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A Hybrid Coral Reefs Optimization–Variable Neighborhood Search Approach for the Unequal Area Facility Layout Problem

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ABSTRACT The Unequal Area Facility Layout Problem (UA-FLP) is a relevant optimization problem related to industrial design, that deals with obtaining the most effective allocation of facilities, that make up the rectangular manufacturing plant layout. The UA-FLP is known to be a hard optimization problem, where meta-heuristic approaches are a good option to obtain competitive solutions. Many of these computational approaches, however, usually fall into local optima, and suffer from lack of diversity in their population, mainly due to the huge search spaces and hard fitness landscapes produced by the traditional representation of UA-FLP. To solve these issues, in this paper we propose a novel hybrid meta-heuristic approach, which combines a Coral Reefs Optimization algorithm (CRO) with a Variable Neighborhood Search (VNS) and a new representation for the problem, called Relaxed Flexible Bay Structure (RFBS), which simplifies the encoding and makes its fitness landscape more affordable. Thus, the use of VNS allows more intensive exploitation of the searching space with an affordable computational cost, as well as the RFBS allows better management of the free space into the plant layout. This combined strategy has been tested over a set of UA-FLP instances of different sizes, which have been previously tackled in the literature with alternative meta-heuristics. The tests results show very good performance in all cases.

INDEX TERMS Coral reefs optimization, meta-heuristics, relaxed flexible bay structure, unequal area facility layout problem, variable neighborhood search.

I. INTRODUCTION

The Unequal Area Facility Layout Problem (UA-FLP), deals with the arrangement of spaces, machinery, or any kind of facilities in a limited area with known dimensions, and complying with a set of requirements or constraints [1]. In general, the facilities layout planning objectives are the minimization of materials handling costs, optimize the use of labor, or improve workers' safety, among others. Material handling costs can account for 20% to 50% of a company budget, so an efficient arrangement of departments can reduce production costs substantially [2], [3]. Moreover, other possible constraints could be: a pair of departments should be near or adjacent to each other due to material handling; a pair of departments need to be far from each other, due to safety, health, or hygiene reasons, among others; a specific department has to be in a specific position due to aesthetic, production logic, federal regulations, etc. [4]. The general problem of facility layout consists of allocating the facilities within the available space in such a way that the material handling costs are minimized as formulated in (1)

$$\sum_{i=1}^{n} \sum_{j=1, i \neq j}^{n} c_{ij} \cdot f_{ij} \cdot d_{ij} \quad (1)$$

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where n is the number of facilities, c_{ij} is the per unit handling cost between facility i and facility j, f_{ij} is the logistics quantity between facility i and facility j, and d_{ij} is the distance between facility i and j [5]. In some cases, $c_{ij} \cdot f_{ij}$ is expressed in a simplified way as just f_{ij} [6].

The general problem of facility layout is known to be NP-hard, so exact methods have extremly high computational costs when the problem size is large [7], and many heuristic approaches have been proposed consequently [8]. Examples of exact methods are the quadratic assignment problem, linear integer programming, mixed-integer programming, graph-theoretic formulations [9], branch and bound [10]–[13], cutting plane algorithms [14], and tabu search [15], among others. In an attempt to obtain good enough solutions without high computational cost, approximated approaches appeared, such as improvement algorithms. This kind of algorithms start with an initial solution that is improved modifying the position of the facilities until the solution cannot be improved anymore, "computerized relative allocation of facilities technique": CRAFT [16]; and "computerized facility aided design": COFAD [17]. Other classes of approximated approaches are construction algorithms. These algorithms build a solution by selecting successively one facility after other and positioning them on the empty space until all of them are placed. Examples of them are "automated layout design program" (ALDEP) [18], "computerized relationship layout planning" (CORELAP) [19]; and "programming layout analysis and evaluation technique" (PLANET) [20]. All these algorithms have an issue in common: It is difficult to obtain optimal solutions due to only one solution is proposed in each execution [21], so heuristic and meta-heuristic methods with population of solutions took place among the most popular approaches.

Among heuristic and meta-heuristic methods, genetic algorithms have been frequently used to solve the UA-FLP [22]–[25], as well as Simulated Annealing [26]–[30], Tabu Search [15], [31]–[33], Ant Colony Optimization [34], [35], Particle Swarm Optimization [36], [37], or Clonal Selection [38]. Nevertheless, most of these methods have the problem of getting stuck in local optima. To avoid it, the variable neighborhood search (VNS) has been recently used. On the contrary to other meta-heuristics, VNS explores increasingly distant neighborhoods of the current solution and jumps to a new one if there is an improvement, allowing a more intensive exploration of the search space [39]. In this way, it keeps favorable characteristics of the current solution and obtain promising neighboring solutions. By allowing the use of different neighborhood search methods, the VNS can easily escape local minima and move towards global optimum [40]–[42]. In the last years, the use of new meta-heuristic strategies has been raising. Specifically, the coral reef optimization (CRO) algorithm has been successfully used in different kind of problems as, for example, the optimal layout of turbines in wind farms [43], wind speed prediction [44], solar radiation prediction [45], prediction of the total energy demand of a nation [46], optimal distribution of different services in mobile communications systems [47], maximization of the network coverage [48]; minimization of the installation cost, and minimization of the electromagnetic pollution caused by the installation of new base stations [49], image thresholding [50], and wifi channel assignment [51], among others. In this context, the CRO has been recently applied to the UA-FLP successfully, improving most of the previously known results by means of combining the CRO with island evolution [52] and multiobjective interactive evolution [53].

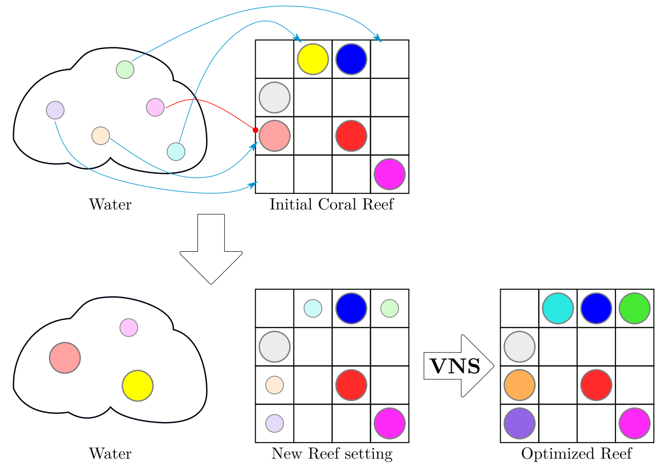


FIGURE 1. CRO and VNS algorithms hybridization.

A. SPECIFIC UA-FLP FORMULATION

The UA-FLP has the goal of finding the optimal positioning of a set of n facilities in a surface associated with a production plant area, in the way that one or more criteria are fulfilled and optimized if possible. Some examples of these criteria are material handling cost (MHC), adjacency requests and distance or closeness requirements between facilities. Logically, the sum of the facilities' areas to place on the plant's surface cannot surpass the area of the plant determined by its width and height ($W \times H$). This constraint is expressed in Equation (2) where A_i is the area of the facility i, W is the plant's width and H its height.

$$\sum_{i}^{n} A_i \leq W \times H \tag{2}$$

Though several criteria can be used in order to optimize a plant's layout, this work is focused only in the material handling cost (material flow) between facilities optimization for solution evaluation, as in [6]. However, in a real world context, the use of this criterion is not enough given that the easier way to reduce material flow is putting all facilities next to each other, "stacking" and stretching them in an unfeasible way. Tate and Smith [6] proposed a way to integrate material flow reduction and a penalization for solutions that have those undesirable "stretched" facilities. Thus, it is needed for each facility to have associated a shape constraint, let it be maximum aspect ratio allowed α (see Equations (3) and (4)) or minimum side length (*minSide*), that determines when a facility is feasible or not. So, if a plant layout is composed of facilities that do not fulfill their shape constraint, its fitness value equals to the material flow value plus a penalty value proportional to the number of unfeasible facilities. With all this in mind, the objective function (fitness) for the UA-FLP is expressed in Equation (5), where t corresponds to a particular layout, n is the number of facilities to place on the plant's surface, f_{ij} corresponds to material flow between two facilities i and j, d_{ij} the distance separating them (rectilinear or euclidean), D_{inf} the number of unfeasible facilities, k a penalty parameter that controls the penalization's gravity (set to 3, following the recommendation in [6]), V_{feas} the minimum fitness value from all non-penalized solutions and V_{all} best fitness value found overall.

$$A_i = w_i \times h_i \tag{3}$$

$$\alpha_i = \frac{max(w_i, h_i)}{min(w_i, h_i)} \tag{4}$$

$$V_t = \sum_i^n \sum_j^n f_{ij} d_{ij} + (D_{inf})^k (V_{feas} - V_{all}) \tag{5}$$

B. CONTRIBUTIONS OF THIS WORK

In this paper, a combination of the CRO with VNS (CRO-VNS ensemble) is proposed, in order to improve the solutions' searching process. The idea of the proposed algorithm is to merge different local and global search procedures, to obtain a final powerful multi-method ensemble approach, able to obtain excellent performance in the UA-FLP. The concept of *ensemble* in optimization refers to the use of a combination of algorithms, search strategies, operators or parameter values to tackle a set of optimization problems [54]. The idea is that the ensemble strategy can obtain better results than a single strategy for the same problems, specifically, better than the ensemble composites working on their own, when applied to the optimization problem. Our proposed multi-method ensemble tries to exploit the possibilities of finding better solutions by means of the VNS, which explores the neighborhood of the candidate solutions, before passing them to the next generation of the global search procedure (the CRO in this case). The CRO applies then different other searching mechanisms (adapted to the UA-FLP), to generate new solutions, in which the VNS can be further applied.

C. STRUCTURE OF THE PAPER

The rest of the paper is structured as follows: Section II gives details on the proposed approach, including the hybridization of the VNS and CRO-SL and the new representation for the problem introduced in this paper (Relaxed Flexible Bay Structure (RFBS)). Section III shows the computational experiments carried out and the results obtained in a number of UA-FLP instances of different size. Comparison with a good number of alternative approaches for this problem is carried out, in order to show the effectiveness of the proposed hybrid approach for this problem. Finally, Section IV closes the paper by giving some conclusions and final remarks on the research carried out.

II. PROPOSED APPROACH

In this section we first detail the proposed relaxed FBS encoding for the UA-FLPs use in this paper. We also describe the Variable Neighborhood Search Algorithm (VNS) along with the neighborhood structures considered and the final CRO-VNS algorithm, that hybridizes the Coral Reef Optimization algorithm with the VNS.

A. FACILITY LAYOUT ENCODING

To represent a given solution for the UA-FLP (phenotype), a particular encoding (genotype) called Relaxed Flexible Bay Structure is used. This encoding is composed of two parts:

1) **Facility** ordering: A permutation vector of the total number of facilities present in the plant.
2) **Bay** cuts: A boolean vector that indicates what facilities are the last per bay.

The relaxed interpretation of the genotype described by both vectors has the objective of making a better use of the available space (if existent), improving material handling cost (MHC or simply, material flow). Following Kulturel-Konak's proposal [55], each facility i has a maximum and minimum acceptable side length that is defined by their shape constraint. Equations (6) and (7) correspond to the case of a aspect ratio constrained facility, whereas Equations (8) and (9) refer to the minimum side restriction.

$$l_i^{min} = \sqrt{\frac{A_i}{\alpha_i}} \tag{6}$$

$$l_i^{max} = \sqrt{A_i \times \alpha_i} \tag{7}$$

$$l_i^{min} = minSide_i \tag{8}$$

$$l_i^{max} = \frac{A_i}{minSide_i} \tag{9}$$

This way, a bay's width w_j is adjusted in the following case-scenarios:

1) Bay width is narrower than the maximum of the minimum side lengths of the facilities belonging to the bay ($w_j < \max\{l_i^{min}\} \leq \min\{l_i^{min}\} \quad \forall i \in D_j$). In this case, the adjustment to perform will increase the bay width, up to the maximum of the minimum side lengths, leading to the existence of empty space at the top and the bottom of the bay (the space is equally split).
2) Bay width is larger than the maximum side length of one or more facilities in the bay ($\max\{l_i^{min}\} \leq \min\{l_i^{min}\} < w_j \quad \forall i \in D_j$). The adjustment to perform in this case will consist of two parts: first, the dimensions of those facilities whose maximum side length is less than the bay width are adjusted to their maximum permitted ($l_i^{max} \times l_i^{min}$) and the new bay width is computed by excluding the previously mentioned facilities. As a result, empty spaces in the bay will be placed equally on both sides of the excluded facilities.

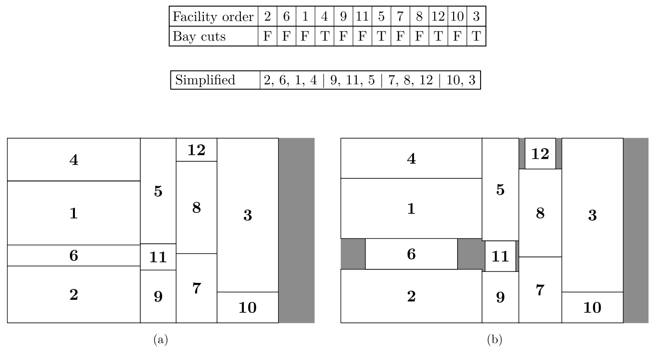


FIGURE 2. Example of FBS and RFBS encodings for an UA-FLP solution; (a) FBS; (b) Relaxed FBS (b) for a certain chromosome.

Fig. 2 shows an example comparison between the classical FBS representation of a plant and its relaxed counterpart, when empty space is available and they share the same genotype, which is also shown.

B. VARIABLE NEIGHBORHOOD SEARCH

Variable Neighborhood Search (VNS) is an advanced search and optimization method based on the systematic change of neighborhood structures, with the goal of escaping local optima and, therefore, exploring more efficiently the search space [56]. Consider an initial solution x and an environment $N(x)$ which is composed of all the neighbor solutions of x, that is, those solutions that can be obtained from a single transform operation applied to x. The environment of a solution is completely determined by the operator chosen to alter it and the use of a single operator is one of the factors that leads to stagnancy in local optima. VNS proposes the usage of several neighborhood operators, so that when a solution cannot be outperformed by one of the neighbors produced by one operator, it is changed so a new neighborhood is generated and the search continues in the new context. If none of the new neighbors is capable of improving the initial solution the context would be changed again with another operator, until no one is left. The process is shown in Algorithm 1. There are essentially two criteria to put an end to the exploration of a solution's environment:

1) **First** improvement: The exploration concludes the moment a solution better that the one of departure is found, regardless of the magnitude of the improvement.
2) **Best** improvement: The best neighbor has to be found in the neighborhood set, so all solutions contained in it have to be evaluated.

1) NEIGHBORHOOD STRUCTURES

Given the fragmented encoding of the UA-FLP solutions, a single neighborhood may not be effective for exploring the search space. Thus, three neighborhood structures are defined (see Fig. 3 for graphic examples):

1) **Facility Order Swap** (FOS): The neighbors generated by this operator are created by means of an exchange of the values of two positions in the facility order vector.

Algorithm 1 VNS Algorithm

Input Initial solution, Neighborhood operators
Output Refined solution

```
procedure vns(init_sol, neigh_ops)        ▷ Variable Neighborhood Search algorithm
    curr_sol ← init_sol
    op_idx ← 0
    repeat
        curr_op ← neigh_ops[op_idx]        ▷ Current neighborhood operator
        repeat
            candidate_set ← Generate neighbors of curr_sol using curr_op
            final_sol ← exploration(candidate_set)        ▷ First/Best improvement
            if final_sol is better than curr_sol then
                curr_sol ← final_sol
            end if
        until curr_sol is not improved
        op_idx ← op_idx + 1        ▷ Use the next neighborhood operator
    until all neigh_ops have been used
    return curr_sol
end procedure
```

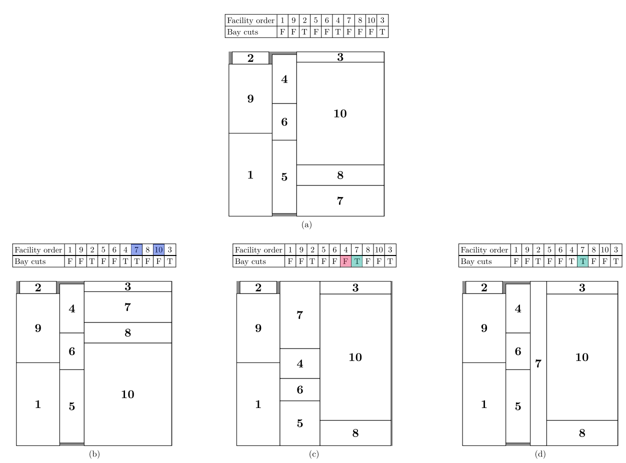


FIGURE 3. Neighborhood operator examples for the UA-FLP. (a) Initial. (b) FOS. (c) BSWP. (d) BInv.

2) **Bay Swap** (BWSP): Changes what facilities mark the end of a bay, without changing the number of bays from the initial solution.
3) **Bit Inversion** (BInv): Inverts the boolean value of the bay cuts vector.

C. THE CORAL REEF OPTIMIZATION ALGORITHM ENHANCED WITH VNS

This section describes the proposed hybrid algorithm for solving the UA-FLP. The basic procedure is the same as in the CRO algorithm [57], [58], but we introduce a larvae optimization with the search method proposed (based in VNS) that will be applied when a larva gets to settle on the reef.

Thus, we hybridize a global search optimization approach (CRO), with a powerful local search heuristic VNS, to obtain a complete hybrid approach able to obtain a high performance in the UA-FLP.

Let Λ be a model representing a rectangular-shaped reef, similar to a two-dimensional matrix of size $M \times N$. Each position $\Lambda(i, j)$ is able to hold a coral $X_k(i, j)$ (potential solution to the UA-FLP) or stay empty, where i and j are the coordinates that point to the position of the coral X_k in the reef. The evolutionary process followed by the CRO is described below:

1) **Initialization**: An initial population of corals of size $\rho_0 \times (M \times N)$ is randomly generated and each solution is placed in the reef choosing any free spot available. Usually the positioning method is based in randomness.
2) **Evolution**: Upon reef population, the evolution starts. Five phases take place in the process:
   a) **Sexual reproduction**: This phase leads to the creation of a new set of corals (larvae set) that will compete for a space in the reef in the next step. The way the larvae are created is by combining corals settled in the reef at the moment. Two different forms of combination are contemplated: external sexual reproduction and internal sexual reproduction. Therefore a percentage F_b of the reef members is selected to pair and perform the external reproduction (also known as Broadcast spawning) and the rest $(100 - F_b)\%$ will reproduce in terms of internal reproduction (brooding). The reproduction processes are described below:
      i) **Broadcast spawning**: Corals are coupled randomly without replacement so a given coral can be a parent just once per generation. Each couple produces a larva (child) and release it to the water, building the larvae set previously presented. The crossover operator used in this work is PMX [59] for facility order and 2-point crossover for bay cuts.
      ii) **Brooding**: Equivalent to a random mutation in classic evolutionary algorithms. Again, all the produced larvae are released to the water. The mutation operators used for an UA-FLP individual are TWORS [60] for facility order vector and 1-bit-swap [60] for bay cuts.
   b) **Larvae setting**: In this step, all the larvae released to the water during the sexual reproduction phase try to settle in the reef up to three times. After that, if it has not been able to settle, it gets discarded (eaten by fish). Reef coordinates (i, j) are chosen randomly and the larva will settle in that spot if one of these two conditions is fulfilled:
      i) The spot is empty.
      ii) The larva has a better health function (fitness) that the coral that currently occupies the spot.

   In case a larva finds a suitable spot to stay, the VNS algorithm comes into play, since this version of the algorithm ensures the best possible version of a coral occupies the reef. Once it is decided that a larva will occupy a certain spot, that larva goes through the process of "refinement" provided by the VNS algorithm described in previous subsections.
   c) **Asexual reproduction**: In this phase (also named budding) the top $F_a\%$ reef members duplicate themselves and, after a small random mutation, try to settle in the reef as in the previous step. Unlike the previous phase, these larvae are not improved if they find a suitable spot.
   d) **Depredation**: Lastly, the $F_d\%$ worst corals in the reef are considered to be predated (erased from the reef) with a low probability (P_d).

Algorithm 2 shows an outline of the whole process with a pseudocode.

Algorithm 2 CRO-VNS Algorithm

Input Algorithm's control parameters
Output Feasible solution with best *fitness*

```
procedure cro-vns(n, m, ρ0, fb, fa, fd, pd)   ▷ Coral Reef Optimization algorithm
    initialize reef with size n × m and occupation rate ρ0
    repeat
        reproduce corals fraction fb by broadcast spawning
        reproduce corals fraction 1 − fb by brooding
        larvae evaluation
        larvae setting ⇄ VNS
        reproduce best corals fraction fa by asexual reproduction
        depredation of fd worst reef corals with pd probability
    until stop condition
    return best feasible solution
end procedure
```

III. COMPUTATIONAL EXPERIMENTS AND RESULTS

A. DESCRIPTION OF BENCHMARK UA-FLPs

This subsection describes the most relevant information and properties of the UA-FLP benchmarks selected to test the proposed CRO-VNS approach. A total of 21 UA-FLP instances have been employed for validating our proposal. All of them have been previously solved using FBS as layout representation. These UA-FLPs are of different size and characteristics, in order to cover the entire spectrum of different possible alternatives. Table 3 details the following data for each UA-FLP instance: UA-FLP instance name, number of facilities that compose the instance, plant layout dimensions, shape constraint (aspect ratio or minimum side), distance metric and reference where data of each particular UA-FLP was taken. Specifically, the UA-FLPs benchmarks which have been considered for testing are: Slaughterhouse from [61]; CartonPacks and ChoppedPlastic taken from [62];

O7 and O8 detailed in [63]; O9 explained by [64]; Vc10Ra (aspect ratio constraint) and Vc10Rs (minimum side requirement) described by [65]; F10 taken from [66]; Ba12 stated in [67]; MB12 detailed by [68]; Ba14 taken from [69]; AB20 defined by [70] and considering different aspect ratio values which are 3, 5, 7, 10, 15 and 50; Tam30 from [66]; SC30 and SC35 explained in [71]. Note that of the total set of problems that have been used to validate our proposal, 3 of them have been taken from real industries located in Córdoba, Spain. Specifically, these are Slaughterhouse, Carton Packs and Chopped Plastic.

The CRO-VNS algorithm's parameters have been tuned in two phases. First, the neighborhood exploration strategy was determined running several independent VNS executions, starting with a certain solution and comparing the performance achieved by the first improvement and best improvement schemes. The best results were obtained using the first improvement strategy in all 10 runs, so that it is the one used in the rest of the experiments performed. The tuning was divided by problem size. Three UA-FLPs have been selected as representatives of the sizes small (S), medium (M) and large (L), which are O9, Ba14 and SC30, respectively.

The second phase of parameter tuning was carried out by the use of an exhaustive grid search. Table 1 collects the parameter values that have been considered for reef size ($N \times M$), initial occupation rate (ρ_0), fraction of broadcast spawners (F_b) and asexual reproduction (F_a), depredation fraction (F_d) and depredation probability (P_d). The selected combination of parameters for the problem of a certain size is the one that has obtained the solution with better fitness. Note that following the tuning experimentation performed by [69], each combination of parameters has been repeated 5 times for each representative UA-FLP, considering a maximum number of iterations of 1000 and 500 the admissible number of iterations without improvement. Finally, Table 2, offers the final parameters used per problem size.

TABLE 1. Grid search parameters.

Parameter	$N \times M$	ρ_0	F_b	F_a	F_d	P_d
Values	10×10	0.7	0.7	0.1	0.01	0.01
	15×15	0.8	0.8	0.15	0.05	0.05
	25×25	0.9	0.9	0.2	0.1	0.1

TABLE 2. Selection of parameter values according to problem size.

Parameter	$N \times M$	ρ_0	F_b	F_a	F_d	P_d	VNS Exploration
Values (S)	10×10	0.7	0.9	0.1	0.1	0.1	First improvement
Values (M)	15×15	0.8	0.7	0.1	0.1	0.1	First improvement
Values (L)	25×25	0.8	0.7	0.2	0.1	0.1	First improvement

Regarding software and computational requisites, the CRO-VNS algorithm has been developed under Python version 3.5. The full experimentation was carried out using a PC with an Intel Core i5 6200U (2.30 GHz $\times$ 4), 8GB RAM and a Linux-based operating system.

B. RESULTS AND COMPARISONS

We present here the results obtained by the hybrid CRO-VNS, and compare them with that of previous proposals over the well-known UA-FLPs. All results obtained are shown in Tables 4 and 5. In particular, the CRO-VNS is compared with existing algorithms: [52] (IMCRO in Table 4), [31], [72] and [55].

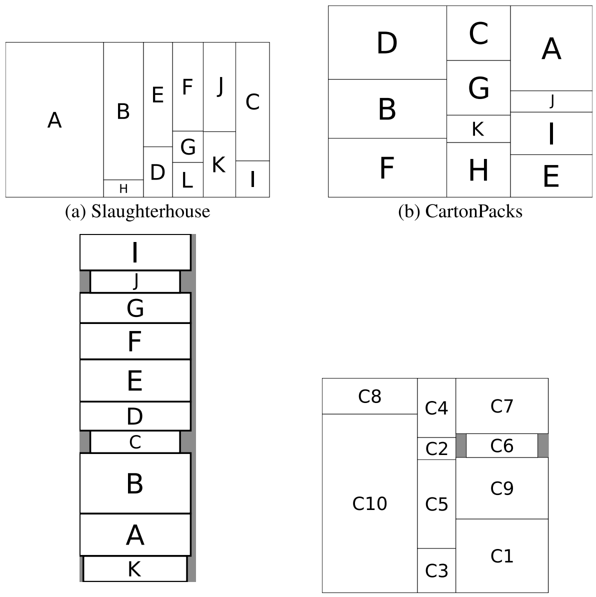
Analyzing the results in Table 4, it is possible to see that the proposed CRO-VNS shows a high performance in the UA-FLP, since it is able to achieve the best solution in 20 instances out of the 21 UA-FLPs which have been tested. The proposed approach has shown an excellent performance when solving UA-FLPs in all size categories. This way, CRO-VNS reaches or overcomes the best known solution values in all UA-FLPs with less than twelve facilities. Specifically, these UA-FLPs are: Slaughterhouse, CartonPacks, ChoppedPlastic, O7, O8, O9, F10, BA12, MB12. Also, the CRO-VNS is able to achieve or improve the best solution values for UA-FLPs that are composed between 14 and 20 departments. In this case, we are talking about the following UA-FLPs: Ba14, AB20_ar3, AB20_ar5, AB20_ar7, AB20_ar10, AB20_ar15, AB20_ar50. Finally, our proposal is capable to reach or win the best known solution values in most tested UA-FLPs with more than thirty facilities, these UA-FLPs are Tam30 ans SC35. There is only a particular case, SC30, where our approach could not reach exactly the best known solution, but it was able to obtain a very similar solution.

TABLE 3. Description of benchmark UA-FLPs.

UA-FLP	*Fac.*	*W × H*	*Shape constr.*	*Dist.*	*Reference*
Slaughterhouse	12	51.14×30.00	α=4	Eucl.	[61]
CartonPacks	11	20.00×14.50	α=4	Eucl.	[62]
ChoppedPlastic	10	10.00×30.00	α=4	Eucl.	[62]
O7	7	8.54×13.00	α=4	Rect.	[63]
O8	8	11.3×13.00	α=4	Rect.	[63]
O9	9	12.00×13.00	α=5	Rect.	[64]
Vc10Ra	10	25.00×51.00	α=5	Rect.	[65]
Vc10Rs	10	25.00×51.00	$side$=5	Rect.	[65]
F10	10	90.00×95.00	α=3	Rect.	[66]
Ba12	12	6.00×10.00	$side$=1	Rect.	[67]
MB12	12	6.00×8.00	α=4	Rect.	[68]
Ba14	14	7.00×9.00	$side$={1,0}	Rect.	[69]
AB20_ar3	20	2.00×3.00	α=3	Rect.	[70]
AB20_ar5	20	2.00×3.00	α=5	Rect.	[70]
AB20_ar7	20	2.00×3.00	α=7	Rect.	[70]
AB20_ar10	20	2.00×3.00	α=10	Rect.	[70]
AB20_ar15	20	2.00×3.00	α=15	Rect.	[70]
AB20_ar50	20	2.00×3.00	α=50	Rect.	[70]
SC30	30	12.00×15.00	α=5	Rect.	[71]
Tam30	30	45.00×40.00	α=5	Rect.	[66]
SC35	35	16.00×15.00	α=4	Rect.	[71]

TABLE 4. Best solutions reached in the benchmark UA-FLP instances considered by the proposed CRO-VNS algorithm and other previous approaches.

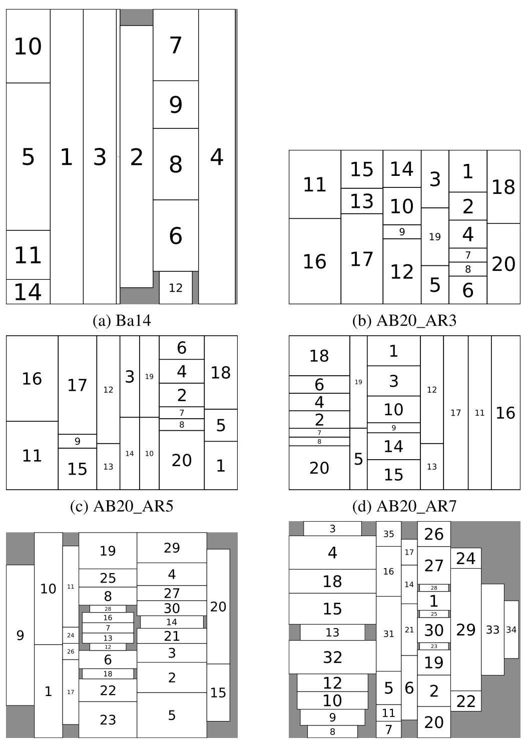
		FBS approaches			
Problem	*CRO-VNS*	*IMCRO (2020)*	*Palomo (2017)*	*Kulturel (2012)*	*Kulturel (2011)*
Slaughterhouse	**3414.35**	3439.96	-	-	-
CartonPacks	**54.82**	85.99	-	-	-
ChoppedPlastic	**195.67**	257.94	-	-	-
O7	**134.16**	**134.16**	134.19	-	-
O8	**245.48**	**245.48**	245.51	-	-
O9	**238.73**	**238.73**	241.06	-	-
Vc10Ra	**20142.13**	**20142.13**	**20142.13**	-	**20142.13**
Vc10Rs	**22899.65**	**22899.65**	**22899.65**	-	**22899.65**
F10	**8556.09**	-	-	8583.53	9020.75
Ba12	**8021.00**	**8021.00**	8435.83	**8021.00**	8129.00
MB12	**125.00**	**125.00**	**125.00**	-	-
Ba14	**4630.46**	4649.22	4665.93	4696.37	4780.91
AB20_ar3	**5372.60**	5396.37	5419.49	-	-
AB20_ar5	**5232.01**	5252.98	5256.1	-	-
AB20_ar7	**4773.05**	4785.96	4844.49	-	-
AB20_ar10	**4367.56**	**4367.56**	**4367.56**	-	-
AB20_ar15	**4099.38**	**4099.38**	4100.17	-	-
AB20_ar50	**2382.73**	**2382.73**	2382.74	-	-
SC30	3482.95	3714.74	3613.11	-	**3443.34**
Tam30	**19236.91**	-	-	19322.98	19462.41
SC35	**3691.73**	4272.21	3885.29	-	3700.75



(a) Slaughterhouse (b) CartonPacks

(c) ChoppedPlastic (d) F10

FIGURE 4. **Best solutions found for some of the tested UA-FLP instances.**



(a) Ba14 (b) AB20_AR3

(c) AB20_AR5 (d) AB20_AR7

(e) Tam30 (f) SC35

FIGURE 5. **Best solutions found for some of the tested UA-FLP instances.**

Continuing with analysis of Table 4, we can affirm that our proposal is able to win all previous approaches in every tested UA-FLP, except in an UA-FLP instance (SC30) in the work of [55]. Specifically, it can extracted from the 4 that the CRO-VNS proposal is able to reach or improve (in 9 instances) every UA-FLP instance (19 well-known problems) when it is compared with the IMCRO proposal [52]. This fact is repeated regarding [72], that is to say, our approach overcomes (in 12 UA-FLPs) or equalizes the solution results

TABLE 5. **Solutions and layouts obtained by the CRO-VNS.**

UA-FLP	*Fitness*	*Diff. (%)*	*RFBS Layout*
Slaughterhouse	**3414.35**	**0.75**	1 | 8, 2 | 4, 5 | 12, 7, 6 | 11, 10 | 9, 3
CartonPacks	**54.82**	**56.85**	6, 2, 4 | 8, 11, 7, 3 | 5, 9, 10, 1
ChoppedPlastic	**195.67**	**31.82**	10, 1, 2, 3, 4, 5, 6, 7, 9, 8
O7	**134.16**	**0.00**	3, 5, 7 | 1, 4, 6, 2
O8	**245.48**	**0.00**	5, 8, 6, 3 | 2, 1, 4, 7
O9	**238.73**	**0.00**	3, 1, 6, 9, 5 | 4, 2 | 7, 8
Vc10Ra	**20142.13**	**0.00**	4, 7, 3 | 5, 8, 10, 9, 2, 6, 1
Vc10Rs	**22899.65**	**0.00**	3, 5 | 9, 10, 8 | 2, 4 | 6, 7 | 1
F10	**8556.09**	**0.32**	10, 8 | 3, 5, 2, 4 | 1, 9, 6, 7
Ba12	**8021.00**	**0.00**	4, 10 | 9, 5, 7 | 3 | 2, 12 | 1 | 11, 8, 6
MB12	**125.00**	**0.00**	12 | 9, 1, 5, 6, 8, 2, 4, 3, 7, 10 | 11
Ba14	**4630.46**	**0.41**	14, 11, 5, 10 | 1 | 3 | 13 | 2 | 12, 6, 8, 9, 7 | 4
AB20_ar3	**5372.60**	**0.44**	16, 11 | 17, 11, 15 | 12, 9, 10, 14 | 5, 19, 3 | 6, 8, 7, 4, 2, 1 | 20, 18
AB20_ar5	**5232.01**	**0.40**	11, 16 | 15, 9, 17 | 13, 12 | 14, 3 | 10, 19 | 20, 8, 7, 2, 4, 6 | 1, 5, 18
AB20_ar7	**4773.05**	**0.27**	20, 8, 7, 2, 4, 6, 18 |5, 19 | 15, 14, 9, 10, 3, 1 | 13, 12 | 17 | 11 | 16
AB20_ar10	**4367.56**	**0.00**	18, 6, 19, 4, 2, 7, 8, 20 | 1, 3, 9, 14, 10, 15, 5 | 12 | 17 | 13 | 16 | 11
AB20_ar15	**4099.38**	**0.00**	11 | 16 | 17 | 12 | 15 | 13, 6 | 5, 3, 14, 10, 9, 19, 4, 2, 7, 8, 20 | 1 | 18
AB20_ar50	**2382.73**	**0.00**	1 | 18 | 5 | 20 | 8 | 7 | 6 | 2 | 4 | 19 | 3 | 10 | 14 | 9 | 15 | 12 | 17 | 13 | 16 | 11
SC30	3482.95	-1.13	11, 10 | 7, 8, 9, 5, 12, 16 | 6, 13, 14 | 2, 15 | 22, 18 | 21, 4 | 19, 3, 17 | 26, 29 | 20, 23, 24, 1, 25, 30, 28, 27
Tam30	**19236.91**	**0.45**	9 | 1, 10 | 17, 26, 24, 11 | 23, 22, 18, 6, 12, 13, 7, 16, 28, 8, 25, 19 | 5, 2, 3, 21, 14, 30, 27, 4, 29 | 15, 20
SC35	**3691.73**	**0.24**	8, 9, 10, 12, 32, 13, 15, 18, 4, 3 | 7, 11, 5, 31, 16, 35 | 6, 21, 14, 17 | 20, 2, 19, 23, 30, 25, 1, 28, 27, 26 | 22, 29, 24 | 33 | 34

in all of the 16 UA-FLP instances. Focusing on [31], it can be stated that our system can achieve or win (in 3 well-known problems) their results in all of the 4 tested UA-FLPs. Finally, comparing our approach with [55], the suggested proposal surpasses their design solutions in almost all the tested UA-FLPs, specifically in 7 out of the 8 tested instances, reaching in 5 of them the best-known result. Only in an instance, that is SC30, the proposal of [34] slightly exceeds the best solution value achieved by our proposed approach.

In addition, Table 5 presents a comparison of the best results obtained by the CRO-VNS against the best-known results obtained by previous algorithms. The information detailed in Table 5 is referred to the best solution result reached by our CRO-VNS, the percent difference of the best-known solution reached by the best alternative algorithm in the literature and the best one achieved by the CRO-VNS, and the chromosome layout of the best solution obtained. In order to complete important information described in Tables 4 and 5, those solutions achieved by the CRO-VNS that overcomes previous results are shown in Figs. 4 and 5.

IV. CONCLUSIONS

This paper presents a hybrid Coral Reefs Optimization algorithm with Variable Neighborhood Search (CRO-VNS), as a new ensemble meta-heuristic to solve the Unequal Area Facility Layout Problem (UA-FLP). The proposed approach introduces two main novel strategies to obtain a high performance behavior in the UA-FLP: enhancing the searching process by combining the global and local search capacities of the CRO and VNS, and improving the representation of solutions using the Relaxed Flexible Bay Structure codification.

Specifically, the VNS combines up to three searching strategies, so the neighborhood exploration improves substantially the efficiency of the algorithm in the local search process. The combination of the CRO and the VNS is carried out after the coral's settlement procedure of the CRO. In turn, the Relaxed Flexible Bay Structure used in this paper is useful to avoid unfeasible solutions and to obtain better fitness values, by managing the available space into the layout design according to aspect ratio restrictions of the facilities.

The combined effect of both of these strategies produces a high performance hybrid search approach for the UA-FLP, which has obtained a substantial improvement over previous existing algorithms for this problem. The results obtained over well-known benchmark UA-FLP instances show that the strategy designed has reached, in general, better solutions than the previous proposed algorithms. So, even though the introduction of the hybrid strategy with the VNS add some extra computational cost, it is worthy to do it, due to in most of the problems tested, the solutions found improved or matched the previously known, with improvement rates of the fitness values that can reach up to 56.85% and only in one case the best solution known wasn't improved.

Further research could take into account the integration of the subjective preferences of the designer, as well as the well-known Slicing Tree Structure to obtain better and more realistic solutions in order to put into practice in real industrial facilities layout problems.

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