A branch and bound method for a clique partitioning problem

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1 Introduction

We consider here the problem of the approximation of m symmetric relations defined on a same finite set X into a so-called *median equivalence relation* (see below and [1]), with in particular two special cases: the one for which the m symmetric relations are equivalence relations (Régnier's problem [4]), and the one of the approximation of only one symmetric relation ($m = 1$) by an equivalence relation (Zahn's problem [6]). These problems arise for instance from the field of classification or clustering: in this case, X is a set of entities (which can be objects, people, projects, propositions, alternatives, and so on) that we want to gather in subsets of X in such a way that the elements of any such subset can be considered as similar while the objects of different subsets can be considered as dissimilar. Each symmetric relation is associated with a criterion specifying, for any pair $\{x, y\}$ of entities, whether x and y are similar or not. Then we try to find the best compromise between all these criteria. This leads us, in Section 2, to state this problem as a graph theoretical problem, that we call CPP for *clique partitioning problem*. As this problem is NP-hard, we design in Section 3 a branch and bound algorithm to solve this problem, based on a Lagrangean relaxation method for the evaluation function.

2 The clique partitioning problem

The problem that we consider here can be mathematically described as follows. We are given a collection $\Pi = (S_1, S_2, ..., S_m)$ of m symmetric binary relations

S_k, $1 \le k \le m$, all defined on a same finite set X of n elements (Régnier's problem [4] corresponds to the case for which all the relations S_k are equivalence relations; Zahn's problem [6] corresponds to the case for which m is equal to 1). We consider the number $\delta(R, S)$ of disagreements between two binary relations R and S:

$$\delta(R, S) = |\{(i, j) \in X^2 \text{ with } [iRj \text{ and not } iSj] \text{ or } [iSj \text{ and not } iRj]\}|.$$

Then, for any equivalence relation E, we consider the *remoteness* $\Delta(\Pi, E) = \sum_{k=1}^{m} \delta(S_k, E)$, measuring the total number of disagreements between Π and E. Our problem thus consists in computing an equivalence relation E^*, called a *median equivalence relation* of Π, which minimizes Δ over the set $\mathcal{E}$ of all the equivalence relations defined on X:

$$\Delta(\Pi, E^*) = \min_{E \in \mathcal{E}} \Delta(\Pi, E).$$

The computation of E^* is NP-hard [5], and remains so even for Régnier's problem or for Zahn's problem.

To state this problem as a 0-1 linear programming problem, let $s^k = (s^k_{ij})_{(i,j)\in X^2}$ ($1 \le k \le m$) be the binary vector defined by: $s^k_{ij} = 1$ if iS_kj (i.e. if i and j are put together by S_k), and $s^k_{ij} = 0$ otherwise. Similarly, let $(x_{ij})_{(i,j)\in X^2}$ denote the vector associated with E: $x_{ij} = 1$ if iEj, $x_{ij} = 0$ otherwise. It is easy to obtain the following:

$$\delta(S_k, E) = \sum_{(i,j)\in X^2} |s^k_{ij} - x_{ij}| = \sum_{(i,j)\in X^2} (s^k_{ij} - x_{ij})^2 = \sum_{(i,j)\in X^2} (s^k_{ij} + (1 - 2s^k_{ij})x_{ij})$$

because of the binary property of the quantities s^k_{ij} and x_{ij}. Then we obtain, for the remoteness:

$$\Delta(\Pi, E) = \sum_{k=1}^{m} \sum_{(i,j)\in X^2} s^k_{ij} + \sum_{k=1}^{m} \sum_{(i,j)\in X^2} (1 - 2s^k_{ij})x_{ij} = C + \sum_{(i,j)\in X^2} w_{ij}x_{ij}$$

where $C = \sum_{k=1}^{m} \sum_{(i,j)\in X^2} s^k_{ij}$ is a constant and with, for $(i, j) \in X^2$:

$$w_{ij} = \sum_{k=1}^{m} (1 - 2s^k_{ij}) = m - 2|\{k \text{ with } 1 \le k \le m \text{ and } iS_kj\}|.$$

So, minimizing $\Delta(\Pi, E)$ is the same as minimizing $\sum_{(i,j)\in X^2} w_{ij}x_{ij}$. Moreover, the constraints to state that E must belong to $\mathcal{E}$ are the following:

- symmetry: $\forall (i, j) \in X^2, x_{ij} = x_{ji}$;
- transitivity: $\forall (i, j, h) \in X^3$ with $i \ne j \ne h \ne i, x_{ij} + x_{jh} - x_{ih} \le 1$.

If we add the binary constraints: $\forall (i, j) \in X^2, x_{ij} \in \{0, 1\}$, we obtain our 0-1 linear programming problem.

We now may state this problem as a graph theoretic one. For this, we associate the complete graph K_n to Π, and we weight every edge $\{i, j\}$ of K_n by w_{ij}. Then the variables x_{ij} equal to 1 define cliques (i.e. complete subgraphs) of K_n, and the value of $\Delta(\Pi, E)$ is equal to the sum of the weights of the edges with both extremities inside a same clique. Hence our clique partitioning problem CPP. Note that the weights of the edges can be non-positive or non-negative integers. Moreover, the number of cliques into which we want to partition K_n is not given. Finally, CPP can be stated as follows: given a complete graph $K_n = (X, A)$ whose edges $\{i, j\}$ are weighted by non-positive or non-negative integers w_{ij}, partition X into p subsets X_1, X_2, ..., X_p, where p is not given, so that $\sum_{h=1}^{p} \sum_{(i,j) \in (X_h)^2} w_{ij}$ (i.e. the sum of the weights of the edges inside the cliques) is minimum.

3 The branch and bound method

To solve CPP, we design a branch and bound method BB. We briefly depict the main ingredients of BB.

The initial bound is provided by a metaheuristic, namely the *noising methods* [2], [3]. The noising methods usually compute very good solutions, quite often optimal, though we cannot know whether these solutions are indeed optimal.

The BB-tree is built as follows. The vertices v_i of K_n are integers belonging to $\{1, 2, ..., n\}$. A partition with p subsets X_1, X_2, ..., X_p is represented as:

$$\underbrace{v_1, v_2, ..., v_{q_1}}_{X_1} \,|\, \underbrace{v_{q_1+1}, v_{q_1+2}, ..., v_{q_2}}_{X_2} \,|...|\, \underbrace{v_{q_{p-1}+1}, v_{q_{p-1}+2}, ..., v_{q_p}}_{X_p}$$

With such an encoding, a partition admits several representations. To avoid this, we suppose that the vertices are ordered by increasing value within a subset and subsets are ordered according to their smallest vertices; with the above notation, it means that we have: $1 = v_1 < v_2 < ... < v_{q_1}$, $v_{q_1+1} < v_{q_1+2} < ... < v_{q_2}$, ..., $v_{q_{p-1}+1} < v_{q_{p-1}+2} < ... < v_{q_p}$, and $v_1 < v_{q_1+1} < ... < v_{q_{p-1}+1}$.

The subsets are progressively constructed. A node N of the BB-tree corresponds to the beginning of a partition encoding, something like:

$$\underbrace{v_1, v_2, ..., v_{q_1}}_{X_1} \,|\, \underbrace{v_{q_1+1}, v_{q_1+2}, ..., v_{q_2}}_{X_2} \,|...|\, \underbrace{v_{q_{h-1}+1}, v_{q_{h-1}+2}, ..., v_{q_{h-1}+t}}_{X_h}$$

We extend N by at most $n - q_{h-1} - t + 1$ new branches. The first branch is obtained by closing the current subset X_h and by creating a new subset X_{h+1} which will contain at least $v_{q_{h-1}+t+1}$. The other branches correspond with the possibilities to expand the current class X_h by adding an extra vertex (greater than $v_{q_{h-1}+t}$) to it: $v_{q_{h-1}+t+1}$, or $v_{q_{h-1}+t+2}$ but not $v_{q_{h-1}+t+1}$, or $v_{q_{h-1}+t+3}$ but neither $v_{q_{h-1}+t+1}$ nor $v_{q_{h-1}+t+2}$, and so on...

Three evaluation functions F_1, F_2, F_3 are designed to evaluate the quality of every node N of the BB-tree. They can be split into two parts. The first part is the same for the three functions: it takes into account the contribution of the vertices already dispatched inside the subsets of the partition under construction associated with N; for this, we only sum the weights of the edges with both extremities in a same subset. The second part depends on the function. For F_1, we add all the negative weights of the edges with at least one extremity greater than $v_{q_{h-1}+t}$. In F_2, we sharpen the design of F_1 by considering some triples of vertices (triangles) $\{a, b, c\}$ and by noting that if the weights of the edges between a, b and c have not the same sign, then the contribution of $\{a, b, c\}$ cannot be the sum of the negative edges, as in F_1; we design a greedy algorithm to choose these triangles in order to improve F_1 as much as possible. The last function, F_3, is the most sophisticated. It is based on the Lagrangean relaxation of the transitivity constraints (see above).

Other ingredients, not described here, allow us also to cut branches of the BB-tree. During the talk, we will discuss the efficiency of the evaluation functions and of the other ingredients, based on experiments dealing with different kinds of graphs: instances of Régnier's problem or of Zahn's problem, instances coming from the literature, random instances, or instances with special combinatorial or algorithmic properties.

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