# LONG TERM VERSUS SHORT TERM EVOLUTIONARY DESIGN[1]

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## 1. Introduction

The concept of evolving design solutions is not new. It is a common design practice and it has been a subject of interest of many design researchers, particularly in the context of evolution occurring over long time periods. For example, Altschuller (Terninko et al 1998) studied the evolution of design concepts (patents) in various engineering domains and discovered the general laws of evolution of engineering systems. More recently, Clarke (2000) proposed Directed Evolution, which deals with the controlled and directed evolution of engineering systems in the desired direction. Also, Arciszewski and Uduma (1988) studied evolution of patents for joints in steel space structures and formulated domain-specific principles of such evolution. However, until very recently the evolution of design solutions was done “manually” by human designers, who analyzed the existing designs and used their expertise to produce new designs.

The Information Technology revolution has created a new generation of technologies, methods and tools, including *evolutionary computation*. By this term, we mean a new computing paradigm, which is based on the use of evolutionary algorithms (DeJong in print). The engineering design aspects of evolutionary computation are well described in (Bentley 1999; Bentley and Corne 2002). Its application in the area of engineering design has led to the concept of an *evolutionary design process* (Bentley 1999). In such a process, design solutions are gradually evolved, utilizing evolutionary computation, from the initial collection of known solutions. In our research, we investigate *inventive evolutionary design* whose objective is to evolve known design solutions into novel solutions, potentially patentable. In particular, we are studying *integrated inventive evolutionary design processes*, which integrates the generation of design concepts with the analysis, design, and optimization of detailed designs. The ultimate goal is to improve our understanding of the integrated inventive evolutionary design process in the context of emerging patterns, which may lead to inventive designs.

As the result of our numerous design experiments, we have realized that there are significant qualitative differences when comparing results of short-, medium-, and long-term evolutionary design processes. By a short-term evolutionary design process we mean a process involving less than 2,500 generations, a medium-term such process has between 2,500 and 5,000 generations, while a long-term process has more than 5,000.

The objective of this paper is to demonstrate the impact of the length of an evolutionary design process, measured by the number of generations, on the final results of such process. The paper provides a brief description of our experiments and of the tool used to perform them. Next, it contains the analysis of our experimental results, including the fitness curve for the entire process, the impact of EA parameters on the long-term evolution in our domain of steel skeleton structures of tall buildings, and the distribution of attribute values at different characteristic stages of the conducted long-term evolutionary design process. Also, the domain-specific results are discussed. These results have revealed the emergence of interesting structural shaping patterns, which are surprisingly consistent with the trends in the structural design of wind bracings in skeleton structures of tall buildings.

## 2. Evolutionary Design Experiments

### 2.1. Integrated Evolutionary Design Tool

To investigate the evolutionary computation process in the context of structural design, an experimental design and research tool was developed at George Mason University and called “Inventor 2000.” Initial experiments let to a modified version, Inventor 2001, which has been used in the experiments reported here. Both systems have been described elsewhere (Arciszewski 2001, Murawski 2000). Here, we briefly summarize the important details of Inventor 2001. The system is intended for design experiments in the area of steel skeleton structures of tall buildings allowing a complete design for buildings of various dimensions and height, within 16-36 stories range. It produces both the design concepts and the detailed designs. It has 5 major components, listed below in the order of the information flow:

1. Evolutionary Computation Component
2. Feasibility Filter
3. Structural Analysis, Design and Optimization Component
4. Wind Forces Analyzer
5. Evaluator

The *Evolutionary Computation Component* utilizes the evolutionary computation process to produce the design concepts, whose feasibility is checked by the *Feasibility Filter*. It has a knowledge base containing feasibility rules since not each combination of qualitative attributes and their values represents a feasible design concept in a given design

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situation. These feasibility rules are introduced by the user of the tool, who formulates all design constraints and requirements to be satisfied by design concepts considered as feasible in a given case. All feasible design concepts are transferred to the *Structural Analysis, Design and Optimization Compon*ent, which is a modified SODA program. It also receives an input in the form of wind forces specific for a given design case, which are produced by the *Wind Forces Analyzer*. It is a modified commercial system Wind Load V2.2.S. The Structural Analysis, Design and Optimization Component produces a complete and detailed structural design and provides values of 26 design parameters, including the total weight, the weight of diagonals, the weight of beams, the weight of columns, the number of diagonals, etc. As of now, only the total weight is transferred to the *Evaluator*, which uses it to determine the value of the fitness function. This value is transferred to back to the Evolutionary Computation Component to be used in the control and management of the evolutionary computation process.

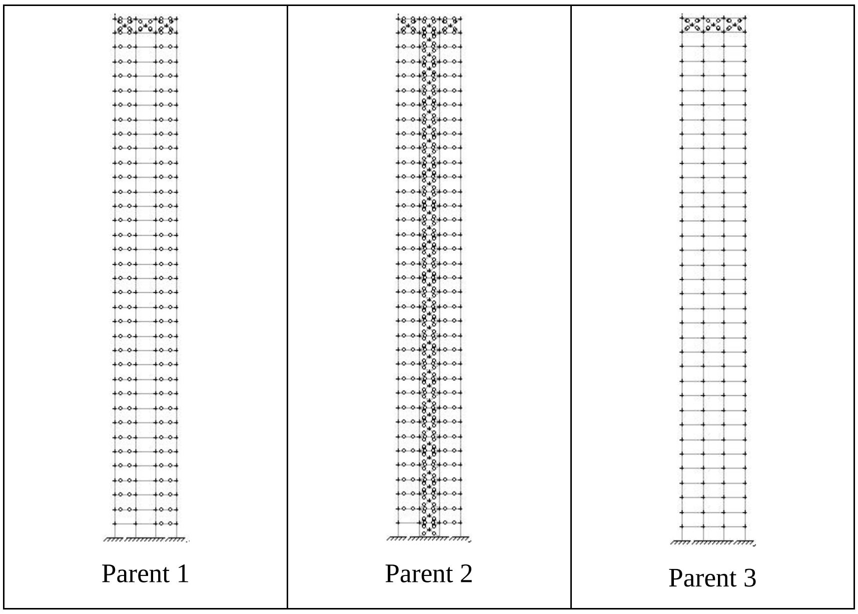
## 2.2. Design Representation Space

In Inventor 2001, steel skeleton structures are represented as planar transverse designs. In the reported experiments, three-bay structures 32 and 36 stories tall have been considered. Bay width has been assumed 20 feet, and story height 14 feet. Six types of bracing (K, X, diagonals \ and /, simple X, and V), two types of joints between beam and columns (rigid and hinged), and two types of ground connections (rigid and hinged) are available for use. Also, the requirement of symmetry can be imposed on all structural designs. In the structural analysis conducted by SODA, dead, live, and wind loads, as well as their combinations were considered. The structural elements have been designed using several groups of sections for beams, columns, and diagonals, i.e. 61 groups of sections for each structural system.

The elements of the structural systems that are evolved are the joints, the bracings, and the ground connections. These elements are described by multi-valued attributes, each of which is an integer encoded gene. The length of the genotype depends on the height of the building. Six genes represent each story (a bracing and beam for each of the 3 bays). Hence, the total genome length is 6 * number_of_stories + 4 (ground connections). More details of the design representation space used are provided in (Murawski et al. 2000)

## 2.3. Experimental Structural Systems

In this paper we report the results of two sets experiments, the first involving 36 story structures and the second involving 32 story structures. The genotypes of design concepts consisted of 220 genes (for 36-story buildings) and 196 genes (for 32-story buildings). For both experiments we used a parent population of size 3 each of which produced five new offspring (designs) each generation. The parents for the next generation were selected by picking the 3 best individuals from the combined set of current parents and 3*5=15 offspring. In most evolutionary computation applications the initial population of parents is generated randomly. However, in our case randomly generated structural concepts would almost be guaranteed to have 0 fitness value (designs would be infeasible). To avoid this we initialize the population with some initial feasible design concepts as illustrated in Figure 1.



Parent 1 Parent 2 Parent 3

**Figure 1: Examples of designs used as initial parents in the experiments**

In the first set of experiments, the reproductive operators chosen were those that proved to be successful in previous experiments (Kicinger and Bird, 2001), namely a mutation rate of type *Random*, and no crossover. To study their short and medium term effects, the evolutionary design process was run for 2,500 generations.

In the second set of experiments, more aggressive exploratory reproductive operators were used, namely a mutation rate 0.86, and a crossover rate 0.54. To study the short, medium, and long-term effects, the evolutionary design process was run for 10,000 generations.

## 3. Experimental Results

### 3.1. Qualitative and Quantitative Differences

***Experiment 1***

This experiment was focused on comparing the results obtained in a short-term (after 100 generations) experiment with medium-term results (2,500 generations). Figure 2 shows the evolving fitness using a classical "best-so-far" graph. The results are quite clear and consistent with other experiments we have run, namely that significant improvements in fitness are obtained by letting the design process run longer than 100 generations. In this case the final fitness function value obtained after 2,500 generations case was equal to 1,262,001, whereas after 100 generations this value was equal to 1,288,465. This represents a 2.05% weight reduction.

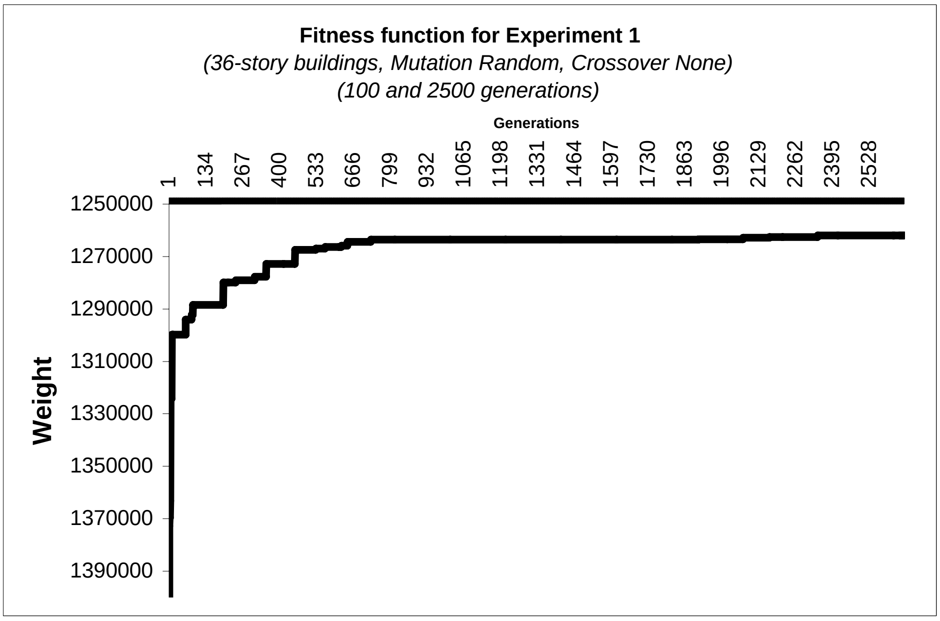
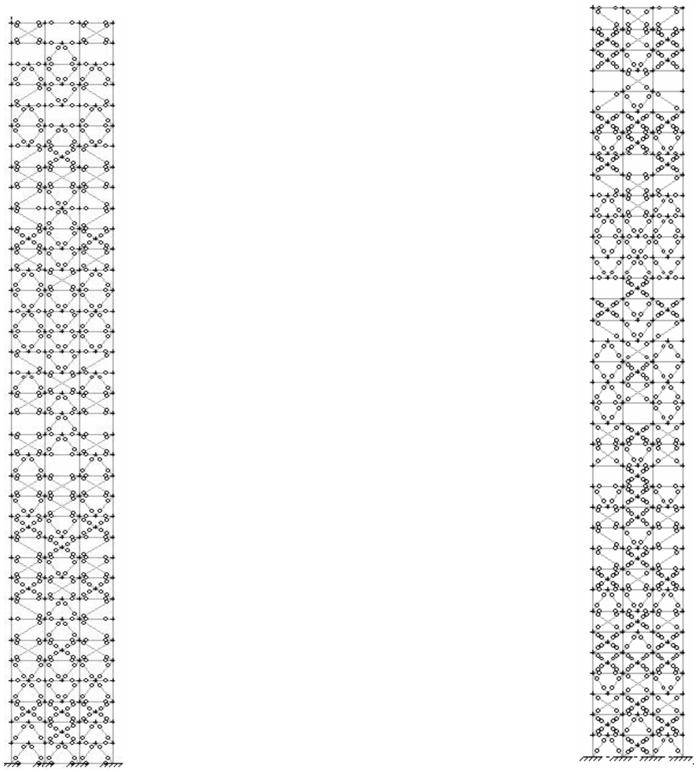


**Figure 2: Best-so-far curve of the evolving design fitness**

A qualitatively comparison of the best designs produced by the evolutionary process has been also conducted. Figure 3 presents the best designs obtained after 100 generations and 2,500 generations. Some interesting emerging patterns have been identified, which are described in detail in (Kicinger and Bird, 2001).

In addition to weight, the differences between the two designs with respect to the other 25 evaluation criteria have been also investigated and the results are presented in Figure 4. Here the major differences between the two designs appear in the number of hinged/rigid beams and K/V bracings. In the first case hinged beams replace some part of the rigid beams, and K-bracings replace some part of V-bracings, and that is consistent with the state of the art in structural shaping of steel structures of tall buildings.



a) b)

**Figure 3: a) fittest design after 100 gen., b) fittest design after 2500 gen.**

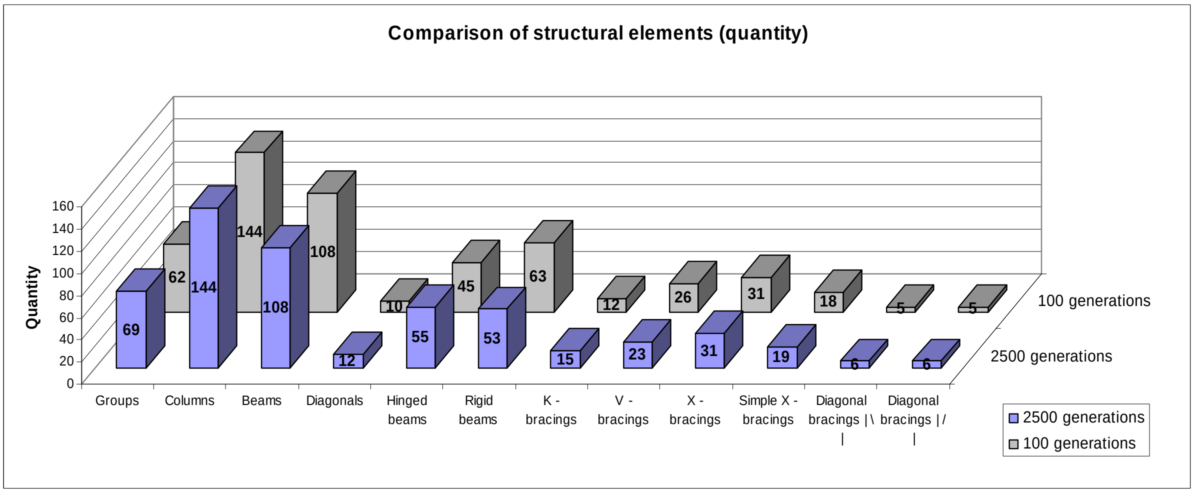


**Figure 4: Quantities of appropriate structural elements in the fittest designs.**

***Experiment 2***

The goal of this experiment was to study the behavior of our evolutionary design system using very aggressive reproductive operators. From the previous research, we have learned that such high values are not optimal in short-term experiments for our particular domain. However, we wanted to investigate whether, or not, they would be more suitable for a long-term evolution of systems considered (10,000 generations).

Figure 5 presents the best-so-far graph of the design fitness. As can be seen, fitness continues to improve. In this case the weight obtained after 10,000 generations was equal to 834,842.9 whereas after 100 generations we had 880,093.9. This represents about 5% increase in the fitness of the wind bracing design, which is a much better result compared to experiment 1.

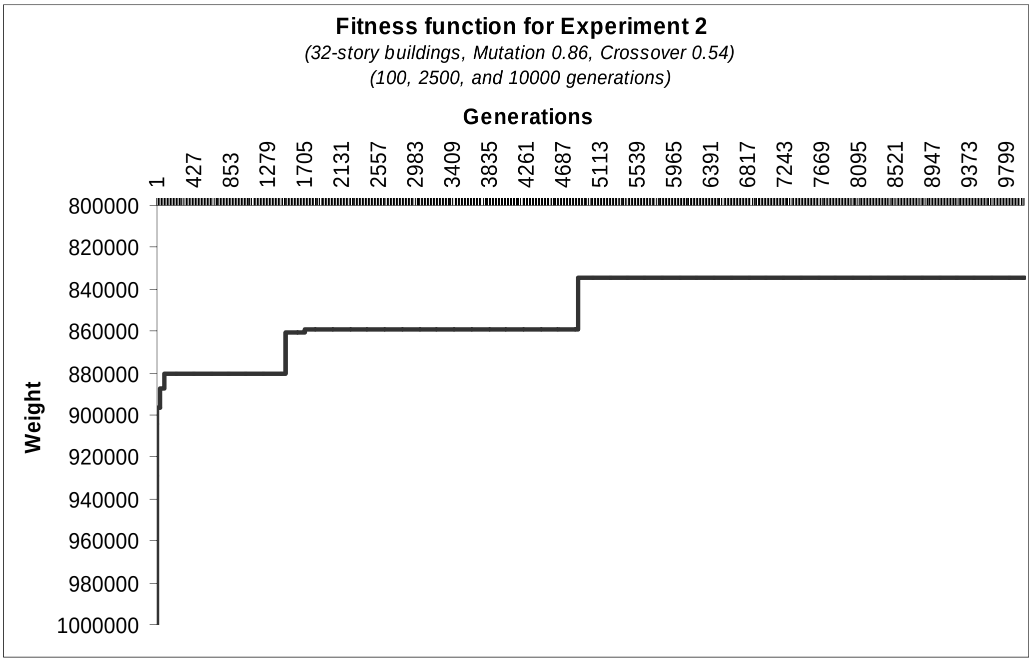


Figure 5: Best-so-far design fitness

Differences between the fittest designs after 100, 2500, and 10000 generations with respect to 25 evaluation criteria are presented in Figure 6. In this case the major difference between the two fittest designs is the ratio of hinged/rigid beams and the number of K/X bracings. Thus, the best design after 10000 generations has more rigid beams and less hinged beams, and more K bracings and less X bracings compared to the design after 100 generations, as such changes would be recommended by a tall buildings expert.

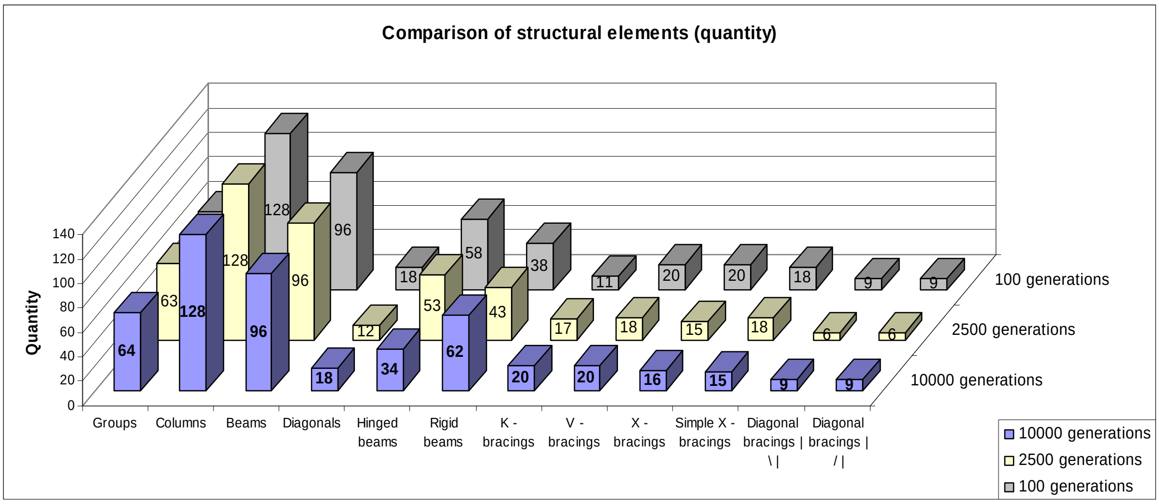


Figure 6: Quantities of appropriate structural elements in the fittest designs.

### 3.2 Effects of EA Parameters and Their Rates

Although only two experimental results have been compared using distinct sets of parameter values, some qualitative differences are visible immediately. Figures 2 and 5 clearly show that different parameters settings have an impact on the evolutionary process. For example, for the experiment using the more conservative reproductive operators, we observe that the evolution progresses more or less steadily, but continuously as shown in Figure 2. On the other hand, in the second experiment in which very high rates of mutation and crossover operators were used, we observe from time to time sudden changes in the function value, without any progress between these changes. Hence, lower values of mutation and crossover seem to be more "creative" and steadily guide the evolution toward better solutions, whereas high values are more disruptive and often resemble a kind of a random search in our design space. These conclusions are consistent with the results obtained from short-term experiments.

### 3.3 Emerging Patterns

In our previous paper we reported some very interesting patterns emerging during the evolution process (Kicinger and Bird 2001). In these long-term experiments we wanted to further investigate this phenomenon. We compared the fittest design after short-term experiment with the fittest designs obtained after medium-, and long-term evolution and found that in fact the evolution was able to evolve interesting multistory substructures as illustrated in Figure 7.

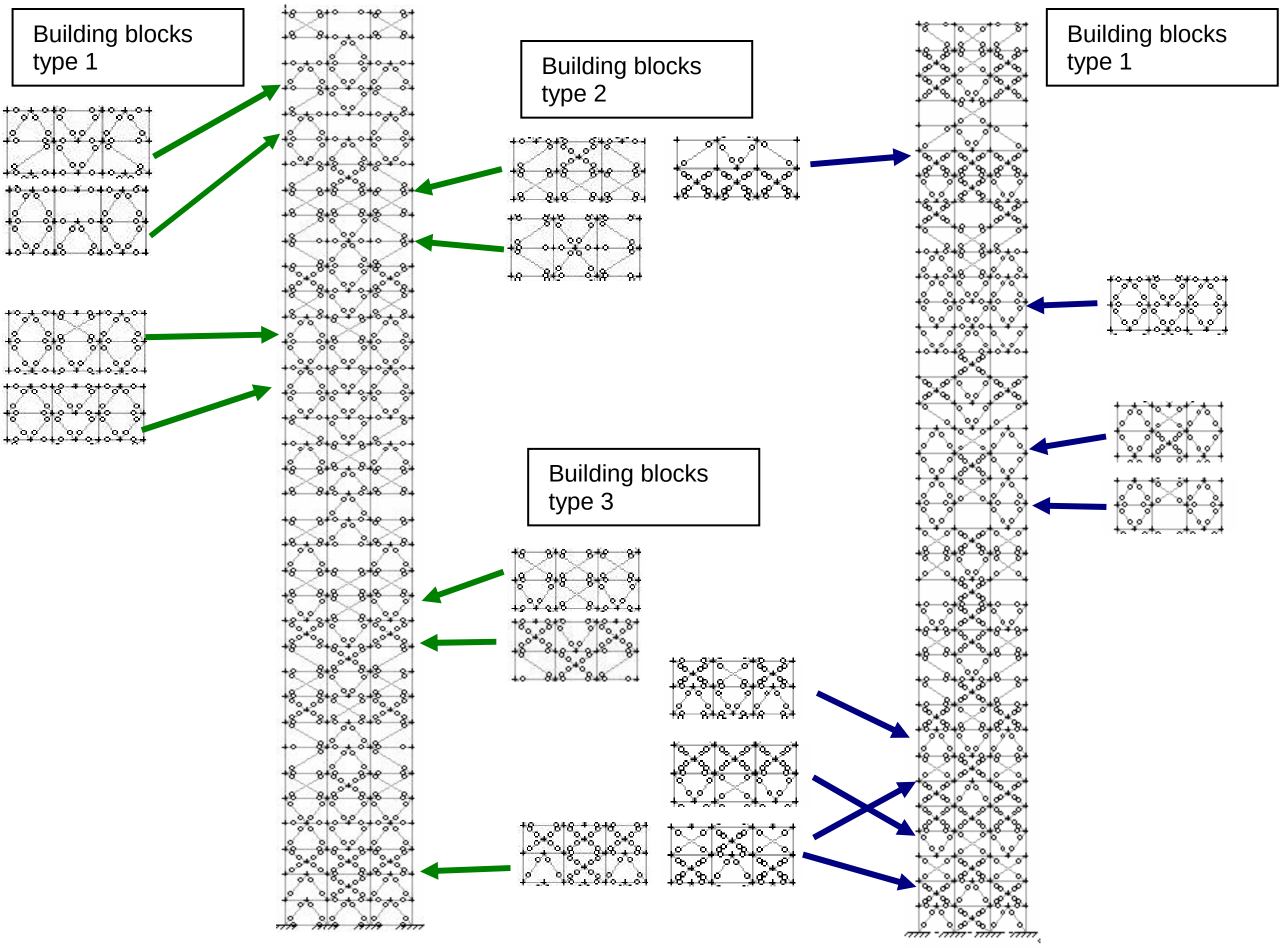


**Figure 7: Emerging substructures in evolving designs: after 100 gen.(left), after 2500 gen. (right)**

Additionally, we could also identify emerging 3-story substructures in the upper part of the design. They are shown in Figure 8.

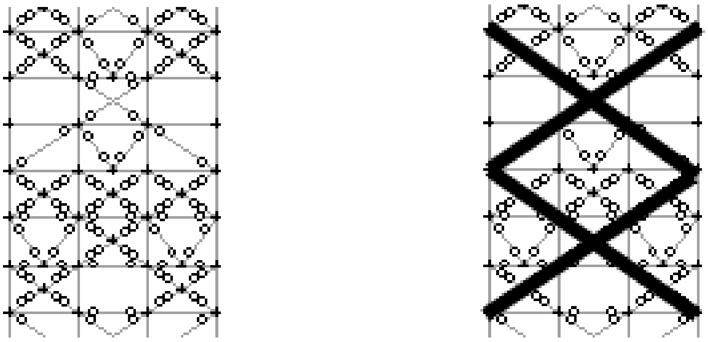


**Figure 8: Emerging 3-story substructures**

Thus, experimental results confirm our previous findings that we indeed observe emergence of multistory substructures. Evolution also "learned" to evolve different types of substructures in different parts of the building structure. In the top part of the building, where forces are the smallest we observe substructures with very few diagonals. Here the system evolved even 3-story substructures. In the middle part, there are more elements in such 2-story substructures. In the bottom part, where the forces have maximum values, we could identify very dense substructures with a large number of diagonals. These results are also consistent with some theoretical work in the area in tall buildings.

## 4. Summary and Conclusions

The reported research is a continuation of previous research in area of structural systems of in tall buildings. Initial results from two long-term experiments are reported. Although only a very limited number of experiments were performed, the initial results are promising and confirm our previous findings for short-term runs. Inventor 2001, as an evolutionary computation support tool proved to be very useful in exploring design representation space of wind bracing designs, and in search for innovative designs. There is a potential possibility of finding novel and creative designs of wind bracing structures, which gradually emerge from simpler substructures evolved by the system, but that may require a longer evolutionary design process.

EA parameters we previously identified as "optimal" for the evolution of structural designs worked also well in large-generation runs. They support steady progress of the evolution in finding fitter and fitter designs. On the other hand, high rates of mutation and crossover tend to increase the fitness of designs in sudden changes, and hence the evolutionary search more resembles random search.

Potentially the most interesting finding is the emergence of complex patterns within structures of the evolving system. We could not only identify emergent multistory substructures appearing in the wind bracing designs, but also we observed some form of "specialization" in different parts of the building. These facts seem to confirm some theoretical work in the area of tall buildings and they might be further utilized in knowledge-driven applications.

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