STRUCTURAL DESIGN OF REINFORCED CONCRETE TALL BUILDINGS: EVOLUTIONARY COMPUTATION APPROACH USING FUZZY SETS

T. Pullmann[1], Z. Skolicki[2], M. Freischlad[3],
T. Arciszewski[2], K. De Jong[2] and M. Schnellenbach-Held[3]

[1]Visiting Scholar, IT&E School, George Mason University, Fairfax, VA, USA. Institute for Concrete Structures and Materials, University of Technology, Darmstadt, Germany;
[2]IT&E School, George Mason University, Fairfax, VA, USA; [3]Institute for Concrete Structures and Materials, University of Technology, Darmstadt, Germany;
{Pullmann, Freischlad, Schnh} @massivbau.tu-darmstadt.de
{Zskolick, Tarcisze, Kdejong} @gmu.edu

Abstract

The paper reports the results of a joint project on evolutionary design of reinforced concrete structures in tall buildings. It has been conducted at the Center for Concrete Structures at the Darmstadt University of Technology in Germany and in the School of Information Technology and Engineering at George Mason University. Its ultimate objective is to revolutionize design of both steel and concrete structural systems through the introduction of evolutionary design processes and tools. In this paper, we first provide a general overview of structural design of reinforced concrete structures in tall buildings. Next, various issues of design representation space are addressed, including a general design space for a building for which both crisp and fuzzy approaches are used. Also, a more specific issue of developing a design representation space for a reinforced concrete structure of a tall building is addressed and the concept of a floor template is introduced. The central part of the paper is a description of the proposed evolutionary design process and of the related computer design support tools. Finally, the results of various conducted design experiments are reported. They include the comparison of various selection strategies and the comparison of evolutionary design processes when crisp and fuzzy evaluation of designs is used.

Keywords: Conceptual design; Design experiments; Fuzzy logic; Evolutionary Computation; Concrete buildings design; ConStiff; Inventor 2003

1 INTRODUCTION

There are three major forces driving progress in the area of computing in civil engineering. The first one is the rapid research advancement in computer science, particularly those related to evolutionary computation. The second one is the progress in computer engineering, which has already reduced the computing costs by the factor of 10,000 over the last 25 years. Finally, during the last 15 years significant progress can be observed in design science in terms of improved understanding of the engineering design process, its stages, and the use of computer tools to support both the conceptual and detailed design stages. The synergistic impact of these three factors may potentially mean a paradigm change in the area of structural design and the emergence of a new generation of structural design processes and computer support tools.

The objective of this paper is to report results of a joint research project on evolutionary design [ARC01, MUR01, BEN99] of reinforced concrete structures in tall buildings. The project has been conducted at the Center for Concrete Structures at the Darmstadt

University of Technology in Germany and in the School of Information Technology and Engineering at George Mason University, Fairfax, USA. Its ultimate objective is to revolutionize the design of both steel and concrete structural systems through the introduction of evolutionary design processes and tools.

2 STRUCTURAL DESIGN OF REINFORCED CONCRETE TALL BUILDINGS

Development of structural designs for reinforced concrete tall buildings is a complicated process in which a large number of design factors and parameters must be considered. In addition to finding an acceptable, if not visually attractive structural configuration, the design must satisfy all structural design code requirements, and should minimize the cost. Usually, even for an experienced designer it is difficult to improve his/her initial design because of the complexity and length of the design process. In this context, the use of design support tools, based on evolutionary computation, may improve the existing situation, ultimately leading to more attractive and novel structural designs, which will be also better in terms of their constructability and costs.

In this paper, we consider a class of structural systems that represent the reinforced concrete skeletons of buildings that are 8-36 stories tall. These structural systems are in the form of a three-dimensional reinforced concrete frame, based on a rectangular grid and supporting reinforced concrete slabs. Both the flexural and torsional rigidity of the building is provided by a system of shear walls and shear beams. The architect imposes the locations of columns and of various parts of the floor slabs while the structural designer makes decisions about the locations of the individual shear walls and shear beams. Therefore, in this specific case, the structural design is understood as a two-stage process of determining locations of the shear walls and shear beams (Stage 1) followed by the analysis, dimensioning and optimization of the entire structural system (Stage 2). The Stage 1, also called “Conceptual Design, or Designing,” is particularly important because the conceptual design decisions regarding the structural configuration are much more important in terms of constructability and cost than the final numerical optimization decisions made in the Stage 2, called “Detailed Design, or Designing.”

In our research, we understand conceptual design as a process of finding a design concept, which in this case is a structural configuration of shear walls and shear beams in a given building. Subsequently, we understand the detailed design as a numerical process of the final analysis, dimensioning, and optimization of the individual structural members. When both processes are sequentially conducted by the same designer, or by the same design support tool, they constitute an “Integrated Design Process”. Such a process is the subject of our interest and Inventor 2003 (described in Section 3.2) has been developed for design experiments involving the integrated design of reinforced concrete structures of tall buildings.

In this project, a reinforced concrete wall with no openings is called a “Shear Wall”. Its reference plane is situated in the vertical plane defined by the longitudinal axis of columns and it is situated between adjacent columns. The length of a given shear wall is at least equal to the distance between adjacent columns (bay length) and its thickness is assumed constant through its entire height which, in our case, is equal to the height of a building. A shear wall has two major structural functions, including the transfer of wind forces to the foundation and contributing to the required flexural and torsional stiffness of the entire structural system. In addition, it transfers the local gravity forces to the foundation.

A short beam, i.e., a beam of substantial depth in respect to its span, here equal to the bay length, is called by us a "Shear Beam." A shear beam has an increased shear force carrying capability, which is between that of a shear wall and of a regular beam. A shear beam is usually located between two shear walls to connect them and thus to improve the distribution of wind forces and to increase the stiffness of the entire system of shear walls. Shear beams are used as a compromise in all places in a given tall building where shear walls cannot be located due to the imposed constraints regarding openings in the walls but where shear walls must be integrated for structural reasons.

The structural design stage for reinforced concrete tall buildings, although very important, is the least analytically understood stage of the design process. Usually, the designer uses his/her experience and assumes the configuration of shear walls and shear beams similar to his/her previous design. In this way a satisfying configuration is obtained, although not necessarily optimal. The entire focus is on the well-understood detailed design process when various analytical and optimization tools can be used. Also, the determination of the structural configuration is generally conducted only once.

We propose here an integrated evolutionary design process, in which evolutionary computation is utilized. In this case, the entire design process (both its conceptual and detailed design stages) is automatically repeated many times until the designer is convinced that, not only has a satisfying design been produced, but also one which is optimal, or quasi-optimal (when time constraints do not allow a long evolutionary design process). Also the novelty of the subsequent designs may be considered and used as one of evolutionary stopping criteria when novelty is important for a given design case.

Usually, concrete tall buildings are designed with identical floor plans, including the identical configurations of shear walls and shear beam through the entire building. This practice is mostly driven by a combination of construction and economic factors. The designer is initially focused on designing the ground floor structural system, which is subjected to the greatest loads and therefore is critical in the building design. The ground floor design is then simply repeated throughout the remaining floors. Therefore, in the conducted research a single floor model has been used. Fitness was based on the weight of the ground floor structural system carrying wind forces (shear walls and shear beams).
Reinforced Concrete Tall Buildings Representation Space

In this project, the "Object Oriented Knowledge Representation Model[1]" (OFWM) [ALB02-1] has been used for the determination of the feasibilities and of the fitness of the produced designs. It has been chosen because it provides a good framework for the formal representation of both standard and non-standard building design knowledge. The declarative knowledge is easy to add and to maintain, and the produced results are provided in a completely transparent form without the "black-box" problem.

In the process of evolutionary design, the individual structural designs are produced from a given design representation space. By this term we understand a necessary and sufficient collection of symbolic and numerical attributes for adequately describing the entire class of the considered structural systems. Symbolic attributes are used during the conceptual design stage while numerical attributes are used in the detailed design stage. The development of an appropriate design representation space for a given design domain is usually extremely difficult and time consuming. Also, it requires good background knowledge and the use of various knowledge engineering methods. Unfortunately, this is still more art than science.

---

[1] *The system has been developed by A. Albert at the Concrete Structures Center at the Darmstadt University of Technology in Germany*

The representation space used in this paper is intended to represent a class of concrete skeleton structures of tall buildings. All structural systems are assumed to be in the form of a system of columns, shear walls, shear beams, and floor slabs. The gravity forces are carried out by floor slabs and columns while wind forces are carried out by shear walls and shear beams only.

The representation space is limited to the buildings designed on a rectangular grid and with the identical square columns (in terms of their cross sectional dimensions) located at the grid's intersection points. Shear walls and shear beams can be located only along the grid lines. All floor slabs are assumed to be subjected to two-directional bending and to be supported only by columns. When a shear wall, or a shear beam is located along an edge of a given floor slab, it also provides its partial support.

In the case of the developed representation space, a design concept represents a feasible combination (configuration) of shear walls and shear beams located within a provided rectangular horizontal grid of a building. During the conceptual design stage the designer has to determine locations of the individual shear walls and shear beams. Usually, he/she is familiar with the major constrains and requirements regarding the imposed locations of elevators, staircases, etc. Also, the designer knows where openings in internal walls are absolutely necessary to provide the required access to various parts of the building. In this situation, not all potential locations of shear walls and shear beams in a given building are feasible, and this fact must be reflected in the evolutionary search for the best configuration of shear walls and shear beams.

In practical terms, all information related to the structural system is best handled when a so called "Floor Template" is used. By this term, we mean a grid of a given building with indicated feasible locations of shear walls and shear beams and locations of all imposed building components, such as elevators or staircases. In addition to the grid dimensions, a floor template may also provide assumed/imposed dimensions (or their range) for the individual structural members, (for example, the thickness of individual shear walls) and may provide information about loads and their combinations to be considered.

3 EVOLUTIONARY DESIGN PROCESS AND TOOLS

The evolutionary design experiments have been conducted using a four-stage-process:

- Floor plan template development
- Design concept generation
- Initial feasibility analysis
- Structural analysis and fitness determination

One of the long-term objectives of the reported research is to create a conceptual, methodological, and a computational foundation for the design of concrete tall buildings, which might ultimately lead to the automation of the entire design process. For this reason, at each stage of our design process a different experimental design support tool was used. In the future, these tools will be integrated and an entire design environment will be created. In this project, the following tools have been used:

1. **KBDT** – a tool for the manual acquisition of background knowledge.
2. **ConStiff** – a tool for the generation of a floor plan template for a specific design case.
3. **Inventor 2003** – it is a multi-population evolutionary design tool which uses provided design representation space, constrains, and requirements in order to produce design concepts.
4. **ConStiff-Calc** – a tool for the feasibility assessment of design concepts using the Post-Knowledge Base.
5. **Z 88** – a structural analytical tool utilizing the finite elements method to determine the behavioral and structural characteristic of a design based on a given design concept.
6. **Fuzzy Classifiers** – two tools for the determination of the fitness values.

These tools are used at different points in the 4-stage evolutionary design process described above. In the first stage **KBDT** and **ConStiff** are used. In the second stage **Inventor 2003** is used. In the third stage **ConStiff-Calc** is applied. Finally, in the last stage both **Z 88** and **ConStiff-Calc are used.**

3.1 Floor Plan Template Building Tool "ConStiff"

In this project, floor templates were prepared using an experimental computer system called "ConStiff". It has been developed at the Darmstadt University of Technology in the Department of Concrete Structures by the first and third authors for the analysis of architectural and functional requirements and constraints in order to produce a floor template for a given building. It is a knowledge-based system containing basic knowledge related to the designing of office buildings, including various German Design Code Provisions. An example of a floor template generated by ConStiff is provided in Fig. 1. It has been used for our initial experiments, and in this case there are few fixed locations of shear walls or shear beams imposed. This floor template allows 58 locations for shear walls and 14 locations for shear beams. Fig. 2 illustrates one of the possible final configurations (design concept), which is based on this template and has been generated as part of our design experiments.

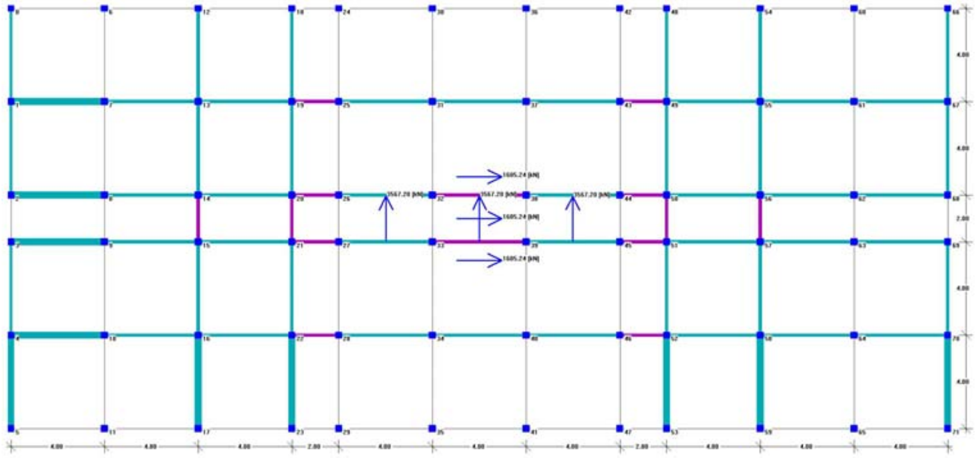

Figure 1: Floor Template Representation in "ConStiff"

3.2 Inventor 2003

The tool *Inventor 2003* being developed at George Mason University was used to perform the evolutionary part of the computations. *Inventor* is a general tool designed for easy integration of various domains with an evolutionary algorithm engine. It supports a graphical user interface and maintains a common framework for all integrated domains.

Inventor 2003 is implemented in Java, using Swing components. Creating a new domain is reduced to extending a few classes. For each domain one has to provide a mechanism for creating a random organism (individual) and an evaluation method (possibly calling some external program).

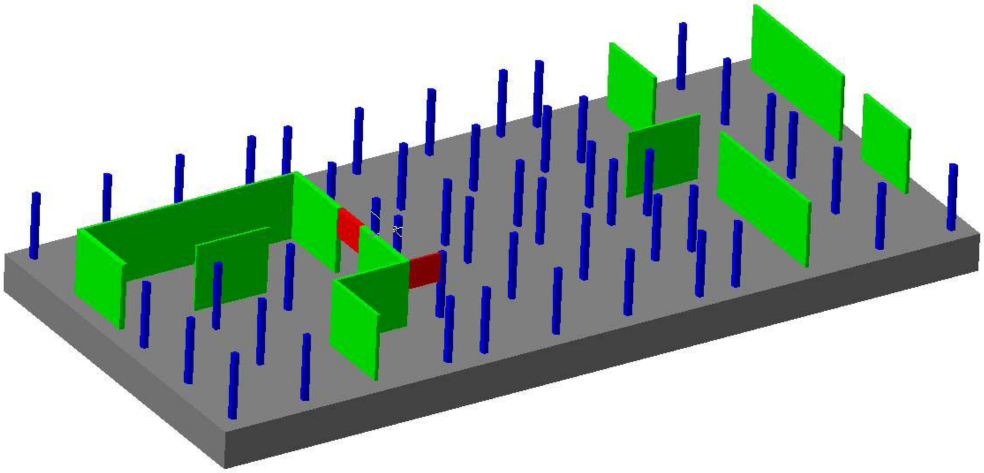

Figure 2: Example of a Possible Final Floor Design

Inventor engine utilizes *eckit* developed by Mitchell Potter [POT99]. It can work in two modes – it can perform evaluations locally, or it can use *JavaSpaces* technology [SUN03] to send tasks to distant workers. The workers perform the evaluation and send the results back to the main program.

For a given population one of various selection strategies can be chosen, the parameters of which can be modified during evolution. *Inventor* has a set of common selection strategies, but it is possible to write a new one and integrate it without recompiling the code of the system.

Inventor has the ability of displaying simple charts (using PtPlot library developed at University of California at Berkeley [PTP01]), where one can see the plot of the best, average and the worst fitness in population(s), as well as the best-so-far curve. Additionally, it stores the evolution data in an external file, which can be later read and analyzed statistically. There is a possibility of starting multiple runs either with pre-assigned random seeds, or with seeds based on time. Also, one can start either with predefined organisms, or let the system generate random individuals at the beginning of each run. The maximum number of generations can be changed in runtime. To facilitate the experiments, the initial settings of *Inventor* depend on a set of configuration files.

4 EXPERIMENTS

4.1 Design of Experiments

The initial design experiments reported in this paper have been conducted to investigate several research questions that are also important from the pragmatic point of view. They included: crisp versus fuzzy evaluation and single- versus multi-criteria optimization. The experiments have been performed for a 20 story reinforced concrete building with a system of shear walls and shear beams. In the building, various locations of elevators and staircases are possible as well as a large number of potential locations of structural components is feasible. In all experiments, all combinations of live, dead, and wind loads were considered in accordance to the German design standard “DIN1055”.

Before the actual design experiments were initiated, the optimal evolutionary selection strategy was chosen. This was done by comparing results of experiments in which the identical group of parents was used and the identical evolutionary processes conducted with various selection strategies. The experiments have been performed for 100 generations. Their results have been compared using as a criterion the cost of the structural system at the end of the individual runs. It has been discovered that in the case of our design experiment Fitness Proportionate Selection is the best one, and it has been chosen for the remaining experiments.

In all conducted experiments, the mutation and recombination rates have been assumed 0.1 and 0.9 respectively and a population size of 10 has been used. Also, randomly selected parents have been chosen without respect to their initial feasibility or any other criterion. However, every used parent represented a feasible and economically acceptable structural design.

The length of experiments in terms of the number of generations has been determined conducting 5 evolutionary design processes and using a classical single criterion optimization with a crisp feasibility assessment. In the experiments, the total costs of the structural system were used as the optimization criterion. The experiments were run for 1,000 generations. It has been observed that the majority of changes occur during the first 250 – 270 generations and after that only marginal improvements occur. Therefore, 300 generations have been assumed as a reasonable length for all further experiments, involving the use of both crisp and fuzzy approaches to the determination of values of the fitness function. With respect to stochastic spreading all experiments have been run multiple times, and the results represent the average of all runs.

4.2 Experimental Results: Comparison of Crisp versus Fuzzy Single Criterion Optimization

The objective of the conducted experiments was to determine the impact of the use of fuzzy classifiers on the progress of the evolutionary design process, which is measured by the total cost reductions.

The first step was to optimize the performance of the fuzzy classifiers in a specific design situation through the fine-tuning of their various controllable parameters. The most important parameter is the weight factor. Too large of a weight factor may produce behavior equivalent to the use of a crisp approach while a too small weight factor “softens” the constraints too much causing the final solutions do not satisfy the imposed initial crisp constraints. A suitable range for the weight factor has been experimentally determined as between 2.0 and 9.0. Therefore, three sets of experiments have been conducted with fuzzy classifiers and the weight factors equal to 3.0, 5.0 and 7.0, respectively. They were compared with an equivalent experiment in which a crisp approach has been used.

Figure 3 illustrates the relationship between generation number and the total cost of a structural system for all 4 cases described above. It should be noticed that in the case of fuzzy approaches the fitness value may not be equal to the total cost. In this case it is important to realize that designs produced using a fuzzy approach may have ratio of the total cost to fitness greater than 1 and that they are not necessarily infeasible, due to the fact that a fuzzy classifier may produce negative results (infeasibility) for values close to those of crisp constraints.

The diagram clearly shows the positive impact of the use of fuzzy classifiers on the optimization process, particularly in the beginning generations. For generation over 200, fuzzy and crisp approaches lead to comparable results, while fuzzy approach still produces marginally better designs. It turns out that a weight factor of approximately 5.0 leads to the most promising results, balancing improvements of the optimization process with the degree of feasibility for final solutions.

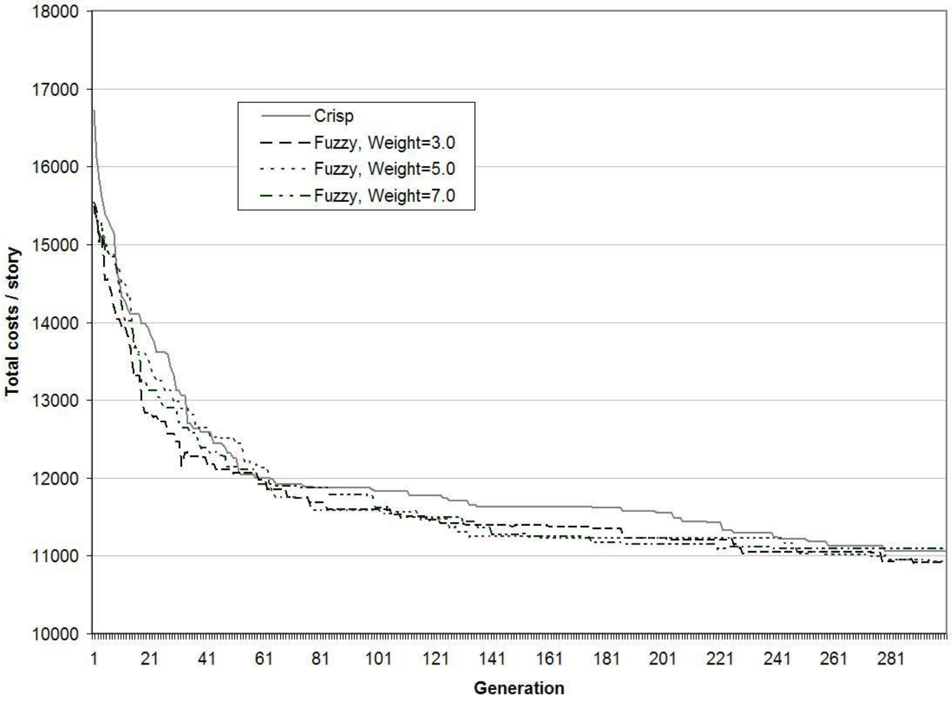

Figure 3: Crisp versus Fuzzy Single Criterion Evaluation

5 CONCLUSIONS

In this paper the initial research results of an international project on evolutionary design of reinforced concrete tall buildings have been presented. In the project, various experimental design support tools developed at the Darmstadt University of Technology and at George Mason University have been used and integrated in order to develop a unique evolutionary design environment. The project clearly demonstrated that international cooperation can be successful, particularly when it is carefully planned and there is a nearly perfect synergy between research teams. In the exceptionally short time period (less than three months) the research teams developed the entire detailed research plan, integrated various design support tools, and, most importantly, conducted the planned evolutionary design experiments (This paper presents only a small portion of the results).

The research results demonstrated that the use of evolutionary design in the areas of both the conceptual and detailed design of concrete tall buildings is not only feasible, but it also results in designs that are better than traditional designs, at least in terms of costs.

In terms of the detailed results, the conducted design experiments revealed advantages of using fuzzy approaches in the evolutionary structural design. Unfortunately, we are only at the beginning of a long investigation the objective of which is to develop a better understanding how fuzzy approaches should be incorporated in the evolutionary design in an optimal way.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support for their research from the NASA Langley Research Center under the grant NAG-1-01030.

REFERENCES

[ALB02-1] A. Albert: *Knowledge-Based-Systems To Support The Early Stages Of Structural Design*; Contribution to 9th Int. EG-ICE–Workshop, Darmstadt, 2002, Fortschrittsberichte VDI Reihe 4 Nr. 180, pages 124-133 VDI Verlag, Duesseldorf, 2002

[ARC01] T. Arciszewski, K. De Jong: *Evolutionary Computation in Civil Engineering: Research Frontiers*; invited article, B.H.V. Topping, (Editor), Civil and Structural Engineering Computing 2001, pp. 161-185.

[BEN99] P. J. Bentley (ed.): *Evolutionary Design By Computers;* Academic Press, 1999

[GAR92] J. Garrett, M. Hakim: *An object-oriented model of engineering design standards*, Journal of computing in civil engineering, 6(3), page. 323-347, 1992

[MUR01] K. Murawski, T. Arciszewski, K. De Jong, *Evolutionary Computation in Structural Design;* Journal of Engineering with Computers, Vol. 16, pp. 275-286, 2001.

[POT99] M. Potter: *Overview of the Evolutionary Computation Toolkit*, http://cs.gmu.edu/~mpotter/eckit/overview.ps.gz, 1999

[PTP01] E. A. Lee, C. Hylands: *Ptolemy II PtPlot – Java Plotter;* http://ptolemy.eecs.berkeley.edu/java/ptplot5.1p1/ptolemy/plot/doc/, 2001

[SCHN00] M. Schnellenbach-Held, A. Albert: *Representation of Crisp and Fuzzy Knowledge for Preliminary Structural Design*, International Conference on Computing in Civil and Building Engineering-VIII, Stanford, 2000

[SUN03] Sun Microsystems: *JavaSpaces Technology*, http://java.sun.com/products/javaspaces/, 2003

[VOI92] H.-M. Voigt: *Fuzzy Evolutionary Algorithms;* International Computer Science Institute, Berkley, CA, USA, 1992