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Vorwort

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Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

The capacitated single-allocation hub location problem revisited: A note on a classical formulation

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Abstract

In this paper a well-known formulation for the capacitated single-allocation hub location problem is revisited. An example is presented showing that for some instances this formulation is incomplete. The reasons for the incompleteness are identified leading to the inclusion of an additional set of constraints. Computational experiments are performed showing that the new constraints also help to decrease the computational time required to solve the problem optimally.

Keywords: Capacitated Hub Location, MIP formulations.

1 Introduction

Denote by $G = (N, A)$ a complete graph where N is the set of nodes and A is the set of edges. Assume that a flow w_{ij} should be sent from each node i to each node j $(i, j \in N)$. One possibility is to send these flows directly between the corresponding pairs of nodes. However, in practice this is often neither efficient nor costly attractive because it would imply that a link was built between each pair of nodes. An alternative is to select some nodes to become hubs and use them as consolidation and redistribution points that altogether process more efficiently the flow in the network. Accordingly, hubs are nodes in the graph that receive traffic (mail, phone calls, passengers, etc) from different origins (nodes) and redirect this traffic directly to the destination nodes (when a link exists) or else to other hubs. The concentration of traffic in the hubs and its shipment to other hubs lead to a natural decrease in the overall cost due to economies of scale.

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The problem of deciding which nodes should become hubs and how the flow in the network should be consolidated and redistributed defines the basic setting of a hub location problem. When a non-hub node has to be assigned to exactly one hub, we face a so-called single-allocation hub location problem. It is also the case in many situations that a limit exists on the maximum amount of flow that can be processed in each hub. This limit may vary from hub to hub and often refers to the incoming flow because in many applications this is the flow that has to be processed in the hubs.

As its name indicates, the capacitated single-allocation hub location problem (CSAHLP) is a single-allocation hub location problem in which hubs have capacity limits.

The CSAHLP has been addressed in numerous papers in the literature. Campbell [2] presents the first mixed integer linear programming (MILP) formulation for the problem. Ernst and Krishnamoorthy [7] extend the formulation that had been proposed by Skorin-Kapov et al. [11] for an uncapacitated version of the problem to the capacitated case and also propose a new MILP formulation, which is an adaptation to the CSAHLP of a formulation that the same authors had proposed for the uncapacitated p-hub median problem (Ernst and Krishnamoorthy [5, 6]). In Ernst and Krishnamoorthy [7] a solution approach based on Simulated Annealing is proposed. The bounds obtained are embedded in a branch-and-bound procedure devised for solving the problem optimally. Labbé *et al* [9] studied a CSAHLP where there is a capacity on the flow that transverses each hub. A branch-and-cut algorithm is proposed for this problem. Costa *et al* [4] present a bi-objective approach. They enlarge the model proposed by Ernst and Krishnamoorthy [7] with the addition of a second objective function to be minimized that quantifies the time to process the flow entering the hubs. More recently, Contreras *el al* [3] present a lagrangean relaxation enhanced with reduction tests that allows the computation of tight upper and lower bounds for a large set of instances. The reader is referred to the recent review by Alumur and Kara [1] for a more detailed overview of the existing literature on this problem.

Among the existing formulations for the CSAHLP, the one that is often considered the most effective is the one proposed in 1999 by Ernst and Krishnamoorthy [7] that, as mentioned above, was based on a formulation that the same authors have developed for the uncapacitated p-hub median problem (Ernst and Krishnamoorthy [5, 6]). In this formulation, two types of decision variables are considered: y_{kl}^{i} $(i, k, l \in N)$ is the amount of flow originated at node i that is routed between hubs k and l; z_{ik} $(i, k \in N)$ is a binary variable that is equal to 1 if node i is assigned to hub k and zero otherwise. For $k \in N$, $z_{kk} = 1$ means that node k is selected to be a hub. The formulation is the following:

$$(EK) \quad min \quad \sum_{i \in N} \sum_{k \in N} d_{ik} \left(\chi O_i + \delta D_i \right) z_{ik} + \sum_{i \in N} \sum_{k \in N} \sum_{l \in N} \alpha d_{kl} y_{kl}^{i} + \sum_{k \in N} f_k z_{kk} \tag{1}$$

$$
\begin{aligned}
s.t. \quad & \sum_{k \in N} z_{ik} = 1 \qquad i \in N & (2)\\
& z_{ik} \le z_{kk} \qquad i,k \in N & (3)\\
& \sum_{i \in N} O_i z_{ik} \le \Gamma_k z_{kk} \qquad k \in N & (4)\\
& \sum_{l \in N} y^i_{kl} - \sum_{l \in N} y^i_{lk} = O_i z_{ik} - \sum_{j \in N} w_{ij} z_{jk} \qquad i,k \in N & (5)\\
& z_{ik} \in \{0,1\} \qquad i,k \in N & (6)\\
& y^i_{kl} \ge 0 \qquad i,k,l \in N & (7)
\end{aligned}
$$

In this formulation, d_{ij} is the distance between nodes i and j $(i, j \in N)$ (it is assumed that these distances satisfy the triangular inequality and also that $d_{ii} = 0$ $(i \in N)$); α is the cost per unit of flow and per unit of distance between hubs (this value is usually known as discount factor or transfer cost and it is often assumed $0 \le \alpha < 1$); χ is the cost per unit of flow and per unit of distance between a non-hub node and a hub (this value is usually known as collection cost); δ is the cost per unit of flow and per unit of distance between a hub and a non-hub node (this cost is usually known as distribution cost); f_k is the fixed cost for installing a hub at node k $(k \in N)$; Γ_k is the capacity of a hub installed at node k $(k \in N)$; O_i is the total flow originating at node i $(i \in N)$ that is, $O_i = \sum_{j \in N} w_{ij}$ and finally, D_i is the total flow destined for node i $(i \in N)$ that is, $D_i = \sum_{j \in N} w_{ji}$.

In formulation EK, the objective function evaluates the overall cost which consists of three parts: i) the cost for routing the flow from the nodes to the hubs and the other way round, ii) the cost for routing the flow between hubs and iii) the cost for installing the hubs. Constraints (2) assure that all nodes are hubs or are assigned to a single hub. Constraints (3) guarantee that the nodes can only be assigned to existing hubs. Constraints (4) refer to the capacity of the hub whereas constraints (5) are divergency equations at node k for flow associated with node i. (6) and (7) are domain constraints. In this formulation, demand and supply at the nodes is determined by the allocation variables z_{ik}.

Formulation EK appeared as a compromise between the formulation proposed by Campbell [2] (which has a set of very weak constraints) and the adaptation to the CSAHLP of the formulation proposed by Skorin-Kapov et al. [11] for the uncapacitated case (which overcomes the weakness of the formulation proposed by Campbell [2] but leads to a too heavy formulation).

The computational experience reported in Ernst and Krishnamoorthy [7] using the AP data set (which is a set of benchmark data introduced by Ernst and Krishnamoorthy [5, 6]) supports the argument that the formulation EK is the most effective for the CSAHLP. Accordingly, it is not surprising that this formulation has been used as a basis for several extensions of the problem (see for instance the recent work by Costa et al. [4]).

2 Incompleteness of the formulation

Despite being a well-known and well-established formulation for the CSAHLP, formulation EK may not give a correct description of the set of feasible solutions to the problem. This is a fact that the authors of the current paper came across while making some experiments with certain instances of hub location problems. We present the relevant part of one of these problem instances.

Example 1 *Consider an instance of the CSAHLP with 6 nodes and the following data:*

$$D = [d_{ij}]_{i,j \in N} = \begin{bmatrix} 0 & 33 & 57 & 96 & 61 & 49 \\ 33 & 0 & 90 & 64 & 63 & 75 \\ 57 & 90 & 0 & 131 & 59 & 25 \\ 96 & 64 & 131 & 0 & 73 & 105 \\ 61 & 63 & 59 & 73 & 0 & 33 \\ 49 & 75 & 25 & 105 & 33 & 0 \end{bmatrix}$$

$$W = [w_{ij}]_{i,j \in N} = \begin{bmatrix} 0 & 1749 & 2278 & 1482 & 1024 & 11238 \\ 1717 & 0 & 754 & 490 & 339 & 3721 \\ 2242 & 756 & 0 & 641 & 442 & 4860 \\ 1453 & 490 & 638 & 0 & 287 & 3149 \\ 1001 & 337 & 439 & 286 & 0 & 2170 \\ 11618 & 3918 & 5103 & 3321 & 2294 & 0 \end{bmatrix}$$

$\Gamma = [203442 \quad 68619 \quad 89365 \quad 58161 \quad 40175 \quad 440864]$

$f = [9744043 \quad 5316914 \quad 4234248 \quad 3906360 \quad 2271056 \quad 13686108]$

$\chi = 3.00$, $\alpha = 0.75$, $\delta = 2.00$.

This instance resulted from a modification of the 81-node instance studied by Tan and Kara [12] (available in the OR Library [10]) in such a way that a small instance more suited for illustrative purposes was obtained.

In the optimal solution of the 6-node instance introduced, the z-variables equal to one are the following: z_{13}, z_{25}, z_{33}, z_{45}, z_{55}, z_{63}. This leads to the optimal network structure depicted in Figure 1, in which the squares represent hubs and the circles refer to non-hub nodes.

Also in the optimal solution we have the following values for the non-zero flow variables:

$$\begin{array}{rcrcrcr} y^1_{33} & = & 13516 & \quad & y^1_{35} & = & 4255 \\ y^2_{53} & = & 6192 & & y^2_{55} & = & 829 \\ y^3_{33} & = & 7102 & & y^3_{35} & = & 1839 \\ y^4_{53} & = & 5240 & & y^4_{55} & = & 777 \\ y^5_{53} & = & 3610 & & y^5_{55} & = & 623 \\ y^6_{33} & = & 16721 & & y^6_{35} & = & 9533 \end{array}$$

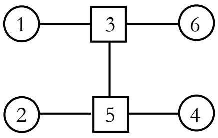

Figure 1: *Optimal network structure for the illustrative instance.*

The optimal value of this instance is 20649044.25*.*

Using formulation EK*, the same optimal network structure would be obtained or, in other words, the variables* z *equal to one in the optimal solution are the same as before. However, in terms of the non-zero flow variables the solution would be*

$$\begin{array}{lcllcl}
y_{36}^{1} & = & 4255 & y_{65}^{1} & = & 4255 \\
y_{56}^{2} & = & 6192 & y_{63}^{2} & = & 6192 \\
y_{36}^{3} & = & 1839 & y_{65}^{3} & = & 1839 \\
y_{56}^{4} & = & 5240 & y_{63}^{4} & = & 5240 \\
y_{56}^{5} & = & 3610 & y_{63}^{5} & = & 3610 \\
y_{36}^{6} & = & 9533 & y_{65}^{6} & = & 9533
\end{array}$$

and the optimal value of the problem would come: 20626042.50*.*

A close observation of this solution shows that it represents a meaningless outcome. ♦

Not only does the previous example show that formulation EK may not give a correct description of the set of feasible solutions to the CSAHLP but it also gives clear indications for the reason why this happens.

In fact, observing closely the solution produced by formulation EK we realize that it allows a variable y_{kl}^{i} to be different from zero while variable z_{ik} is zero. At a first glance this might seem surprising because one might expect that in constraints (5) at most one sum in the left side was different from zero, which would be enough to assure that no variable y_{kl}^{i} is different from 0 with $z_{ik} = 0$. However, nothing in the formulation prevents this situation to occur. It is on the contrary. Due to the fact that variables y appear only in constraints (5) nothing prevents an outcome in which the cost structure makes attractive a solution such that the left side of constraints (5) is equal to zero with some of the y-variables involved being different from zero. In fact, this may allow the z variables involved in the constraint to become zero leading to a decrease in the overall cost. In the previous example, this is the case for instance with the pair $(i = 1, k = 6)$.

Accordingly, it becomes clear that the set of feasible solutions to formulation EK does not necessarily coincide with the set of feasible solutions to the CSAHLP. Therefore, this formulation may allow infeasible points to the CSAHLP. Moreover, in terms of the CSAHLP, the feasibility of the optimal solution of model EK becomes dependent on the data structure, which may make a non-feasible solution costly attractive. It should be noted that this is not the case with the instances generated from the AP data set, which have been the instances with which formulation EK has been tested.

It is important to emphasize that the formulation for the CSAHLP proposed by Campbell [2] and also the formulation presented by Ernst and Krishnamoorthy [7] that is based upon the formulation by Skorin-Kapov et al. [11] do not have the problem reported above.

3 The missing cuts

The illustrative example presented in the previous section gives also an indication of a possibility to overcome the flaw in formulation EK. In fact, taking into account that the formulation allows a variable y^i_{kl} to be different from zero with z_{ik} equal to zero, the following set of constraints appear to be a natural way for preventing this to occur:

$$\sum_{l \in N} y^i_{kl} \leq O_i z_{ik}, \qquad i, k \in N \tag{8}$$

Result 1 *Formulation* EK + (8) *gives a complete description of problem CSAHLP.*

Proof: A feasible solution to the CSAHLP is characterized by three components: i) the nodes selected to become hubs; ii) the allocation of the non-hub nodes to the hubs and iii) the flows, which not only must respect the capacity of the hubs but also should assure that the quantities to be delivered between each pair of nodes are achieved.

It is straightforward to verify that every feasible solution for the CSAHLP is such that all constraints (2), (3), (4), (5), (6), (7), and (8) are satisfied (and therefore, this would also be true considering only the constraints in formulation EK).

The goal is then to show that a solution satisfying (2), (3), (4), (5), (6), (7), and (8) is feasible to the CSAHLP.

Constraints (2) assure that all nodes are hubs or else are allocated to some hubs. Constraints (3) assure that a (non-hub) node can only be allocated to an existing hub. Therefore, constraints (2) and (3) together assure a correct definition of the network structure namely the hubs and the allocation of the non-hubs to hubs.

Constraints (4) assure that the capacity of the hubs is not violated. In fact, the left hand side in these constraints represents the amount that will be sent to each hub; the right hand side states that the capacity of a hub k is Γ_k if node k is a hub ($z_{kk} = 1$) and 0 otherwise.

Finally, we only have to verify that the flows in the network are correctly defined by constraints (5) and (8).

Constraints (8) assure that flow can only be sent from a node i to a hub k (and afterwards to another hub l) if in fact i is allocated to k (which in turn can only be the case if k is a hub). The example presented in the previous section shows that formulation EK did not prevent this to happen.

Consider now constraints (5) and in particular, consider a pair $i, k \in N$. Two cases can occur:

i) $z_{ik} = 1$. In this case, node i is allocated to hub k. Accordingly, only the first sum in the left side of the constraints will be different from 0 which is assured by constraints (2) and (8) together. Note this would not be necessarily the case without constraints (8), as the example in section 2 shows. Therefore, the left hand side of constraints (5) gives the total flow sent from node i via hub k to other hubs l. In fact, this flow must be equal to all the flow originated in i minus the flow originated in i that is destined to nodes also allocated to hub k.

ii) $z_{ik} = 0$. In this case, due to constraints (8), the first sum in the left hand side of (5) is equal to zero. In such a situation, this constraint assures that all flow originated in i with destination j allocated to k should be sent via some other hub before arriving at hub k.

In any case, constraints (5) and (8) together assure that the flows are well defined in the network. $\square$

Remarks:

1. By assuring that a variable y^i_{kl} can only be different from zero if z_{ik} is equal to one, constraints (8) together with constraints (2) also assure that it is not possible to have both sums in the left side of constraints (5) different from zero. This is the key feature that was missing in formulation EK. In fact, now, even if the cost structure encourages a compensation effect in the left side of constraints (5), this can not occur in the presence of (8).

2. Note that in constraints (8) we could have considered "$=$" instead of "$\leq$".

It is interesting to observe that not only are constraints (8) important to assure the completeness of the formulation but also they can help decreasing the CPU time required to obtain the optimal solution for instances of the CSAHLP in which formulation EK gives the optimal solution. This conclusion was drawn after a computational experience using the instances from the AP data set (Ernst and Krishnamoorthy [5, 6]) was performed. The results are reported in table 1 and were obtained using the general solver ILOG CPLEX 11.2 [8]. No change was made in the solver default parameters. Two formulations were considered in this experimentation: formulation EK (which leads to the optimal solutions when the instances in the AP data set are considered) and formulation $EK + (8)$. The tests were performed in a machine with a processor with 2.9 GHz and 2 GB of RAM.

In table 1, for each formulation we present the CPU time in seconds that was required to solve optimally the instance as well as the number of nodes analyzed in the branch tree. Instance 50TT led to an out of memory error using both formulations. The final gap upon termination was 5.65% using formulation EK and 5.56% using EK+(8). We do not report in the table the CPU time required to solve the linear relaxation of both models because it was not significant: An average of 0.66 seconds was achieved with formulation EK and 0.70 seconds with formulation EK+(8).

In table 1 we can observe that for the smaller instances the CPU time required by formulation $EK + (8)$ is comparable with the CPU time required by formulation EK. However, for the largest instances, the former formulation clearly outperforms the latter. In terms of the number of nodes, the superiority of formulation $EK + (8)$ is clear. These results give an indication that even in the instances in which model EK gives a correct optimal solution to CSAHLP (which is the case with the instances in the AP data set), model $EK + (8)$ can do it faster.

4 Conclusion

In this note we have shown that a well-known formulation for the CSAHLP, which is also considered in the literature as the most effective, is not complete and under certain data leads to infeasible results. We were able to complete the formulation by the introduction of a new set of constraints which also turned out to be computationally very effective as a cut.

It would be interesting to revisit the work that has been produced considering formulation EK as the basis and see the effect of using this new cut (e.g. the p-hub median problem studied by Ernst and Krishnamoorthy [5]).

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	Formulation EK		Formulation EK+(8)	
Instance	CPU (seconds)	# nodes	CPU (seconds)	# nodes
10LL	<1	0	<1	0
10LT	<1	3	<1	0
10TL	<1	2	<1	0
10TT	<1	0	<1	0
20LL	<1	0	<1	0
20LT	1	23	2	15
20TL	<1	0	<1	0
20TT	1	59	1	25
25LL	1	9	2	7
25LT	2	37	3	29
25TL	<1	5	<1	0
25TT	2	99	3	65
40LL	5	25	5	18
40LT	8	28	8	19
40TL	5	3	3	0
40TT	135	1034	35	694
50LL	7	13	6	0
50LT	148	637	38	238
50TL	26	75	17	35
50TT	o.m.	—	o.m.	—
Average	18	108	6	60

Table 1: Computational experience performed with formulations EK and $EK + (8)$.

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