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Survey Paper

A survey on applications of the harmony search algorithm

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ABSTRACT

This paper thoroughly reviews and analyzes the main characteristics and application portfolio of the so-called Harmony Search algorithm, a meta-heuristic approach that has been shown to achieve excellent results in a wide range of optimization problems. As evidenced by a number of studies, this algorithm features several innovative aspects in its operational procedure that foster its utilization in diverse fields such as construction, engineering, robotics, telecommunications, health and energy. This manuscript will go through the most recent literature on the application of Harmony Search to the aforementioned disciplines towards a three-fold goal: (1) to underline the good behavior of this modern meta-heuristic based on the upsurge of related contributions reported to date; (2) to set a bibliographic basis for future research trends focused on its applicability to other areas; (3) to provide an insightful analysis of future research lines gravitating on this meta-heuristic solver.

1. Introduction

The application of optimization algorithms to real world problems has gained momentum in the last decade. Dating back to the early 1940s, diverse traditional mathematical methods such as linear programming (LP), nonlinear programming (NLP) or dynamic programming (DP) were first employed for solving complex optimization problems by resorting to different relaxation methods of the underlying formulation. These techniques are capable of cost-efficiently obtaining a global optimal solution in problem models subject to certain particularities (e.g. optimal substructurability and subproblem overlap for dynamic programming), but unfortunately their application range does not cover the whole class of NP-complete problems, where an exact solution cannot be found in polynomial time. In fact, the solution space (and hence, the solving time) of the problem increases exponentially with the number of inputs, which makes them unfeasible for practical applications.

In order to cope up with the above shortcoming, meta-heuristic techniques—conceived as intelligent self-learning algorithms stemming from the study and mimicking of intelligent processes and behaviors arising in nature, sociology and other disciplines (see Fig. 1 for a general overview)—have come into sight for efficiently tacking this type of *hard* optimization paradigms. In many cases (especially when large-scale problems are addressed), meta-heuristics are deemed one of the most efficient alternatives to seek and determine a near-optimal solution[1] without relying on exact yet computationally demanding algorithms, and by overcoming the major drawback of local search algorithms, i.e. getting trapped in biased local regions far from the sought global solution. Indeed, on the latter lies one of the main design challenges of modern meta-heuristic methods: to avoid local optima so as to get global optima, which can be achieved by exploring the whole search space through the use of intelligent stochastically driven operators. On this purpose, it is of utmost importance for enhancing the overall search performance of the meta-heuristic to balance the tradeoff between two important related aspects: diversification and intensification. On one hand, diversification refers to a form of randomization added to the deterministic components driving the algorithm operation in order to explore the search space in a diverse manner, while intensification stands for the improvement of existing partial solutions to the problem by exploring the vicinity of such solutions in the region space (e.g. by means of elitism mechanisms). If diversification is strong enough, a great number of zones of the search space may be loosely explored, which will reduce the convergence rate of the algorithm. By contrast, if diversification is kept low in the algorithm design, there is a significant risk of leaving a fraction of the solution space unexplored or even producing far-from-optimal solutions due to trapping in local optima. An appropriate intensification is carried out

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[1] In words, a solution that offers the best trade-off between the computational cost and the quality or fitness of the solution.

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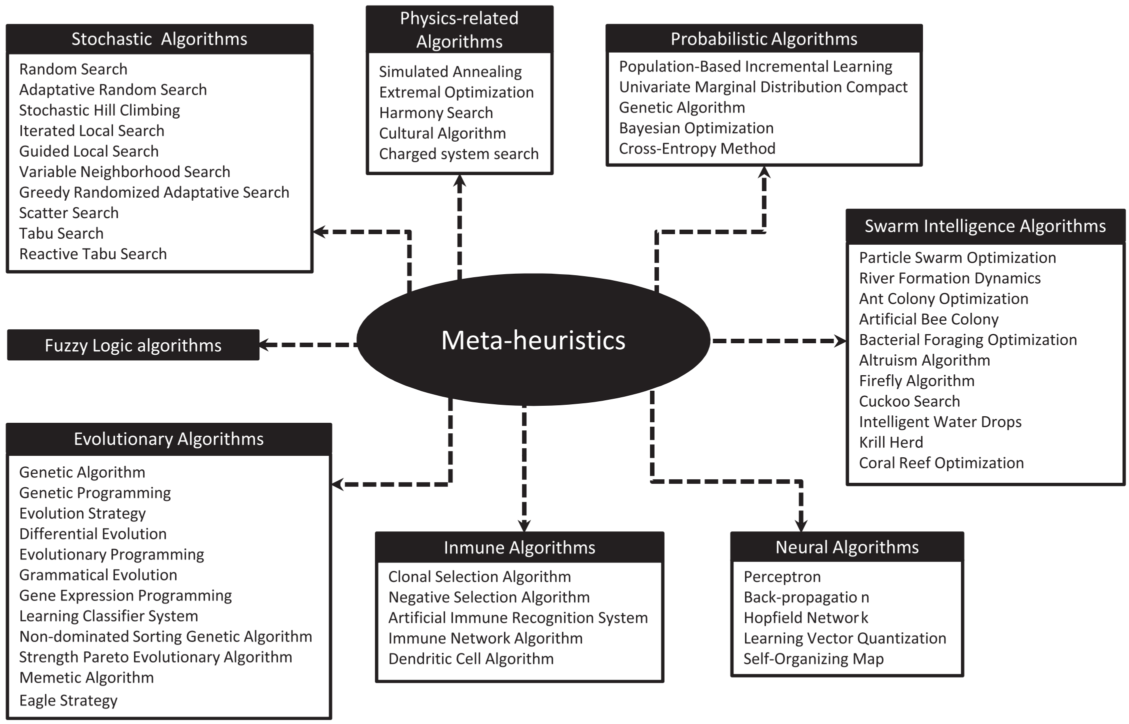

Fig. 1. General classification of meta-heuristics based on their operational procedure.

by means of exploiting the knowledge acquired from past solutions, and by properly fine-tuning the parameters that control the performance of the algorithm for a particular problem so as to enhance its convergence properties.

Based on the above rationale, the last four decades have witnessed the advent and rise of new innovative meta-heuristic algorithms, grouped on many branches based on their working methodology, and applied to a wide variety of different optimization problems such as resource allocation, industrial planning, scheduling, decision making, medical, engineering and computer science applications, among many others. Many of them are actually inspired by natural phenomena and have been developed by mimicking the intelligence characteristics of biological and physical agents such as Genetic Algorithms, Cuckoo Search, Ant Colony Optimization, Simulated Annealing, Particle Swarm Optimization or Harmony Search. The main difference among existing meta-heuristics concerns (1) the way diversification and intensification are mutually balanced in the algorithm thread; (2) the search path they follow; and/or (3) the observed phenomena that inspires the algorithm design. Another characteristic of meta-heuristic algorithms is the distinction between memory usage versus memoryless methods, as well as the definition of population-based and single-point search-based strategies. For instance, in Ant Colony Optimization a memory of previously obtained solutions is kept in the pheromone trail matrix in order to construct new refined solutions. Likewise, the population in Genetic Algorithms can be regarded as a memory register of recently encountered partial solutions. On the contrary, Simulated Annealing exemplifies the case of a memoryless algorithm in which no record of past solutions is employed.

In contrast to single-point search-based algorithms in which a unique solution is generated at each iteration, population-based meta-heuristic algorithms maintain a set of solutions (i.e. population) which evolve at each iteration. Therefore, population-based algorithms provide an efficient and natural way for exploring the search space and obtaining an acceptable solution. Interestingly, Memetic Algorithms hybridize these two strategies in order to balance the diversification and intensification of its search procedure. Most of single-point search algorithms such as Simulated Annealing and Tabu Search are based on a single neighborhood structure which defines the allowed movements through the search space. However, Iterated Local Search algorithms normally define two different neighborhood structures among which the algorithm shifts when reaching a local optimum.

This paper focuses on the principles of Harmony Search, its comparative analysis with respect to other meta-heuristics, and a detailed report of recent applications and associated developments attained during the last few years. This review allows the interested reader not only to get a clear insight on the design and working principles of this algorithm, but also to identify technical advances and application trends of Harmony Search in diverse fields. To fulfill these goals, the manuscript is structured as follows: once the structure and steps of the original algorithm have been posed in Section 1.1, its intrinsic characteristics are analyzed and compared to other meta-heuristics in Section 1.2. Then, an overview of its application areas and an outline of current trends in such fields is tackled by classifying the applications cases in the related literature by discipline area, and by highlighting the modifications and improvements of each particular field in Sections 2 and 3. Finally, Section 4 draws some concluding remarks and outlines several future research lines of interest.

1.1. Fundamentals of the harmony search algorithm

Harmony Search (hereafter HS) is a relatively new population-based meta-heuristic algorithm which has obtained excellent results in the field of combinatorial optimization (Geem, 2000). It mimics the behavior of a music orchestra when aiming at composing the most harmonious melody, as measured by aesthetic standards. When comparing the improvisation process of musicians with the optimization task, we can realize that each musician corresponds to a decision variable; the musical instrument's pitch range refers to the alphabet of the decision variable; the musical harmony improvised at a certain time corresponds to a solution vector at a given iteration; and audience's aesthetic impression links to the objective function of fitness of the optimization problem at hand. Just like musicians improve the melody time after time, the HS algorithm progressively enhances the fitness of the solution vector in an iterative fashion.

As previously mentioned, HS is a population-based algorithm; it hence maintains a set of solutions in the so-called Harmony Memory (HM). An estimation of the optimal solution is achieved at every iteration by applying a set of optimization parameters to the HM, which produces a new harmony vector every time. Fig. 2 illustrates the flow diagram of the HS algorithm, which can be summarized in four steps: (i) initialization of the HM; (ii) improvisation of a new harmony; (iii) inclusion of the newly generated harmony in the HM provided that its fitness improves the worst fitness value in the previous HM; and (iv) returning to step (ii) until a termination criteria (e.g. maximum number of iterations or fitness stall) is satisfied.

The above improvisation procedure is mainly controlled by two different probabilistic operators, which are sequentially applied to each note so as to produce a new set of improvised harmonies or candidate solutions:

- The Harmony Memory Considering Rate, HMCR $\in[0,1]$, establishes the probability that the new value for a certain note is drawn uniformly from the values of this same note in all the remaining melodies. Otherwise (i.e. with a probability 1−HMCR), the note values are randomly chosen according to their alphabet. This case is commonly referred to as *random consideration*, as it increases the diversity of the solutions towards the global optimality; however, some works (e.g. Gil-Lopez et al., 2011) implement the random consideration as a third, separated probabilistic operator.
- The Pitch Adjusting Rate, PAR $\in[0,1]$, establishes the probability that the new value x_{new} for a given note value x is obtained by adding a small random amount to the existing value x_{old}.

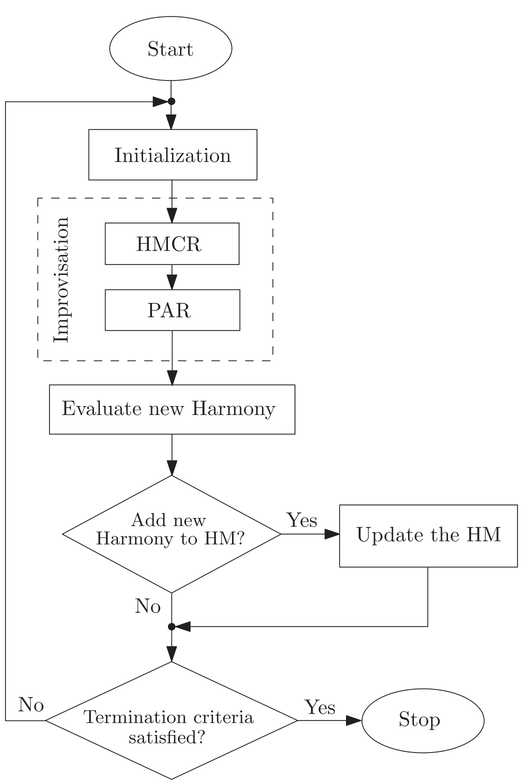

Fig. 2. Flowchart of the HS algorithm (Geem, 2000).

For continuous alphabets, this operation reduces to

$$x_{new}=x_{old}+\omega_x\cdot\epsilon, \tag{1}$$

where ω_x represents the pitch bandwidth, and ϵ is a random number drawn from an uniform distribution with support $[-1,1]$. A low pitch adjusting rate with a narrow bandwidth may restrict the diversification of the algorithm within a small search subspace and consequently, decrease the convergence rate of the overall solver. On the other hand, a high pitch adjusting rate with a high value of ω_x may force the algorithm to unnecessarily escape from areas with potentially near-optimal solutions. When dealing with discrete alphabets, a similar definition holds for this PAR operator, the difference being that the underlying alphabet must be sorted under some vicinity ordering criteria, which in general depends roughly on the characteristics of the metric defining the problem at hand.

By analyzing these parameters in detail, it can be identified how the HS algorithm balances diversification and intensification. Both the pitch adjusting rate and the random consideration parameter control the diversification factor. The pitch adjustment can be essentially viewed as a refinement process of local solutions, while the randomization procedure allows examining the search space in a more explorative fashion. The intensification in the HS algorithm is represented by the harmony memory considering rate, which fixes the level of elitism, i.e. the amount of solutions from the harmony memory to be kept for subsequent generation. If the considering rate is set to a low value, the algorithm will converge slowly to the optimum solution; however, a high HMCR value will favor the intensification based on the knowledge contained in the present harmony memory, but at the risk of trapping the algorithm into local optima. In summary, it is essential to properly adjust the parameters controlling the above operators in order to boost the algorithm performance.

1.2. Intrinsic characteristics and comparison to existing algorithms

Given their strong dependency on the shape of the solution space drawn by the metric function at hand, the outperforming convergence and behavior of any meta-heuristic algorithm cannot be claimed in a general manner, but instead needs to be assessed by focusing on a certain problem, along with the side constraints that may hold in the mathematical formulation at hand. Therefore, even though a globally optimal algorithm that renders the best performance in all optimization schemes does not exist (in line with the statements of the so-called *No Free Lunch Theorem* Wolpert and MacReady, 1997), the HS algorithm has so far elucidated in practice a great potential and efficiency in comparison with other meta-heuristic methods in a wide spectrum of real applications. HS possesses a similar structure to other existing population-based meta-heuristic solvers, but it incorporates some distinctive features that make it widely utilized in the literature.

Similarly to other related population-based algorithms, i.e. Genetic Algorithms or Ant Colony Optimization, the HS relies on a group of solutions that can be simultaneously exploited for improving the efficiency of the algorithm. However, the naïve Genetic Algorithm considers only two vectors (referred to as *parents*) for generating a new solution or offspring, whereas the original implementation of HS takes into account, component-wise and on a probabilistic basis, all the existing solutions (melodies) in the harmony memory. Nevertheless, further modifications of the naïve Genetic Algorithm have been proposed in the literature, such as the multi-parent crossover. It modifies the original formulation of the algorithm to take into account more than two individuals in the generation of the new population. On the contrary, the HS Algorithm, in its original version, is able to

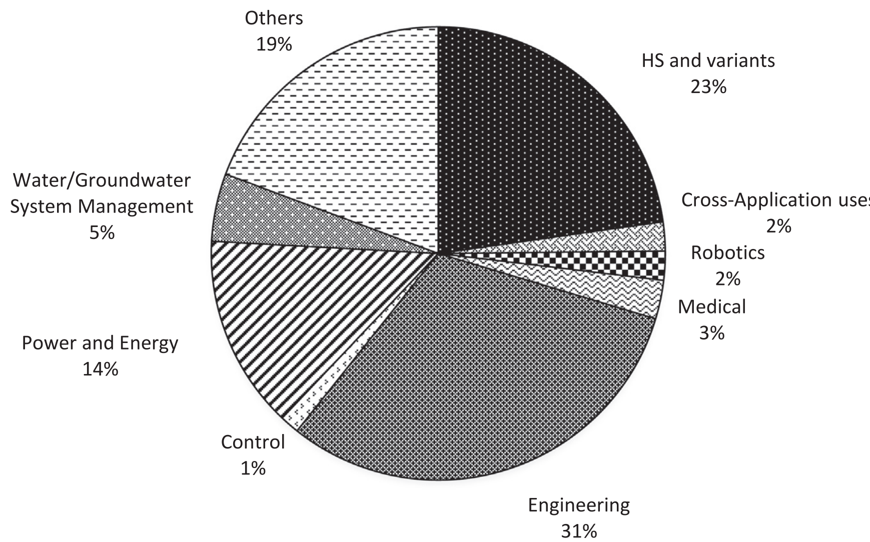

Fig. 3. Approximate distribution of HS applications by discipline areas.

infer new solutions merging the characteristics of all individuals by simply tuning the values of its probabilistic parameters. Besides, it independently operates on each constituent variable (*note*) of a solution vector (*harmony*), to which stochastic operators for fine-tuning and randomization are applied. As opposed to gradient-search techniques, the convergence rate of HS and the quality of its produced solutions are not dramatically affected by the initialized values of the constituent melodies in the harmony memory. Besides, HS utilizes a probabilistic gradient which, in contrast to traditional gradient-based mathematical methods, does not require the derivative of the fitness function to be analytically solvable, nor even differentiable over the whole solution space. Instead, the probabilistic gradient converges to progressively better solutions iteration by iteration, since the operators driving the algorithm behavior intelligently guide the harmony memory to regions of the solution space with better fitness without addressing at all the differentiability of the metric function. As a result, HS has been shown to perform satisfactorily in both continuous and discrete optimization problems: indeed, it is able to handle both decimal and binary alphabets without modifying the definition of the original HMCR and PAR parameters of the algorithm.

Another remarkable strength of HS hinges on its improvisation operators, which play a major role in achieving a good trade-off between diversification and intensification. As mentioned before, the correct choice of the parameters becomes essential in order to attain progressively better candidate solutions, and HS facilitates this refinement stage by significantly reducing the number of configurable parameters. In addition, the steps and the structure of the HS algorithm are relatively simple, which makes it flexible for its combination with other meta-heuristics (Fesanghary et al., 2008) and implementation in parallel hardware architectures. Consequently, since the advent of this algorithm, the research community has thoroughly proposed and examined variants of HS based on incorporating new components into the HS structure and/or hybridizing it with other solvers so as to improve its searching capabilities.

2. Application areas

Originally, applications where HS was first assessed as an effective meta-heuristic focused mainly on the design of water distribution networks (Geem, 2006), benchmark optimization (Li and Li, 2007), structural design (Lee et al., 2005) and vehicle routing problems (Geem, 2005; Geem et al., 2005). In 2004 a flowchart representation of HS was published in Lee and Geem (2004) and since then several studies were devoted to the development of new HS variants and hybridizations with other meta-heuristic algorithms (Li et al., 2005). Since then, the activity around this algorithm has increased sharply, spanning its applicability to a very heterogeneous portfolio of application scenarios. This section presents an overview of the discipline areas in which the HS algorithm has been applied during recent years.

In order to get a clear overview of the classification and analysis presented in the following sections, Fig. 3 depicts the current approximate distribution of areas of HS application as measured by the number of publications of each particular topic. This literature survey is based on a reference repository including 160 papers indexed during the last years in relevant scientific databases such as Elsevier, IEEE and Springer. As shown in this figure, the range of activity spans from engineering problems—which comprise a great portion (31%) of the related literature—to variants of the HS algorithm (23%), which have also acquired a notable importance. In Table 1 the distinct areas of activity are presented together with a classification of articles from recent years.

3. Overview of HS applications by application area

In this section we delve into the previously presented discipline areas by describing some of the optimization challenges arising therein, as well as analyzing the modifications done to the original HS algorithm in order to efficiently cope with such problems.

3.1. HS and its variants

Approximately 20% of the recent HS-related publication track reviewed in this manuscript incorporates some modification to the original HS algorithm in Geem et al. (2001) without targeting any specific application scenario. These variants include (1) alternative initialization procedures for the HM; (2) variable parameters for the improvisation procedure; (3) options for handling constraints when generating new harmonies; (4) different criteria for filtering and selecting new harmonies for the HM; (5) distinct termination criteria; and finally (6) modifications in the structure of the algorithm by adding or removing blocks or hybridizing it with other existing heuristics. Reviews on the existing HS flavors

Table 1
Articles classified by application area.

HS and its variants	Geem et al. (2001), Al-Betar et al. (2010, 2012a,b), Geem (2006, 2007, 2012), Lee and Geem (2005), Majid and Esmaile (2010), Zou et al. (2010c,d, 2011a), Wang et al. (2011a), Mashinchi et al. (2011), Zhao et al. (2010) Luo et al. (2011), Omran and Mahdavi (2008), Mahdavi et al. (2007), Fesanghary (2010), Yildiz and Öztürk (2010), Gao et al. (2009), Cheng (2009) Cobos et al. (2011), Parikshit et al. (2012), Ricart et al. (2011), Wang and Li (2012), Alsewari and Zamli (2012), Duan et al. (2013), Alatas (2010), Pan et al. (2010), Wang and Huang (2010) Geem and Sim (2010), Das et al. (2011)
Engineering	Lee and Geem (2004), Lee et al. (2005), Saka (2009a,b), Erdal et al. (2011), Fesanghary et al. (2009, 2012), Zarei et al. (2009), Kaveh and Talatahari (2009), Kaveh and Shakouri (2010), Kaveh and Ahangaran (2012) Shariatkhah et al. (2012), Khazali et al. (2010), Parizad et al. (2010), Wei et al. (2010), Verma et al. (2010), Barzegari et al. (2010), Srinivasa et al. (2011), Kudikala et al. (2011), Mehdizadeh et al. (2011) Kermani et al. (2011), Nezhad et al. (2010), Zhang and Hanzo (2010), Gao et al. (2010b, 2011), Jafarpour and Khayyambashi (2010), Bekda and Nigdeli (2011), Degertekin (2012), Sarvari and Zamanifar (2010), Fesanghary (2009) Yadav et al. (2010), Askarzadeh and Rezazadeh (2012), Sanchez-Montero et al. (in press), Landa-Torres et al. (2012a,b,d,e), Manjarres et al. (2013, 2012a,b), Gil-Lopez et al. (2012), Harrou and Zeblah (2011) Del Ser et al. (2011, 2012)
Water/groundwater system management	Geem (2006, 2009), Geem et al. (2009), Ayvaz (2008, 2009, 2010), Cisty (2010)
Medical	Panchal (2008, 2009), Gandhi et al. (2012), Landa-Torres et al. (2012f)
Robotics	Yazdi et al. (2011), Xu et al. (2011), Tangpattanakul et al. (2010)
Control	Coelho et al. (2010a), Das Sharma et al. (2010)
Power and energy	Coelho and Mariani (2009), Geem (2010a, 2011), Khorram and Jaberipour (2011), Pandi and Panigrahi (2011), Vasebi et al. (2007), Sivasubramani and Swarup (2011a,b), Chatterjee et al. (2011), Afshari et al. (2011), Sinsupan et al. (2010), Gao et al. (2010c) Sirjani et al. (2011, 2012), Sirjani and Mohamed (2011), Ceylan et al. (2010), Coelho et al. (2010b), Ceylan and Ceylan (2009), Javaheri and Goldoost-Soloot (2012), Sui et al. (2010)
Cross-application uses of HS	Yadav et al. (2011), Wang et al. (2010b, 2011c), Peiying et al. (2012), Ayachi et al. (2011), Geem (2010b), Habib et al. (2013), Diao (2010), Diao and Shen (2012), Ramos et al. (2011), Cobos et al. (2010) Krishnaveni and Arumugam (2012), Sarvari et al. (2010), Navi et al. (2011), Chandran and Nazeer (2011), Hoang et al. (2010), Alexandre et al. (2009), Ezhilarasi and Swarup (2012), Alia et al. (2010), Mandava et al. (2010), Ahmed et al. (2011) Yusof et al. (2011), Forsati and Mahdavi (2010), Ko and Sim (2011), Li et al. (2011, 2012), Pan et al. (2011a,b), Hua et al. (2012), Kaizhou et al. (2010), Gao et al. (2010a), Ren et al. (2011), Fu and Zhang (2011) Han et al. (2010), Jing et al. (2011), Geem (2007), Ahmad et al. (2012)
Others	Zou et al. (2010a,b, 2011b), Fourie et al. (2008, 2010), Mohsen et al. (2010), Cheng and Yong (2010), Bo et al. (2010), Kattan et al. (2010), Geem (2007), Landa-Torres et al. (2012c), Mun and Geem (2009a,b) Coelho and Bernert (2009), Kayhan et al. (2011), Taleizadeh et al. (2012), Geem and Choi (2007), Jaberipour and Khorram (2010), Geem and Williams (2008), Wang et al. (2010a, 2011b) Wong and Guo (2010), Kulluk et al. (2011, 2012), Kattan and Abdullah (2011), Alsewari and Zamli (2011), Ma et al. (2009), Huang et al. (2010), Salcedo-Sanz et al. (2013)

abound in the literature, e.g. Alia and Mandava (2011) and references therein. Yet far from the application-oriented perspective on which this manuscript is intended to focus, this subsection aims at shedding some light on several modifications of the nominal HS algorithm grounded on recent bibliographic examples. Nevertheless, the authors recommend to resort to any of the previously cited reviews to get a broader insight on HS variants.

A research work exemplifying different HS modifications can be found in Al-Betar et al. (2012a), where a hybrid HS algorithm is used in order to tackle the so-called university course timetabling problem (UCTP). This problem is considered to be a hard combinatorial optimization problem based on allocating a set of events to a set of rooms and time slots. The algorithm presented in this work builds on the hybridization of HS and a local search approach in order to reach a balance between diversification and intensification of the search procedure on the solution space. Specifically, a classical Hill Climbing approach is combined with the global search process performed by HS so as to improve the local intensification of the overall solver. In addition, a global-best Particle Swarm Optimization approach is further incorporated in order to achieve a best convergence rate than that rendered by the HMCR operator. Other considerations and adjustments to the original HS algorithm performed in Al-Betar et al. (2012a) include (1) novel repair methods for maintaining the feasibility of the solutions in the HM; and (2) a modification of the PAR procedure under which only pitch adjustments improving the quality of the produced solutions are accepted. Besides, the hybridization of the algorithm changes the behavior of the original HMCR operator; instead of randomly selecting harmonies (which may exclude the best solutions from the HM and consequently, decrease the convergence rate), in this scenario this parameter is designed so as to keep the feasibility of existing solutions. Additionally, a local optimizer based on a Hill Climbing approach is introduced in this hybrid scheme in an attempt at guaranteeing the fine-tuning of the new harmonies and the avoidance of getting stuck in local optima.

Another modification widely adopted for improving the performance of the HS algorithm hinges on imposing a certain progression along iterations on the values of its operational parameters of HMCR and PAR. For instance, an improved harmony search algorithm that uses variable PAR and a pitch bandwidth ω_x in the improvisation step is proposed in Coelho and Bernert (2009) for the tuning of a proportional integral derivative (PID) controller aimed at the synchronization of two identical discrete chaotic systems. The value of the PAR is dynamically updated according to

$$\mathrm{PAR}(t) = \mathrm{PAR}_{\min} + (\mathrm{PAR}_{\max} - \mathrm{PAR}_{\min}) \cdot \xi(t) \quad (2)$$

where $\mathrm{PAR}_{\min}$ and $\mathrm{PAR}_{\max}$ are minimum and maximum values of the adjusting rate, and $\mathrm{PAR}(t)$ is the pitch adjusting rate for iteration t. The grade $\xi(t)$ is calculated based on the maximum and minimum objective function values in iteration t, denoted as $\psi_h(t)$ and $\psi_l(t)$, namely

$$\xi(t) = \frac{\psi_h(t) - \overline{\psi}(t)}{\psi_h(t) - \psi_l(t)}, \quad (3)$$

where $\overline{\psi}(t)$ stands for the average value of the objective function value computed over the whole harmony memory. Other progression rules proposed in the literature range from purely linear to more involved logarithmic models driven by a single concavity parameter (Del Ser et al., 2012).

In order to cope with realistic design situations, Geem (2007) proposed a novel derivative for discrete design variables based on the HS algorithm. In such a reference, the HS can ultimately find the optimal solution or near-optimal solutions by the help of the stochastic derivative for discrete variables. Based on the contents of the HM at a given iteration of the algorithm, the stochastic derivative for discrete variables provides the algorithm with information on the probability of selecting optimal values, which in general increases progressively along the iterations. While the traditional calculus-based derivative generates information on the search direction and step size for a function of continuous variables, the stochastic derivative utilized in this work computes the probabilistic trend of the algorithm to select a certain discrete point based on multiple vectors stored in the HM for a function of discrete variables. This approach evidences that optimal and neighboring values have higher chances to be selected along the iterative process.

To conclude with, an interesting contribution focused on deriving a new variant of this algorithm from a simple yet intuitive mathematical analysis on its exploratory behavior (Das et al., 2011). In this work Das et al. analytically show that the standard deviation of the naïve HS algorithm computed over the harmony memory can be used as a proportionality factor for adaptively controlling the bandwidth ω_x. This approach introduces no additional complexity burdens to the original HS framework, and is assessed, through computer simulations over a benchmark of unconstrained and constrained numerical problems, to outperform other HS variants and well-known evolutionary counterparts.

3.2. Engineering

Let us start with the application-oriented review by addressing uses of the HS algorithm in problems related to engineering disciplines, where this solver has been reported to be a viable alternative to other conventional optimization techniques. Hence, it has been broadly utilized in complex optimization problems arising in most engineering applications such as design optimization of heat exchangers, steel, electronic, mechanical, telecommunication, construction and engineering structures problems, among others. In the next subsections different problems stemming from several of these engineering areas and their solving via HS heuristics are described in detail.

3.2.1. Steel

Typical steel engineering problems involve structural design optimization problems. Such problems generally require the selection of steel sections for its beams and columns under the criteria that the frame satisfies the serviceability and strength requirements while minimizing the material cost of the frame. In addition to the budget constraint, this selection is commonly carried out in such a way that the steel frame has the minimum weight.

The problem presented in Saka (2009b) falls into discrete optimization problems in which finding the optimum feasible solution results in a difficult task. The proposed design algorithm imposes the behavior and performance constraints in accordance with BS5950 (British Standard for the design, fabrication and erection of structural steelwork). In this approach, the BS5950 imposes eight restrictions to the structures that limit the deflections in beams, weight of the steel section, the horizontal deflection of columns due to imposed load and wind loads, among others. The HS algorithm implemented in this paper follows the traditional scheme and adds a repair procedure for the harmonies that violate the problem constraints. The initialization step generates random values for each note within the specified alphabet for each design variable. During the iterative process, unfeasible solutions are accepted following a novel method; once the new harmony vector is obtained, it is then checked whether it violates the problem constraints. If the new harmony vector is severely unfeasible, it is discarded, whereas if it is slightly unfeasible, there are two ways to be followed: the first reduces to including it in the harmony memory by imposing a penalty on its associated fitness value. Thereby, the violated harmony, which is slightly unfeasible in any or several of its constraints, is used as a basis for the pitch adjustment operation to provide a new feasible harmony. The other option is to resort to larger tolerance values for the acceptability of the new unfeasible harmonies, and reduce this tolerance gradually during the iterative process. This adaptive error strategy results to be quite effective when handling the constraints established in this design problem.

Another recent work that can be included in this discipline area involves the optimum design of cellular beams, i.e. the hole diameter, the total number of holes in the beam, and the sequence number of Universal Beam section, in order to obtain the minimum weight of the cellular beam (Erdal et al., 2011). The study also incorporates some design constraints taken from the Steel Construction Institute (Publication Number 100, which contents are consistent with the specifications in BS5950 parts 1 and 3). Specifically, the constraints to be considered include the displacement limitations, overall beam flexural capacity, beam shear capacity and the overall beam buckling strength, among others. As a result, the cellular beam is subject to 12 geometrical and behavioral restrictions. The proposed algorithm to efficiently tackle this problem consists of five steps: (1) selection of the parameters' values of the HS algorithm; (2) initialization of the harmony memory by randomly selecting the sequence numbers of steel sections from a discrete list, as well as the hole diameters and number of holes for cellular beam; (3) improvisation of new harmonies and analysis of the cellular beam under the external loading, checking whether the design limitations are satisfied or not (if this vector is severely unfeasible it is discarded and another harmony is sought, whereas if it is slightly unfeasible, it is included in the harmony memory); (4) filtering of the best harmonies, which are kept in the harmony memory for subsequent iterations; and (5) repetition of steps (3) and (4) until the termination criterion is satisfied. The design examples presented in this paper utilize constant values for the algorithm parameters obtained from a modest optimization process, and clearly reflects the strong dependence between the HS results and the selected parameter values.

3.2.2. Shell and tube heat exchangers

Shell and tube heat exchangers (STHXs) are the most widely used heat exchangers in process industries because of their relatively simple manufacturing and their adaptability to different operating conditions. The design of STHXs, including thermodynamic and fluid dynamic design, cost estimation and optimization, represents a complex process containing an integrated whole of design rules and empirical knowledge from various fields. The study presented in Fesanghary et al. (2009) demonstrates a successful application of the HS algorithm for the optimal design of shell and tube heat exchangers. It explores the joint use of Global Sensitivity Analysis (GSA Saltelli et al., 2005) and the HS algorithm for design optimization of shell and tube heat exchangers from the economic point of view. First, it is necessary to identify the geometrical parameters that have the largest impact on total cost of STHXs. This task is successfully achieved by means of the GSA. Next, the HS algorithm is applied for optimizing the influential parameters. The end goal lies on finding the STHX optimal design capable of accomplishing the prescribed thermal duty with minimum combined investment and operating cost.

Among all the benefits that HS presents, three of them are particularly interesting for this involved application scenario: first, HS imposes fewer mathematical requirements and does not require initial value settings of the decision variables. Second, as it resorts to stochastic random operators for guiding the search process, derivative information is deemed unnecessary. Third, HS is capable of searching for solutions from disjoint feasible domains. These features enhances the applicability of HS to the design of thermal systems, setup where the problems are usually non-convex and have a large amount of discrete variables and discontinuities in the fitness function.

3.2.3. Telecommunications

The increasingly close attention grasped by the so-called Wireless Sensor Network (WSN) concept during the last decade arises from its capacity to efficiently and collaboratively sense physical phenomena without the need of any wired link and at a reduced per-node computational complexity. Traditional approaches are focused on extending the WSN coverage and lifetime of the network, such as the work in Mahdavi et al. (2007) which proposes an Improved Harmony Search algorithm in a k-covered and connected wireless sensor network. The aim of this work is to achieve a sensor node deployment with optimal coverage and energy efficiency by preserving node connectivity and k-coverage property for hot-spot areas. Through computer simulations, Improved Harmony Search algorithm is shown to find better solutions (i.e. maximum covered area and lower energy consumption) than the original HS algorithm and their genetically-inspired counterparts.

Within this line of research, besides the classical monitoring applications which WSNs initially targeted, their proliferation and the intrinsic value of their sensed information have ignited the research interest in context-aware services and applications, in which the availability of accurate nodes' location information is essential to make collected data meaningful. Hence, in such applications it is important to associate the captured data with the location of the node. In order to efficiently tackle this problem, novel localization approaches based on the combination of the HS algorithm and a novel local search procedure have been recently proposed in Manjarres et al. (2012a, 2013). The latter presents a comparative study of a multi-objective HS algorithm and a Pareto Archived Evolution Strategy (PAES) approach concluding in a better performance of the proposed multi-objective HS in terms of accuracy, further buttressed by a statistical Wilcoxon hypothesis test. Connectivity-based geometrical constraints are defined in these works in order to exploit and limit the areas in which sensor nodes can be located.

When turning the scope to metropolitan wireless local area networks, a shared-infrastructure deployment problem is proposed in Landa-Torres et al. (2012b) where the coverage level of the deployed network must be maximized while meeting an assigned maximum budget. Specifically, an approach based on the HS algorithm is proposed with three main technical contributions: (1) the adaptation of the HS algorithm (i.e problem encoding) to a grouping scheme, used for mapping users to access points; (2) the adaptation of the improvisation operators driving the algorithm to the specific characteristics of the optimization problem to be tackled; and (3) its performance assessment via a simulated experiment inspired by real statistics in the city of Bilbao, Spain. The HS algorithm utilized in this contribution not only adapts its encoding to tackle this clustering problem, but it also includes a coverage matrix and access point's information into the definition of the improvisation operators.

Other telecommunication areas where HS has been recently shown to efficiently solve computationally hard optimization challenges include multiuser detection in CDMA systems (Zhang and Hanzo, 2010), dynamic resource management in wireless systems (Del Ser et al., 2011, 2012), design of radar codes (Gil-Lopez et al., 2012) and maintenance planning of communication equipment (Harrou and Zeblah, 2011).

3.2.4. Construction and engineering structures

The improvement of energy efficiency and environmental performance of buildings is considered a major priority worldwide. New building regulations have an explicit orientation toward low-emission and energy-efficient designs. However, the optimal design of residential buildings should consider multiple and usually competitive objectives such as energy consumption optimization, financial costs reduction and minimization of environmental impacts.

The approach presented in Fesanghary et al. (2012) proposes a multi-objective HS solver for minimizing the life cycle cost and CO_2 emissions of residential buildings. These objectives are naturally competitive: the cost of environmental friendly materials is usually higher than those of the corresponding conventional ones, while the energy-efficient materials may be less environmental friendly than other materials that are less efficient. As a result, the need for a multi-objective optimization approach to efficiently take both issues is evident. On the one hand, the life cycle cost (LCC) can be obtained from the initial investment costs, replacement costs, energy costs, operational, maintenance and repair costs. The second objective is to minimize CO_2, CH_4 and N_2O emissions over the life cycle of the building. The schema developed in this multi-objective approach provides a range of non-dominated solutions along the Pareto front in which a reduction in the CO_2 emission can only be achieved by increasing the life cycle cost. A trade-off between these two objectives is needed and thus, several optimum solutions that favor each criterion at a higher or lower level are given.

Another aspect of relevant importance nowadays includes engineering structures tasks in which distinct structures are optimized according to several parameters and technological constraints. In Zarei et al. (2009) a HS algorithm is presented in order to determine the optimum cutting parameters for multi-pass face-milling. The optimization task involves obtaining the number of passes and also the corresponding speed, feed and depth of cut for each pass that minimize the total production cost while considering technological constraints such as available speeds, depth of cut, feed, cutting force and power, tool life and machine tool capabilities. Then, from all of the possible cutting strategies, the best one according to the value of the corresponding objective function is selected.

Another set of studies deal with the optimization of truss structures (Kaveh and Talatahari, 2009), which involves obtaining the optimum values for member cross-sectional areas that minimize the structural weight. This minimum design has to satisfy inequality constraints that limit the design variable sizes and the structural responses. Thus, the optimal design problem must minimize the weight of the structure, the number of nodes, the number of compression elements, the material density and the length of members and cross-sectional areas. In this paper, a Heuristic Particle Swarm Ant Colony Optimization (HPSACO) is presented for optimum design of trusses. The algorithm is based on the Particle Swarm Optimizer with Passive Congregation (PSOPC), an Ant Colony Optimization (ACO) and a HS scheme. HPSACO applies PSOPC for global optimization, whereas the ACO is used for updating the positions of particles in order to attain a feasible solution space. Besides, there are some problem-specific constraints in this type of optimization problems that must be considered. Hence, the proposed approach handles these constraints by employing a fly-back mechanism in which the particle will be forced to fly-back to its previous position if any of the constraints is violated. Furthermore, if it flies off the variable boundaries, the solution cannot be used even if the problem-specific constraints are satisfied. In order to do so, the HS heuristic has been used to check whether the variables' boundaries have been violated. The resulting method has a good control on the diversification and intensification when compared to PSO and PSOPC. It increases the diversification and properly guides the intensification. As a result the convergence rate of the proposed algorithm is higher than that of other heuristic approaches.

3.3. Water/groundwater system management

Several studies have focused on the design of water distribution networks, in particular on the selection of optimal pipe diameters. Typically, there is one fixed-pressure supply node and many demand nodes which connectivity makes the structure of the distribution network. Both the elevations and distances between nodes (pipe lengths) are specified. Therefore, the aim of these studies is to select the diameter for each pipe segment that minimizes the total cost of the water distribution network. The problem is subjected to certain constraints, such as the continuity equation, the conservation of energy equation, minimum pressure requirements, the maximum pressure, the flow velocity and the reliability.

In the water distribution network design problem described in Geem (2006), the objective function is the pipe cost function; the pipe diameter is the decision variable; the number of decision variables corresponds to the number of pipes in the network and the set of decision variable values is the range of possible candidate diameters. Thus, the cost of the water network design is mathematically assumed to be a cost function of pipe diameters and lengths. In this work the nominal HS algorithm is implemented for a wide range of HM sizes, HMCR and PAR values. On the other hand, the number of iterations is determined based on the number of objective function evaluations of other competitive algorithms. It is important to note that for the sake of its practical implementability, this approach interfaces with the popular hydraulic simulator EPANET to check the hydraulic constraints; if the design solution vector violates the hydraulic constraints, the amount of violation is considered in the cost function as a penalty.

3.4. Medical

The potential characteristics of the HS algorithm has made it also suitable for its application in medical issues. On the one hand, in therapeutic medical physics, ionizing radiation is employed to treat patients with cancer in which a radiation treatment planning is essential to improve patient care. This planning requires the optimization of radioisotope placement as well as the radiation beam intensities by means of meta-heuristic algorithms (Panchal, 2009).

Following this line of research, the study presented in Panchal (2008) delves into high dose-rate prostate brachytherapy optimization using HS. It involves calculating and determining the best dose distribution to the target and organs-at-risk by means of optimizing the time that the radioactive source dwells at specified positions within the catheters. Another recent work focuses on the detection of the epileptic seizure activity with fast and high accuracy from electro encephalogram data (Gandhi et al., 2012). The proposed scheme, a wavelet based Probabilistic Neural Network (PNN) classifier, is based on the discrete wavelet packet transform followed by the application of Differential Harmony Search algorithm (DHS) and a Probabilistic Neural Network (PNN). The proposed robust method for selecting optimal features by DHS maximizes the classification accuracy with reduced computational complexity. Specifically, it is designed to discern between two signal classes: normal and epileptic. After the data is decomposed into several features obtained from the discrete wavelet packet transform, DHS is utilized for selecting optimal features that are introduced into a PNN classifier. To that end, the dimension of each vector used in the optimization algorithm is reduced, as DHS chooses the features that maximize the classification accuracy. Furthermore, the problem of premature convergence encountered in the classical HS algorithm is alleviated due to the greater explorative capability featured by DHS.

3.5. Robotics

One of the most important challenges nowadays is to apply heuristic algorithms to several applications in the robotic field such as the optimal design of reconfigurable robots, the optimal trajectory planning and the control of robot's movements. In this context, a desired trajectory generation method based on the combination of neural networks and HS (the latter used for feature selection) has been applied to three-dimensional bipedal walking in Yazdi et al. (2011). This controller is able to control the arm movements during walking with emphasis on make robot's walking more stable and faster. Thus, in order to reach smoother walking and increase speed and robustness this system controls roll of arms during locomotion. In this regard, Matsuoka neural oscillators have been used to generate control signals for governing the locomotion of a humanoid robot. The neural network designed for robot motion needs 18 parameters where 10 of them are used for Matsuoka neural oscillators, 6 parameters for linear neurons, and 2 for gait period and knee threshold. Therefore, each solution in the HM is encoded as an array of 18 elements which is randomly filled during the initialization process. Alternatively, upper and lower bounds have been defined for initialization of each variable. Regarding the HS algorithm, a nominal structure is employed in order to find optimum values for these parameters, i.e. to find the best angular trajectory and optimize neural oscillator parameters. Finally, in order to achieve stable and faster walk, a fitness function based on robot's straight movement is assumed. The amount of deviation from straight walking is subtracted from the fitness as a punishment to force the robot to walk straight.

3.6. Control

In recent years, Fuzzy Logic Control (FLC) schemes have been broadly utilized in many technical and industrial applications as a potential tool for handling the uncertainties and nonlinearities of modern control systems. The success of these techniques relies on the ability of incorporating human expertise in control strategies. Nevertheless, the main drawback of FLC methodologies is the considerable amount of parameters that need to be tuned. To overcome this issue, a wide class of meta-heuristic solvers have been developed for control optimization purposes. As to mention, in Das Sharma et al. (2010) an hybrid stable adaptive fuzzy controller utilizes the conventional Lyapunov theory jointly with the HS algorithm. The goal of this approach is to optimize both structures and free parameters such that the designed controller can guarantee desired stability and satisfactory performance with a high degree of automation in the design process. Two variants of this hybrid model are proposed and implemented for simulated and real-case studies.

3.7. Power and energy

Another discipline area in which the HS algorithm has achieved successful results is power and energy, where several related optimization problems have been addressed such as the optimal design of wind generators, the efficient model for transport energy demand, the power flow problem and the optimal allocation of capacitors and compensators in power systems.

The majority of the power related works focus on the power flow optimization problem which aim is to specify the loads in megawatts to be supplied at certain nodes or busbars of a transmission system in such a way that a minimum cost is needed. In mathematical terms, the problem can be reduced to a set of non-linear equations where real and imaginary components of the nodal voltages are the variables to be optimized. On this purpose, the authors in Sivasubramani and Swarup (2011a) propose a multi-objective HS approach in which a fast elitist non-dominated sorting strategy and a crowding distance procedure are used to find and populate an estimation of the Pareto optimum front. The objective functions to be minimized are the total fuel cost and the real power transmission line losses of the system. Finally, a fuzzy-based mechanism selects a compromise solution from the estimated Pareto set.

Several other studies have concentrated on the so-called power economic dispatch problem, which aims at minimizing the energy production cost while meeting the power demands. Nowadays, the conversion of primary fossil fuels—such as coal and gas—to electricity is a relatively inefficient process in which even the most modern combined cycle plants are able to achieve efficiencies only between 50 and 60%. Most of the energy loss in this conversion process is released to the environment as waste heat. The principle of combined heat and power (CHP), also known as cogeneration, is to recover and make beneficial use of this heat towards significantly raising the overall efficiency of the conversion process (the best CHP schemes can achieve fuel conversion efficiencies in the order of 90%). In this context, the authors in Vasebi et al. (2007) deal with the CHP economic dispatch problem by means of a HS algorithm, which essentially consists of determining the heat and power production so that the system production cost is minimized while heat-power demands and other side constraints are met. In order to illustrate the utilized method a test case taken from the literature (as well as a new one proposed by the authors) is presented. The steps of the proposed HS technique and also the parameters driving the algorithm follow the traditional scheme, and in the improvisation step, the Harmony Memory Size, HMCR and PAR values are kept constant along the iterations.

In Sivasubramani and Swarup (2011b) a multi-objective harmony search algorithm is presented in order to optimize simultaneously two competing objectives: fuel cost and emission. The algorithm utilizes a non dominated sorting and a ranking procedure based on crowding distance values to develop and maintain a well distributed Pareto-optimal set. The obtained results are compared with the Non-dominated Sorting Genetic Algorithm (NSGA-II) showing a better performance of the proposed multi-objective HS method in the achievement of the Pareto-optimal solutions.

3.8. Cross-application uses of HS

HS has so far been thoroughly utilized as a support algorithm for different knowledge inferring techniques used in different disciplines and diverse application fields, such as feature selection, clustering and scheduling. This subsection elaborates on the contributions corresponding to each of these techniques in an application-agnostic fashion, since all share the same HS-inspired algorithmic strategy.

Regarding the first, one of the main aims of feature selection (FS) is to determine a minimal feature subset from a problem domain while retaining a high accuracy in the representation of the original feature set. Harmony search is best suited to solve problems with a fixed set of decision attributes and an objective function to be optimized, whereas feature selection is a problem with variable-sized solutions. Therefore, there is a need to map each key concept of HS into elements in FS. It can be done by considering evident analogies, i.e. each feature subset can be seen as a harmony and the objective function can be substituted by a subset evaluation method such as the so-called fuzzy-rough dependency measure.

In this context, the goal of the recent work presented in Diao (2010) is to develop two HS-based, stand alone, reusable search strategies capable of finding optimal feature subsets according to a wide range of subset evaluation methods. In particular, the HS algorithm utilized in this approach is an improved version of the original scheme in which different methods are included for dynamically tuning parameters, similar to what was done previously in Mahdavi et al. (2007). Such two different strategies can be summarized as

- *Horizontal approach*: The horizontal approach maps musicians onto the available features to be selected. The note domain of each musician is then a binary value, indicating whether or not the corresponding feature is included in the harmony. Therefore, in this approach the HMCR operator has little practical impact and can be seen as a simple bit flip rate.
- *Vertical approach*: The vertical approach tackles the problem of FS from a different viewpoint. It treats musicians as independent experts, i.e. each musician can vote for one feature to be included in the feature subset when improvising a new harmony. The harmony is then the combined vote from all musicians, indicating which features are being nominated. Thus, the vertical approach allows a much greater range of notes for musicians, which enables the use of the HMCR to its full potential and increases the chance of escaping from local optima.

Experimental comparative studies show that the horizontal approach requires much longer processing time in order to find comparable quality subsets. The vertical approach makes better use of the algorithm and can converge much faster than the horizontal scheme with a smaller harmony memory and fewer number of iterations. Besides, it is capable of identifying similar or superior feature subsets for most of the datasets with notable classification accuracy.

On the other hand, clustering is one of the most powerful data mining techniques used for discovering intentional structures in data and grouping instances that have similar features. As a result, it has become an important technique for managing databases and extracting new knowledge therefrom. Many different applications have arisen based on clustering such as knowledge discovery, data compression, vector quantization, pattern recognition and pattern classification. In order to decrease the computational effort when handling large problems, meta-heuristic algorithms have been also utilized in this area.

Within this research scope, the authors in Alia et al. (2010) present a Dynamic Clustering algorithm called DCHS based on the HS algorithm hybridized with a Fuzzy C-means (FCM) algorithm to automatically segment the brain Magnetic Resonance Imaging (MRI) image in an intelligent manner. DCHS is used as an image segmentation algorithm to dynamically segment both simulated normal and multiple sclerosis-damaged brain MRI images. The proposed algorithm has the ability to cluster the given data set automatically without any prior knowledge of the number of clusters. Therefore, the capability of standard HS is modified to automatically tailor the number of clusters as well as the locations of cluster centers. By incorporating the concept of variable length in each harmony memory vector, DCHS is able to encode a variable numbers of candidate clusters at each iteration. To further enhance the concept of variable-length of the harmony memory vectors, a new HS operator called the "empty operator" is proposed. This new operator is introduced to minimize the variation of the results (i.e. number of clusters) that are obtained from DCHS in case of multiple runs. The inconsistent results from multiple runs can be due to the dominating effect of a number of solution vectors of the HM through the improvisation process (premature convergence problem). Therefore, the ability of generating a new vector with different number of cluster centers is very poor. In order to cope with this issue, the new operator is introduced to add a new method of having empty "don't care" decision variables in the newly generated harmony vector. By virtue of this additional operator, the DCHS algorithm has the ability to generate a new harmony vector with distinct number of clusters, even in the final stages of the DCHS algorithm search process.

Additionally, an hybridizing step with a FCM algorithm is introduced to increase the quality of the clustering results by fine tuning the best solution that has been optimized by DCHS. The solution vector with highest fitness value is selected from the harmony memory and considered as initial values for FCM's cluster centers. In this case, FCM modifies the cluster centers values until the variance of the clusters is minimum, thus yielding more compact clusters. Consequently, the clustering results achieved by DCHS will decrease the variation within each cluster members (intra-cluster variation) and, at a same time, increase the variation between clusters (inter-cluster variation). Then, the PBMF cluster validity index is used as an objective function to validate the clustering result obtained from each harmony memory vector.

Finally, the need for a scheduling algorithm arises from the requirement of most modern systems to perform several tasks and/or transmit multiple flows simultaneously. In real environments, the scheduling is concerned with the optimal allocation of scarce resources to activities over time, which is crucial for keeping the system stable and meeting deadlines. More generally, scheduling problems involve the planning of the tasks subject to certain constraints in order to optimize an objective function. In this context, a large variety of scheduling problems have been tackled in the literature which have been solved by means of meta-heuristic algorithms.

An example of the application of the HS algorithm to scheduling problems is Ayachi et al. (2011). In this paper an adaptation of HS is presented in order to solve the unbound container storage location problem, in which the main goal is to reduce the unloading time of all containers when they are delivered to their customers. Specifically, the wait time of customer trucks and the transfer time of the yard crane are regarded as optimization variables in the formulation. In the algorithm implementation, the initial harmony memory is randomly generated and every stored solution must meet all the problem constraints. The decision variables represent the possible locations for the containers according to the allocated storage area. After that, a new solution is improvised based on the nominal HS proposed in Geem (2000). In order to assess the performance of the proposed approach, the value of the parameters driving the algorithms' behavior is also optimized. In fact, the harmony memory size (HMS), the harmony memory considering rate (HMCR), the pitch adjustment rate (PAR) and the number of generations undergo an enumerative optimization process in order to select the values that best balance optimality for computational time. This enumerative optimization stage comprises seven independent experiments for different HMS, HMCR and PAR values, as well as a method for measuring the number of iterations needed for the algorithm to stabilize.

Other scheduling problem capturing the interest of the research community in recent years is the so-called flow shop scheduling problem, in which an appropriate sequence order for each task is sought in order to obtain a minimum idle and waiting time. The authors in Ren et al. (2011) propose several HS-based heuristics for minimizing the maximum completion time (*makespan*) and the total flow time for non-idle flow shop problems. Other scheduling-related contributions include the multi-mode resource constrained project scheduling problem (Fu and Zhang, 2011), and the broadcast scheduling in packet radio networks (Ahmad et al., 2012).

3.9. Other applications

Other related applications delve into distinct categories such as chemical (Zou et al., 2010a), visual tracking (Fourie et al., 2008), bioinformatics (Mohsen et al., 2010), mathematics (Cheng and Yong, 2010), logistics (Bo et al., 2010), image (Fourie et al., 2010), neural network training (Kattan et al., 2010), puzzle solving (Geem, 2007) and commercial consulting services (Landa-Torres et al., 2012c), among many others (see attached bibliography).

4. Concluding remarks

This article has posed an overview of the recent applications where the music-inspired Harmony Search algorithm has been shown to be an effective meta-heuristic to solve computationally involved optimization paradigms. This overview is broken down into a set of categories divided by application area, which serves as an useful tool for experimented practitioners and beginners to get a brief description of the latest activity and trends around HS in every such area. For the sake of brevity each category is briefly introduced to the reader by commenting on the most-cited articles found at each application group.

As stated in most of the contributions cited in this review manuscript, the HS algorithm features a great potential and efficiency when seeking near-optimal solutions to computationally hard optimization problems. Indeed, the excellent behavior of this meta-heuristic solver has been widely proven in such references by resorting to intensive simulation-based studies, further buttressed by different statistical hypothesis tests. In light of the sharp increase of activity around HS noted in the last years, it is expected that the computational benefits stemming from this meta-heuristic will span to other emerging fields (e.g. genomics, business intelligence, crime prevention, forensics, smart grids, renewable energy and many other disciplines linked to the so-called Big Data concept), as well as unchain new functionalities and variants of the nominal HS algorithm itself.

Indeed, the upsurge of activity around this algorithm paves the way to interesting lines of future research, some of which are already being pursued by the scientific community. Computationally speaking, methods for an efficient management of the memory and for speeding up the performance of the algorithm are within such next steps and directions in this area. In fact, many meta-heuristic approaches make use of the whole memory in order to obtain the new set of solutions. Therefore, the parallelization of the code for reducing the computation time to its minimum yields a research target of utmost relevance when tackling optimization problems of extremely high dimensionality (as those mentioned above).

From the theoretical side, the parameter-setting-free technique (often called as *adaptive* technique in other meta-heuristic algorithms Geem and Sim, 2010) is to be further developed because in practical applications engineers and decision makers are willing to use HS without performing any parameter tuning procedure. In many cases, they just want to "push the button" to get good solutions for their systems instead of getting seriously involved in the algorithm. Thus, how to provide more user-friendly parameter-setting-free environments to end-users is critical for the future success of this algorithm.

Last but not least, the communication between algorithm developers and field users is another critical factor for the future of this algorithm. So far, assorted variants of HS have been proposed by many researchers. However, they seldom feed field users' requests back to their algorithmic derivations, but instead resort to a number of assumptions relatively far from the needs and demands of end users. Thus, more cooperation between research and field user groups is expected in order for HS to endure as a practical tool for obtaining better solutions in real-world decision-making problems.

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