Harmony Search Applications in Industry

Zong Woo Geem

Environmental Planning and Management, Johns Hopkins University, USA

1 Introduction

In this chapter, the recently-developed music-inspired harmony search (HS) algorithm is introduced and its various industrial applications are reviewed.

The HS algorithm (Geem et al 2001) mimics the behaviors of musicians improvising to find a fantastic harmony in terms of aesthetics. Similarly, the optimization process seeks a superior vector in terms of objective function. This is the core analogy between improvisation and optimization in the HS algorithm.

This soft-computing algorithm could overcome the drawbacks of conventional calculus-based optimization techniques because it has a novel derivative based on solution density and selection probability (Geem et al 2001). This new derivative provides a search direction for discrete decision variables that are undifferentiable. For example, the design variables (= pipe diameters) in water distribution networks are discrete because they are commercially manufactured in factories (Mott 2005). Also, HS does not require initial values for decision variables, which gives HS an increasing flexibility in finding global optimum (Geem, 2006a).

The HS algorithm has been successfully applied to various benchmark and recreational examples, such as Rosenbrock's banana function (Lee and Geem 2005), multiple local optima functions (Lee and Geem 2005), the traveling salesperson problem (Geem et al 2001), artificial neural networks (Geem et al 2002), various continuous functions (Tian et al. 2005; Mahdavi et al. 2007), tour route planning (Geem et al. 2005b), Sudoku puzzle solving (Geem 2007c), and music composition (Geem and Choi 2007).

Also, HS has been extensively applied to various real-world industrial problems as follows:

- **Civil Engineering**
  - Water network design (Geem 2006b & c)
  - Multiple Dam Scheduling (Geem 2007a)
- **Structural Engineering**
  - Dome truss design (Lee and Geem 2004)
  - Grillage structure design (Erdal and Saka 2006)
  - Mix proportioning of steel and concrete (Lee 2004)
- **Traffic Engineering**
  - School bus routing (Geem et al. 2005a)

B. Prasad (Ed.): Soft Computing Applications in Industry, STUDFUZZ 226, pp. 117–134, 2008.
springerlink.com

- **Aerospace Engineering**
  - Satellite heat pipe design (Geem and Hwangbo 2006)
- **Petroleum Engineering**
  - Petroleum structure mooring (Ryu et al. 2007)
- **Industrial Engineering**
  - Fluid-transport minimal spanning tree (Geem and Park 2006)
- **Environmental Engineering**
  - Parameter calibration of flood routing model (Kim et al. 2001)
  - Parameter calibration of rainfall-runoff model (Paik et al. 2005)
- **Energy Engineering**
  - Energy-saving pump operation (Geem 2005)
- **Mechanical Engineering**
  - Pipeline leakage detection (Kim et al. 2006)
- **Chemical Engineering**
  - Prediction of oil well heat wash (Liu and Feng 2004)
- **Geological Engineering**
  - Soil slope stability (Li et al. 2005)
- **Agricultural Engineering**
  - Large-scale irrigation network design (Geem 2007b)
- **Information Technology**
  - Web-based optimization (Geem and Geem 2007)

As the above list demonstrates, HS applications in industry are described in various journals, conference proceedings and degree theses. Since Geem and Tseng (2002) first summarized the industrial applications, many articles have been published recently. Thus, the objective of this chapter is to provide a common understanding of the "big picture" of HS algorithm applications for researchers and students in the above mentioned fields.

2 Harmony Search Algorithm

The music-based HS algorithm has the following six steps:

2.1 Problem Formulation

An optimization problem solved by the HS algorithm can be formulated in a general framework as follows (Mays and Tung 1992):

$$\begin{aligned} \text{Optimize} \quad & f(\boldsymbol{x}) \\ \text{Subject to} \quad & \mathbf{g}(\boldsymbol{x}) \geq 0 \\ & \mathbf{h}(\boldsymbol{x}) = 0 \\ & \boldsymbol{x} \in \boldsymbol{S} \end{aligned} \tag{1}$$

where $\boldsymbol{x}$ is a solution vector of n decision variables ($x_1, x_2, \ldots, x_n$), $f(\boldsymbol{x})$ is an objective function, $\mathbf{g}(\boldsymbol{x})$ is a vector of inequality constraints, $\mathbf{h}(\boldsymbol{x})$ is a vector of equality constraints, and $\boldsymbol{S}$ is the solution space. If the decision variable x_i is discrete, $\boldsymbol{S} = \{x_i(1), x_i(2), ..., x_i(k), \ldots, x_i(K)\}$; if x_i is continuous, $\underline{x_i} \le \boldsymbol{S} \le \overline{x_i}$.

2.2 Harmony Memory Initialization

Before a new harmony is improvised (= generated) by HS, a matrix, named harmony memory (HM), is filled with a group of randomly-generated vectors.

$$\left[\begin{array}{cccc|c} x_1^1 & x_2^1 & \cdots & x_n^1 & f(\boldsymbol{x}^1) \\ x_1^2 & x_2^2 & \cdots & x_n^2 & f(\boldsymbol{x}^2) \\ \vdots & \cdots & \cdots & \cdots & \vdots \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_n^{HMS} & f(\boldsymbol{x}^{HMS}) \end{array}\right] \tag{2}$$

In Eq. 2, each row represents each solution vector, and the number of total vectors is HMS (harmony memory size).

In order to start HS computation with better HM, random vectors may be generated more than HMS, then only better vectors are collected in the HM.

2.3 New Harmony Improvisation

Once the HM is prepared, a new vector (= harmony) $\boldsymbol{x}^{New} = (x_1^{New}, x_2^{New}, ..., x_n^{New})$ is improvised based on the following three operations.

2.3.1 Memory Consideration

A value of decision variable x_i^{New} can be chosen from any values stored in the HM with a probability of HMCR (harmony memory considering rate).

$$x_i^{New} \leftarrow x_i^{New} \in \{x_i^1, x_i^2, ..., x_i^{HMS}\} \quad \text{w.p.} \quad HMCR \tag{3}$$

2.3.2 Random Selection

Instead of memory consideration, a value of decision variable x_i^{New} can be chosen from any values in solution space $\boldsymbol{S}_i$ rather than in the HM.

$$x_i^{New} \leftarrow x_i^{New} \in \boldsymbol{S}_i \quad \text{w.p.} \quad (1 - HMCR) \tag{4}$$

2.3.3 Pitch Adjustment

Once a value of decision variable x_i^{New} is obtained from the memory consideration operation rather than the random selection operation, the value can be further modified into its neighboring values with a probability of PAR (pitch adjusting rate).

$$x_i^{New} \leftarrow \begin{cases} x_i(k+m) & \text{w.p.} \quad PAR \\ x_i(k) & \text{w.p.} \quad (1-PAR) \end{cases} \tag{5}$$

where $x_i(k)$ is identical to the value of the decision variable x_i^{New} obtained in the memory consideration operation; and neighboring index m can have -1 or 1.

For continuous-valued variables, the following scheme is used for pitch adjustment (Lee and Geem 2005).

$$x_i^{New} \leftarrow \begin{cases} x_i^{New} + \Delta & \text{w.p.} \quad PAR \\ x_i^{New} & \text{w.p.} \quad (1-PAR) \end{cases} \tag{6}$$

where Δ is non-uniform amount for pitch adjustment.

2.4 Other Consideration

2.4.1 Ensemble Consideration

A value of decision variable x_i^{New} can be chosen from the relationship among decision variables (Geem, 2006d).

$$x_i^{New} \leftarrow f(x_j^{New}) \quad \text{where} \quad \max_{i \neq j} \left\{ | Corr(\boldsymbol{x}_i, \boldsymbol{x}_j) | \right\} \tag{7}$$

2.4.2 Rule Violation

Once the new harmony vector $\boldsymbol{x}^{New}$ is generated, it is then checked to determine whether it violates any constraint. As accomplished composers like Bach and Beethoven used rule-violated harmonies (for example, parallel fifths), HS uses rule-violated vectors by adding a penalty (Geem and Choi 2007) to the objective function value.

2.5 Harmony Memory Update

If the new harmony vector $\boldsymbol{x}^{New}$ is better than the worst harmony vector in the HM in terms of the objective function value, including the penalty, the new vector is included in the HM and the worst vector is excluded from the HM. There may exist a maximum number of identical vectors in order to prevent premature HM.

2.6 Termination of Computation

If the number of harmony improvisations reaches MaxImp (maximum improvisations), the computation stops. Otherwise, the process described in sections 2.3 - 2.6 is repeated.

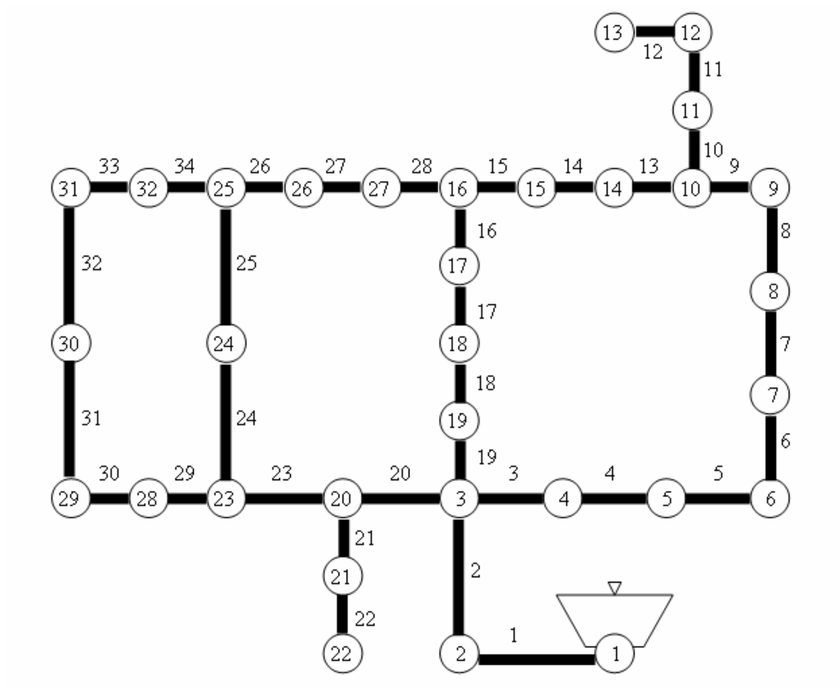


Fig. 1. Hanoi water distribution network

3 Harmony Search Applications in Industry

3.1 Water Network Design

The harmony search algorithm was applied to the design of water distribution networks. Figure 1 shows one of examples (Geem 2006b; Geem and Kim 2007). The objective of the problem is to minimize design cost by choosing minimal pipe diameters while satisfying pressure and quantity demand at each node.

HS was successfully applied to the water network design, and its result was compared with those of other soft computing algorithms, such as genetic algorithm (GA) (Wu et al. 2001), simulated annealing (SA) (Cunha and Sousa 2001), tabu search (TS) (Cunha and Ribeiro 2004), ant colony optimization (ACO) algorithm (Zecchin et al. 2006), and shuffled frog leaping (SFL) algorithm (Eusuff and Lansey 2003). The feasible solution obtained by HS ($6,081,000) was the best one when compared with those of GA ($6,183,000), SA ($6,093,000), and ACO ($6,134,000). Although TS ($6,056,000) and SFL ($6,073,000) claimed that they found better solutions, their solutions violated the nodal pressure constraint when examined with a standard hydraulic analyzer, EPANET 2.0 (Rossman 2000).

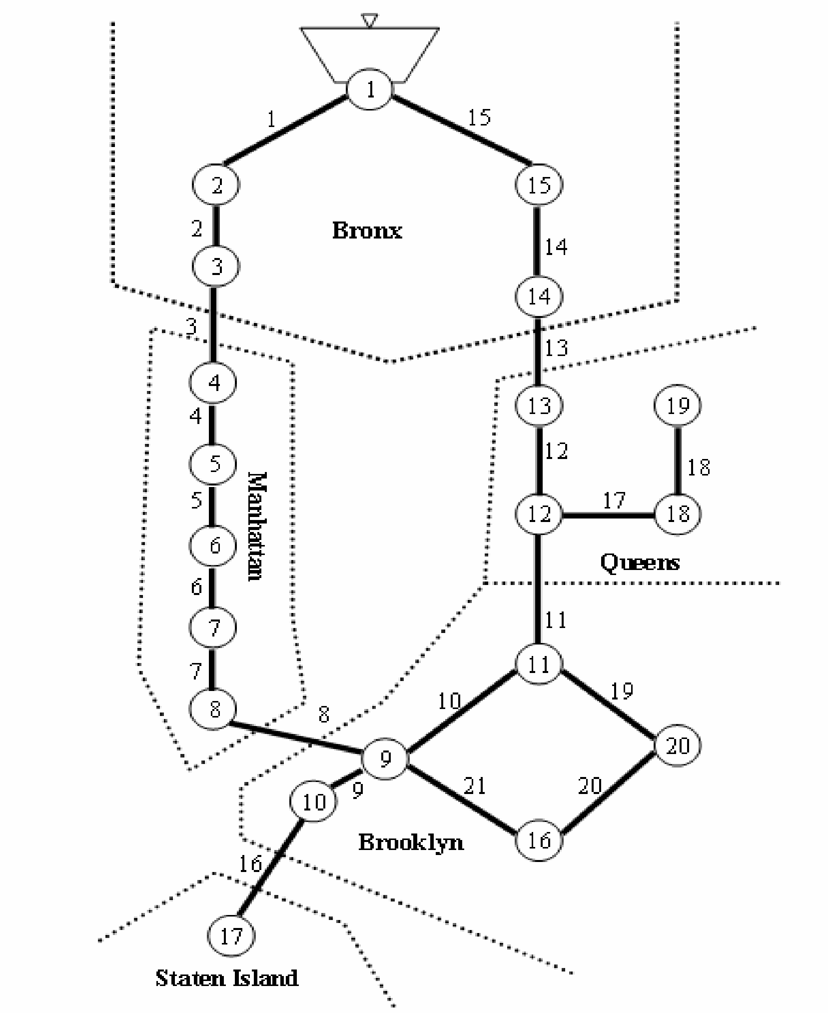


Fig. 2. New York City water distribution network

HS also was applied to the expansion problem for a water network shown in Figure 2. The objective of the problem is to find minimal diameters of additional pipes while satisfying pressure requirements at remote nodes.

HS (Geem 2006c), GA (Broad et al. 2005), ACO (Maier et al. 2003), and CE (Perelman and Ostfeld 2005) found the identical lowest expansion cost ($38.64 million) while SA (Cunha and Sousa 2001) and SFL (Eusuff and Lansey 2003) found the second best cost ($38.80 million). Although Cunha and Ribeiro (2004) claimed that the TS found $37.13 million, their solution violated nodal pressure constraint at three nodes (nodes 16, 17, and 19).

Fig. 3. Balerma water distribution network

Among the soft-computing algorithms that reached the identical least cost ($38.64 million), HS reached the cost with the least number of objective function evaluations: HS made a determination after 3,373 evaluations (2.5 seconds on Intel Celeron 1.8GHz) while ACO after 7,014 evaluations, CE after 70,000 evaluations, and GA after 800,000 evaluations.

HS also challenged a large-scale water network (4 reservoirs, 8 loops, 443 nodes, and 454 pipes) shown in Figure 3.

Reca and Martinez (2006) originally proposed the network, and obtained 2.302 million € using improved GA (an integer coding scheme, use of penalty multiplier, rank-based roulette wheel, three crossover strategies, uniform one-point mutation, and steady-state-delete-worst reproduction plan). Geem (2007b) applied HS to the same problem, and obtained 2.018 million € (12.4% less than that of GA).

3.2 Structural Design

The HS algorithm has been applied to the design of various structures. The objective of the problem is to minimize total weight by choosing minimal member size

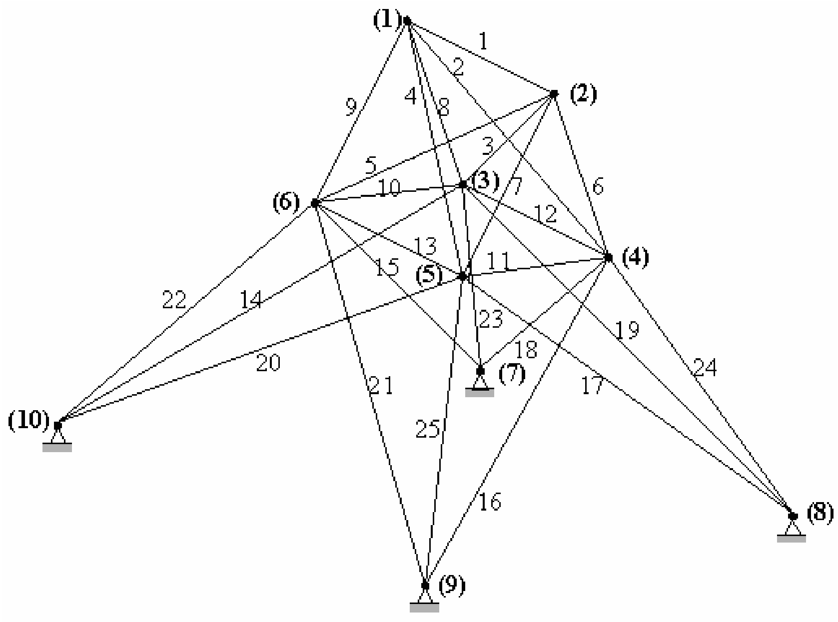


Fig. 4. 25-member transmission tower

while satisfying stress, displacement, and buckling limit constraints that can be checked by the finite element method (FEM) routine. Figure 4 shows one of structural examples.

For the 25-member tower problem, HS (Geem et al. 2005c) found the least weight (484.85 lb) while GA 485.05 lb (Camp et al. 1998), SA 537.23 lb (Park and Sung 2002), and artificial neural network (ANN) 543.95 lb (Adeli and Park 1996).

HS was also applied to the design of a dome structure shown in Figure 5, and found a reasonable solution.

HS was sometimes combined with other algorithms to solve optimization problems. Li et al. (2007) developed an algorithm (HPSO) based on HS and particle swarm, and applied it to various structural designs. While the HPSO obtained better solutions than those of most algorithms, it could not outperform the original HS (Lee and Geem 2004) in most cases.

3.3 Dam Scheduling

A dam is a barrier structure built across a river or stream to store water. HS was applied to the scheduling of multiple dam system as shown in Figure 6.

The objective of the problem is to maximize total benefits from both hydropower generation and irrigation by choosing water release amount at each dam while satisfying release and storage limit constraints.

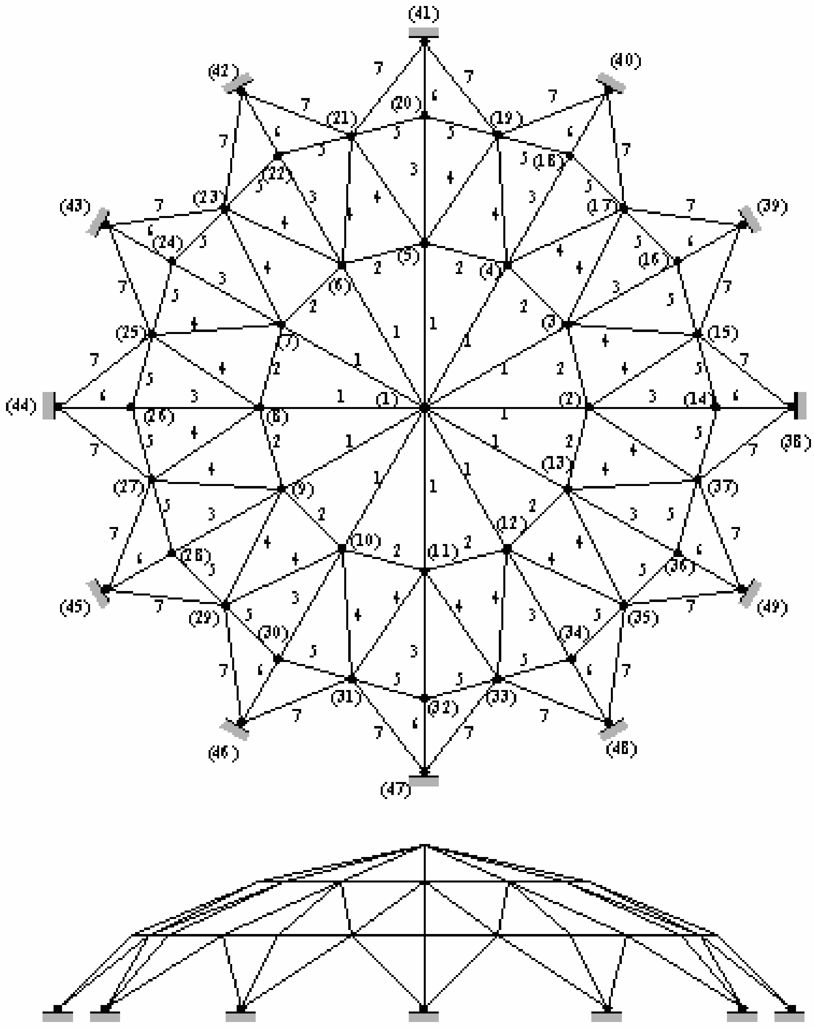


Fig. 5. 120-member dome structure

Wardlaw and Sharif (1999) obtained near-optimum benefits (400.5 units total) using improved GA (binary, gray & real-value representations, tournament selection, three crossover strategies, and uniform & modified uniform mutation), whereas Geem (2007a) obtained five different global optima (401.3 units) using HS (HMS = 30, HMCR = 0.95, PAR = 0.05, and MaxImp = 35,000).

Figure 7 shows one example of the water release trajectories from five global optima.

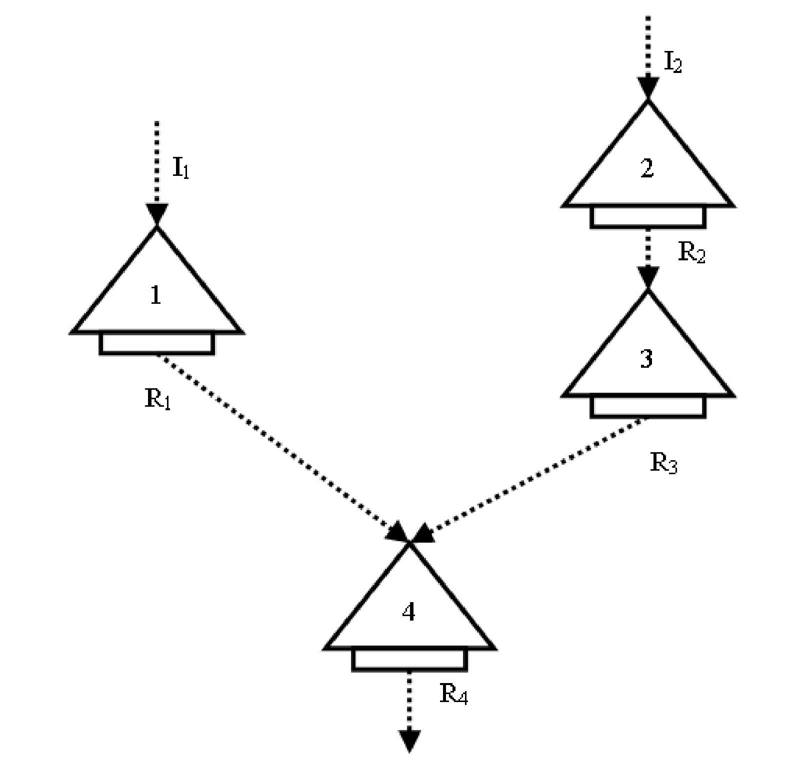


Fig. 6. Four-dam system

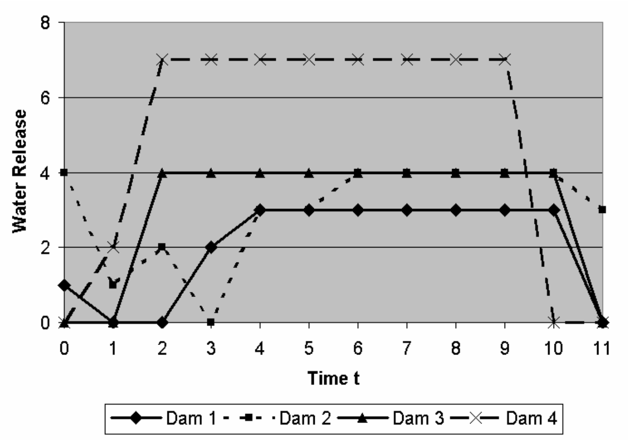


Fig. 7. Water release trajectory at each dam

3.4 Vehicle Routing

The vehicle routing problem (VRP) requires one to design a set of routes for multiple vehicles from a single depot in order to serve a set of customers who are geographically dispersed. HS was applied to a school bus routing problem, one of VRP's, as shown in Figure 8.

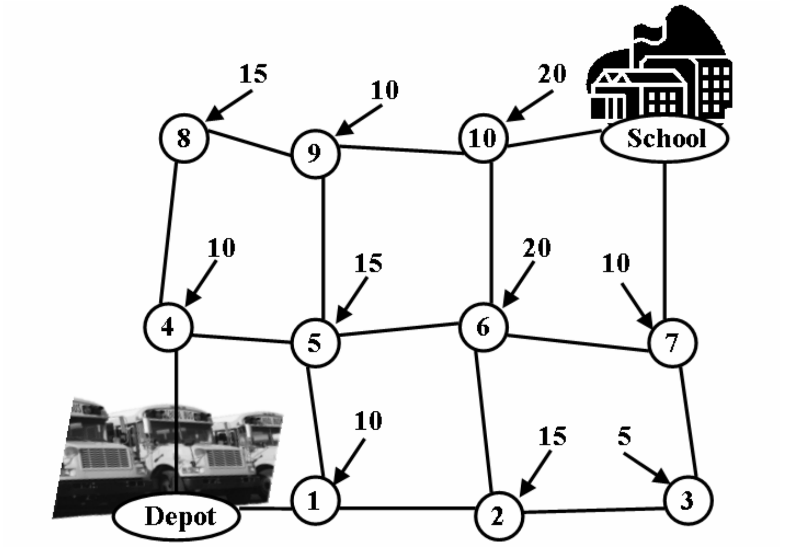


Fig. 8. School bus routing network

The objective of the problem is to minimize both the number of buses and their travel times, while satisfying bus capacity and time-window constraints.

HS found an average solution of \$399,870 over 20 different runs, while the GA found that of \$409,597 over the same number of runs (Geem et al. 2005a).

3.5 Satellite Heat Pipe Design

A heat pipe is heat transfer device having effective thermal conductivity and the capability of transporting heat over a considerable distance. In space, a satellite needs this device to balance temperature over its entire body. HS was applied to the design of a satellite heat pipe, as shown in Figure 9.

The multiple objectives of the problem are to maximize the heat transfer conductance, as well as to minimize total mass (Because the heat pipe is used in space, mass instead of weight is considered).

HS (Geem and Hwangbo 2006) found a Pareto solution (thermal conductance = 0.381 W/K and total mass = 26.7 kg) when compared with that of Broyden-Fletcher-Goldfarb-Shanno (BFGS) technique (thermal conductance = 0.375 W/K and total mass = 26.9 kg).

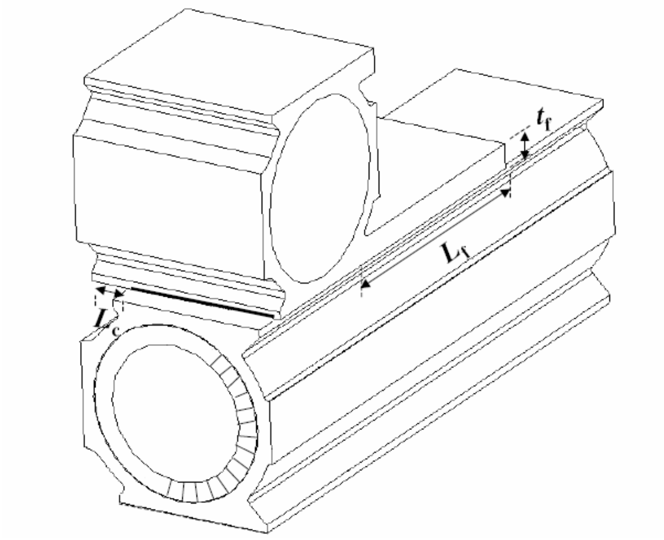


Fig. 9. Satellite heat pipe

3.6 Petroleum Vessel Mooring

Mooring (or anchoring) means to hold an offshore vessel in a stable fashion. HS was applied to the mooring of a Floating Production, Storage & Offloading (FPSO) vessel, as shown in Figure 10.

The objective of the problem is to minimize the cost of offshore vessel mooring by finding the appropriate size of each component while satisfying the constraints of platform offset, mooring line tension, and bottom chain length.

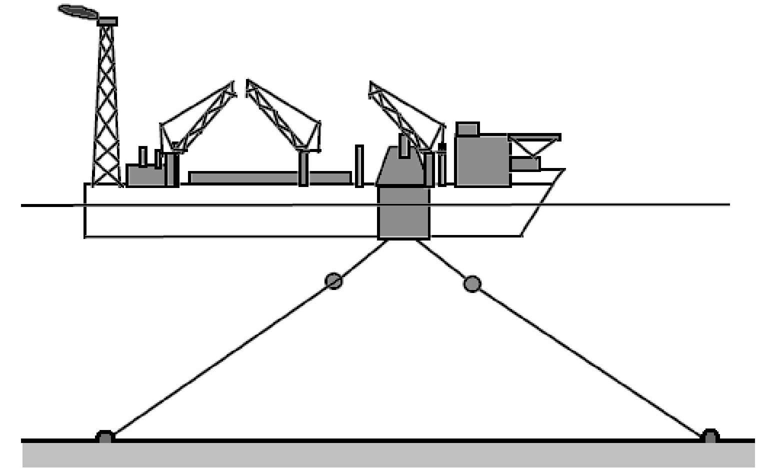


Fig. 10. Floating production, storage & offloading vessel

HS (Ryu et al. 2007) found a reasonable mooring cost ($4.8 million) after having started with a feasible cost of $30.0 million.

3.7 Branched Network Layout

HS was applied to the layout design of a branched fluid-transport network as shown in Figure 11. The objective of the problem is to find a minimal-cost branched layout from numerous candidate layouts. For the 64-node rectilinear network in Figure 11, HS (Geem and Park 2006) found the global optimum (layout cost = 5062.8). In contrast, the evolutionary algorithm (EA) (Walters and Smith 1995) found 5095.2 and GA (Walters and Lohbeck 1993) found 5218.0. In addition, HS reached the optimum after 1,500 function evaluations, while the number of total enumerations is 1.26×10^{26}.

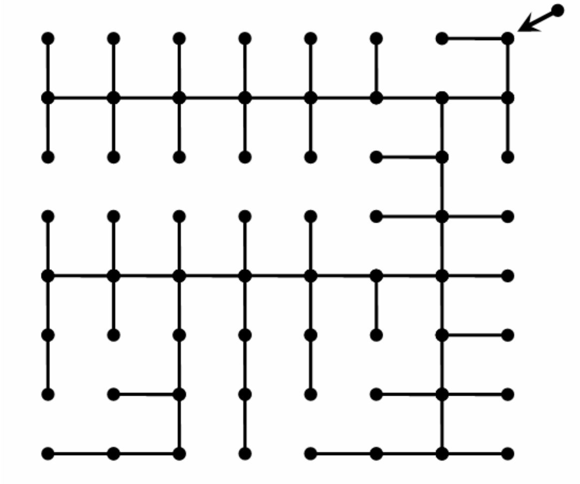


Fig. 11. Schematic of Branched Network

3.8 Model Parameter Calibration

HS was applied to the parameter calibration for a flood routing model, as shown in Figure 12.

The objective of the problem is to minimize the difference between observed and routed (computed) flows by varying model parameter values. HS (Kim et al. 2001) obtained the least error solution (36.78), while the least-squares method (Gill 1978) obtained an error of 145.69, the Lagrange multiplier method (Das 2004) obtained 130.49, the Hooke-Jeeves pattern search (Tung 1985) obtained 45.61, and GA (Mohan 1997) obtained 38.24. The improved HS (Lee and Geem 2005) for considering continuous-valued decision variables found an even better solution (36.77), which is very close to global optimum (36.7679) (Geem 2006a).

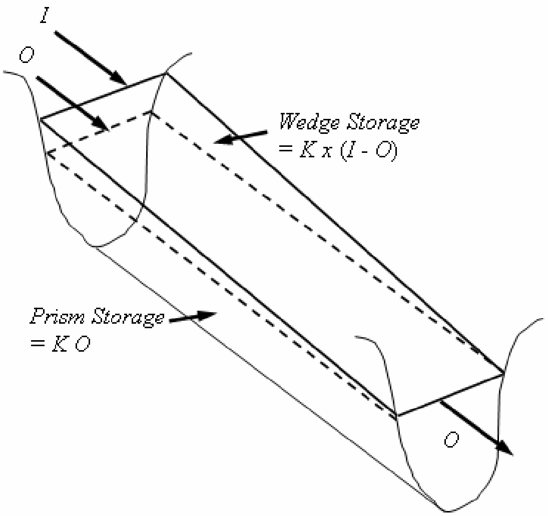
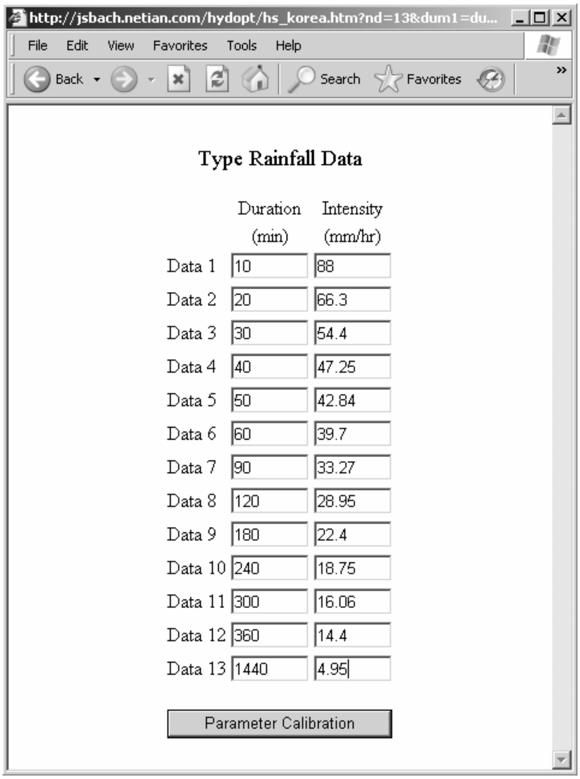


Fig. 12. Schematic of flood routing model



Type Rainfall Data

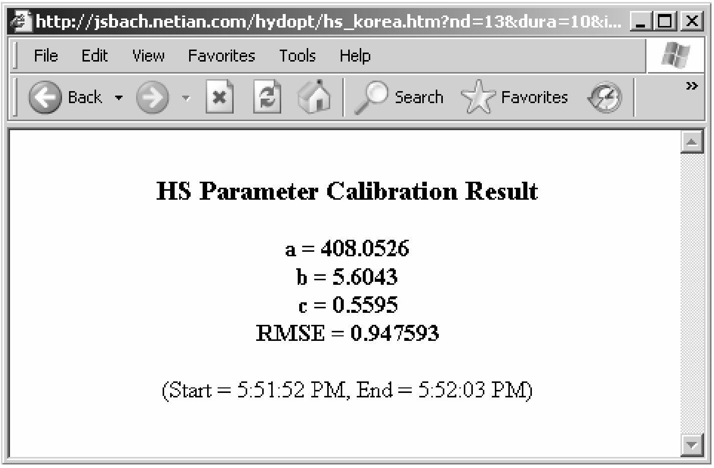
	Duration (min)	Intensity (mm/hr)
Data 1	10	88
Data 2	20	66.3
Data 3	30	54.4
Data 4	40	47.25
Data 5	50	42.84
Data 6	60	39.7
Data 7	90	33.27
Data 8	120	28.95
Data 9	180	22.4
Data 10	240	18.75
Data 11	300	16.06
Data 12	360	14.4
Data 13	1440	4.95

Fig. 13. Screen of hydrologic data entry

3.9 Web-Based Optimization

HS was performed on a web-based platform for the parameter calibration of a rainfall intensity model, as shown in Figure 13.

HS calibrated the hydrologic parameters on a web-browser using a client-side scripting-language called VBScript. HS obtained better solutions than those of Powell and GA (Geem and Geem 2007). Figure 14 shows a result screen of the HS computation.



HS Parameter Calibration Result

a = 408.0526
b = 5.6043
c = 0.5595
RMSE = 0.947593

(Start = 5:51:52 PM, End = 5:52:03 PM)

Fig. 14. Screen of HS computation result

4 Conclusions

This chapter showed various industrial applications of the recently-developed music-inspired HS algorithm. The applications include water network design, structural design, dam scheduling, vehicle routing, satellite heat pipe design, petroleum vessel mooring, branched network layout, model parameter calibration, and web-based optimization.

The HS algorithm has generally outperformed other soft-computing algorithms in the above-mentioned problems. When compared with GA, HS explicitly considers the relationship among variables using ensemble operation, while the GA implicitly considers the relationship using building block theory which does not work very well when the variable positions in a chromosome are not carefully considered (Geem 2006d).

When compared with mathematical methods, HS does not require complex calculus or starting values, and it easily handles discrete variables as well as continuous variables. HS also finds better solutions for combinatorial optimization problems when compared with the branch and bound method (Geem 2005).

For future study, a parameter-free HS algorithm should be developed because HS users are currently required to set proper values for algorithm parameters such as HMS, HMCR, and PAR. Also, the development of HS software will facilitate the use of this soft-computing theory by engineers in industry.

References

Adeli, H., Park, H.S.: Hybrid CPN-neural dynamics model for discrete optimization of steel structures. Microcomputer Civil Engineering 11, 355–366 (1996)

Broad, D.R., Dandy, G.C., Maier, H.R.: Water distribution system optimization using metamodels. Journal of Water Resources Planning and Management, ASCE 131, 172–180 (2005)

Camp, C., Pezeshk, S., Cao, G.: Optimized design of two-dimensional structures using a genetic algorithm. Journal of Structural Engineering, ASCE 124, 551–559 (1998)

Cunha, M.C., Ribeiro, L.: Tabu search algorithms for water network optimization. European Journal of Operational Research 157, 746–758 (2004)

Cunha, M.C., Sousa, J.: Hydraulic infrastructures design using simulated annealing. Journal of Infrastructure Systems, ASCE 7, 32–39 (2001)

Das, A.: Parameter estimation for Muskungum models. Journal of Irrigation and Drainage Engineering 130, 140–147 (2004)

Erdal, F., Saka, M.P.: Optimum design of grillage systems using harmony search algorithm. In: Proceedings of 8th International Conference on Computational Structures Technology (CST 2006), Las Palmas de Gran Canaria, Spain (2006) (CD-ROM)

Eusuff, M., Lansey, K.E.: Optimization of water distribution network design using the shuffled frog leaping algorithm. Journal of Water Resources Planning and Management, ASCE 129, 210–225 (2003)

Geem, Z.W.: Harmony search in water pump switching problem. In: Wang, L., Chen, K., S. Ong, Y. (eds.) ICNC 2005. LNCS, vol. 3612, pp. 751–760. Springer, Heidelberg (2005)

Geem, Z.W.: Parameter estimation for the nonlinear Muskingum model using BFGS technique. Journal of Irrigation and Drainage Engineering, ASCE 132, 474–478 (2006a)

Geem, Z.W.: Optimal cost design of water distribution networks using harmony search. Engineering Optimization 38, 259–280 (2006b)

Geem, Z.W.: Comparison harmony search with other meta-heuristics in water distribution network design. In: Proceedings of 8th Annual International Symposium on Water Distribution Systems Analysis (WDSA 2006), ASCE, Cincinnati, OH, USA (2006c) (CD-ROM)

Geem, Z.W.: Improved harmony search from ensemble of music players. In: Gabrys, B., Howlett, R.J., Jain, L.C. (eds.) KES 2006. LNCS (LNAI), vol. 4251, pp. 86–93. Springer, Heidelberg (2006d)

Geem, Z.W.: Optimal scheduling of multiple dam system using harmony search algorithm. In: Sandoval, F., Prieto, A.G., Cabestany, J., Graña, M. (eds.) IWANN 2007. LNCS, vol. 4507, pp. 316–323. Springer, Heidelberg (2007a)

Geem, Z.W.: Harmony search algorithm for the optimal design of large-scale water distribution network. In: Proceedings of the 7th International IWA Symposium on Systems Analysis and Integrated Assessment in Water Management (Watermatex 2007), IWA, Washington DC, USA (2007b) (CD-ROM)

Geem, Z.W.: Harmony search algorithm for solving Sudoku (submitted. In: Apolloni, B., Howlett, R.J., Jain, L. (eds.) KES 2007, Part I. LNCS (LNAI), vol. 4692, pp. 371–378. Springer, Heidelberg (2007c)

Geem, Z.W., Choi, J.Y.: Music composition using harmony search algorithm. In: Giacobini, M. (ed.) EvoWorkshops 2007. LNCS, vol. 4448, pp. 593–600. Springer, Heidelberg (2007)

Geem, Z.W., Geem, W.B.: Cutting-edge optimization technique and its applications to the civil engineering. Magazine of the Korean Society of Civil Engineers, KSCE 55, 155–171 (2007)

Geem, Z.W., Hwangbo, H.: Application of harmony search to multi-objective optimization for satellite heat pipe design. In: Proceedings of US-Korea Conference on Science, Technology, & Entrepreneurship (UKC 2006), Teaneck, NJ, USA (2006) (CD-ROM)

Geem, Z.W., Kim, J.H.: Efficient design of urban water supply network using improved harmony search. In: Proceedings of the 4th IWA Specialist Conference on Efficient Use and Management of Urban Water Supply (Efficient 2007), IWA, Jeju Island, South Korea (2007) (CD-ROM)

Geem, Z.W., Kim, J.H., Loganathan, G.V.: A new heuristic optimization algorithm: Harmony search. Simulation 76, 60–68 (2001)

Geem, Z.W., Kim, J.H., Loganathan, G.V.: Application of harmony search algorithm to water resources problems. In: Proceedings of 2002 Conference of the Environmental and Water Resources Institute, ASCE, Roanoke, VA, USA (2002) (CD-ROM)

Geem, Z.W., Lee, K.S., Park, Y.: Application of harmony search to vehicle routing. American Journal of Applied Sciences 2, 1552–1557 (2005a)

Geem, Z.W., Lee, K.S., Tseng, C.L.: Harmony search for structural design. In: Proceedings of 2005 Genetic and Evolutionary Computation Conference (GECCO 2005), Washington, DC, USA, pp. 651–652 (2005c)

Geem, Z.W., Park, Y.: Harmony search for Layout of Rectilinear Branched Networks. WSEAS Transactions on Systems 6, 1349–1354 (2006)

Geem, Z.W., Tseng, C.L.: Engineering applications of harmony search. In: Late-Breaking Papers of 2002 Genetic and Evolutionary Computation Conference (GECCO 2002), New York City, USA, pp. 169–173.

Geem, Z.W., Tseng, C.L., Park, Y.: Harmony search for generalized orienteering problem: Best touring in China. In: Wang, L., Chen, K., S. Ong, Y. (eds.) ICNC 2005. LNCS, vol. 3612, pp. 741–750. Springer, Heidelberg (2005b)

Gill, M.A.: Flood routing by the Muskingum method. Journal of Hydrology 36, 353–363 (1978)

Kim, J.H., Geem, Z.W., Kim, E.S.: Parameter estimation of the nonlinear Muskingum model using harmony search. Journal of the American Water Resources Association 37, 1131–1138 (2001)

Kim, S.H., et al.: Transient analysis and leakage detection algorithm using GA and HS algorithm for a pipeline system. Journal of Mechanical Science and Technology, KSME 20, 426–434 (2006)

Lee, C.H.: Optimized mix proportioning of steel and hybrid fiber reinforced concrete using harmony search algorithm. Master Thesis, Department of Civil and Environmental Engineering, Korea University, South Korea (2004)

Lee, K.S., Geem, Z.W.: A new structural optimization method based on the harmony search algorithm. Computers & Structures 82, 781–798 (2004)

Lee, K.S., Geem, Z.W.: A new meta-heuristic algorithm for continuous engineering optimization: Harmony search theory and practice. Computer Methods in Applied Mechanics and Engineering 194, 3902–3933 (2005)

Li, L., Chi, S.C., Lin, G.: Genetic algorithm incorporated with harmony procedure and its application to searching of non-circular critical slip surface in soil slopes (In Chinese). Shuili Xuebao 36, 1–8 (2005)

Li, L.J., et al.: A Heuristic particle swarm optimizer for optimization of pin connected structures. Computers & Structures 85, 340–349 (2007)

Liu, T.N., Feng, Z.B.: Adaptive identification and filtering based on harmony search (In Chinese). Journal of Jilin University 22, 306–309 (2004)

Mahdavi, M., Fesanghary, M., Damangir, E.: An improved harmony search algorithm for solving optimization problems. Applied Mathematics and Computation 188(2), 1567–1579 (2007)

Maier, H.R., et al.: Ant colony optimization for design of water distribution systems. Journal of Water Resources Planning and Management, ASCE 129, 200–209 (2003)

Mays, L.W., Tung, Y.K.: Hydrosystems engineering and management. McGraw-Hill, New York (1992)

Mohan, S.: Parameter estimation of nonlinear Muskingum models using genetic algorithm. Journal of Hydraulic Engineering 123, 137–142 (1997)

Mott, R.L.: Applied Fluid Mechanics. Prentice-Hall, Englewood Cliffs (2005)

Paik, K., et al.: A conceptual rainfall-runoff model considering seasonal variation. Hydrological Processes 19, 3837–3850 (2005)

Park, H.S., Sung, C.W.: Optimization of steel structures using distributed simulated annealing algorithm on a cluster of personal computers. Computers and Structures 80, 1305–1316 (2002)

Perelman, L., Ostfeld, A.: Water distribution systems optimal design using cross entropy. In: Proceedings of the 2005 Conference on Genetic and Evolutionary Computation (GECCO 2005), Washington, DC, USA, pp. 647–648 (2005)

Reca, J., Martinez, J.: Genetic algorithms for the design of looped irrigation water distribution networks. Water Resources Research 42 (2006)

Rossman, L.A.: EPANET2 Users Manual. US Environmental Protection Agency. Cincinnati, OH, USA (2000)

Ryu, S., et al.: Offshore mooring cost optimization via harmony search. In: Proceedings of 26th International Conference on Offshore Mechanics and Arctic Engineering, ASME, San Diego, CA, USA (2007)

Tian, Y.H., Bo, Y.M., Gao, M.F.: Parameters choice criteria in harmony annealing for function optimization (In Chinese). Computer Simulation 22, 70–74 (2005)

Tung, Y.K.: River flood routing by nonlinear Muskingum method. Journal of Hydraulic Engineering 111, 1447–1460 (1985)

Wardlaw, R., Sharif, M.: Evaluation of genetic algorithms for optimal reservoir system operation. Journal of Water Resources Planning and Management, ASCE 125, 25–33 (1999)

Walters, G., Lohbeck, T.: Optimal layout of tree networks using genetic algorithms. Engineering Optimization 22, 27–48 (1993)

Walters, G., Smith, D.: Evolutionary design algorithm for optimal layout of tree networks. Engineering Optimization 24, 261–281 (1995)

Wu, Z.Y., et al.: Using genetic algorithms to rehabilitate distribution systems. Journal of the American Water Works Association 93, 74–85 (2001)

Zecchin, A.C., et al.: Application of two ant colony optimization algorithms to water distribution system optimization. Mathematical and Computer Modelling 44, 451–468 (2006)