"A SET PARTITIONING HEURISTIC FOR THE GENERALIZED ASSIGNMENT PROBLEM"

by

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A Set Partitioning Heuristic for the Generalized Assignment Problem

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Abstract

This paper discusses a heuristic for the generalized assignment problem (GAP). The objective of GAP is to minimize the costs of assigning J jobs to M capacity constrained machines, such that each job is assigned to exactly one machine. The problem is known to be NP-Hard, and it is hard from a computational point of view as well. The heuristic proposed here is based on column generation techniques, and yields both upper and lower bounds. On a set of relatively hard test problems the heuristic is able to find solutions that are on average within 0.13% from optimality.

Keywords: generalized assignment problem, set partitioning, column generation, dual ascent.

1 Introduction

The generalized assignment problem (GAP) is the problem of determining an assignment of J jobs to M capacity constrained machines, such that each job is assigned to exactly one machine, while total costs are minimized. It has applications in e.g. routing (Fisher and Jaikumar, 1981), grouping and loading for flexible manufacturing systems (Mazolla, Neebe, and Dunn, 1988), design of communication networks (Grigoriadis, Tang and Woo, 1974), and job scheduling in computer networks (Balachandran, 1976).
Mathematically, GAP is formulated as:

$$Z_{GAP} = \min \sum_{j=1}^{J} \sum_{m=1}^{M} c_{j,m} x_{j,m} \tag{1}$$

subject to

$$\sum_{j=1}^{J} a_{j,m} x_{j,m} \leq b_m \qquad m = 1, \ldots, M \tag{2}$$

$$\sum_{m=1}^{M} x_{j,m} = 1 \qquad j = 1, \ldots, J \tag{3}$$

$$x_{j,m} \in \{0, 1\} \qquad j = 1, \ldots, J;\ m = 1, \ldots, M \tag{4}$$

where decision variables $x_{j,m}$ are equal to one when job j is assigned to machine m, and zero otherwise. Furthermore, $c_{j,m}$ is the cost, and $a_{j,m}$ the capacity used when assigning job j to machine m. The total capacity of machine m equals b_m.
The objective (1) states that total costs are to be minimized, while restrictions (2) and (3) ensure that machine capacity is not violated and each job is processed exactly once. Constraints (4) state that decision variables are binary.

There exists a broad literature on GAP. Fisher, Jaikumar and Van Wassenhove (1986) show that GAP is NP-hard. Exact and approximation algorithms for solving GAP have been suggested by Ross and Soland (1975), Klastorin (1979), Martello and Toth (1981), Benders and van Nunen (1983), Fisher, Jaikumar and Van Wassenhove (1986), Jörnsten and Näsberg (1986), Guignard and Rosenwein (1987), Wilcox (1989), among others. For an extended review on GAP the reader is further referred to Cattrysse and Van Wassenhove (1990), and Martello and Toth (1990).
Computational experiments reported in literature show that the above-mentioned procedures are rather effective in solving certain categories of GAP instances. However, for the more difficult highly capacitated problems (for which $\frac{1}{M}\sum_{m=1}^{M}\sum_{j=1}^{J} a_{j,m} \approx \sum_{m=1}^{M} b_m$) the average deviation of the heuristic solution from optimality may become considerable. Moreover, computation times for optimal solution methods may become prohibitively large.
In this paper we propose a column generation heuristic which attempts to fill this gap, in that it generates extremely good quality solutions, while computation times -although perhaps large for a heuristic- are nowhere near the times required to find an optimal solution.
The paper is organized as follows. Section 2 outlines the basic components of the heuristic. In Section 3 (Section 4) we describe the way in which the heuristic generates lower (upper) bounds. Section 5 presents the results of a computational study, while in Section 6 some conclusions are drawn.

2 Column generation

The heuristic we propose is based on column generation. A column represents a feasible assignment of a subset of jobs to a single machine. The *master problem* is formulated as a Set Partitioning Problem (SPP):

$$Z_{SPP} = \min \sum_{m=1}^{M}\left(\sum_{n=1}^{N_m} d_m^{(n)} y_m^{(n)} + B s_m\right) \tag{5}$$

subject to

$$\sum_{m=1}^{M}\sum_{n=1}^{N_m} \alpha_{j,m}^{(n)} y_m^{(n)} = 1 \qquad j = 1,\dots,J \tag{6}$$

$$\sum_{n=1}^{N_m} y_m^{(n)} + s_m = 1 \qquad m = 1,\dots,M \tag{7}$$

$$y_m^{(n)}, s_m \in \{0,1\} \qquad m = 1,\dots,M;\ n = 1,\dots,N_m \tag{8}$$

In this model formulation the total number of columns generated for machine m is denoted by N_m. The decision variable $y_m^{(n)} = 1$ if the n-th column (schedule) is implemented for machine

m, and $y_m^{(n)} = 0$ otherwise. If no feasible column for machine m is found, the corresponding slack variable $s_m = 1$ and a cost equal to Bs_m (B some large number) is added to the objective, such that $Z_{SPP} \geq B$ whenever a GAP instance is infeasible. Furthermore, $d_m^{(n)}$ represents the cost of the n-th schedule for machine m, while $\alpha_{j,m}^{(n)} = 1$ if job j is assigned to machine m in the n-th schedule, and $\alpha_{j,m}^{(n)} = 0$ otherwise. New columns (schedules) for the master problem are generated by solving for each machine m the following knapsack problem $KP_m(u)$:

$$Z_{KP_m}(u) = \min \sum_{j=1}^{J} (c_{j,m} - u_j) z_j \tag{9}$$

subject to

$$\sum_{j=1}^{J} a_{j,m} z_j \leq b_m \tag{10}$$

$$z_j \in \{0,1\} \qquad j = 1, \ldots, J \tag{11}$$

In $KP_m(u)$ the decision variable $z_j = 1$ if job j is assigned to machine m, and $z_j = 0$ otherwise. Furthermore, $u = (u_1, \ldots, u_J)$ is the vector of dual variables corresponding to (6) in the LP-relaxation of SPP, denoted by LP(SPP). In order to solve KP_m to optimality, we use the branch-and-bound procedure suggested by Fayard and Plateau (1984). It is well known that $Z_{GAP} = Z_{SPP}$ when all columns have been generated. However, since the number of feasible columns is often prohibitively large, we apply a heuristic procedure in order to compute upper- and lower bounds to Z_{SPP}. In Section 3 (Section 4) we describe these lower (upper) bounding procedures.

3 Lower bounding procedure

A lower bound can be obtained by solving LP(SPP) using the column generation procedure stated below.

Column Generation Procedure:

Initialisation: Generate starting solution using *(i)* columns generated by the heuristic of Martello and Toth (1981), and *(ii)* randomly generated columns.

Step 1: Solve LP(SPP) and pass dual multipliers u to the subproblems $KP_m(u)$.

Step 2: Generate one new column for each machine $m = 1, \ldots, M$, by solving $KP_m(u)$. If the column *prices out* when compared to the dual variables δ_m corresponding to (7), i.e. when $Z_{KP_m}(u) < \delta_m$, then add the column to the master problem. If no column prices out, then STOP. Otherwise, return to Step 1.

The lower bound obtained at the end of the column generation procedure dominates the bound obtained from solving the LP-relaxation to GAP, since the integrality property does not apply to the knapsack problems KP_m (see Geoffrion, 1974). Furthermore, $Z_{LP(SPP)}$ is equal to the bound obtained by applying Lagrangean relaxation to the assignment constraints (3) of GAP, and subsequently solving the remaining Lagrangean dual problem to optimality. Computational studies performed by e.g. Chalmet and Gelders (1976), and Fisher, Jaikumar, and Van Wassenhove (1986) show that this bound tends to be rather tight in practice. We have opted to implement the column generation procedure instead of the Lagrangean approach, since in many computational studies the method has shown to converge rather quickly.

A problem in solving LP(SPP) using the simplex method is, that LP(SPP) is highly degenerate, yielding many alternative dual optimal solutions. Aucamp and Steinberg (1982) argue that the standard simplex method, available in LP-packages, will find one of the extreme points of the polytope related to the dual problem, although convex combinations are acceptable too. In such situations a dual ascent heuristic has proven to be successful in finding appropriate values for the dual variables in many computational studies. Therefore we replace Step 1 of the column generation procedure by a heuristic dual-ascent procedure. Before we state the dual ascent procedure in detail, we first consider the dual of LP(SPP), ($LP\widehat{(SPP)}$), which is formulated as follows:

$$Z_{LP\widehat{(SPP)}} = \max \sum_{j=1}^{J} u_j + \sum_{m=1}^{M} \delta_m \qquad (12)$$

subject to

$$\sum_{j=1}^{J} \alpha_{j,m}^{(n)} u_j + \delta_m \le d_m^{(n)} \qquad m = 1, \ldots, M;\ n = 1, \ldots, N_m \quad (13)$$

$$u_j \text{ unrestricted }, \delta_m \ge 0 \qquad j = 1, \ldots, J;\ m = 1, \ldots, M \quad (14)$$

The dual ascent procedure tries to decrease one u_j variable while increasing several δ_m variables in such a way that the dual objective function (12) increases while maintaining dual feasibility with respect to (13) and (14). The procedure is summarized as follows:

Dual Ascent Procedure (Multiplier Adjustment Procedure):

Initialisation: Let dual variables u be predetermined and compute dual variables δ as:

$$\delta_m = \begin{cases} 0 & \text{if } \mu_m < 0 \\ B & \text{if } \mu_m > B \\ \mu_m & \text{otherwise} \end{cases}$$

where $\mu_m = \min_n \{d_m^{(n)} - \sum_{j=1}^{J} \alpha_{j,m}^{(n)} u_j\}$. Furthermore, let $\pi_m^{(n)}$ be the slack variables defined as $\pi_m^{(n)} = d_m^{(n)} - \sum_{j=1}^{J} \alpha_{j,m}^{(n)} u_j - \delta_m$.

Step 1: Let $\mathcal{N}_{j,m}$ be the set of columns for which $\alpha_{j,m}^{(n)} = 0$ and define $\mathcal{M}_j^{(1)} = \{m \mid \mathcal{N}_{j,m} = \emptyset\}$. Compute $\gamma_{j,m} = \min_{n \in \mathcal{N}_{j,m}} \pi_m^{(n)}$ and let $\mathcal{M}_j^{(2)}$ be the set of machines for which $\gamma_{j,m} > 0$. Set $\beta_j = \min[\min_{m \in \mathcal{M}_j^{(1)}} \{B - \delta_m\}, \min_{m \in \mathcal{M}_j^{(2)}} \{\gamma_{j,m}, B - \delta_m\}]$. Let $\mathcal{M}_j = \mathcal{M}_j^{(1)} \cup \mathcal{M}_j^{(2)}$ and determine $j^* = \arg\max_j \beta_j(|\mathcal{M}_j| - 1)$

Step 2: Update $u_{j^*} := u_{j^*} - \beta_{j^*}$ and $\delta_m := \delta_m + \beta_{j^*}$ for all $m \in \mathcal{M}_{j^*}$. Moreover, update slack variables $\pi_m^{(n)} := \pi_m^{(n)} - \beta_{j^*}$ for all $m \in \mathcal{M}_{j^*}$ and $n \in \mathcal{N}_{j^*,m}$. If $\beta_{j^*} > 0$ go to Step 1, otherwise STOP.

Since the dual ascent procedure does not usually reach the optimum to the dual of LP(SPP), we attempt to improve upon the lower bound using a subgradient optimization procedure[1]. In order to do so, we define LR(SPP) as the Lagrangean problem corresponding to the relaxation of constraints (6) of SPP. Mathematically, LR(SPP) is formulated as:

LR(SPP):

$$Z_{LR(SPP)}(u) = \min \sum_{m=1}^{M} \left(\sum_{n=1}^{N_m} (d_m^{(n)} - \sum_{j=1}^{J} \alpha_{j,m}^{(n)} u_j) y_m^{(n)} + B s_m \right) + \sum_{j=1}^{J} u_j \tag{15}$$

subject to

(7), (8)

The dual variables u are updated for a fixed number of iterations using *subgradient optimization*:

$$u_j := u_j + \lambda \left(1 - \sum_{m=1}^{M} \sum_{n=1}^{N_m} \alpha_{j,m}^{(n)} y_m^{(n)} \right) \quad \text{for } j = 1,..,J.$$

where λ is a positive scalar step size, determined as:

$$\lambda = \frac{\omega(UB - Z_{LR(SPP)}(u))}{\sum_{j=1}^{J} \left(1 - \sum_{m=1}^{M} \sum_{n=1}^{N_m} \alpha_{j,m}^{(n)} y_m^{(n)}\right)^2}$$

The scalar ω is initialized at 1.5 and halved whenever the lower bound has failed to increase for some fixed number of iterations. The initial upper bound (UB) is given by the best known solution to GAP so far (see Section 4). During the subgradient optimization procedure new lower bounds are obtained from solving LR(SPP) for each set of dual variables u. Note that LR(SPP) can be solved by simple inspection, using the rule:

$$y_m^{(n)} = \begin{cases} 1 & \text{if } \min_\ell \{d_m^{(\ell)} - \sum_{j=1}^{J} \alpha_{j,m}^{(\ell)} u_j\} < B \text{ and} \\ & \text{this minimum is obtained for } \ell = n. \\ 0 & \text{otherwise.} \end{cases}$$

[1]In our computational study (Section 5) it appears that on average 70% of the duality-gap is closed by the dual-ascent routine, while the remaining gap is closed by the subgradient procedure.

and $s_m = 1$ if $y_m^{(n)} = 0$ for all $n = 1, .., N_m$ and $s_m = 0$ otherwise.
The Dual Ascent Column Generation Procedure can now be summarized as follows:

Dual Ascent Column Generation Procedure:

Initialisation: Generate starting solutions using the aforementioned heuristic of Martello and Toth (1981) and randomly generated columns. Set $u_j = c_{j,m}$ if $x_{j,m} = 1$ in the starting solution.

Step 1: Use the Dual Ascent Procedure to update dual variables u, starting with dual variables u obtained in the preceding iteration. Then apply 100 iterations of the subgradient optimization. Pass on the (approximately optimal) dual variables u to the subproblems $KP_m(u)$.

Step 2: Generate one new column for each machine $m = 1, \ldots, M$, by solving $KP_m(u)$. If the column prices out then add the column to the master problem. If no column prices out, then STOP. Otherwise, return to Step 1.

4 Finding a primal feasible solution

Upper bounds are obtained in two different ways. First, a feasible solution to SPP, and consequently also to GAP, may be found by coincidence during the column generation procedure, when performing the subgradient optimization procedure. In what follows we denote an upper bound obtained in this way by $UB^{(1)}$. Second, at the end of the column generation procedure we search for a feasible solution among the columns generated so far, using the enumeration procedure due to Garfinkel and Nemhauser (1969). However, this procedure turns out to be too time consuming for larger sized problem instances. In order to reduce computational efforts, we try to eliminate some columns (schedules) based on their reduced costs. This is done using the following reduction scheme:

Reduction Scheme:

Step 1: Solve LP(SPP) using the Dual-Ascent Column Generation Procedure.

Step 2: Assign jobs j to machines m for which $\sum_{n=1}^{N_m} \alpha_{j,m}^{(n)} y_{j,m}^{(n)} = 1$ in the solution to LP(SPP). Let the cost corresponding to these fixed assignments be equal to Z_F. Eliminate fixed jobs from the original GAP instance, and adjust the input parameters (problem dimensions and machine capacity) accordingly. Call the resulting problem GAP_R.

Step 3: Solve GAP_R using the Dual Ascent Column Generation Procedure as described in Section 3. Apply the procedure due to Garfinkel and Nemhauser to GAP_R in order to obtain an integer solution. Let this integer solution be equal to Z_{GAP_R}. Compute the upper bound $UB^{(2)} = Z_F + Z_{GAP_R}$.

Step 4: Eliminate all columns for which $\pi_m^{(n)} > \min\{UB^{(1)}, UB^{(2)}\} - Z_{LP(SPP)} - 1$. Call the reduced problem $SPP^{(R)}$. Solve the reduced problem $SPP^{(R)}$, using the Garfinkel and Nemhauser enumeration scheme. This yields a third upper bound $UB^{(3)}$.

Finally, our heuristic integer solution H is obtained by putting $UB^H = \min\{UB^{(1)}, UB^{(2)}, UB^{(3)}\}$.

5 Computational results

We have implemented our heuristic in Microsoft-FORTRAN version 4.0 on an IBM PS/2 Model 80, with 16 Mhz and a 80387 mathematical co-processor. To investigate the effectiveness of the proposed heuristic, we apply it to a set of randomly generated test problems. The problems are generated based on the following characteristics:

- the number of machines M equals 5, 8 and 10, while the ratio $R = \frac{J}{M}$ is set to 3,4,5 and 6, to fix the number of jobs J,
- cost coefficients $c_{j,m}$ are taken from a discrete uniform distribution $DU(15, 25)$, capacity absorption coefficients $a_{j,m} \sim DU(5, 25)$, and machine capacity coefficients $b_m = \frac{0.8}{M} \sum_j a_{j,m}$.

For each machine/job combination we generate 5 problems, yielding 60 problems in total. The test-problems obtained in this way are highly capacitated. From literature it is known that these types of problems are difficult from a computational point of view (see Martello and Toth, 1990).

	lower bounds			*upper bounds*					
problem	LP(GAP)	MAM	LP(SPP)	MT		MT-BB		H	
set	$\Delta_{LP(GAP)}$	Δ_{MAM}	$\Delta_{LP(SPP)}$	Δ_{MT}	O	Δ_{MT-BB}	O	Δ_H	O
M05R3	3.75	3.82	0.21	5.95	0	0.00	5	0.08	4
M05R4	2.82	2.21	0.13	4.60	0	0.00	5	0.11	4
M05R5	1.11	1.86	0.01	4.27	0	0.00	5	0.09	3
M05R6	1.40	2.38	0.19	5.64	0	0.76	3	0.04	4
M08R3	2.20	1.96	0.19	6.46	0	0.75	3	0.35	4
M08R4	1.55	1.68	0.18	6.48	0	4.49	0	0.15	1
M08R5	0.88	1.44	0.09	4.72	0	3.70	0	0.00	5
M08R6	0.83	2.68	0.10	6.08	0	5.06	0	0.23	2
M10R3	1.88	2.05	0.21	6.47	0	4.05	1	0.12	3
M10R4	1.08	1.58	0.08	4.21	0	3.49	0	0.25	3
M10R5	0.71	0.79	0.10	4.51	0	3.76	0	0.00	5
M10R6	0.43	0.75	0.06	4.16	0	3.91	0	0.10	2
Average	1.49	1.93	0.13	5.30		2.50		0.13	

Table 1. Quality of upper- and lower bounds

	lower bounding procedure			total procedure		
problem set	LP(GAP)	MAM	LP(SPP)	MT	MT-BB	H
M05R3	0.83	0.83	8.54	≤ 1	21	9.79
M05R4	1.67	1.67	18.33	≤ 1	190	21.46
M05R5	2.29	2.71	32.50	≤ 1	7371	36.25
M05R6	3.33	5.42	66.67	≤ 1	15497	73.75
M08R3	4.37	2.29	18.33	≤ 1	12147	30.62
M08R4	6.67	7.08	60.62	≤ 1	18000	94.37
M08R5	9.58	17.29	101.87	≤ 1	18000	110.00
M08R6	13.12	16.46	235.83	≤ 1	18000	363.96
M10R3	8.54	4.79	34.58	≤ 1	18000	146.67
M10R4	12.71	14.17	71.46	≤ 1	18000	373.75
M10R5	17.50	15.00	121.46	≤ 1	18000	721.46
M10R6	23.54	31.67	273.54	≤ 1	18000	1931.04
Average	8.68	9.67	86.98	≤ 1	13456	326.10

Table 2. CPU times (in seconds) for upper- and lower bounding procedures.

Table 1 shows for each problem set (problem set M05R3 consists of 5 machine problems with ratio $R = 3$) the average deviation $\Delta_{LB} = \frac{Z_{GAP}-Z_{LB}}{Z_{GAP}} \times 100\%$ for three *lower bounds* (LB). The lower bounds are obtained from *(i)* solving the linear programming relaxation of GAP (LP(GAP)), using LINDO (Schrage, 1987), *(ii)* performing the multiplier adjustment method (MAM) due to Fisher, Jaikumar and Van Wassenhove, and *(iii)* solving the linear programming relaxation of SPP (LP(SPP)), using the Dual Ascent Column Generation Procedure. Table 1 also indicates the average deviation $\Delta_{UB} = \frac{Z_{UB}-Z_{GAP}}{Z_{GAP}} \times 100\%$ for three *upper bounds* (UB). Upper bounds are obtained from *(i)* the Martello and Toth (1981) heuristic (MT), *(ii)* the Martello and Toth (1990) branch-and-bound procedure (MT-BB) (with an upper limit on CPU-time of 5 hours), and *(iii)* the upper bounding heuristic (H) described in Section 4. The number of problems solved to optimality is found in the columns denoted by O.
Table 2 shows average CPU-times (in seconds) for each of the procedures described above. The results under the heading *lower bounding procedure* refer to CPU-times required for the computation of lower bounds, while the results under the heading *total procedure* refer to CPU-times required for the lower -and upper bounding part of the procedure.

With respect to the *lower bounding procedures* it can be concluded that *(i)* the bound obtained by solving LP(SPP) using the Dual Ascent Column Generation heuristic is better than the bound obtained by solving LP(GAP) using LINDO, *(ii)* the bound obtained by applying the Dual Ascent Column Generation heuristic on LP(SPP) outperforms the bound obtained by solving the Lagrangean problem -resulting from relaxation of constraints (3)- using the multiplier adjustment method, and *(iii)* the dual ascent heuristic is expensive in terms of computational requirements when compared to the other procedures.
For the *upper bounding procedures* it can be concluded that the heuristic procedure (H) appears to be very effective - with respect to the average deviation from optimality- when compared to Martello and Toth's (MT) heuristic, even when the latter heuristic is extended with an enumeration scheme (MT-BB) with a limitation on CPU-time of 5 hours. A drawback of the heuristic procedure H is, that it is time consuming compared to MT (although it should be mentioned again that the quality of the results is on average about 5% better in return). Furthermore,

the procedure is much faster and gives (on average) better results than the limited enumeration scheme MT-BB.

Remark: Optimal solutions to GAP (denoted by Z_{GAP}) are obtained by applying a branch-and-bound procedure with initial bounds from the heuristic H (see Cattrysse, 1990). Computation times ranged from a few seconds to several hours on the aforementioned hardware.

6 Conclusions

In this paper we propose a set partitioning heuristic for the generalized assignment problem. From the computational results it appears that our heuristic succeeds in finding extremely good solutions to a set of large and notably difficult -highly capacitated- GAP instances. The quality of the solutions, obtained by our approach, for instance dominates the quality of the solutions obtained by well known heuristics like Martello and Toth, and Fisher, Jaikumar, Van Wassenhove. Furthermore, our procedure outperforms the (limited) branch-and-bound scheme proposed by Martello and Toth (with a time-limit of 5 hours) both in terms of average deviation from optimality and in computational speed.
A possible drawback of our procedure is that CPU-times may grow large when problem dimensions increase. However, there are many situations in which the decision maker is certainly willing to accept higher computation times in order to achieve a cost reduction of several percent.

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91/04 FIN	Lars Tyge NIELSEN	"Two-Fund Separation, Factor Structure and Robustness," January 1991
91/05 OB	Susan SCHNEIDER	"Managing Boundaries in Organisations," January 1991
91/06 OB	Manfred KETS DE VRIES, Danny MILLER and Alain NOEL	"Understanding the Leader-Strategy Interface: Application of the Strategic Relationship Interview Method," January 1990 (89/11, revised April 1990)

91/07 EP	Olivier CADOT	**"Lending to Insolvent Countries: A Paradoxical Story,"** January 1991
91/08 EP	Charles WYPLOSZ	**"Post-Reform East and West: Capital Accumulation and the Labour Mobility Constraint,"** January 1991
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91/17 TM	Dirk CATTRYSSE, Roelof KUIK, Marc SALOMON and Luk VAN WASSENHOVE	**"Heuristics for the Discrete Lotsizing and Scheduling Problem with Setup Times"**, March 1991
91/18 TM	C.N. POTTS and Luk VAN WASSENHOVE	**"Approximation Algorithms for Scheduling a Single Machine to Minimize Total Late Work"**, March 1991

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