by given sets of of course offerings, each consisting of several courses. Each student enrolls in one or more offerings having some small amount of choice among elective offerings. Such problem can be modeled with help of disjunctive scheduling and global `disjunctive` constraints[1]. One `disjunctive` constraint expresses the requirement for non-overlapping of courses within one offering or related offerings

```
disjunctive([Start1,...,StartN],[Duration1,...,DurationN])
```

[1] For details about `disjunctive` (or `serialized`) and `cumulative` constraints see for example CLP(FD) library of SICStus Prolog [3].

where `StartI` and `DurationI` represent starting time and duration of course `I`. Allocation of courses into the available number of classrooms is often included in the problem definition via global `cumulative` constraint[1]

```
cumulative([Start1,...,StartN],[Duration1,...,DurationN],
           [1,...,1], NbOfRooms)
```

which states that at most `NbOfRooms` courses can be taught at the same time. Each course needs just one classroom from the available pool of classrooms which is expressed by the list `[1,...,1]`. Let us note that the problem may contain several `cumulative` constraints representing classrooms with different equipment or size [10].

Representation of the various course separations for each student by the `disjunctive` constraint would certainly lead into an over-constrained problem without any existing solution. Our idea is to propose a soft version of the `disjunctive` constraint which would lead to a minimization of violated student requirements. Unsatisfied constraints will be handled via preferences associated with each value in the domain of the variable. This type of preferences will be also subsequently used for complementary solving methods in cumulative scheduling which allow us to reflect the current value of preferences in the problem via updating the lower bound.

This work is based on our earlier research and the implementation of a timetabling system for Faculty of Informatics described in [11]. This paper proposed the so called student conflict minimization problem which is in close relation with the minimization of unsatisfied constraints considered here. Our current intent is to generalize the earlier proposed approach to be able to extend the problem solution by adopting other methods for handling preferences. This extension will be shown in discussion of cumulative scheduling.

2 Soft Disjunctive Scheduling

Let us propose a *soft disjunctive (scheduling) constraint*. Disjunctive scheduling will be understood in its standard interpretation as the scheduling of disjunct activities [1,9]. The adjective soft will express that some of the activities may overlap, as disjunctive scheduling may result in an over-constrained problem, within the context of a broader problem definition. The degree of satisfaction of the soft disjunctive constraint $\mathrm{soft\_disj}(a_1, \dots a_n)$ wrt. assignment θ of activities $a_1 \dots a_n$ may be expressed by the number of its pairwise overlapped activities a_i, a_j

$$\omega(c\theta) = \sum_{\forall i,j: i<j} \neg \mathrm{disj}(a_i\theta, a_j\theta)$$

where $\mathrm{disj}(a_i\theta, a_j\theta)$ evaluates to 1 iff activities a_i and a_j are disjunctive for assignment θ of their starting time and duration variables. Optimal satisfaction of this constraint is then defined as the minimum value for $\omega(c\theta)$. In this way, the $\mathrm{soft\_disj}(a_1, \dots a_n)$ constraint was transformed into a set of soft disjunctive constraints soft_disj(a_i, a_j) over each pair of its activities a_i, a_j. This interpretation also corresponds with MAX-CSP [5] aimed at satisfying the maximum of constraints[2].

Let us consider set C of soft disjunctive constraints each defined over some subset of the set of activities A. Taking into account optimal satisfaction of overall constraint set, we end up with minimization of $\sum_{c \in C} \omega(c\theta)$ over instantiations θ of activities in A. In the case where particular soft disjunctive constraints share some activities, each soft_disj(a_i, a_j) may contribute to the final sum several times. This contribution will be understood as the weight w_{ij} of a constraint between activities a_i, a_j. Such an interpretation leads to a weighted CSP [5], with aim to minimize weighted sum of violated constraints. Satisfaction degree of that problem corresponds to

$$\min_{\theta} \sum_{\forall a_i, a_j \in A : i < j} w_{ij} \times \neg \mathrm{disj}(a_i\theta, a_j\theta) \ . \tag{1}$$

where w_{ij} is equal to 0 if no soft disjunctive constraint between a_i and a_j exists.

For any given assignment θ, it could be also interesting to consider the number $u(a_i\theta)$ of unsatisfied soft disjunctive constraints posted on activity a_i

$$u(a_i\theta) = \sum_{\forall a_j \in A : a_j \neq a_i} w_{ij} \times \neg \mathrm{disj}(a_i\theta, a_j\theta) \ . \tag{2}$$

Such evaluation would tell us how many overlaps this activity has with other activities. When activities are relatively equal in importance, we may want to consider minimization of the worst case unsatisfaction of $u(a_i\theta)$. This interpretation will subsequently lead to a combination of fuzzy CSP [4] and weighted CSP. Let us describe this proposal in the following paragraph.

We will consider m soft disjunctive constraints over set of activities A having cardinality $|A| = n$. Then the maximal value of $u(a\theta)$ corresponds to $m(n-1)$ because each activity may occur at most once in each constraint having maximal number of $(n-1)$ remaining variables as possible candidates for overlap. The set of soft disjunctive constraints included in $u(a_i\theta)$ defines one fuzzy constraint with a level of preference corresponding to $1 - \frac{u(a_i\theta)}{m(n-1)}$. Transformation of $\frac{u(a_i\theta)}{m(n-1)}$ is required to normalize into $\langle 0, 1 \rangle$ unit interval. Computing the complement within unit interval corresponds to usual interpretation of the level of preference in fuzzy CSP: the better the satisfaction of a fuzzy constraint is, the closer its value should be to 1. Finally we may describe the best assignments by

$$\max_{\theta} \min_{a_i \in A} \left[1 - \frac{u(a_i\theta)}{m(n-1)} \right] \ . \tag{3}$$

2.1 Correspondence with Timetabling Problem

Let us describe the relationship of evaluation methods proposed in Eqns. 1 and 3 with the above presented timetabling problem (see Sect. 1).

[2] Our interpretation is complementary as we need to minimize number of unsatisfied constraints.

First we will consider the weighted CSP interpretation from Eqn. 1. The requirement for non-overlapping of courses for one student may be taken into account by one soft disjunctive constraint. Summarized timetabling requests from all students are transformed into a set of soft disjunctive constraints over two courses representing activities a_i and a_j. The weight w_{ij} of this constraint corresponds to the number of joint enrollments between courses a_i and a_j. Generally the number of joint enrollments is critical information which is used during construction of timetables of described shape.

Expression $u(a_i\theta)$ in the second objective (Eqn. 3) sums the number of students having requested other course(s) during the expected time of their enrolled course a_i. This means that $u(a_i\theta)$ evaluates satisfaction of soft requirements towards the course a_i. Therefore, the overall objective function in Eqn. 3 incorporates the fact that the number of students measured by u should not be "too bad" wrt. any particular course as it could even force its cancellation. The disadvantage of this measure is that the proposed expression may take into account one student in course a_i several times due to concurrent scheduling of his (her) other courses (at least two other courses). However, this inaccuracy of the solution decreases with increasing quality of generated timetable and it could be even abandoned for sufficiently good solutions[3].

The second objective compares the number of students wrt. each course. Such an approach could also profit from inclusion of the ratio between violated requirements per course $u(a_i\theta)$ and the number s_i of enrolled students in course a_i. This type of evaluation could be handled in a similar approach as was proposed in Eqn. 3, i.e., by corresponding transformation of the ratio $\frac{u(a_i\theta)}{s_i}$.

3 Soft Cumulative Scheduling

The proposed handling of soft disjunctive constraints defines objective functions with accumulating weights of violated disjunctions over pairs of activities. This type of preference introduces new information within the problem which could be also interesting to use in other parts of problem solution.

Let us consider a `cumulative` constraint which constrains the maximal number of activities to be scheduled at the same time due to discrete capacity of an existing resource they all require. We may also need to constrain the minimal number of activities on that resource (e.g., by set of `atleast` constraints[4]). Taking into account only the classical hard version of these constraints, we are not able to handle available resource space (minimal–maximal usage) assigned to the set of activities by means of preferences included in the problem. In this

[3] Let us expect that at least 90 % requirements in course pre-enrollment would be satisfied. Having average number of courses for each student equal to 10, it would result in approximately one course per student which he/she is not able to attend. Taking into account number of time periods within a week, such average overlapping does not become substantial for discussed fail contributions.

[4] For each `Time`, we can post one `atleast(Time, TimeList, Minimum)` constraint expressing that at least `Minimum` domain variables from `TimeList` has to be equal `Time`.

section, we would like to propose possible directions for complementary solution methods which also reflect preferences included in problem. This approach will define a *soft cumulative constraint* for one discrete capacity resource. Let us note that these methods will not change preferences in the problem as no new violations of soft constraints are generated.

First let us define a model of preferences: each valid starting time of an activity a_i is associated with a weight expressing how desirable a given time is — the smaller the weight is, the more desirable the corresponding starting time is. The objective is to find an assignment θ of activities which minimizes the sum of these weights, i.e., $\min_\theta \sum_i w(a_i\theta)$. Having some set of activities constrained by a discrete capacity resource, we can consider weights of its possible candidates to be assigned at each time. The basic premise of the following consideration is that sufficiently "good" candidates, and a sufficient number of the "good" candidates, have to exist for this resource at any time.

Let us expect that we are given some minimal weight $m(a_i)$ for each activity a_i. In the simple case, this weight corresponds to $\min_\theta w(a_i\theta)$, but it may be computed (or even approximated) via any other method. Then the expression $L = \sum_i m(a_i)$ defines the lower bound of the solution. Our aim is to compute how any existing discrete capacity resource may worsen this lower bound by their accumulated weights.

Let us note that the results of computation for one discrete resource directly influence value of $m(a_i)$. These incremented values should be used by all soft cumulative constraints sharing corresponding activities.

Our consideration will take into account activities requesting unit capacity of a discrete resource. The requirements for a non-unit capacity could be handled considering the activity number of times equal to the required resource capacity.

We will consider a discrete capacity resource defined over a subset of activities $A' \subseteq A$ during time interval $t \in t_{\min} \ldots t_{\max}$. Its capacity may vary over time, i.e., we have given minimal $c_t^{\min}$ and maximal $c_t^{\max}$ capacities of all times t. Let $\theta_{a_i \leftarrow t}$ be an assignment which assigns starting time t to activity $a_i \in A'$ with maximal duration d_i. Then we will denote

$$
\begin{aligned}
d(t, a_i) = \min\{0, \min\{w(a_i\theta_{a_i\leftarrow s}), & [s = (t - d_i - 1)\ldots t \wedge (t - d_i - 1) > t_{\min}] \vee \\
& [s = t_{\min} \ldots t \wedge (t - d_i - 1) \leq t_{\min}] \\
\} - m(a_i)\} &
\end{aligned}
$$

as a difference between the possible weight contribution of activity a_i at time t and the minimal expected weight $m(a_i)$ of activity a_i. Weight contribution at time t needs to be selected among all weights $w(a_i\theta_{a_i\leftarrow s})$ for such starting times s of activity which possibly include processing of a_i at time t.

Now let us order activities $a_i \in A'$ at each time t such that expression $d(t, a_i)/d_i \leq d(t, a_j)/d_j$ holds for all activities a_i, a_j having $i < j$. Then value $L_{\min} = \sum_{t=t_{\min}}^{t_{\max}} \sum_{i=1}^{c_t^{\min}} d(t, a_i)/d_i$ introduces the minimal contribution of the soft cumulative constraint to the lower bound L. This lower bound increase includes only the minimal number of activities which should be scheduled at given time t. The importance of such criteria greatly increases when we also have information about the expected number of activities $c_t^{\exp}$ to be scheduled at time t. This would allow us to consider a stronger lower bound contribution given by $L_{\exp} = \sum_{t=t_{\min}}^{t_{\max}} \sum_{i=1}^{c_t^{\exp}} d(t, a_i)/d_i$.

This proposed lower bound does not require constant duration of all activities as we have considered maximal duration of each activity. However, the quality of the lower bound decreases if the duration of activities is over estimated.

4 Constraint Solver

Constraint propagation algorithms for the soft scheduling methods discussed are implemented as a part of the preference constraint solver for timetabling problem at Purdue University. This constraint solver is built on top of the CLP(FD) solver of SICStus Prolog [3] and implemented with help of attributed variables. An advantage of this implementation consists in possible inclusion of both hard constraints of CLP(FD) library and soft constraints of a new preference constraint solver.

4.1 Preference Variables

The constraint solver implemented handles preferences for each value in the domain of the variable which will be called *preference variable*. Each preference corresponds to a natural number with a value indicating the degree to which any soft requirement dependent on that value is violated. Zero preference therefore means complete satisfaction for the corresponding value in the domain of the variable. Any higher value of preference expresses a degree of violation which would result from assignment of that value to variable. Preferences for each value in the domain of the variable may be initialized by natural number which allows us to handle initial costs of values in the domain of variables.

Example 1. The following predicate creates the preference variable `A`

```
pref( A, [7-5, 8-0, 10-0] )
```

with initial domain containing values `7`, `8`, and `10` and preferences `5`, `0`, and `0`, resp. It means that the value `7` is discouraged wrt. other values.

4.2 Soft Disjunctive Constraint

Propagation of preferences for soft disjunctive constraints is ensured via global constraint

```
soft_disjunctive( S_i, D_i, ListS_j, ListD_j, ListW_ij ) ,
```

where S_i is a preference variable for starting time of activity i, ListS_j is a list of preference variables for starting time of all activities requesting soft disjunction with activity i. D_i and ListD_j represent corresponding constant[5] durations of activities. ListW_ij contains the number of soft disjunctive requirements between activity i and particular activities from ListS_j (w_{ij} from Eqn. 1).

Constraint soft_disjunctive is invoked as soon as the preference variable S_i is instantiated. Then we know exactly which values in the domain of preference variables in ListS_j should be discouraged, i.e., the values that overlap with current instantiation of S_i. For these values, preferences are incremented by corresponding weight from ListW_ij. When some preference variable does not already contain critical values in its domain no change need to be done.

Let us expect that θ assigns value v to variable for starting time S_i of activity a_i. During computation, preference for value v corresponds to part of sum from Eqn. 2 representing contributions of violated soft disjunctive constraints which already have an assigned starting time for the second activity. These contributions are accumulated up to instantiation of starting time S_i. The sum of preferences for complete assignment of starting times corresponds to the sum from Eqn. 1, representing degree of satisfaction for the assignment.

Discrimination among multiple activities is handled by inclusion of maximal allowed value for any $u(a_i\theta)$ (for the definition see Eqn. 2). When any partial contribution to $u(a_i\theta)$ stored in preference variable exceeds this threshold, corresponding value is filtered from the domain of variable to disallow such instantiation. In order to search for (sub-optimal) solution reflecting objective from Eqn. 3, maximal allowed value could be subsequently decreased during search for better solution wrt. final preferences of last generated solution. The same filtering of values could be applied in order to exclude a large ratio of violated student requirements.

Propagation rules for soft disjunctive constraints included only constant duration activities. Variable duration activities could be easily incorporated, however. Values of preferences would be incremented up to the minimal duration. When the minimal duration is increased preferences are updated accordingly. This step would be repeated up to instantiation of domain variable for duration.

4.3 Soft Cumulative Constraint

In this section, we would like to discuss basic implementation issues of soft cumulative constraints. However, their realization is a major topic for future work.

Soft cumulative constraint

```
soft_cumulative( ListS_i, ListD_i, ListC_t)
```

is defined over preference variables for starting times ListS_i, durations ListD_i of activities, and constant capacities ListC_t representing expected use of discrete capacity resource at each time.

[5] Possible extension towards durations as domain variables is discussed at the end of the section.

Section 3 proposed a method for computing lower bound of solution based on preferences associated with each value in the domain of variable. This lower bound can be updated during the search for a solution of the problem wrt. removed values from the domain of variables and increased values of preferences by soft disjunctive constraints. Finally this lower bound may be used to prune the search space when current partial assignment exceeds it.

During computation preference variables from `ListS_i` are subsequently instantiated. This fact needs to be reflected by removing newly instantiated preference variable from lists `ListS_i` and `ListD_i` and by decreasing capacity in `ListC_t` for all times when activity is processed.

Because each soft cumulative constraint may increase the minimal weight $m(a_i)$ of activity i from `ListS_i` (see Sect. 3), we need to share minimal weights for all activities among all existing soft cumulative constraints.

4.4 Search

As a part of constraint solver, we have implemented anytime branch and bound algorithm — user may specify time limit of computation or interrupt the optimization and request the currently best solution. An additional value ordering applies preferences via preferred-first strategy, i.e., values with the best preferences are selected first. From an optimistic point, this could be a value violating the smallest number of constraints. A new variable ordering heuristic based on preferences selects the most constrained variable first. However, the measure is based on the number of soft constraints suspended on the variable. Ties are broken by selecting variable having the best preference.

Let us note that the most constrained heuristics currently corresponds with selection of a course having the largest number of joint enrollments with other courses.

5 First Computational Results

Let us present our first computational results based on real data from large lecture timetabling problem at Purdue University. Data set includes 258 courses and 35 classrooms with average classroom occupation about 74 %. Problem definition contains data for joint enrollments between courses and basic faculty preferences for starting time of courses. In the future, problem definition should be extended by constraints for multi-hour courses, more detailed capacity constraints, and additional faculty preferences.

Problem solution includes soft disjunctive constraints and initial costs for values in domains of preference variables. Cumulative scheduling is included via hard constraints only. A solution was computed by search method described in Sect. 4.4. First solution was found during 15 seconds on a Pentium III/933 MHz PC violating less than 1 % of requirements from joint enrollment matrix and 1 % of requirements given by initial preferences. Quality of generated solution was slightly improved during the following runs of branch and bound search.

However, this increase was not significant. This is probably a consequence of the high satisfaction degree of the first generated solution.

6 Conclusions and Future Work

We have proposed general instances of soft disjunctive and soft cumulative scheduling constraints based on real timetabling problems at Purdue University and at the Faculty of Informatics. Soft disjunctive constraint was decomposed into a set of soft disjunctive constraints over pairs of activities. This decomposition allows us to handle problem via weighted CSP and combined fuzzy and weighted CSPs. Preferences assigned to each value of a variable were considered to handle a discrete capacity resource. It was shown how each discrete capacity resource contributes to a lower bound on the solution by preferences place on its activities.

A soft constraint solver for handling preferences of each value in the domain variable was implemented in SICStus Prolog. Current implementation includes propagation rules for soft disjunctive constraints and a basic search method applying preferences. Solver extension by soft cumulative constraint was discussed.

First computational results were presented for timetabling problem with requirements of individual students for a set of courses. Because the quality of the first generated solution was very high additional search of solution space does not improve solution significantly. We expect that this situation will be changed for extended problem definition. Initial preferences will increase and the set of hard constraints will be enlarged. We also intend to handle problems containing up to 800 courses.

Our future work will include further improvement of propagation rules for soft disjunctive scheduling and implementation of proposed soft cumulative constraint. Computing the lower bound by soft cumulative constraint does not consider any relation between activities scheduled at different times. This could introduce possible directions for further improvements of computed lower bound.

We would also like to apply a preference solver to compute a new solution based on existing solution such that their distance is minimized. Aim of this methods will be incremental change of generated solution. This would allow us to reflect changes in the problem definition without critical changes of solution.

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