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A NEW EFFICIENT RLF-LIKE ALGORITHM FOR THE VERTEX COLORING PROBLEM

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Abstract: The Recursive Largest First (RLF) algorithm is one of the most popular greedy heuristics for the vertex coloring problem. It sequentially builds color classes on the basis of greedy choices. In particular, the first vertex placed in a color class C is one with a maximum number of uncolored neighbors, and the next vertices placed in C are chosen so that they have as many uncolored neighbors which cannot be placed in C. These greedy choices can have a significant impact on the performance of the algorithm, which explains why we propose alternative selection rules. Computational experiments on 63 difficult DIMACS instances show that the resulting new RLF-like algorithm, when compared with the standard RLF, allows to obtain a reduction of more than 50% of the gap between the number of colors used and the best known upper bound on the chromatic number. The new greedy algorithm even competes with basic metaheuristics for the vertex coloring problem.

Keywords: Graph coloring, Greedy algorithm.

MSC: 05C15, 05C85.

1. INTRODUCTION

Let G be an undirected graph. A *vertex coloring* of G is the assignment of a color to every vertex such that no two adjacent vertices have the same color. The *chromatic number* $\chi(G)$ of G is the minimum number of colors used in a vertex coloring of G. A *stable set* is a set of pairwise non adjacent vertices. Hence, a vertex coloring of G is a partition of its vertex set into stable sets called *color classes*. The *Vertex Coloring Problem* (VCP) is to determine the chromatic number of a given graph. This well known NP-hard problem [4] has many real world applications in many engineering fields, including scheduling, timetabling, register allocation and frequency assignment [20]. While exact algorithms [2,9,11,12,15,17–19] can hardly solve instances with more than 100 vertices, real world instances can have thousands of vertices, and the use of approximate algorithms, heuristics or metaheuristics is then necessary.

The best known polynomial-time algorithm for approximating $\chi(G)$ has an approximation ratio of $O(n(\log\log n)^2/(\log n)^3)$ [10], where n is the number of vertices in G. Metaheuristics for the VCP generally produce colorings with much less colors, but without any performance guarantee. The first ones, proposed in the eighties, were based on *simulated annealing* [3,14] and *tabu search* [13]. Nowadays, a much wider variety of metaheuristics is available, a bibliography being maintained by Chiarandini and Gualandi [6]. A vast majority of these metaheuristics solve the k-VCP which is, for a given integer k, to determine whether a graph admits a vertex coloring that uses at most k colors. An upper bound on the chromatic number is therefore needed to fix an initial value for k which is then decreased until no solution to the k-VCP can be found. Such an upper bound is typically obtained by using fast heuristics for the VCP.

The most popular fast heuristics for the VCP are based on greedy constructive procedures. These algorithms sequentially color the vertices following some rule for choosing the next vertex to color and the color to use. The best known such heuristics are the DSATUR [1] and RLF [16] algorithms. Computational studies on these algorithms [7] have shown that RLF outperforms DSATUR in terms of quality on most instances, while RLF is more time consuming with a complexity of $O(mn)$ to be compared with the $O(n^2)$ complexity of DSATUR, where n is the number of vertices and m the number of edges.

The aim of this paper is to propose new greedy algorithms for the VCP that can compete with basic metaheuristics. In particular, we will show that greedy choices made in the RLF algorithm can be modified in a very simple way, often with the effect of reducing the number of colors used. The new proposed RLF-like algorithms have a complexity that ranges from $O(mn)$ to $O(mn^2)$.

In the next section, we describe the standard RLF algorithm, as well as some of its variations. The proposed alternative greedy choices are given in Section 3. Computational experiments are reported in Section 4, where we compare the new RLF-like algorithms with the standard RLF as well as with DSATUR, and the Tabu Search metaheuristic.

2. THE RLF ALGORITHM AND SOME VARIATIONS

The *Recursive Largest First* (RLF) algorithm was proposed in 1979 by F. Leighton [16]. Roughly speaking, this algorithm builds a sequence of stable sets, each one corresponding to a color class. Let C be the next color class to be constructed, let U denote the set of uncolored vertices and let W be the set (initially empty) of uncolored vertices with at least one neighbor in C. Every time a vertex in U is chosen to be moved to C, all its neighbors in U are moved from U to W. The first vertex $v \in U$ to be included in C is one with the largest number of neighbors in U. The rest of C is built as follows : while U is not empty, the next vertex to be moved from U to C is one having the largest number of neighbors in W. Ties are, if possible, broken by choosing a vertex with the smallest number of neighbors in U.

For a vertex $u \in U$, we denote its number of neighbors in U and W, respectively, with $A_U(u)$ and $A_W(u)$. Also, when v is the first vertex placed in a color class, we denote with C_v the color class that contains it. Given a vertex v, the algorithm in Figure 1 summarizes how C_v is constructed by the RLF algorithm.

```
Construction of $C_v$
Input A set $U$ of uncolored vertices and a vertex $v \in U$.
Output A stable set $C_v$ that contains $v$.

Initialize $W$ as the set of vertices in $U$ adjacent to $v$.
Remove $v$ and all its neighbors from $U$ and set $C_v \leftarrow \{v\}$.
while $U \neq \emptyset$ do
    Select a vertex $u \in U$ with largest value $A_W(u)$. In case of ties, choose one
    with smallest value $A_U(u)$.
    Move $u$ from $U$ to $C_v$, and move all neighbors $w \in U$ of $u$ to $W$.
end while
```

Figure 1: Construction of a color class.

The construction of C_v can easily be implemented by updating the numbers $A_U(x)$ and $A_W(x)$ each time a vertex is removed from U. More precisely, $A_W(x)$ is initially (when $W = \emptyset$) set equal to 0 for all $x \in U$, and the initial values $A_U(x)$ can easily be obtained in $O(m)$ time. Then, each time a vertex w is moved from U to W, $A_W(x)$ is incremented by one unit and $A_U(x)$ is decreased by one unit for all neighbors $x \in U$ of w. Also, when a vertex $u \in U$ is moved from U to C_v, $A_U(x)$ is decreased by one unit for all neighbors $x \in U$ of u. Hence, there are $O(m)$ such updates, and since the selection of the next vertex to be moved to C_v can be done in $O(n)$ time, the construction of C_v has a total complexity of $O(m + n|C_v|)$.

As mentioned above, the RLF algorithm constructs a sequence of such stable sets. It is summarized in Figure 2. Since every vertex belongs to exactly one color class, the overall complexity of the RLF algorithm is $O(km + n^2)$, where k is the number of colors used. The RLF algorithm has therefore a $O(mn)$ worst case complexity.

```
Algorithm RLF
Input A graph $G$.
Output A coloring of the vertices of $G$.

$k \leftarrow 0$.
while $G$ contains uncolored vertices do
    Let $U$ be the set of uncolored vertices. Set $k \leftarrow k + 1$.
    Choose a vertex $v \in U$ with largest value $A_U(v)$.
    Construct $C_v$ and assign color $k$ to all vertices in $C_v$.
end while
```

Figure 2: The standard RLF algorithm.

Several greedy choices are made by the RLF algorithm. The first one occurs when selecting the first vertex v to be placed in a color class. Also, the selection of the next vertices to be placed with v in C_v is based on greedy choices. As observed by Johnson et al. [14], better results can be obtained by modifying these choices, which explains why they proposed two variations of the RLF algorithm.

> *First variation: algorithm RLF**
>
> The greedy choices made during the construction of C_v aim to minimize the number of edges in the residual graph G' obtained by removing the colored vertices from the original graph. Let P denote the problem of finding a color class C such that the number of edges in the residual graph G' is minimized. The RLF* algorithm iteratively builds color classes by solving P with an exact procedure.
>
> *Second variation: algorithm XRLF*
>
> The XRLF algorithm plays with four parameters T, L, R, E in the following way.
>
> - Each color class is built first, by generating a given number T of stable sets $I_1, \cdots, I_T$, and then, by choosing as a color class the stable set I_i that induces a residual graph G' with a minimum number of edges.
> - The first vertex placed in each I_i is chosen at random among the uncolored vertices. Then, additional vertices are added to I_i until the number of vertices in U is less than a fixed limit L. The rest of I_i is obtained by using an exhaustive search with always the same aim of minimizing the number of edges in the residual graph G'.

- The selection of additional vertices to be added to I_i (when $|U| > L$) is done as follows: R vertices $w_1, \cdots, w_R$ are chosen at random in U, and a vertex w_j with the largest value $A_W(w_j)$ is added to I_i.
- Color classes are obtained in this way until the residual graph contains less than a fixed number E of vertices, in which case, an exact coloring algorithm is used to build the last color classes.

As noticed by Johnson et al. [14], RLF* solves a series of NP-hard problems, but there is no guarantee that it produces a coloring with $\chi(G)$ colors. Concerning XRLF, different values can be assigned to the four parameters E, R, T, L. In particular, if $E = L = 0$, $T = 1$, and R is sufficiently large, then XRLF is similar to the original RLF, while if $E = 0$ and $L = n$, then XRLF is equivalent to RLF*.

Both RLF* and XRLF combine the greedy choices of the standard RLF with exact non polynomial-time procedures. In this paper, we rather propose RLF-like algorithms with a polynomial-time complexity. They are obtained from the original RLF by changing some of the greedy rules. As will be shown, these very simple modifications make it possible to get an algorithm that produces much better results than the original RLF, and even competes with basic metaheuristics.

3. ALTERNATIVE GREEDY CHOICES

In what follows, we use the same notations as in the original RLF. In particular, for a vertex $x \in U$, $A_W(x)$ denotes the number of neighbors of x in W. When a vertex x is moved from U to W, the value $A_W(x)$ is frozen in that sense that it is not updated anymore. Hence, the value $A_W(x)$ for a vertex $x \in W$ is equal to the last value $A_W(x)$ before the move of x to W. Now, we describe two modifications of the greedy choices made in RLF.

3.1. Alternative greedy choice for the selection of the next vertex to be placed in C_v.

The first greedy choice for which we propose an alternative is the one done when selecting a vertex $w \neq v$ to be placed in C_v. For a vertex $u \in U$, the value $A_W(u)$ is a kind of *similarity measure* between u and the vertices already in C_v. Indeed, it corresponds to the number of uncolored neighbors of u, which are also neighbors of vertices in C_v. The RLF algorithm selects the vertex $u \in U$ with maximum value $A_W(u)$. We propose another selection rule. For every vertex $u \in U$, let

$$B(u) = \sum_{w \in W \cap N(u)} (d(w) + A_W(w))$$

where $N(u)$ is the set of neighbors of u and $d(w)$ is the number of uncolored neighbors of w at the beginning of the construction of C_v. The next vertex to be placed in C_v is then chosen among those with maximum value $B(w)$. The idea behind this rule is twofold and can be explained as follows. Let G' be the graph induced by the uncolored vertices at the end of the construction of C_v:

- by maximizing $\sum_{w \in W \cap N(u)} d(w)$, we aim to favor the choice of a vertex u with mainly uncolored neighbors w of large degree in W so that the maximum degree in the residual graph G' is minimized;

- by maximizing $\sum_{w \in W \cap N(u)} A_W(w)$, we aim to have many vertices in the residual graph G' similar to those in C_v, so that the next color class can be as large as C_v.

Let $L = \{u \in U \mid B(u) = \max_{x \in U} B(x)\}$ and $L' = \{u \in L \mid A_W(u) = \max_{x \in L} A_W(x)\}$. The next vertex u placed in C_v is one in L' with the smallest value $A_U(u)$. In other words, we choose a vertex u with the largest value $B(u)$, we break ties by choosing a vertex with the largest value $A_W(u)$, and if this is not sufficient, by selecting one with the smallest value $A_U(u)$.

As was the case for the values $A_W(u)$ and $A_U(u)$ in the original RLF algorithm, the initial values for $B(u)$ can easily be obtained in $O(m)$. Then, each time a vertex u is moved to W, $B(x)$ is incremented by $A_W(x)$ units for all neighbors $x \in U$ of u. Hence, this does not change the complexity of the construction of the stable set C_v. The procedure is summarized in Figure 3.

```
Construction of $C_v$ based on function $B$
Input A set $U$ of uncolored vertices and a vertex $v \in U$.
Output A stable set $C_v$ that contains $v$.

Initialize $W$ as the set of vertices in $U$ adjacent to $v$.
Remove $v$ and all its neighbors from $U$ and set $C_v \leftarrow \{v\}$.
while $U \neq \emptyset$ do
    Let $L = \{u \in U \mid B(u) = \max_{x \in U} B(x)\}$ and $L' = \{u \in L \mid A_W(u) = \max_{x \in L} A_W(x)\}$.
    Select a vertex $u \in L'$ with the smallest value $A_U(u)$.
    Move $u$ from $U$ to $C_v$, and move all neighbors $w \in U$ of $u$ to $W$.
end while
```

Figure 3: Alternative procedure for the construction of a color class.

3.2. *Alternative selection of the first vertex of a color class.*

We propose to change the selection rule for the first vertex v to be placed in a color class. In the RLF algorithm, v is a vertex with a maximum number $A_U(v)$ of neighbors in U. We propose several alternatives.

(a) The first one is to build a stable set C_v for every uncolored vertex v and to choose one that induces a residual graph with a minimum number of edges. This gives an algorithm with total complexity $O(mn^2)$.

(b) In order to avoid increase the complexity from $O(mn)$ to $O(mn^2)$, we propose to construct a stable set C_v for a constant number M of uncolored vertices v, having the highest values $A_U(v)$.

(c) A solution in-between is to follow alternative (b), but with $M = \lfloor pn \rfloor$ and $0 < p < 1$, which also gives an $O(mn^2)$ overall complexity, but approximately decreases the total computing time by a factor p when compared with alternative (a).

4. COMPUTATIONAL EXPERIMENTS

While the proposed changes to the original RLF algorithm might seem of little importance, we show in this section that their impact on the performance of the algorithm is significant. We analyze the results obtained by eight versions of the proposed algorithm. These versions are denoted α-RLF-β, where $\alpha = A$ or B, and $\beta = n, 10\%, 10, 1$:

- $\alpha = A$ means that we use the standard values $A_W(u)$ to decide which vertex u is added to C_v, while $\alpha = B$ stands for the proposed alternative that uses values $B(u)$;
- The various values for β indicate which strategy we follow to determine the first vertex v of a color class: $\beta = n$ is for alternative (a); β=10 or 1 are for alternative (b) with M =10 and 1, respectively; $\beta = 10\%$ is for alternative (c) with $p = 0.1$.

Hence, A-RLF-1 is the standard RLF algorithm, both α-RLF-1 and α-RLF-10 have an $O(mn)$ complexity, and both α-RLF-10% and α-RLF-n have an $O(mn^2)$ complexity. Because α-RLF-10, α-RLF-10% and α-RLF-n are about 10, $\frac{n}{10}$ and n times slower than α-RLF-1, we also consider the 10-RLF, 10%-RLF and n-RLF algorithms which consist of applying the standard RLF 10, $\frac{n}{10}$ and n times, respectively, and to store only the best of the produced colorings. The β-RLF and α-RLF-β algorithms have therefore comparable computing times, which helps to better analyze the impact of the proposed selection rules for the first vertex of a color class. Note that when the standard RFL is applied several times on an instance, the results may differ from one run to another run, because ties in the greedy choices are broken randomly.

We have tested the A-RLF-β and β-RLF algorithms on random graphs $R_{n,d}$ constructed as follows : given a positive integer n and a real number $d \in [0, 1]$, $R_{n,d}$ has n vertices and all $\frac{n(n-1)}{2}$ ordered pairs of vertices have a probability d of being linked by an edge. Computational results on $R_{n,d}$ graphs with $n = 700, 800, \dots, 1500$, and $d = 0.1, 0.5, 0.9$ are reported in Table 1. Each result is an average on 5 instances. We indicate the average number of colors produced by each algorithm, as well as the average computing times in seconds (shown in parenthesis), using a 3 GHz Intel Xeon X5675 machine with 8 GB of RAM. In Figure 4, we represent the evolution of the computing time (using an logarithmic scale) for $d = 0.5$ and $d = 0.9$ when the number of vertices increases. The top curve corresponds to $10^{-8}mn^2 = 10^{-8}dn^3(n-1)/2$, and indicates the expected shape of the curves for algorithms A-RLF-10% and A-RLF-n.

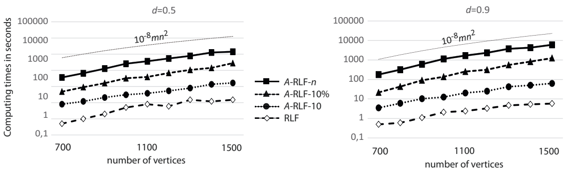

Figure 4: Evolution of the computing time for random graphs.

We observe that the A-RLF-β algorithms are faster than the β-RLF ones, which means that the construction of a stable set C_v for a number M of vertices v increases the computing time by a factor smaller than M. But the increase is real and makes the A-RLF-10% and A-RLF-n less attractive for large graphs. For example, while *RLF* finds a coloring of $R_{1500,0.9}$ in 6 seconds, about 100 minutes are needed by A-RLF-n. But the number of colors is reduced from 407.4 to 332, which represents a gain of 18%. For comparison, applying the RLF algorithm $n = 1500$ times on the same graph (i.e., using n-RLF) decreases the number of colors by only 7 units. These absolute and relative (in percent) gains in colors of the A-RLF-β and β-RLF algorithms with respect to the standard RLF are shown in Figure 5 for $d = 0.5$ and 0.9. Similar curves can be obtained by comparing B-RLF-β with β-RLF. We clearly observe that the alternative selection rules (i.e., parameter β) for the first vertex of a color class have very positive impact on the performance of the RLF algorithm.

		number of vertices								
d	algorithm	700	800	900	1000	1100	1200	1300	1400	1500
0.1	RLF	19.00 (0)	20.60 (0)	22.60 (0)	24.40 (0)	26.00 (0)	28.00 (0)	30.00 (0)	31.60 (0)	33.40 (0)
	10-RLF	18.40 (0)	20.20 (0)	22.00 (0)	24.00 (0)	25.80 (1)	27.60 (1)	29.20 (1)	31.20 (1)	33.00 (1)
	10%-RLF	18.00 (1)	20.00 (1)	22.00 (2)	24.00 (3)	25.80 (6)	27.00 (8)	29.00 (9)	31.00 (13)	33.00 (17)
	n-RLF	18.00 (8)	20.00 (13)	22.00 (22)	24.00 (33)	25.80 (53)	27.00 (76)	29.00 (92)	31.00 (130)	32.80 (168)
	A-RLF-10	18.00 (0)	19.60 (0)	21.40 (0)	23.20 (0)	25.00 (0)	26.60 (0)	28.00 (1)	30.00 (1)	31.80 (1)
	A-RLF-10%	17.80 (1)	19.00 (1)	21.00 (1)	22.80 (2)	24.00 (3)	26.00 (5)	27.20 (8)	29.20 (10)	30.80 (19)
	A-RLF-n	17.00 (3)	19.00 (6)	21.00 (9)	22.60 (15)	24.00 (23)	25.60 (31)	27.00 (49)	29.00 (84)	30.20 (93)
0.5	RLF	79.80 (0)	90.40 (0)	99.00 (0)	107.80 (1)	117.60 (1)	126.60 (1)	135.00 (2)	144.20 (1)	152.80 (2)
	10-RLF	79.20 (1)	88.40 (1)	97.60 (3)	107.00 (3)	116.80 (6)	125.40 (8)	134.20 (11)	142.80 (11)	151.80 (15)
	10%-RLF	78.80 (6)	88.20 (12)	97.40 (23)	106.00 (35)	115.40 (68)	124.40 (95)	133.60 (142)	142.00 (153)	150.80 (204)
	n-RLF	78.20 (62)	87.80(118)	96.80(260)	105.80 (402)	115.00 (702)	123.60 (922)	133.00(1432)	141.40(1554)	150.00(1975)
	A-RLF-10	72.20 (1)	80.60 (1)	89.40 (2)	97.20 (3)	106.20 (4)	114.40 (5)	121.80 (8)	130.40 (14)	137.60 (17)
	A-RLF-10%	69.00 (5)	77.40 (9)	85.00 (16)	92.00 (33)	100.00 (39)	107.40 (69)	114.80 (106)	122.20 (142)	129.20 (280)
	A-RLF-n	67.00 (37)	75.00 (66)	82.40(127)	89.60 (258)	97.00 (368)	104.00 (543)	111.40 (788)	118.80(1261)	126.00(1420)
0.9	RLF	207.00 (1)	235.80 (1)	259.40 (1)	286.40 (2)	308.40 (2)	335.80 (3)	358.60 (5)	382.60 (5)	407.40 (6)
	10-RLF	205.20 (4)	230.80 (7)	256.40 (12)	280.80 (20)	306.00 (25)	331.00 (33)	354.00 (45)	379.20 (51)	403.80 (60)
	10%-RLF	204.20 (28)	230.00 (52)	255.00(103)	279.60 (193)	303.60 (259)	328.80 (406)	352.40 (603)	376.40 (710)	400.60 (906)
	n-RLF	202.60(280)	229.20(542)	253.00(961)	277.00(2050)	302.60(2837)	327.60(4074)	351.00(5757)	375.00(7667)	398.60(9014)
	A-RLF-10	188.60 (4)	210.80 (6)	233.20 (10)	255.60 (13)	280.60 (20)	301.60 (25)	325.80 (43)	346.80 (50)	371.00 (63)
	A-RLF-10%	182.00 (22)	203.20 (43)	225.40 (90)	245.60 (138)	267.20 (254)	287.00 (315)	306.20 (554)	325.40 (820)	343.80(1247)
	A-RLF-n	177.20(178)	197.80(318)	217.80(605)	236.60(1126)	255.20(1681)	275.20(2315)	294.20(3740)	314.60(4280)	332.00(5999)

Table 1: Comparison of the A-RLF-β and β-RLF algorithms on random graphs.

We have tested the eight versions of the α-RLF-β algorithm on the DIMACS benchmark graph coloring instances that come from various sources. For a detailed description of these instances, the reader can refer to [20]. We only report results for the seemingly most challenging instances, those for which the DSATUR algorithm is not able to produce a coloring with k colors, where k is the best known upper bound on $\chi(G)$. This gives a total of 63 instances with $36 \le n \le 10,000$ and $290 \le m \le 990,000$. Two measures are used to analyze the performances of the algorithms. The first one is the total absolute percent deviation (TAPD) from

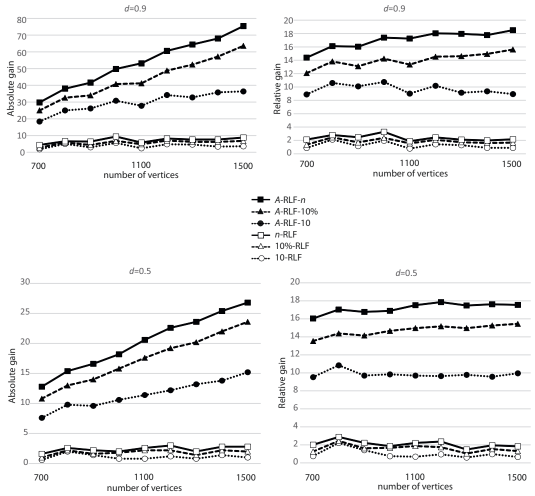

Figure 5: Color gains of the A-RLF-β and β-RLF algorithms with respect to RLF on random graphs.

the best known results. More precisely, for a set S of instances, let b_s be the best known upper bound on the chromatic number of $s \in S$, and let a_s be the number of colors produced by one of the algorithms. The TAPD of this algorithm is then defined as follows :

$$\text{TAPD} = 100\frac{\sum_{s\in S}(a_s - b_s)}{\sum_{s\in S} b_s}.$$

This measures gives more importance to results on graphs with a large number of colors. For example, assume that there are only two instances s_1 and s_2 in S with $b_{s_1} = 10$ and $b_{s_2} = 100$. If an algorithm Algo$_1$ finds a coloring of s_1 with 11 colors and a coloring of s_2 with 100 colors, then its TAPD is $\frac{100}{110} = 0.909$. If a second algorithms Algo$_2$ finds $a_{s_1} = 10$ and $a_{s_2} = 110$, then its TAPD is 10 times larger, which means that Algo$_1$ could appear to be better than Algo$_2$. Both algorithms have, however, similar results since they have reached the best known upper bound on one of the two instances, and produced a coloring with 10% more colors then the best known upper bound on the other instance. To compensate such a bias, we also compute the average relative percent deviation (ARPD) which is defined as follows :

$$\text{ARPD} = \frac{100}{\mid S \mid}\sum_{s\in S}\frac{a_s - b_s}{b_s}.$$

For the above example, both algorithms Algo$_1$ and Algo$_2$ have an ARPD of 5. The detailed results of our experiments on DIMACS benchmark instances appear in Table 2. Each line in the table corresponds to a particular graph. The first columns indicate the name, the number of vertices, and the number of edges of the considered graph. The next column displays the best known upper bound k on the chromatic number. Note that all versions of the α-RLF-β algorithm possibly make random choices when choosing a first vertex v for a color class C_v, or the next vertices to be added to C_v. Such choices occur when ties cannot be broken by the proposed selections rules. Each algorithm was therefore run 10 times, and we report the minimum (column min), the average (column av.) and the maximum (column max) numbers of colors used by each version of the algorithm. The last line of table 2 indicates the total number of colors for the 63 instances. In Figure 6, we indicate the TAPDs and ARPDs associated with the best, average and the worst results of each algorithm.

Graph	*n*	*m*	*k*	A-RLF-1			B-RLF-1			A-RLF-10			B-RLF-10			A-RLF-10%			B-RLF-10%			A-RLF-*n*			B-RLF-*n*		
				min	av.	max	min	av.	max	min	av.	max	min	av.	max	min	av.	max	min	av.	max	min	av.	max	min	av.	max
DSJC125.1	125	736	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6.2	7	6	6	6
DSJC125.5	125	3,891	17	20	20.4	21	20	20	20	19	19.7	20	20	20	20	19	19.4	20	19	19.4	20	19	19.1	20	18	18.4	19
DSJC125.9	125	6,961	44	48	49.1	50	49	49	49	45	46.1	47	45	45.7	47	45	46.3	48	46	46.5	47	45	46.1	47	45	45.8	46
DSJC250.1	250	3,218	8	9	9.8	10	9	9.3	10	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
DSJC250.5	250	15,668	28	34	34.2	35	36	36	36	31	31.7	32	31	31.2	32	31	31.4	32	31	31	31	30	30.9	31	31	31	31
DSJC250.9	250	27,897	72	83	83.6	85	85	85	85	78	79.6	81	78	80.1	82	76	77.4	79	78	78.7	80	75	75.8	77	75	76	77
DSJC500.1	500	12,458	12	14	14.8	15	15	15	15	14	14.1	15	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
DSJC500.5	500	62,624	48	59	59.6	60	61	61.3	62	54	55	56	56	56	56	52	53.1	54	53	53	53	51	51.8	52	51	51.1	52
DSJC500.9	500	112,437	126	151	152.8	155	155	155.1	156	143	143.4	145	141	143.4	145	136	137.4	139	136	136.6	138	134	134.9	136	133	134.6	136
DSJR500.1	500	3,555	12	12	13	14	12	12	12	12	12.5	13	12	12.4	13	13	13	13	12	12.4	13	12	12.8	13	13	13	13
DSJR500.1c	500	121,275	84	89	90.2	92	96	96	96	91	93.3	96	90	90.1	91	90	90.8	92	91	91.4	92	96	96.7	98	92	92.9	94
DSJR500.5	500	58,862	122	130	131.7	133	133	133	133	132	132.7	134	131	133	134	128	128.4	129	129	130.5	131	126	127.5	128	125	126.5	128
DSJC1000.1	1,000	49,629	20	24	24	24	24	24.1	25	23	23	23	23	23	23	22	22.6	23	23	23	23	22	22.1	23	22	22	22
DSJC1000.5	1,000	249,826	83	106	107.1	108	109	109	109	96	97	98	97	97.9	99	92	92.5	93	92	92.9	93	90	90.3	91	89	89.1	90
DSJC1000.9	1,000	449,449	222	275	279.7	283	290	290	290	255	256.7	258	255	257.4	259	244	245.9	247	245	246.7	248	236	236.7	238	236	236.7	238
latin_square	900	307,350	97	122	124.6	129	132	135.4	140	114	116.1	118	117	121.3	126	110	111.6	114	109	111.5	114	109	109.7	111	107	108.6	111
le450_15_a	450	8,168	15	16	16.4	17	16	16.1	17	16	16.4	17	16	16	16	16	16	16	16	16	16	16	16.4	17	16	16	16
le450_15_b	450	8,169	15	16	16.1	17	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
le450_15_c	450	16,680	15	23	23.1	24	23	23	23	21	21	21	21	21	21	20	20.9	21	21	21	21	18	18.7	19	20	20	20
le450_15_d	450	16,750	15	23	23	23	23	23	23	22	22	22	22	22	22	21	21	21	21	21	21	18	18.8	19	19	19	19
le450_25_a	450	8,260	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
le450_25_b	450	8,263	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
le450_25_c	450	17,343	25	27	27.9	28	28	28	28	27	27	27	28	28	28	27	27	27	28	28	28	26	26.7	27	27	27	27
le450_25_d	450	17,425	25	28	28.1	29	29	29	29	27	27.2	28	27	27	27	27	27	27	27	27	27	27	27.3	28	27	27	27
le450_5_a	450	5,714	5	7	7.9	8	7	7	7	6	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5
le450_5_b	450	5,734	5	7	7	7	7	7	7	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
le450_5_c	450	9,803	5	5	5	5	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
le450_5_d	450	9,757	5	5	5	5	7	7	7	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
school1	385	19,095	14	26	27.3	28	24	24	24	16	16	16	16	16	16	14	14	14	14	14	14	14	14	14	14	14	14
school1_nsh	352	14,612	14	22	23.2	24	21	21	21	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
queen6_6	36	290	7	8	8	8	8	8	8	8	8.1	9	7	7.9	8	7	7.8	8	7	7.8	8	8	8	8	7	7.6	8
queen7_7	49	476	7	9	9.2	10	9	9	9	7	7.2	9	7	7	7	8	8.9	9	7	8	10	7	7	7	7	8.2	9
queen8_12	96	1,368	12	13	13	13	13	13	13	13	13	13	12	12.9	13	12	12.9	14	12	12.9	13	12	12.8	13	13	13	13
queen8_8	64	728	9	10	10.3	11	10	10.3	11	9	9.9	10	10	10	10	9	9.7	10	10	10	10	10	10	10	9	9.6	10
queen9_9	81	2,112	10	11	11.1	12	11	11.8	12	10	10.7	11	10	10.9	11	10	10.4	11	10	10.5	11	10	10.7	11	10	10.1	11
queen10_10	100	2,940	11	12	12.6	13	12	12.2	13	11	11.8	13	12	12.1	13	11	11.9	13	12	12.1	13	11	11.7	12	12	12	12
queen11_11	121	3,960	11	13	13.9	14	13	13.9	14	13	13	13	13	13	13	12	12.7	13	13	13	13	12	12.3	13	13	13	13
queen12_12	144	5,192	12	14	14.9	15	15	15	15	14	14	14	14	14	14	14	14	14	14	14.1	15	13	13.6	14	14	14	14
queen13_13	169	6,656	13	15	15.9	16	15	15.8	16	15	15	15	15	15	15	15	15	15	15	15.2	16	14	14.9	15	14	14	14
queen14_14	196	8,372	14	17	17.2	18	17	17.8	18	16	16.1	17	16	16.5	17	16	16	16	16	16.2	17	15	15.8	16	16	16	16
queen15_15	225	10,360	15	17	18.2	19	19	19	19	17	17.1	18	17	17.4	18	17	17	17	17	17.1	18	16	16.6	17	17	17	17
queen16_16	256	12,640	16	19	19.5	20	19	19.4	20	18	18.1	19	18	19	20	18	18.1	19	18	18.4	19	17	17.8	18	17	17.9	18
abb313	1,557	53,356	9	11	11	11	11	11	11	12	12.1	13	10	10	10	11	11.2	12	10	10	10	11	11	11	10	10.2	11
ash331	662	4,185	4	4	4	4	4	4.8	5	4	4.3	5	5	5	5	4	4.2	5	4	4.3	5	4	4.2	5	4	4.2	5
ash608	1,216	7,844	4	5	5	5	5	5.2	6	4	4.2	5	5	5.1	6	4	4	4	5	5	5	4	4.2	5	5	5	5
ash958	1,916	12,506	4	5	5	5	5	5.2	6	5	5	5	5	5	5	4	4.8	5	5	5	5	4	4.8	5	5	5	5
will199	701	6,772	7	7	7.6	8	7	7	7	7	7.1	8	7	7	7	7	7	7	7	7	7	7	7.6	8	7	7	7
wap01	2,368	110,871	42	46	46.3	47	45	45.2	46	45	46.4	47	45	45	45	45	46.4	47	46	46.8	47	45	45.8	47	45	45	45
wap02	2,464	111,742	41	44	44.4	45	43	43.8	44	44	44.2	45	44	44	44	43	43.6	44	44	44	44	44	44.3	45	44	44.5	45
wap03	4,730	286,722	44	50	51.1	52	50	50.8	52	48	49.7	51	51	51	51	48	49	51	49	50.3	51	47	47.7	49	51	51	51
wap04	5,231	294,902	42	46	46.2	47	46	46.7	49	45	45.9	47	47	47	47	46	46.5	48	45	45.1	46	45	45.7	47	46	46	46
wap05	905	43,081	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	51	51	51	50	50	50
wap06	947	43,571	40	44	44	44	44	44	44	43	43.7	45	42	42.2	43	42	42.3	43	44	44.4	45	42	42.5	43	43	43	43
wap07	1,809	103,368	42	45	45.8	47	46	46	46	44	44.9	46	45	45	45	45	45.5	46	46	46	46	45	45.4	46	45	45	45
wap08	1,870	104,176	42	45	45.4	46	45	45.7	46	43	44.3	46	48	48	48	43	43.9	45	45	45	45	44	45.4	46	45	45	45
qg.order60	3,600	212,400	60	60	60.7	61	60	60.5	61	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
qg.order100	10,000	990,000	100	100	100.9	101	100	100.6	101	100	100.2	101	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
flat300_20	300	21,375	20	36	36.8	38	38	38	38	32	32.1	33	34	34	34	24	24	24	22	22	22	20	20	20	20	20	20
flat300_26	300	21,633	26	38	38.6	39	39	39	39	35	35.4	37	35	35	35	34	34.5	35	35	35	35	34	34	34	33	33.6	34
flat300_28	300	21,695	28	37	37.9	39	39	39	39	35	35.7	36	35	35.4	36	34	34.7	35	35	35	35	33	33.4	34	34	34	34
flat1000_50	1,000	245,000	50	104	105.4	106	108	108	108	94	95.4	96	96	96.5	97	90	90.5	91	90	91.1	92	87	87.8	89	86	87.3	88
flat1000_60	1,000	245,830	60	105	105.7	107	108	108	108	95	96	97	96	96.6	97	90	91.2	92	90	90.9	91	88	88.3	89	88	88.8	89
flat1000_76	1,000	246,708	76	104	105.2	106	106	106	106	96	96.4	97	97	97	97	90	91.1	92	91	91.2	92	88	89.2	90	88	88.1	89
total			2,136	2,581	2,621.4	2,662	2,649	2,663	2,682	2,445	2,474.5	2,515	2,465	2,487	2,509	2,377	2,405.5	2,435	2,395	2,414	2,436	2,342	2,370	2,398	2,348	2,363.8	2,382

Table 2: Results of the α-RLF-β algorithms on challenging graphs

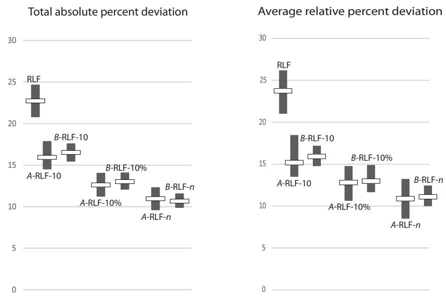

Figure 6: Comparisons of the α-RLF-β algorithms on DIMACS benchmark instances.

For $\beta = 1$, we observe that the standard function A, proposed by Leighton, produces better results than function B. The difference between the best and the worst results is however much smaller with $\alpha = B$ than with $\alpha = A$, which indicates that the proposed alternative greedy choice is more stable. This becomes even more evident with $\beta = 10$. Indeed, while the best minimum and average results are obtained with $\alpha = A$, the best worst case comes with $\alpha = B$. For $\beta = 10\%$, the difference in terms of total number of colors between the worst and the best case with $\alpha = A$ is 58 (2435-2377) while this difference is equal to 41 (2436-2395) with $\alpha = B$. Interestingly, by comparing the TAPDs, we observe that A-RLF-n has better best case than B-RLF-n, but worse average and worst cases. The gap between the total average number of colors produced by A-RLF-1 and the best known upper bound k is equal to 485.4 (2621.4-2136). This gap is reduced to 234 (2370-2136) with A-RLF-n, which represents an improvement of 51.8%. When comparing B-RLF-1 with B-RLF-n, the improvement is even larger since the difference between the total average number of colors and k is reduced from 527 (2663-2136) to 227.8 (2363.6-2136), which corresponds to an improvement of 56.8%. The majority of this improvement is already obtained by setting $\beta = 10$ instead of 1. Indeed, the gain is of 30.3% for $\alpha = A$ and of 33.4% for $\alpha = B$. The importance of modifying the greedy choices made in RLF is very clear on some instances. One of the best illustrations is given by instance school1 where the standard RLF algorithm uses 26 colors while A-RLF-10 and B-RLF-10 find colorings with only 16 colors. The best known upper bound for this instance is 14, and is reached with $\beta = 10\%$ and $\beta = n$. Another good example is instance flat300_20 where the best coloring produced by RLF uses 36 colors, while only 20 colors are used by A-RLF-n and B-RLF-n (which is the chromatic number of the considered graph). Note however that the standard RLF eventually produces better results than all proposed variations. For example, for instance DSJR500.1c, RLF uses 89 colors, while the best coloring obtained with all proposed alternatives contains 90 colors.

Graph	n	m	RLF	A-RLF-10	A-RLF-10%	A-RLF-n
DSJC125.1	125	736	0	0	0	0
DSJC125.5	125	3,891	0	0	0	0
DSJC125.9	125	6,961	0	0	0	0
DSJC250.1	250	3,218	0	0	0	0
DSJC250.5	250	15,668	0	0	0	1
DSJC250.9	250	27,897	0	0	1	2
DSJC500.1	500	12,458	0	0	0	1
DSJC500.5	500	62,624	0	1	1	7
DSJC500.9	500	112,437	0	1	4	27
DSJR500.1	500	3,555	0	0	0	1
DSJR500.1c	500	121,275	0	1	2	11
DSJR500.5	500	58,862	0	1	2	13
DSJC1000.1	1,000	49,629	0	0	2	16
DSJC1000.5	1,000	249,826	0	3	35	283
DSJC1000.9	1,000	449,449	2	15	158	875
latin_square	900	307,35	1	5	25	187
le450_15_a	450	8,168	0	0	0	1
le450_15_b	450	8,169	0	0	0	1
le450_15_c	450	16,680	0	1	0	1
le450_15_d	450	16,750	0	0	0	1
le450_25_a	450	8,260	0	0	1	1
le450_25_b	450	8,263	0	0	0	1
le450_25_c	450	17,343	0	0	0	2
le450_25_d	450	17,425	0	0	1	1
le450_5_a	450	5,714	0	0	0	1
le450_5_b	450	5,734	0	0	0	1
le450_5_c	450	9,803	0	0	0	0
le450_5_d	450	9,757	0	0	0	1
school1	385	19,095	0	0	0	1
school1_nsh	352	14,612	0	0	0	1
queen6_6	36	290	0	0	0	0
queen7_7	49	476	0	0	0	0
queen8_12	96	1,368	0	0	0	0
queen8_8	64	728	0	0	0	0
queen9_9	81	2,112	0	0	0	0
queen10_10	100	2,940	0	0	0	0
queen11_11	121	3,960	0	0	0	0
queen12_12	144	5,192	0	0	0	0
queen13_13	169	6,656	0	0	0	0
queen14_14	196	8,372	0	0	0	0
queen15_15	225	10,360	0	0	0	0
queen16_16	256	12,640	0	0	0	1
abb313	1,557	53,356	0	0	4	21
ash331	662	4,185	0	0	0	1
ash608	1,216	7,844	0	1	2	9
ash958	1,916	12,506	0	1	7	44
will199	701	6,772	0	0	1	1
wap01	2,368	110,871	1	4	64	454
wap02	2,464	111,742	1	4	82	590
wap03	4,730	286,722	2	16	643	5218
wap04	5,231	294,902	2	15	739	6208
wap05	905	43,081	0	0	2	15
wap06	947	43,571	0	1	3	16
wap07	1,809	103,368	1	2	26	201
wap08	1,870	104,176	1	2	27	195
qg.order60	3,600	212,400	2	11	501	2899
qg.order100	10,000	990,000	16	130	17330	91064
flat300_20	300	21,375	0	0	1	1
flat300_26	300	21,633	0	0	0	1
flat300_28	300	21,695	0	0	0	1
flat1000_50	1,000	245,000	1	4	34	178
flat1000_60	1,000	245,830	1	4	35	177
flat1000_76	1,000	246,708	1	5	36	179

Table 3: Average computing times (in seconds) of the A-RLF-β algorithms on DIMACS benchmark instances.

					$\beta = 1$			$\beta = 10$			$\beta = 10\%$			$\beta = n$			
Graph	n	m	k	DS	min	av.	max	min	av.	max	min	av.	max	min	av.	max	ST
DSJC125.1	125	736	5	6	6	6	6	6	6	6	6	6	6	6	6	6	5
DSJC125.5	125	3,891	17	21	20	20	20	19	19.7	20	19	19.4	20	18.4	18	19	17
DSJC125.9	125	6,961	44	50	48	48.8	49	45	45.5	46	45	46.2	47	45.8	45	46	44
DSJC250.1	250	3,218	8	10	9	9.1	10	9	9	9	9	9	9	9	9	9	8
DSJC250.5	250	15,668	28	38	34	34.2	35	31	31.2	32	31	31	31	30.9	30	31	29
DSJC250.9	250	27,897	72	91	83	83.6	85	78	79.5	80	76	77.4	79	75.6	75	76	72
DSJC500.1	500	12,458	12	16	14	14.8	15	14	14	14	14	14	14	14	14	14	13
DSJC500.5	500	62,624	48	67	59	59.6	60	54	55	56	52	52.9	53	51	51	51	50
DSJC500.9	500	112,437	126	161	151	152.8	155	141	142.8	143	136	136.6	138	134.4	133	136	130
DSJR500.1	500	3,555	12	12	12	12	12	12	12.4	13	12	12.4	13	12.8	12	13	12
DSJR500.1c	500	121,275	84	87	89	90.2	92	90	90.1	91	90	90.7	91	92.9	92	94	86
DSJR500.5	500	58,862	122	130	130	131.7	133	131	132.5	134	128	128.4	129	126.4	125	128	128
DSJC1000.1	1,000	49,629	20	26	24	24	24	23	23	23	22	22.6	23	22	22	22	22
DSJC1000.5	1,000	249,826	83	114	106	107.1	108	96	97	98	92	92.5	93	89.1	89	90	89
DSJC1000.9	1,000	449,449	222	297	275	279.7	283	255	256.5	258	244	245.7	247	236.7	236	238	245
latin_square	900	307,350	97	126	122	124.6	129	114	116.1	118	109	111.4	114	108.4	107	110	106
le450_15_a	450	8,168	15	16	16	16.1	17	16	16	16	16	16	16	16	16	16	15
le450_15_b	450	8,169	15	16	16	16	16	16	16	16	16	16	16	16	16	16	15
le450_15_c	450	16,680	15	24	23	23	23	21	21	21	20	20.9	21	18.7	18	19	16
le450_15_d	450	16,750	15	24	23	23	23	22	22	22	21	21	21	18.8	18	19	16
le450_25_a	450	8,260	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
le450_25_b	450	8,263	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
le450_25_c	450	17,343	25	29	27	27.9	28	27	27	27	27	27	27	26.7	26	27	27
le450_25_d	450	17,425	25	28	28	28.1	29	27	27	27	27	27	27	27	27	27	27
le450_5_a	450	5,714	5	10	7	7	7	6	6	6	5	5	5	5	5	5	5
le450_5_b	450	5,734	5	9	7	7	7	5	5	5	5	5	5	5	5	5	5
le450_5_c	450	9,803	5	6	5	5	5	5	5	5	5	5	5	5	5	5	5
le450_5_d	450	9,757	5	11	5	5	5	5	5	5	5	5	5	5	5	5	5
school1	385	19,095	14	17	24	24	24	16	16	16	14	14	14	14	14	14	14
school1_nsh	352	14,612	14	25	21	21	21	15	15	15	15	15	15	15	15	15	14
queen6_6	36	290	7	9	8	8	8	7	7.9	8	7	7.7	8	7.6	7	8	7
queen7_7	49	476	7	10	9	9	9	7	7	7	7	7.8	9	7	7	7	7
queen8_12	96	1,368	12	13	13	13	13	12	12.9	13	12	12.7	13	12.8	12	13	12
queen8_8	64	728	9	12	10	10.1	11	9	9.9	10	9	9.7	10	9.6	9	10	9
queen9_9	81	2,112	10	14	11	11	11	10	10.7	11	10	10	10	10	10	10	10
queen10_10	100	2,940	11	13	12	12.2	13	11	11.7	12	11	11.8	12	11.7	11	12	11
queen11_11	121	3,960	11	15	13	13.8	14	13	13	13	12	12.7	13	12.3	12	13	11
queen12_12	144	5,192	12	15	14	14.9	15	14	14	14	14	14	14	13.6	13	14	13
queen13_13	169	6,656	13	17	15	15.7	16	15	15	15	15	15	15	14	14	14	14
queen14_14	196	8,372	14	18	17	17.2	18	16	16	16	16	16	16	15.8	15	16	15
queen15_15	225	10,360	15	19	17	18.2	19	17	17	17	17	17	17	16.6	16	17	16
queen16_16	256	12,640	16	21	19	19.2	20	18	18	18	18	18	18	17.8	17	18	17
abb313	1,557	53,356	9	11	11	11	11	10	10	10	10	10	10	10.2	10	11	11
ash331	662	4,185	4	5	4	4	4	4	4.3	5	4	4	4	4.2	4	5	5
ash608	1,216	7,844	4	5	5	5	5	4	4.2	5	4	4	4	4.2	4	5	5
ash958	1,916	12,506	4	6	5	5	5	5	5	5	4	4.8	5	4.8	4	5	6
will199	701	6,772	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
wap01	2,368	110,871	42	46	45	45.2	46	45	45	45	45	46.3	47	45	45	45	45
wap02	2,464	111,742	41	45	43	43.8	44	44	44	44	43	43.6	44	44	44	44	44
wap03	4,730	286,722	44	54	50	50.7	51	48	49.7	51	48	49	51	47.7	47	49	53
wap04	5,231	294,902	42	48	46	46	46	45	45.9	47	45	45.1	46	45.6	45	46	48
wap05	905	43,081	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
wap06	947	43,571	40	46	44	44	44	42	42.2	43	42	42.3	43	42.5	42	43	44
wap07	1,809	103,368	42	46	45	45.7	46	44	44.7	45	45	45.5	46	45	45	45	45
wap08	1,870	104,176	42	45	45	45.4	46	43	44.3	46	43	43.9	45	44.9	44	45	45
qg.order60	3,600	212,400	60	62	60	60.3	61	60	60	60	60	60	60	60	60	60	60
qg.order100	10,000	990,000	100	103	100	100.6	101	100	100	100	100	100	100	100	100	100	100
flat300_20	300	21,375	20	40	36	36.8	38	32	32.1	33	22	22	22	20	20	20	20
flat300_26	300	21,633	26	41	38	38.6	39	35	35	35	34	34.5	35	33.6	33	34	27
flat300_28	300	21,695	28	41	37	37.9	39	35	35.4	36	34	34.7	35	33.4	33	34	31
flat1000_50	1,000	245,000	50	112	104	105.4	106	94	95.4	96	90	90.5	91	87.3	86	88	92
flat1000_60	1,000	245,830	60	113	105	105.7	107	95	95.8	96	90	90.9	91	88.1	88	89	93
flat1000_76	1,000	246,708	76	114	104	105.2	106	96	96.4	97	90	90.9	91	88	88	88	88
total			2,136	2,733	2,576	2,606.9	2,64	2,436	2,460.8	2,482	2,369	2,394.5	2,416	2,326	2,349.9	2,371	2,331

Table 4: Comparison of *AB*-RLF-β with DSATUR and Short_Tabu.

It is important to mention that the improvement in quality obtained by using $\beta = 10\%$ or $\beta = n$ instead of $\beta = 1$ or $\beta = 10$ has a price. Indeed, we report in Table 3 the average computing times of the A-RLF-β algorithms (similar times are needed by the B-RLF-β algorithms). For example, for instance DSJC1000.9, the best coloring produced by RLF uses 275 colors and is obtained in 2 seconds, while only 236 colors are used by A-RLF-n, such a coloring being obtained in about 14 minutes. Also, the optimal coloring in 100 colors of instance qg.order100 is obtained by RLF in 16 seconds, while 15 hours are needed by A-RLF-n, and 5 hours by A-RLF-10%. But for instances of a reasonable size like flat300_20, the reduction from 36 to 20 colors mentioned above is obtained in one second. Also, for instance school1, one second is sufficient to reduce the number of used colors from 26 to 14. It is also interesting to observe that while A-RLF-n and B-RLF-n show similar behaviors, they produce very different results on some instances. For example, B-RLF-n is able to find a coloring with 92 colors for DSJR500.1c while the best coloring produced by A-RLF-n for this instance contains 4 additional colors. On the opposite, the best coloring produced by B-RLF-n for wap03 has 51 colors, while colorings with only 47 colors were found by A-RLF-n. In summary, the two algorithms seem complementary, which explains why we now report results obtained by running both A-RLF-β and B-RLF-β, and keeping only the best of the two produced colorings. This new algorithm, called AB-RLF-β is compared to DSATUR [1] and to the Short_Tabu algorithm studied in [8], which consists in taking the best result of 5 runs with 100,000 iterations of the TABUCOL algorithm of Hertz and de Werra [13]. Comparisons between these algorithms are shown in Table 4, while their TAPDs and ARPDs appear in Figure 7. The first four columns of Table 4 are the same as those in Table 2. The next columns display the best result produced by DSATUR (column DS), the minimum, average and maximum numbers of colors used by each version of the AB-RLF-β algorithm, and finally the best result produced by Short_Tabu (column ST). The last line of Table 4 shows totals on the 63 instances. We observe that while the best total number of colors used by α-RLF-n is 2342 for $\alpha = A$ and 2348 for $\alpha = B$ (see Table 2), it is reduced to 2326 by AB-RLF-n, which is even better than the total of 2331 colors produced by Short_Tabu. The best TAPDs and ARPDs of the AB-RLF-β algorithms, as well as those of DSATUR, RLF and Short_Tabu are shown in Figure 8. We see, for example, that while DSATUR has a TAPD of 27.95%, the standard RLF reduces it to 20.8%, and the AB-RLF-n algorithm to 8.9%, which corresponds to an additional gain of 11.9%. A perfect illustration of the effectiveness of the proposed algorithms is given by instance DSJC1000.9. The DSATUR algorithm finds a coloring with 297 colors, while only 275 are necessary with RLF. With α-RLF-n, we were able to gain 39 (275-236) additional colors, which is 6 units better than the result produced by Short_Tabu. The coloring with 236 colors that we have obtained is however 14 units above the best results produced by more complex and more time-consuming metaheuristics.

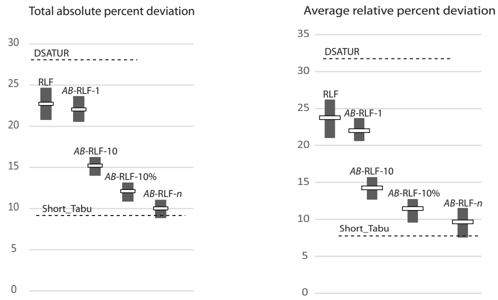

Figure 7: Comparisons of the *AB*-RLF-β algorithms on DIMACS benchmark instances.

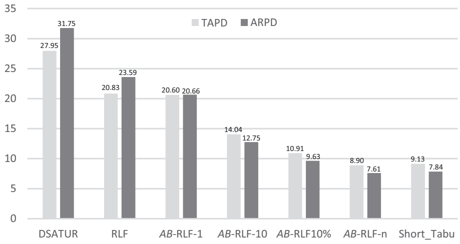

Figure 8: Some TAPDs and ARPDs for the DIMACS benchmark instances.

5. CONCLUSION

The RLF algorithm is a very popular heuristic for the vertex coloring problem, mainly because it is easy to implement and has a relatively low complexity in $O(mn)$. Since various greedy choices made in RLF can have a very big impact on the performance of the algorithm, we have proposed alternative choices. Experiments have shown that much better colorings can be obtained with these alternative greedy choices. The proposed *AB*-RLF-n algorithm has an $O(mn^2)$ complexity, and competes with basic metaheuristics like Short_Tabu. The difference between the number of colors used and the best known upper bound is, on average, reduced by more than 50% when compared with the standard RLF. More than 30% of this improvement can be obtained with *AB*-RLF-10 which is an $O(mn)$ algorithm, like RLF. By implementing the different versions of our algorithms, we have not sought to optimize the code, our goal being rather to demonstrate the quality gain that can be achieved by modifying the greedy choices made in the standard RLF algorithm. Better implementations based on the same ideas as those presented in [5] would certainly lead to faster algorithms. We finally note that the *AB*-RLF-n algorithm is a perfect candidate for a parallel implementation since each color class is obtained by choosing among different stable sets C_v (one for every uncolored vertex v), and these stable sets can be generated independently by different processors.

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